Modeling Construction Equipment in 4D Simulation and Application in VR Safety Training

Roya Amrollahibuki

A thesis

In the Department of

Building, Civil, and Environmental Engineering

Presented in Fulfillment of the Requirements

For the Degree of Master of Applied Science (Building Engineering) at

Concordia University

Montreal, Quebec, Canada

June 2019

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

By: Roya Amrollahibuki

Entitled: **Modeling Construction Equipment in 4D Simulation and Application in VR Safety Training**

And submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Building Engineering)

Complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final Examining committee:

Dr. Osama Moselhi ______________________ Chair

Dr. Fereshteh Mafakheri ______________________ Examiner

Dr. Sang Hyeok Han ______________________ Examiner

Dr. Osama Moselhi ______________________ Examiner

Dr. Amin Hammad ______________________ Supervisor

Approved by ______________________

Chair of Departmental or Graduate Program Director

____

Dean of Faculty

Date ______________________

ABSTRACT

Modeling Construction Equipment in 4D Simulation and Application in VR Safety Training

Roya Amrollahibuki

Enhancing safety and productivity in construction sites is of principal importance, especially in congested sites. Scheduling and visualizing the construction progress in a Four-dimensional (4D) model with a high Level of Detail (LOD) are expected to improve safety, productivity, and constructability in construction sites. In spite of the large number of studies using Building Information Modeling (BIM) for visualization of the construction activities at the macro-level, these research works do not fully consider the scheduling and animating the equipment operations at the micro-level. This study aims to visualize the construction equipment activities to model the erection of a structure with prefabricated components along with other resources, such as workers and temporary equipment. The construction process is modeled in Fuzor Virtual Design and Construction (VDC) and the collision test is run to find the upcoming dangers. In addition, one of the areas where 4D can be used is for safety training. It is expected that the combination of 4D BIM with Virtual Reality (VR) improves the safety knowledge of construction workers, students, and equipment operators. Despite the large number of research works on the use of Three-dimensional (3D) VR in construction training, 4D VR is not sufficiently used for training purposes. This study aims to improve the safety knowledge of construction students by using a VR-based training approach. The specific objectives of the research are: (1) Identifying the requirements for construction equipment modeling and comparing the available commercial and research platforms in terms of visualizing, animating, and simulating equipment movements; (2) Animating and scheduling the construction processes at the micro-level in 4D BIM; and (3) Enhancing and

evaluating the safety knowledge of construction management students in terms of Personal Protective Equipment (PPE) and equipment-related hazards using VR. In the first stage, the construction 4D context was developed and the safety scenarios about PPE- and equipment-related hazards were added. Secondly, construction students were given the initial VR-based training regarding hazard scenarios. Then, their safety knowledge was tested and they were asked to express their learning experience.

The conclusions of this research are as follows: (1) When equipment tasks are visualized and scheduled at the micro-level in 4D BIM, the conflicts can be detected in advance and the cycle time of equipment can be determined, leading to the improvement of safety, productivity, and constructability in construction sites; (2) VR safety training improves hazard recognition of construction students since they can experience risky conditions in virtual construction sites; and (3) The capability of students in identifying equipment-related hazards would improve when they experience safety risks applied in 4D VR.

ACKNOWLEDGEMENT

Foremost, I would like to express my sincere gratitude to my supervisor, Dr. Amin Hammad for his support, encouragement, and patience. His guidance helped me at all stages of research and writing of this thesis. Without his support, I could not have made such progress in this research.

I appreciate my supportive lab mates who made the lab a pleasant and friendly environment for working and studying together. Besides, I thank Fuzor company and Erica Jamerson for helping me in the implementation of the case studies.

Last but not least, I would like to thank my supportive parents, Mina Amrollahi Buki and Alireza Amrollahi Buki and my brother Saeid for their endless love and encouragement.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Description
3D	Three-dimensional
4D	Four-dimensional
AEC	Architecture, Engineering, and Construction
AR	Augmented Reality
BIM	Building Information Modeling
CAD	Computer-Aided Design
CAVE	Cave Automatic Virtual Environment
DEW	Dynamic Equipment Workspaces
DOF	Degrees of Freedom
FBX	Filmbox
GPS	Global Positioning System
HMD	Head-Mounted Display
IFC	Industry Foundation Classes
IVE	Immersive Virtual Environment
LOD	Level of Detail
MR	Mixed Reality
NBIMS	National Building Information Modeling Standards
OSHA	Occupational Safety and Health Agency
PPE	Personal Protective Equipment
RFID	Radio Frequency Identification
UWB	Ultra Wideband
VDC	Virtual Design and Construction
VR	Virtual Reality
WLAN	Wireless Local Area Network

CHAPTER 1 INTRODUCTION

1.1 General information

Construction equipment constitutes an important portion of the resources used on construction sites. Every year, many construction workers die at work due to being struck by equipment, caught between objects, and falls. In 2017, 4,674 labor fatalities in the private industry were documented in the United States, within which 971 deaths (or 20.7%) were in construction (OSHA, 2017).

Four-dimensional (4D) Building Information Modeling (BIM) is developed by linking a Three-dimensional (3D) BIM and the corresponding activities in the schedule. In the planning and construction phase, equipment movements and workers' activities can be simulated and visualized in a 4D model with a high Level of Detail (LOD) to improve the safety, productivity, and constructability of construction projects. This type of high 4D-LOD modeling requires a very detailed schedule, which can capture micro-tasks (e.g. the swing movement of the boom of a crane). Linking the detailed 3D BIM model with the micro-tasks executed by equipment (e.g. cranes) can lead to better simulation of construction activities (Akhavian and Behzadan, 2015).

On the other hand, Virtual Reality (VR) and Augmented Reality (AR) are used in various industries (e.g. medical, game, and construction) for different purposes such as education, entertainment, and facilities management. Safety knowledge is an important factor that promotes safety and health in the construction industry. Some research works have used these technologies for construction safety education with the purpose of enhancing the safety knowledge of the construction workers (Sacks et al., 2013), equipment operators (Wang et al., 2004b), and construction students (Lin et al., 2011; Le et al., 2015). However, the existing research studies have not used 4D VR for construction safety training.

1.2 Problem statement

Some research issues have been identified in accordance with the conducted literature review explained in Chapter 2: They are classified as the followings: (1) Visualization of equipment operations in 4D, (2) Use of 4D VR in construction safety training.

(1) Visualization of equipment operations in 4D

Although many research works discussed the possibility of improving the safety of construction sites using sensors and analyzing the equipment workspaces, these works cannot be linked with available 4D BIM tools, which cannot easily represent equipment movements. On the other hand, 4D BIM tools provide the users with the basic functions for animating and scheduling equipment activities.

(2) Use of 4D VR in construction safety training

The available research works focused on training workers, equipment operators, and students in the 3D virtual environments. However, they need to visualize and experience hazards in a realistic field, in which the construction processes and equipment movements are demonstrated with attention to the schedule. Many accidents and fatalities happen because workers are not familiar with the equipment operations and the risks that may threaten their lives. For example, when the components of a crane (boom and hook) are moving to unload a component, no one should stand or walk in the danger zone.

1.3 Research objectives

The objectives of the present research are the followings:

(1) Identifying the requirements for construction equipment modeling and comparing the available commercial and research platforms in terms of visualizing, animating, and simulating equipment movements, and identifying the potential improvements based on the discussed requirements;

(2) Animating and scheduling the construction processes at the micro-level in 4D BIM, such as construction equipment operations along with all resources available on construction sites; and

(3) Enhancing and evaluating the safety knowledge of construction management students in terms of Personal Protective Equipment (PPE) and equipment-related hazards using VR.

1.4 Thesis organization

This thesis will be organized as follows:

Chapter 2 Literature Review: The most related and significant topics, including the development trends of BIM, applications of 3D and 4D BIM in the construction industry, visualization of equipment activities and equipment workspaces are covered in this chapter.

This chapter also reviews the development of VR technologies as well as their usage in the construction industry. Furthermore, some research works that focus on the use of these technologies in construction safety training are reviewed.

Chapter 3 Proposed Approach: This chapter is divided into three parts. In the first part, the requirements for modeling construction equipment are presented. A method for generating articulated equipment and a safe zone around its components is proposed in the second part. This chapter finishes with a framework, at which 4D VR is used for safety training of construction students. In addition, seven safety training scenarios and protocols related to training and testing are presented in this chapter.

Chapter 4 Case Studies: In this chapter, the available commercial and research platforms are compared based on the requirements for construction equipment modeling, discussed in the previous chapter. Case studies are provided, at which the equipment activities are animated and scheduled at the micro-level with attention to workers' activities and the existing details in the construction site. Furthermore, a 4D virtual construction site with some potential hazards is used for safety knowledge training. The research method is validated through a learning experience evaluation and statistical analysis.

Chapter 5 Summary, Conclusions, and Future Work: In this chapter, the present research work is summarized and its contributions are highlighted. Additionally, the limitations and some recommendations for future work are discussed.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter reviews the previous research, frameworks, and methods in the areas of BIM, 4D applications, visualization of equipment activities, VR in construction, and construction safety training. Section 2.2 focuses on the development trends of BIM, and applications of 3D and 4D in construction, especially in safety. Some research that visualized the equipment activities in 4D is reviewed in Section 2.3. The available trends in research are analyzed to identify the gaps for modeling and scheduling the construction activities and especially the equipment tasks. This chapter finishes with the explanation of VR and AR technologies and their usages in the construction industry. Some research works that have used these technologies for construction safety training for construction workers, operators, and students are reviewed.

2.2 Development trends of BIM

In the late 1970s and early 1980s, some studies conducted in USA and Europe about parametric modeling that formed the basis of BIM, though it was used practically in the projects from the middle 2000s (Salman Azhar et al., 2015). The National Building Information Modeling Standards (NBIMS) defined BIM as follows: "A BIM is a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward (NBIMS, 2016)."

3D tools enable Architecture, Engineering, and Construction (AEC) sector and project managers to visualize the construction projects through realistic images. However, it does not provide the planners with the scheduling and construction progress control. 4D can be used to check the integrity of construction orders and schedules, to evaluate site accessibility, spatio-temporal conflicts, temporary structures, and various construction methods (Hartmann et al., 2008)

At the beginning of the 1990s, an enthusiasm has been formed for 4D applications in construction project management (Heesom and Mahdjoubi, 2004). A center at Stanford University, which is named Integrated Facility Engineering, utilized the idea of 4D-CAD for the first time in 1996 (Wang et al., 2004a).

In spite of the advantages of using CAD, it is faced with the following flows: (1) 3D CAD is a combination of independent 3D views such as plans and elevations. If the user edits and changes one of these views, all other views need to be updated. This process is time- consuming and error-prone. (2) The existing data in CAD drawings are only graphical entities such as arcs and lines. The entities do not carry any information about the physical and functional features of the project resources within its life cycle (Salman Azhar et al., 2015)

2.2.1 3D and 4D applications in construction

Heesom and Mahdjoubi (2004) reviewed the research about 4D models related to the construction industry and identified three different categories based on their specific areas of applications: Product modeling and visualization, process modeling and analysis, and collaboration and communication. Project managers use 4D to dynamically visualize the sequence of construction, resource utilization, workspace logistics, and equipment operations (Wang et al., 2004a).

Hartmann et al. (2008) categorized the application areas of 3D/4D models based on the 26 reviewed case studies into seven parts: photorealistic renderings, virtual design review, analyzing design options/building operations, cost estimating, analyzing construction operations, construction document production, bid package preparation.

Photo realistic renderings allow the project stakeholders and AEC sector to visualize facilities. When the project is simulated and visualized from the view of a human's perspective through 3D walkthroughs and movie clips, the communication between the stakeholders related to the proposed design will improve (Whyte et al., 2000). Project designers use 3D virtual models to communicate design concepts to the stakeholders and other designers in various sectors. This communication results in detecting and resolving the unexpected conflicts that may happen among the designs of electrical, mechanical, and plumbing sectors (Hartmann et al., 2008).

3D models can be used as input in simulation software for analyzing the design options and building operations. Fischer and Kam (2002) described the application of 3D on predicting the energy consumption and the interior lighting of a building. Furthermore, 3D models can be utilized to estimate the project cost and provide a bill of quantity. A direct link between the model and the cost estimating database can also be established.

4D can be used to analyze construction operations within most phases of the project. However, it is mainly used to plan the construction operations before the beginning of erection of the related part. 3D/4D models can improve and accelerate the development of design and construction documents, and facilitate the provision of the bid package for the contractors and subcontractors since they can visualize the construction sequences (Hartmann et al., 2008).

2.2.2 4D applications in construction safety

The control of construction processes in 4D leads to the safety improvement in construction sites through detecting the time-space conflicts (Koo and Fischer, 2000; Akinci and Fischer, 2000; Heesom and Mahdjoubi, 2004; Trebbe et al., 2015; Choi et al., 2014; Hartmann and Dorée, 2015; Shang and Shen, 2016). Some research studies identified time-space conflicts and categorized them based on the problems that they make (Akinci and Fischer, 2000).

4D simulation can be used to analyze safety measures in construction sites (Hammad et al., 2012). Combination of safety rules, 3D models, and schedule information can be used to develop a system that automatically checks safety rules to detect hazards (Zhang et al., 2011). Zhang et al. (2013) developed a safety rule translation algorithm to automatically find safety dangers in the 4D BIM. However, this research is limited to fall protection.

Choi et al. (2014) recommended a 4D BIM-based framework for workspace planning, in which a spatial clash-detection algorithm and problem solutions with attention to movability and functionality of each activity were proposed. In addition, Shang and Shen (2016) developed a spatio-temporal matrix and workspace conflict matrix to detect workspace conflicts on construction sites. Conflict data were analyzed with the proposed frequency index and severity index for 4D site safety assessment.

2.3 Visualization of equipment activities in 4D

Simulated equipment operations can graphically be visualized in 3D (Kamat and Martinez, 2001; Kamat and Martinez, 2005), though the temporal aspects of equipment movements are ignored in 3D visualization. Pradhananga and Teizer (2013) created a user interface (RAPIDS GPS Data

Visualizer) that displays temporal positioning data of construction equipment using Global Positioning System (GPS) data. Additionally, Cheng and Teizer (2013) proposed a framework that streams data from location tracking sensors (GPS and UWB) to a VR visualization platform in real-time. The resources sensor data (equipment, workforce, materials), which were linked to the elements of the virtual construction site, were updated by a local real-time data server. Nevertheless, not only the equipment tracking data should be considered, but also equipment tasks need to be visualized.

Kim et al. (2011) presented a case study where a cable-stayed bridge construction was modeled at three different levels of detail in 4D CAD: activity, discrete, and continuous operations. Activity and discrete operations did not show the movements of the equipment components, although the boom movements of a derrick crane were visualized in the continuous operation level in Autodesk Inventor platform. However, this process is time-consuming and constraint conditions should be defined for derrick crane manually. Zhou et al. (2015) presented a 4D case study explored in the oil and gas industry at the operation level and activity level. They established a 4D BIM model with the animated crane in Navisworks and integrate mathematical algorithms with 4D models to simulate the construction activities in detail. For visualizing the crane movements (e.g. lifting the object by the hook and boom rotation), the parts of the crawler crane were deconstructed and animated separately.

2.3.1 Generation of construction equipment workspace

Capabilities of tools to generate workspaces for construction resources (e.g. building components, equipment, and crew) can reduce hazardous accidents and improve productivity. Some research studies focused on generating workspaces automatically in 4D (Akinci and Fischer, 2000; Akinci et al., 2002a). Akinci et al. (2002b) categorized spaces into three main groups, including macro-level spaces, micro-level spaces, and paths. The spaces for equipment, crew, protected, and hazard areas were included in micro-level spaces. Akinci and Fischer (2000) suggested a prototype system, 4D WorkPlanner, which automatically generates micro-level spaces.

Additionally, there are some research works that concentrated on equipment workspace generation (Tantisevi and Akinci, 2007; Vahdatikhaki and Hammad, 2015). Zhang et al. (2015) utilized remote sensing (GPS data) and workspace modeling technologies for automated visualization of workspaces (worker, equipment, building components, etc.) in BIM. Shang and Shen (2016) developed a method that visualized and modeled 3D workspaces of equipment and workers, categorized into static and dynamic workspaces. Vahdatikhaki and Hammad (2015) proposed an approach for producing Dynamic Equipment Workspaces (DEW) for increasing earthwork safety, at which both the present state and position of the equipment and the speed features of each movement were considered (Figure 2-1).

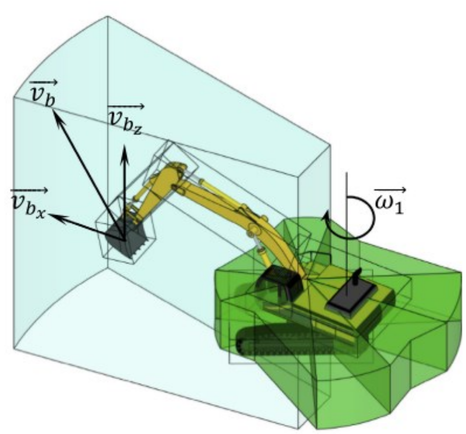


Figure 2-1 2D DEW representation of an excavator in swinging condition (Vahdatikhaki and Hammad, 2015)

2.4 Virtual Reality (VR) and Augmented Reality (AR)

2.4.1 Definition and scope

VR is a kind of technology enabling users to immerse in and interact with a 3D/computer-generated virtual environment, a simulation of either the real world or imaginary world. VR technologies can be used for different purposes such as education, building design, construction, check of safety, and entertainment (Mazuryk and Gervautz, 1996).

VR was taken into consideration in the 1950s, though it drew public's attention in the late 1980s and 1990s. Jaron Lanier used the term 'virtual reality' for the first time in 1987 (Mandal, 2013). Ivan Sutherland suggested the first concept of making an artificial world in 1965, in which force feedback, sound, and interactive graphics were included (Tommaso and Paolis, 1994). As Figure 2-2 shows, he also built the first Head Mounted Display (HMD) with head tracking in 1968, at which the views became updated based on the positions and orientation of the consumer's head (Sutherland, 1968). Figure 2-3 shows the different types of common HMD.

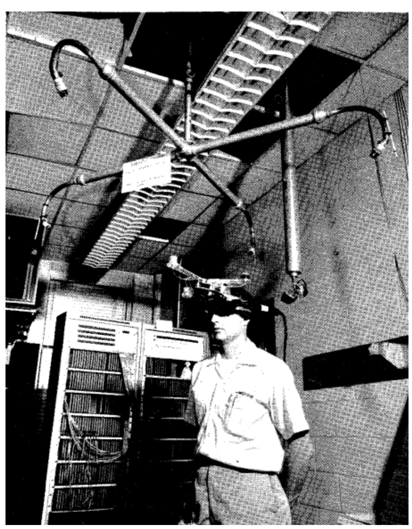


Figure 2-2 The first head-mounted three-dimensional display (Sutherland E., 1968)

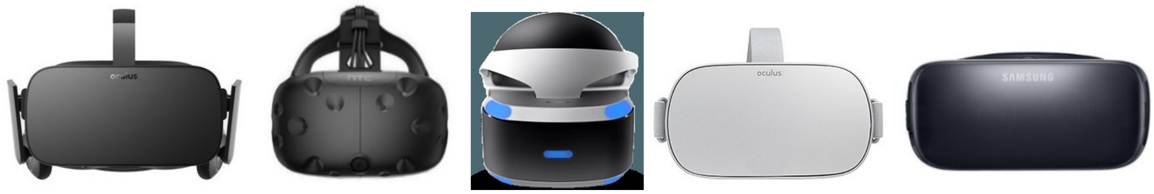


Figure 2-3 Oculus Rift (2019), HTC Vive (2019), Sony PlayStation VR (2019), Oculus Go (2019), and Samsung Gear VR (2019) (from left to right)

In 1992, Cave Automatic Virtual Environment (CAVE) as a VR environment and a room-sized immersive visualization system was utilized besides using HMD (Figure 2-4). It overcomes the limitations of HMD by: (1) providing a wider and larger field of view; (2) visualizing high quality and resolution images; (3) wearing light pieces of equipment (e.g. LCD shutter glasses); and (4) Immersing simultaneously multi users in the same VR environment (Mandal, 2013).

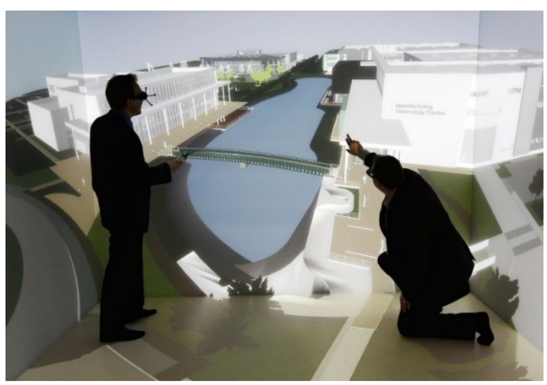


Figure 2-4 The usage of CAVE in VR (the picture is retrieved from (ESI Group, 2017))

VR technologies are faced with some challenges that should be improved or solved within the next years: (1) managing large-scale VR projects with a large amount of data; (2) improving the current tracking systems; and (3) reducing the required time for generating virtual spaces.

On the other hand, AR is a modern technology that superimposes computer-generated information onto the real world (Chi et al., 2013). AR technologies are used in different domains such as education, design and construction, maintenance and repair, medical visualization, advertising, and entertainment (Carmigniani et al., 2011). It is expected that the usage of AR applications will be increased in the near future and widely utilized in the industrial field.

Caudell and Mizell (1992) from Boeing coined the term "Augmented Reality" and talked about the advantages of AR as supposed to VR. Furthermore, They prototyped a heads-up display headset (HUDset) system with position sensing technologies, in which the head was tracked in six degrees of freedom (Figure 2-5). In 2000, Bruce Thomas developed the first mobile AR game, ARQuake, in which users walk around in the real environment and play the Quake game through their mobile phones (Thomas et al., 2000).

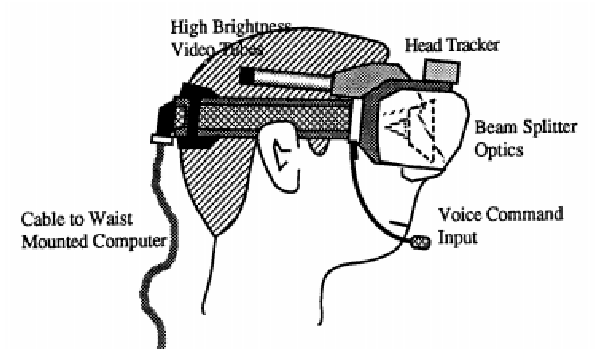


Figure 2-5 The components of a HUDset (Caudell and Mizell, 1992)

2.4.2 Research trends of VR and AR in construction

Li (2010) introduced some applications of VR in construction: (1) visualizing construction space; (2) urban planning; (3) web-based information system for construction; (4) a Distributed Virtual Reality (DVR) tool for construction and education; and (5) visualizations of building structural behavior. Figure 2-6 shows the number of VR/AR-CS articles related to construction safety that were published in selected journals from 2000 to 2017 (Li et al., 2018).

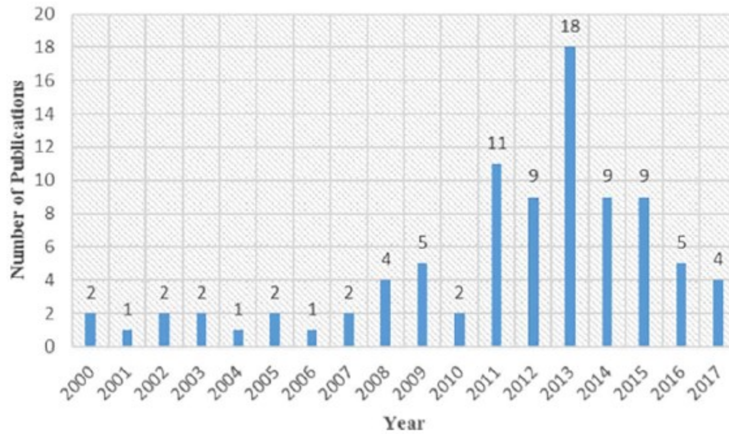


Figure 2-6 Number of VR/AR published articles in journals (e.g. AIC, JCCE, ITCon, etc.) between 2000 and 2017 (Li et al., 2018)

2.4.2.1 VR/AR in construction visualization

Since computers enable the creation and visualization of sophisticated graphics, VR technology is used in construction planning (Dunston et al., 2005), structural analysis and architectural design (Li, 2010) to visualize and interact with difficult concepts. The design model can be visualized in the 3D VR environment, and the sequencing of construction activities can be visualized in 4D VR (Dunston et al., 2005).

Behzadan and Kamat (2007) proposed a method to graphically simulate the scheduled construction activities for the erection of a steel structure in outdoor 4D AR. Golparvar-Fard et al. (2009) utilized a location-based image processing technique to visualize and compare differences between as-planned and as-built performances in the 4D AR, using traffic light metaphor.

In construction sites, accurate and long-term trackers and sensors are required to track location and movement of equipment, workers, and materials (Dunston et al., 2005). Various tracking technologies can be used such as Radio Frequency Identification (RFID), Ultra Wideband (UWB), and GPS (Vahdatikhaki et al., 2015). Behzadan et al. (2008) used location tracking techniques such as Wireless Local Area Network (WLAN) and GPS to visualize the construction operations in AR.

2.4.2.2 VR/AR and BIM

The AEC industries have focused on the usage of digital information so that advanced visualization platforms and technologies are required to efficiently use this information (Chi et al., 2013). Mixed Reality (MR) technologies can enhance the information accessibility for decision makers in different parts of the project such as design review, planning, monitoring, and inspection. In particular, AR is useful to the construction industry because in the AEC sector, workers and operators can interact with digital information in real-time while performing their work tasks (Dunston et al., 2005).

The systems integrating BIM with AR enable the display of an immersive model into the real world and the visualization of the as-planned data onto the as-planned environment (Wang et al., 2014). AR enables the visualization and representation of building information through virtual models (Gu et al., 2010). Wang et al. (2013) proposed a conceptual framework for integrating BIM with AR, which enables the visualization of the physical context of construction tasks in real-time. It addressed the gap between integrating BIM and real-time communication on-site.

Gu et al. (2010) suggested an AR interface for a BIM server, in which on-site construction data is coordinated and integrated with the BIM model for the updating and verification of the construction progress. This leads to the improvement of the collaboration and information exchange on the construction site.

The concept of BIM+AR can be used for improving the following aspects related to construction site activities: interdependency, linking digital to physical, synchronization of mental models for communication, project control and monitoring (as built versus as planned), procurement, visualization from design to production, and site plan and storage (Wang and Love, 2012).

However, AR technologies are faced with some limitations when a huge amount of information is required. Therefore, at the construction site, at which a huge amount of data should be processed, databases, convenient methods, and additional integrated technologies with AR should be utilized. Figure 2-7 shows four technologies that influence directly on the development of AR applications including localization, cloud computing environment, portable and mobile devices, and natural user interface (Chi et al., 2013).

Data Phase	**Computing Phase**	**Tangible Phase**	**Presentation Phase**
Cloud Computing Environment	Localization Technologies	Portable and Mobile Devices	Natural User Interface
• BIM • Database • SOA • Internet	• GPS • UWB • SLAM • RFID • Barcode	• Cheap • Small • Light • Wearable • Ubiquitous	• Gesture • Kinesthetic • Intuitive Control • Motion Capture

Figure 2-7 Architecture of an AR application (Chi et al., 2013)

2.4.3 Construction safety training using VR/AR

One of the areas that VR/AR technologies are used is training (Lin et al., 2013; Le et al., 2015). The inherent dangers of construction sites cause difficulties in onsite training so that it is needed to instruct trainees on how to expose and overcome dangers in a safe way. Construction workers and equipment operators can virtually be trained to be able to identify and analyze the magnitude of potential construction risks (Lucas et al., 2008; Sacks et al., 2013).

Different training methods are used in the construction industry such as lectures, pictures, demonstrations, and videos. These traditional methods, which are common in construction, do not allow trainees to engage deeply in the project. Based on the findings of a meta-analysis study of research works between 1971 to 2003 (Burke et al., 2006), which analyzed and compared the effectiveness of the safety and health training methods, high engaging training approaches (e.g. behavioral modeling and hands-on training) were approximately three times as effective as low engaging training in terms of knowledge and skill development.

Immersive Virtual Environment (IVE), which is considered as a high engagement training, engages the senses of trainees. Sacks et al. (2013) compared the role of conventional methods and VR technology in enhancing the safety knowledge of construction workers by using IVE power-wall (cave automatic virtual environment). According to their findings, the following items can be considered as the benefits of using VR in construction safety training: (1) trainees can interact realistically with hazards available on construction sites; (2) safety training with VR catches trainees' attention more than conventional training methods; (3) VR gives users more opportunities to control the construction environment.

2.4.3.1 Safety training for students, workers and equipment operators

Students should be taught to identify job hazards for having a safe working environment in the real construction site. Lin et al. (2011) proposed a 3D video game to promote the ability of students for identifying construction hazards and safety violations.

Le et al. (2015) proposed a framework for utilizing mobile-based VR and AR for construction safety education. Based on their method, firstly safety guidelines and regulations were introduced to construction students based on accident samples by utilizing VR/AR technology. Secondly, students were asked to inspect a virtual construction site to identify the hazards. Finally, trainees' safety knowledge was assessed through the use of VR serious games and AR multiple choice exams. Since the development of hazard scenarios in virtual and augmented contents are time-consuming, BIM model of a construction project can be utilized.

VR-based simulators (Vahdatikhaki et al., 2017) and AR-based system (Wang et al., 2004b) can be used in equipment training programs. The safety on construction sites would improve when heavy equipment operators are properly trained for risky and complex scenarios. It should be mentioned that VR equipment training simulators such as Vortex simulators (CM Labs Simulations, 2018) are developed contingent on hypothetical scenarios, while different factors affect the performance of the equipment operators on actual construction sites such as the location of the site and the performance of other pieces of equipment and workers. The uncertainties resulting from human decisions on real construction sites can be simulated within VR-based training simulators (Vahdatikhaki et al., 2017).

Wang and Dunston (2007) designed an AR-based system with some scenarios for the training of heavy construction equipment operators. This system enabled operator trainees to practice operations on a predesigned construction site while sitting in a piece of heavy equipment. Lucas et al. (2008) suggested the use of VR for conveyor belt training. Based on their proposed safety training structure, mine employees can interactively experience working with conveyor belt systems. Additionally, crane movements (e.g. lifting up loads) can be controlled in a virtual crane training system using control commands that are extracted from facial gestures of users (Rezazadeh et al., 2011). The summary of the previous studies related to the use of VR and AR in construction safety training is given in Table 2-1.

Table 2-1 Research studies about construction safety training using VR and VR

Author (s) and year of publication	Specified group for training			Technology		Domain (s) of safety training
	Equipment operators	Students	Workers	VR	AR	
Vahdatikhaki et al. (2017)	✓			✓		Operating the equipment safely alongside other equipment movements
Le et al. (2015)		✓		✓	✓	Falling
Sacks et al. (2013)			✓	✓		General site safety, stone cladding work & cast-in-situ concrete work
Lin et al. (2011)		✓		✓		Varied
Lucas et al. (2008)			✓	✓		Conveyor belt safety
Wang and Dunston (2007)	✓				✓	Earth-moving, material-handling, and pipe-laying operation
Wang et al. (2004)	✓				✓	Loading operation

2.4.3.1 Mobile-based VR and AR

VR, AR, and mobile computing can be used for construction safety training. Mobile computing such as mobile devices and laptops provide users with computing service anytime and anywhere (Anumba and Wang, 2012). It allows construction field managers and facilities managers to check the project on the site and communicate with AEC stakeholders. The usage of mobile computing in training would provide students with fast information access, easy communication and collaboration, and situated learning (Gikas and Grant, 2013).

The use of AR technologies is increasing every day since cell phones, pads, and other mobile devices are becoming smaller, lighter, cheaper, and more user-friendly and powerful (Chi et al., 2013). MR technology-based systems can provide the AEC sectors with handheld aids for workers in dangerous situation supplying information about 3D models in near at the construction site (Dunston et al., 2005). Moreover, new forms of remote collaboration and shared experiences can be achieved by MR technologies (Keneman and Waller, 2016).

2.5 Summary and conclusions

This chapter reviewed the concepts and main technologies that are utilized in the current research such as 4D applications, safety, 4D BIM, VR systems, and construction safety training. The literature showed that 4D has been widely used in construction. Specifically, 4D BIM is broadly used for visualizing, animating, and scheduling the construction activities. However, the review of previous research works has shown that construction equipment tasks are not animated and scheduled at the micro-level. Modeling and scheduling the construction equipment activities and its workspaces increase the safety and productivity in construction sites.

Additionally, the usage of MR technologies has increased in recent years in various areas such as training and education. Some researchers have benefited from VR and AR-based technologies in construction safety training for workers, operators, and students. Nevertheless, many construction accidents arise from insufficient knowledge of student about equipment operations. There is a research gap on equipment-oriented VR/AR training in order to enhance students' capabilities for identifying on-site hazards.

CHAPTER 3 PROPOSED METHODOLOGY

3.1 Introduction

As explained in Chapter 2, many research works have simulated equipment activities by using different methods and applications. More research can be carried out to simulate and schedule equipment operations at the micro-level in 4D BIM. In addition, many researchers used 3D VR technologies to train construction workers; however, training in the 4D virtual environment can provide new opportunities.

This chapter is divided into three parts. In the first part, requirements for modeling construction equipment are represented in seven main categories. To visualize the construction progress from the beginning to the end with all related details, the conditions needed for simulating the equipment operations should be taken into account.

In the second part, the author moves one step beyond introducing requirements for equipment modeling and proposes an approach for modeling equipment tasks in different software tools with regard to the discussed requirements. Different types of construction equipment can be made articulated through the proposed method. In addition, a method for generating dynamic workspace for equipment is designed, which can help in developing more detailed simulation, and consequently, can result in improving safety on construction sites.

Based on the comparison, Fuzor VDC was utilized to create the 4D simulation and to use it for application in VR safety training (Figure 3-1). In the third part, a VR-based framework, which focuses on safety knowledge training and testing, is proposed to improve students' capability for identifying on-site hazards. Through the proposed framework, learners can navigate in a BIM model in the virtual environment and recognize PPE–related safety issues in the 3D/4D VR. Additionally, the existing hazards during the construction activities and equipment operations can be detected in the 4D VR.

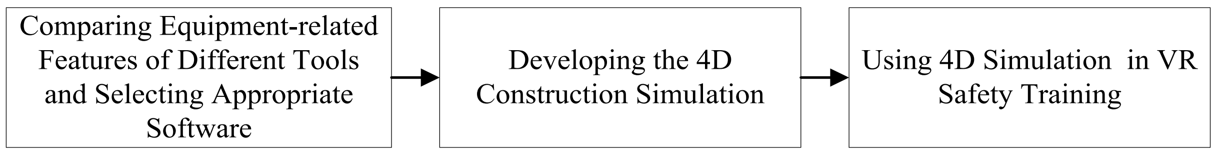


Figure 3-1 Overall methodology

3.2 Proposed method for comparing equipment-related features of different tools

To compare the available commercial and research platforms in terms of animating and simulating construction equipment, the steps shown in Figure 3-2 can be followed. The requirements for equipment modeling are identified and the specific software tools to be compared are selected. An example is developed in each tool to evaluate its capabilities for making articulated equipment. Then, a comparison based on the mentioned requirements is carried out to summarize the strengths and limitations of each tool.

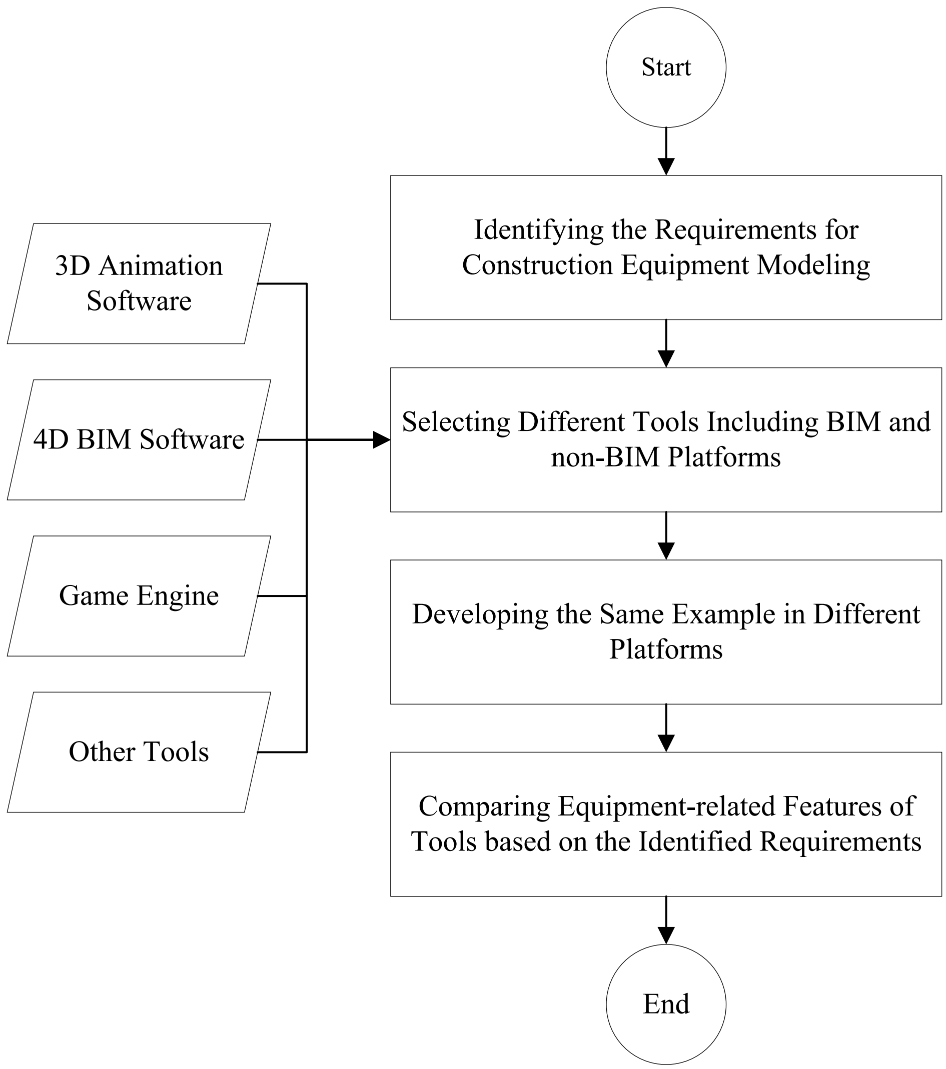


Figure 3-2 Comparing equipment-related features of different tools

3.2.1 Requirements for construction equipment modeling

To prevent accidents and mismatches in the construction phase, the whole construction activities and equipment tasks should be scheduled and visualized in the planning phase. Each of the tools has some strengths and limitations for animating and visualizing equipment-related features, which will be discussed in the next chapter. To appropriately visualize the construction progress and improve safety and constructability in construction sites, the tools should satisfy some requirements for animating and simulating construction equipment activities.

3.2.1.1 BIM compatibility

BIM has the capability to schedule, simulate, and visualize equipment tasks in detail. Compatibility between construction equipment modeling and BIM results in better visualization of the progress of the construction activities by simulating equipment movements and the changes in workspaces at the micro-schedule level.

IFC (Industry Foundation Classes) is an open and neutral data format for openBIM, which is developed by buildingSMART (2018) to support the seamless information exchange among AEC participants. Several BIM platforms provide visualization and schedule of equipment activities. However, there are limitations to exchange equipment-oriented information in BIM since the equipment is not considered in the current version of IFC, except as an abstract type of IfcResource (2019).

3.2.1.2 Equipment library

BIM tools usually have a library of common objects, ranging from materials and furniture to equipment. However, most of the tools do not have a library of construction equipment. The vehicle objects, which are available in most of these libraries, lack the inverse kinematics feature.

Additionally, the dissimilarity between simulated equipment objects and the real pieces of equipment can cause errors and misunderstanding. Ideally, the equipment library should include not only the set of equipment commonly used in construction projects (e.g. excavators, cranes, compactors, etc.) but also the specific types of the equipment based on different brands, sizes, etc. Some crane simulation tools (e.g. 3D Lift Plan, 2019) have a detailed library of cranes including the crane models and the load charts.

3.2.1.3 Ability to model multiple Degrees of Freedom (DOFs)

The DOFs of articulated equipment with moving parts define the pose of the equipment. In general, there are six degrees of freedom for solid objects including three translations and three rotations, which show the movement freedom of a rigid body in three-dimensional space. As a result, to properly control the equipment movements, its DOFs should be easily controllable in the simulation tool. Platform users should be able to select a specific value within the range of each DOF of the equipment.

As shown in Figure 3-3, a typical boom lift (cherry picker) could be controlled through eight DOFs: W1, W2, W3, W4, W5 (Vb), W6, W7, and W8 (V). It consists of two translation transformations; the whole boom lift moves toward the left and right direction through V vector while Vb controls extensions of an arm. Also, the boom lift is controlled by four pitch rotations (W2, W3, W4, and W6) and two yaw rotations (W1 and W7). Two or more DOFs might be combined at any point in time. However, the movements and rotations of some parts are constrained. For example, the boom lift's bucket should be kept horizontal. Appendix A represents more pieces of equipment with their DOFs.

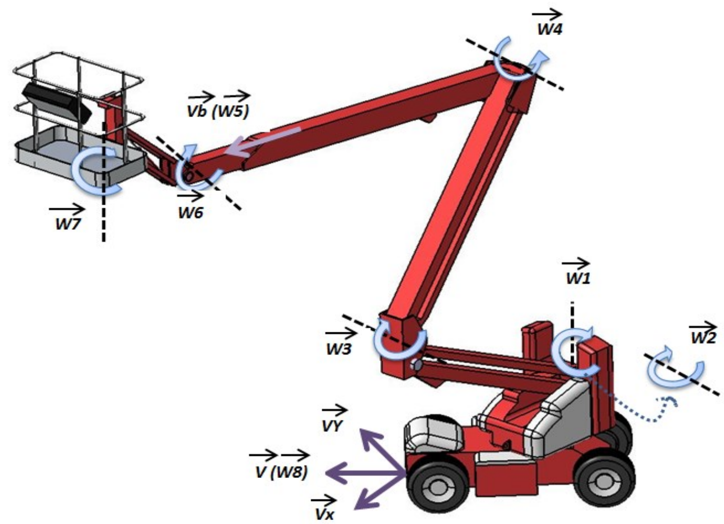


Figure 3-3 DOFs of a boom lift (Model of the boom lift is retrieved from (GrabCAD, 2019))

3.2.1.4 Ability to model at high 4D-LOD

With the purpose of full analysis of construction equipment activities, 4D-LOD for equipment simulation should be able to link micro-tasks of the movement of the equipment components with the detailed schedule of these tasks (e.g. the swinging of the boom of a crane). Equipment tasks should be broken to high LOD to enhance the safety, productivity, and constructability in construction sites. Project managers can create an efficient plan if they model equipment on construction sites based on accurate activity time. If an error is observed prior to or during the construction phase, they can reschedule tasks through changes in start time, end time, duration, and sequence of tasks.

Six LODs are defined for 3D BIM models including LOD 100, LOD 200, LOD 300, LOD 350, LOD 400, LOD 500 (AIA, 2017).On the other side, LODs for schedules are classified into five levels: level 1 to level 5 (Stephenson, 2007). However, there is no specific definition for 4D-LOD.

Guevremont and Hammad (2019) proposed new guidelines for defining 4D-LODs at different phases of a project by considering the needs of different stakeholders.

3.2.1.5 Path and motion planning

Path and motion planning of the construction equipment is an important part of 4D construction simulation. This planning has two parts: planning the relocation path of equipment (e.g. relocation of an excavator between two locations on the site), and planning of the movements of the parts of equipment (e.g. the boom swing, trolley and hook movements of a tower crane). Although the former planning may be available in some simulation tools, planning of the movements of equipment parts is still done manually in these tools, which is time-consuming. Also, it is important to be able to simultaneously plan the movements of several parts of the equipment and to support the motion planning of complex repetitive tasks (e.g. for cranes and excavators).

3.2.1.6 Collision avoidance

Congested site conditions often result in poor safety and productivity performance (Zhang et al., 2015). Congestion causes objects to move slowly, which results in an increase in cycle time and a decrease in productivity. On the other hand, it is important to be able to detect conflicts between different resources available in the construction sites. The probability of accidents between pieces of equipment, workers and equipment, and equipment and building components increases when the pieces of equipment do not have enough spaces to do their tasks. If equipment conflicts can be identified in advance, productivity and safety would be enhanced through rescheduling. The same approach used for time-dependent clash detection in the 4D simulation can be utilized for equipment conflict detection. The conflict detection and collision avoidance can be based on the actual 3D model of the equipment or based on its dynamic workspace, which can be generated automatically (Vahdatikhaki and Hammad, 2015).

3.2.1.7 Other requirements

Setting speed of movements

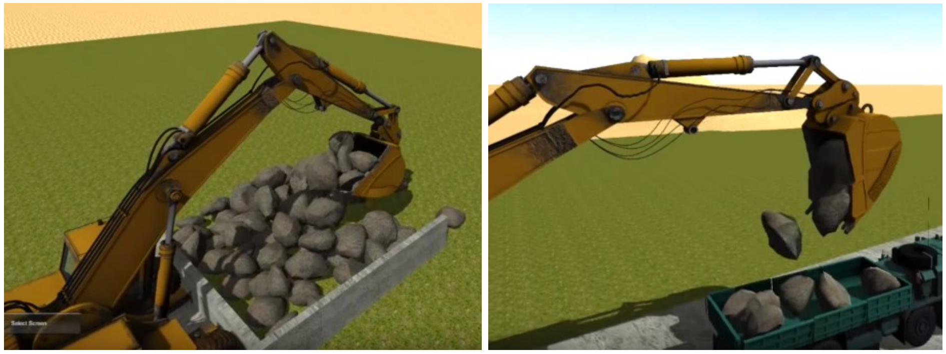
Different components of equipment (e.g. the boom and hook of a crawler crane) move at variable speeds based on the type of activity. It is important to set a specific speed for each equipment movement because this affects the cycle time and productivity. From a safety point of view, an accident may happen due to task interference when the speed of movements are ignored during modeling. This increases the probability of conflicts due to differences between planned and actual activity times.

Time scale

Each piece of equipment performs a set of activities during the construction project that may take minutes or even seconds. For modeling and visualizing equipment activities at high LOD, their tasks should be scheduled at the micro-level in 4D.

Physics, terrain following, and ability to simulate weather conditions

The physical behavior of objects, such as wind effects, gravity, and terrain following have direct effects on equipment performance. The users can use computer-simulated construction sites and the physical behavior of objects can be controlled with built-in physics engines. Figure 3-4 (a) and (b) show an excavator loading stones from the ground and dumping them in a truck considering gravity physics in Unity game engine.



(a) (b)

Figure 3-4 Loading and dumping stones using built-in physics in Unity game engine (AndersOrum, 2015)

In addition, it is important to consider terrain following in the modeling of equipment activities since it affects the equipment performance. Terrain following makes equipment move on the terrain based on the elevation and slope of the ground. Figure 3-5 shows that the trucks' movement on the terrain is influenced by the soil unevenness. Furthermore, weather conditions impact the equipment movement and its performance. For example, when the weather is snowy or rainy, the operators move the equipment with reduced speed, which affects equipment efficiency.

Figure 3-5 Effect of terrain following on the truck movement (AndersOrum, 2015)

Dynamic work spaces

Workspace is designed to promote safety (Mital and Karwowski, 1991). Workers, building components, materials, and construction equipment occupy static and variable spaces at different stages of a project. Since different parts of the equipment move and rotate, dynamic workspaces for each part should be automatically generated leading to safety improvement. Moreover, workers on foot and who are working on the equipment should also be able to work safely. Figure 3-6 shows the work space around a worker working on a joint of a steel structure.

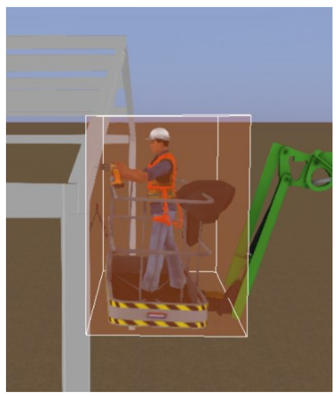


Figure 3-6 Workspace around a working man in the construction site

3.3 Proposed method for generating articulated equipment

3D animation software focuses on producing 3D models and animations used commonly in the game industry. These platforms can be used to animate the movements of a piece of equipment. On the other hand, BIM platforms have progressed in recent years in terms of visualizing equipment operations and generating workspaces. In addition, game engines are able to simulate equipment activities, although special scripts should be written and applied.

Figure 3-7 proposed the process for animating equipment activities along with their workspace in three different categories of platforms: (1) animation software and basic 4D BIM tools; (2)

advanced 4D BIM software; and (3) game engine. To model equipment activities, several tools may be required to combine with each other. Based on the first category, after importing a 3D solid equipment model and adding bones in 3D animation software, static workspace that is created in either 3D animation or 4D BIM software is added to the model. Then, equipment activities are animated and visualized in the construction site. The detailed process is explained in Section 4.3. On the other hand, advanced BIM software can be utilized to animate and schedule equipment activities at micro-level. In the first step, a structure is modeled in a 3D BIM software and imported into the 4D BIM platform. Subsequently, pieces of equipment are selected from the software library before animating their tasks and adding workspace. Their tasks are scheduled by the AEC sector in the planning phase. Two cases in Sections 4.4 and 4.5 are presented based on the mentioned steps. In the third category, after importing 3D model of equipment and adding workspace, related scripts are written to visualize the equipment movements. After these processes, equipment-related characteristics of tools are compared and their positive and negative points are determined.

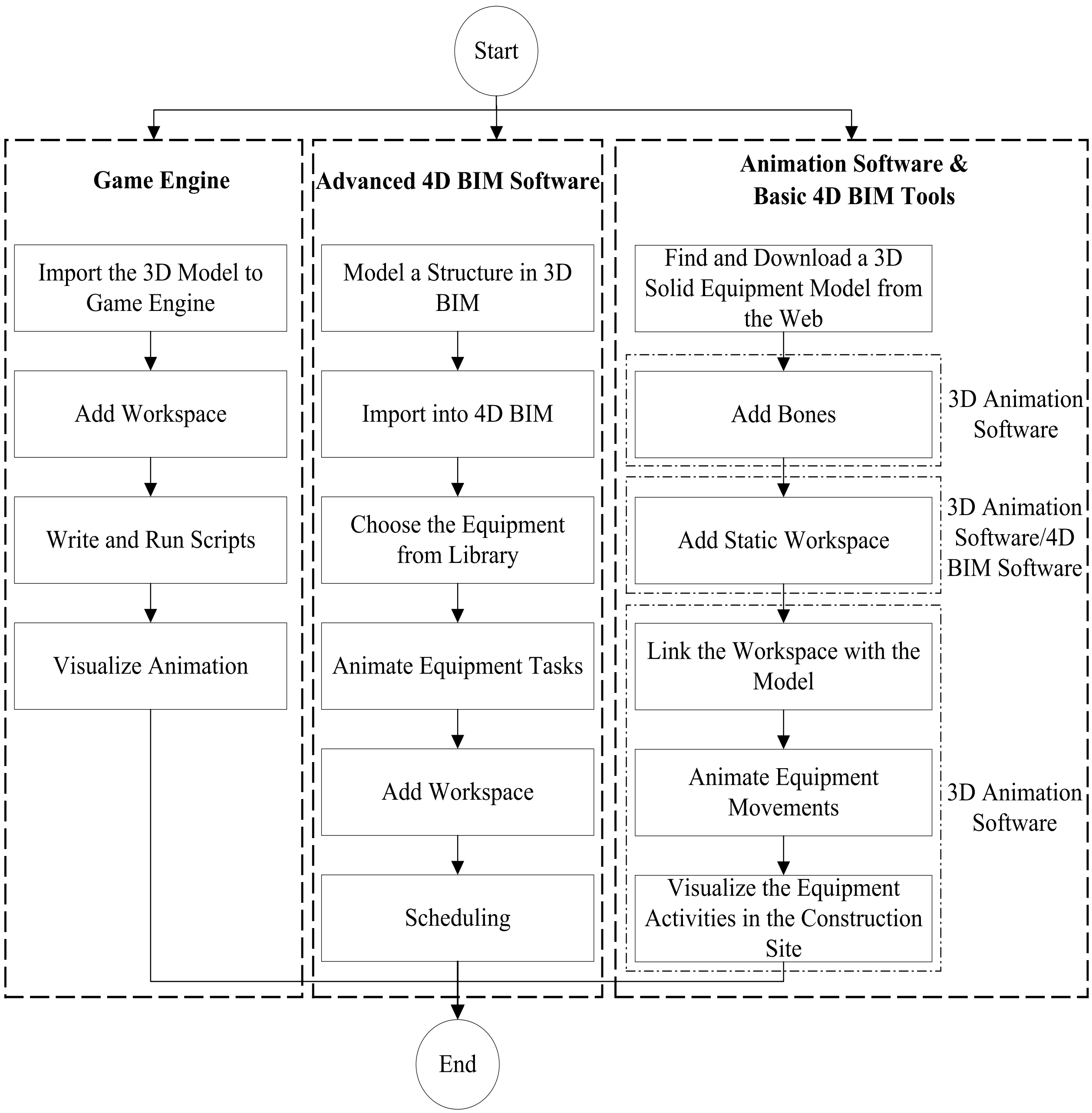


Figure 3-7 Proposed method for generating articulated equipment and its workspace in different tools

3.4 A framework for using 4D VR for safety knowledge training

This study aims to provide construction management students with a realistic construction site to improve their safety knowledge. To achieve the study purpose, a VR-based approach is proposed for construction safety training consisting of two phases: (1) Training phase, (2) Testing phase.

Based on the requirements explained in 3.2.1, an appropriate tool is selected to visualize construction activities and equipment operations, as shown in Figure 3-8. In the next step, a construction site along with all details is developed in 4D before adding the safety scenarios for training. Some on-site construction hazards are applied to the model including PPE- and equipment-related hazards. Equipment-related hazards can be better visualized in 4D. However, PPE-related hazards can be observed in both 3D and 4D. In addition, the activities of workers are scheduled based their working hours and can be visualized in VR mode. Then, construction students are selected and provided with the initial safety training for VR in accordance with the prepared training protocol.

Subsequently, students' safety knowledge is evaluated by running a test based on the testing protocol. They should view the construction activities in the virtual environment to find the hazards. Participators are informed of their performance.

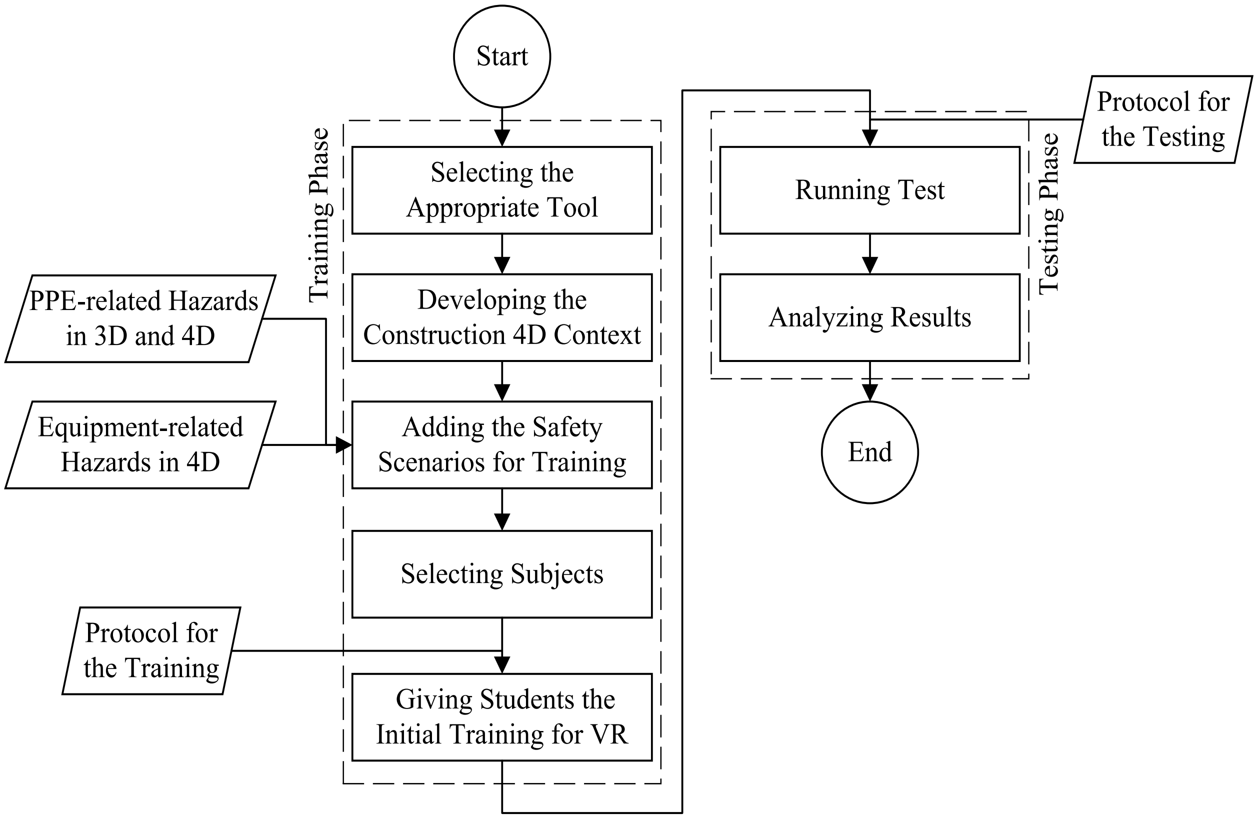


Figure 3-8 Proposed VR-based method for construction safety training

3.4.1 Safety scenarios for training

Some safety training scenarios are selected based on the hazards that threaten construction workers' lives. Safety knowledge of students can be improved by training about common on-site hazards and the appropriate related remedies. Additionally, immersing in the high-risk construction project with 4D VR and visualizing the equipment operations helps them in detecting dangers and taking preventative measures. From this point of view, seven virtual safety training scenarios are developed. The types of hazards, descriptions, and required VR environment are explained in Table 3-1.

Table 3-1 Safety training scenarios

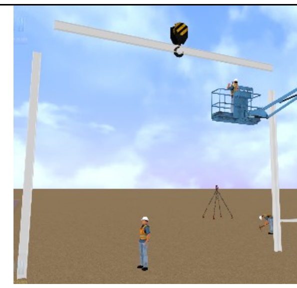
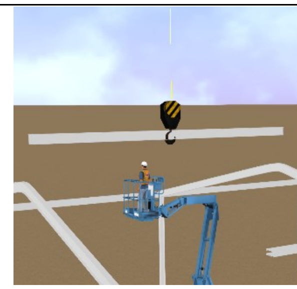
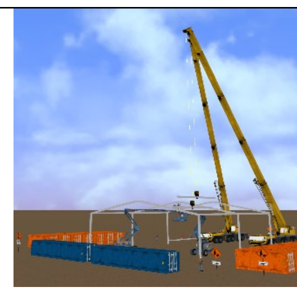
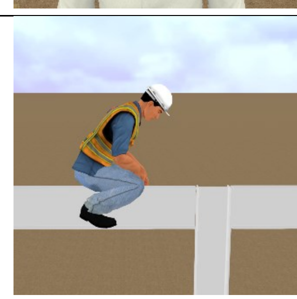
No.	Hazard	Description	Virtual environment	Example
1	Walking worker under crane while its components move	The worker walks on the site without attention to the cranes' operation. The component may fall from the hook of the crane.	4D	
2	Lack of safe distance between the crane component and the worker on the boom lift	The worker is waiting to release the steel component from the crane. The hook of the crane or the component may hit the worker.	4D	
3	Lack of timing and proper coordination between crane operators	Two cranes are operated to erect a steel structure in a limited time and congested site. Due to a lack of proper timing, they can hit each other.	4D	
4	Workers without a hard hat	A component falls from an elevated height while the worker works at the site without wearing the hard hat. It can hit his/her head.	3D/4D	
5	Workers without a safety harness	The worker assembles a steel component at height, not wearing the safety harness. He/she may fall from the structure due to loss of balance.	3D/4D	

Table 3-1 Safety training scenarios (continued)

6	Workers without high visibility clothing (reflective clothing)	The operator of heavy equipment does not see the workers clearly due to the difficult visibility condition.	3D/4D	
7	Workers who do not wear gloves	The worker welds the steel component without wearing gloves. It can cause burns, cuts, and scratches.	3D/4D	

3.4.2 Safety knowledge training

Some construction management students are selected for the training phase. The purpose of this phase is transferring the safety knowledge to students based on construction hazards. Table 3-2 shows the protocol designed for the safety training of students. Students are trained through two different methods, conventional and VR training. At first, the Occupational Safety and Health Agency (OSHA) guidelines specified in certain domains are introduced. Students become familiar with some accident cases by photos and videos. Learners are supposed to develop their safety knowledge based on the safety regulations and hazard samples.

In the next step, the usage of Oculus Rift as a VR device is explained to students. Users navigate in the virtual site and see the construction processes in the 4D VR. A risky construction project should be utilized as a sample to show students the probable on-site hazards. While they are navigating in the virtual site, the instructor explains the safety risks and appropriate preventative measures for each hazard. Through this experiential approach, students can improve their safety knowledge about safety issues prior to entering the construction site.

Table 3-2 Protocol for the training

No.	Tasks		Technology support	Purpose
	Tutor	Students		
1	Explanation of safety standards and guidelines (OSHA)	Receiving	Conventional training (lectures)	To make students aware of safety rules
2	Introduction of hazard samples	Receiving	Conventional training (photos and videos)	To learn about the importance of recognizing hazards
3	Explanation of the usage of Oculus Rift	Receiving	Conventional training	To familiarize students with the device
4	Idle	Experience of the virtual environment	VR	To make students familiar with VR mode
5	Introduction and explanation of hazard scenarios and preventative measures	Navigation through the virtual construction site in 3D and 4D	VR	To enhance the safety knowledge of students

3.4.3 Safety knowledge testing

After the training stage, the safety knowledge of learners should be tested. This process ensures that the students acquire sufficient safety knowledge to be able to detect safety issues of the construction site. The protocol provided for the testing of students' knowledge is provided in Table 3-3. The Testing phase is carried out by utilizing a 4D VDC platform. Students are provided with the VR technology (Oculus Rift) to immerse in and interact with the construction project. They should navigate in the 3D/4D virtual site for observing issues related to PPE and equipment. They identify hazards by marking around them and suggest measures. By using this approach, the capabilities of students for detecting hazards and their safety-related knowledge are measured.

Table 3-3 Protocol for the testing

No.	Tasks		Purpose
	Tutor	Students	
1	Providing a VR device (Oculus Rift) for students	Idle	To begin the test
2	Idle	Navigating in the virtual construction site in 3D	To observe the virtual site and find PPE-related hazards
3	Idle	Playing 4D animation and walk around the site	To look around the environment to discover PPE- and equipment-related hazards
4	Evaluating the performance of student	Identifying the hazards and suggesting preventative measures	To test the capabilities of students to identify hazards
5	Giving a score to performance based on the detected hazards	Idle	To measure the safety knowledge of students

3.4.4 Learning experience evaluation

After training students about the safety hazards using AR and testing their hazard recognition, they are invited to answer some prepared questions about their learning experience. The following questions have formed the questionnaire: (1) The hazards were represented realistically; (2) The training improved your safety knowledge; (3) You remember what you have experienced clearly; (4) You are interested in experiencing similar training sometimes in the future; (5) You suggest others (your friends) to have similar training; and (6) Visualizing the equipment operations in specific training method has impact on improving your safety knowledge.

These questions are asked in four different areas: (1) Visualization, to assess students' point of view regarding the reality of demonstrations; (2) Safety recognition, which focused on how well students recognize the hazard on the virtual construction sites; (3) Memory response, which assessed students' memory to remember what they have learned; (4) Attractiveness, which evaluated the enthusiasm of participants to repeat similar experience; and (5) Safety knowledge (equipment), to compare the difference between the effectiveness of training methods in terms of visualizing equipment operations. In general, the purpose for providing questionnaire is (1) comparing learning experience of students in 4D VR with 3D VR and conventional methods, and (2) evaluating the most effective aspect of each learning method.

3.5 Summary and conclusions

This chapter has presented an overview of the proposed methods and explained the requirements for modeling equipment. In the first part, the main requirements for modeling equipment operations are presented. One of them is the compatibility between BIM and equipment simulation. The desired equipment should be available within the tools and its DOFs should be controllable. When all DOFs are specified, the equipment can be modeled properly. It is important to define the 4D LOD and to visualize equipment operations at the highest 4D-LOD. Additionally, since pieces of equipment always move across the site and their components are moving to operate the planned activities, path and motion planning should be taken into consideration. During these movements, many conflicts may happen, which result in decreasing the safety and productivity in the construction sites. Thus, all potential collisions and accidents should be identified and analyzed prior to the construction phase. Other items should be considered, such as time scale, ability to set speed for movements, generating dynamic workspace, and the physics and weather conditions.

In the second part, a method is proposed to make the equipment articulated using 3D animation software, 4D BIM tools, and game engine. The equipment activities can be animated in a 3D environment that lacks the temporal aspects of the movements. Then, the workspace is added and linked to the equipment. However, this process is time consuming. Equipment movements can be animated and scheduled directly in some advanced 4D BIM tools. In addition, the game engine can be used for this purpose; although related scripts should be prepared.

This chapter finishes with a safety training framework that uses VR technology to enhance student' safety knowledge. Based on the proposed method, several safety hazards are modeled in 4D virtual construction sites and the protocols for training and testing are provided. To verify the proposed methods, several case studies are carried out in the next chapter.

CHAPTER 4 IMPLEMENTATION AND CASE STUDIES

4.1 Introduction

This chapter is arranged in five sections. In Section 4.2, the available BIM and non-BIM platforms are compared with each other based on the requirements for construction equipment modeling discussed in Chapter 3. Eight software tools are classified in the following categories: 3D animation software, 4D BIM software, game engine, and other applications. In Section 4.3, the movements of a piece of equipment are animated and the workspace for each component is created and dynamically visualized using 3D animation software.

In the case studies presented in Section 4.4 and Section 4.5, articulated crawler cranes and boom lifts are modeled and scheduled to erect a simplified steel framed structure using 4D BIM software. The workers' activities are visualized from the beginning to the end of the project. The 3D model of a structure is built and the construction equipment is added, animated, and scheduled in 4D. A crawler crane is animated and scheduled to rig and move the steel columns and beams to their locations based on the BIM model. Simultaneously, the workers, who are standing on the bucket of boom lifts, are scheduled to assemble these components. In another case study (Section 4.5), some conditions are applied to show the challenges when the project is built in a shorter period of time. Additionally, the site is more congested and occupied with more pieces of equipment.

In Section 4.6, seven hazard scenarios identified in Chapter 3 are added to the 4D BIM model and explained to construction management students using conventional and VR training methods. While they navigate in the 3D/4D virtual site, their safety knowledge is tested. At the end of the test, an evaluation is provided to compare the effectiveness of the conventional and 3D/4D VR safety training, and to identify the most influential aspect of each learning method.

4.2 Comparison of tools

In this section, several modeling and simulation tools are compared based on equipment-related features, such as their capabilities to simultaneously move equipment components, visualize dynamic workspaces, detect equipment and workspace conflicts, animate complex repetitive tasks, etc. These features are compared for the following tools: (1) 3D animation software: 3DS Max and Lumion; (2) 4D BIM software: Synchro, Navisworks, and Fuzor; (3) Game engine: Unity; and (4) Other applications such as equipment training simulators. In some cases, more than one tool should be used to fulfill the desired purpose. Table 4-1 shows the comparison of these tools.

4.2.1 3D animation software

4.2.1.1 3DS Max

Since 3DS Max (Autodesk, 2019) is commonly used for producing animation in the game industry, it has a large number of options and a library of tools, facilitating the creation of objects with different types of motions. 3DS Max can produce objects with kinematics and equipment animation with workspace linked to it. In order to animate the detailed movements of equipment in 3DS Max, kinematics should be added to it.

4.2.1.2 Lumion

Lumion (2019) is a powerful 3D visualization engine for architectural design. However, it can be used to visualize construction processes along with all the details of the construction site. Lumion supports path planning of equipment. However, it does not provide inverse kinematics for equipment parts. It can import keyframe equipment animations from any 3D modeling software, such as 3DS Max, Revit, AutoCAD, SketchUp, and ArchiCAD.

4.2.2 4D BIM software

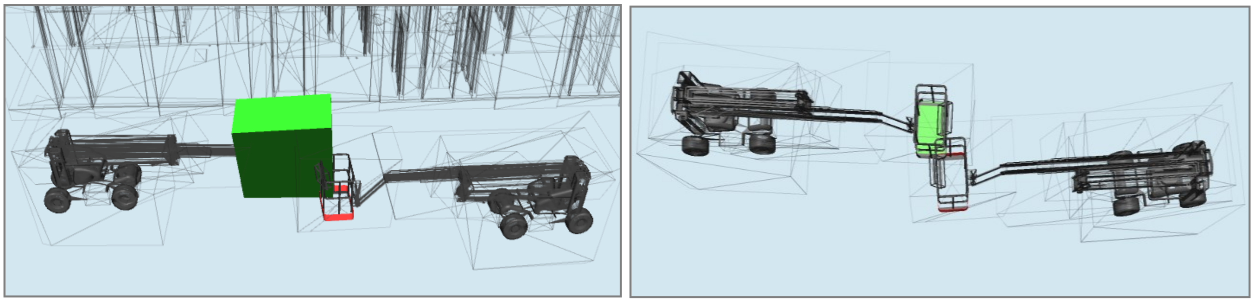
4.2.2.1 Synchro

Synchro Professional (Bentley, 2019) is a 4D BIM software for construction project management. It provides workspace generation, animation of equipment path planning, conflicts detection, and clash reports. This platform enables the straightforward creation of objects' workspaces statically as shown in Section 4.3.2. Synchro can detect several types of soft and hard clashes: (1) conflicts between equipment workspaces and other types of workspaces: (2) conflicts between equipment and workspaces.

4.2.2.2 Navisworks

Navisworks Manage (Autodesk, 2019b) is a 4D BIM software widely utilized in the construction industry. It supports the animation of path planning (relocation), equipment/workspace collision avoidance, and conflict reports. This tool can be used to identify, inspect, and report the following construction clashes in a 3D model: (1) clashes between a couple of equipment, (2) conflicts between equipment and workspaces.

Figure 4-1 shows two pieces of equipment moving toward each other. Their movements caused conflicts between both equipment/equipment and workspace/equipment. The 3D model of a boom lift is downloaded from a website (GrabCAD, 2019) in STP format, before importing it into Synchro software to add workspaces. After both the equipment and the workspaces around them are prepared, the model is saved in FBX format and imported into Navisworks software. After creating the animation, a hard clash test is applied between two boom lifts and their workspaces.



(a) (b)

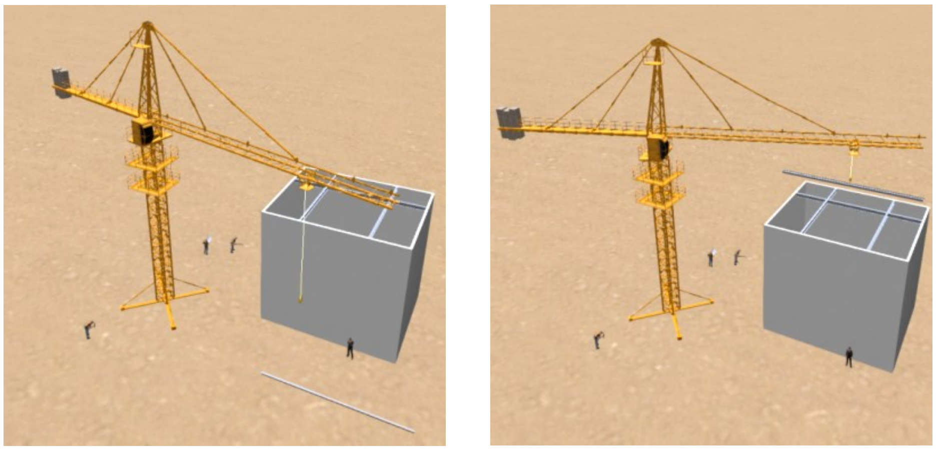
Figure 4-1 (a) Conflicts between equipment and workspace, (b) Clashes between two Equipment

4.2.2.3 Fuzor

Fuzor (Kalloc Studios, 2019) is the new generation of Virtual Design and Construction (VDC) applications in the construction sector. It enables the user to walk around the project in VR while observing the BIM data and information of every component in real-time. In the software environment, construction site logistics can be designed with simulated workers and articulated equipment, which leads to better visualization of the entire project. Fuzor VDC library is classified into three main categories: (1) Vehicles, (2) Foliage, (3) and Entourage. Vehicles are divided into the standard library, construction vehicles and equipment, and temporary construction equipment. The vehicle category has about hundred types of construction equipment, providing a user-friendly interface for interactively modeling keyframed articulated equipment. Appendix A shows some important equipment available in the construction equipment library.

As shown in Figure 4-2, a tower crane is animated while grabbing a beam from the location it should be loaded and releasing it at the final location in the BIM model. This process is linked to the construction schedule and has an adjustable speed of simultaneous movements. As shown in

Figure 4-2(a), the crane hook goes down to grab the beam and hoists it before the jib slews toward the location the beam should be unloaded. Then, after moving the trolley to the final location, the hook is lowered down to place the beam, as shown in Figure 4-2(b).



(a) Picking (b) Installing

Figure 4-2 Two frames of an animated crane

In addition, Fuzor (2019) supports VR, MR, and AR technologies, including HTC Vive, Oculus Rift, Windows Mixed Reality, Microsoft HoloLens, and Google Cardboard. Its VR mode provides users with the following options: (1) adding comments (e.g. markup clashes); (2) viewing BIM-related information; (3) visualizing the construction sequences in 4DVR/AR; and (4) collaborating in real-time through host view and guest view.

A QR code can be generated in Fuzor mobile and attached to a projects' element. When the QR code is scanned, that specific object and all related information are shown on the mobile screen (Figure 4-3). This leads to better communication between different participants of the project.

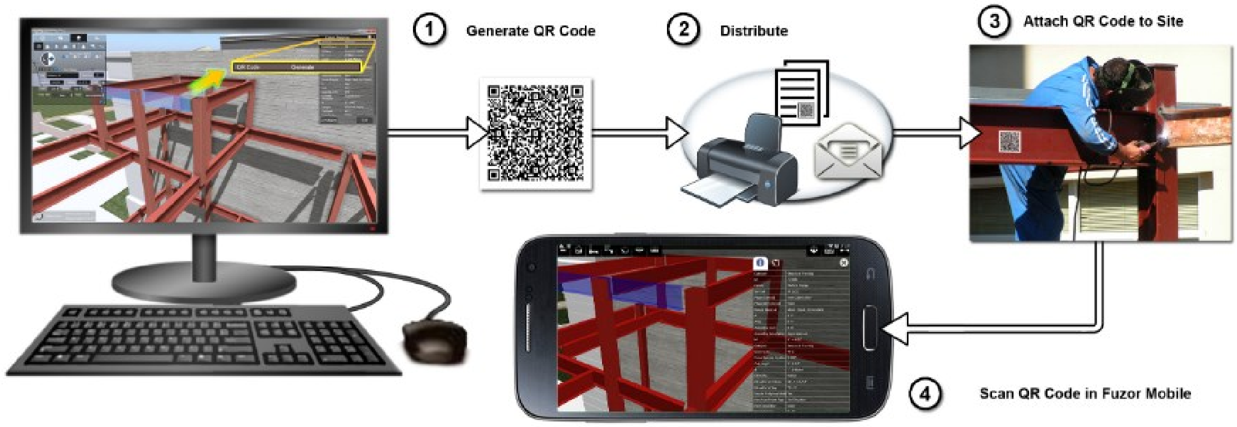


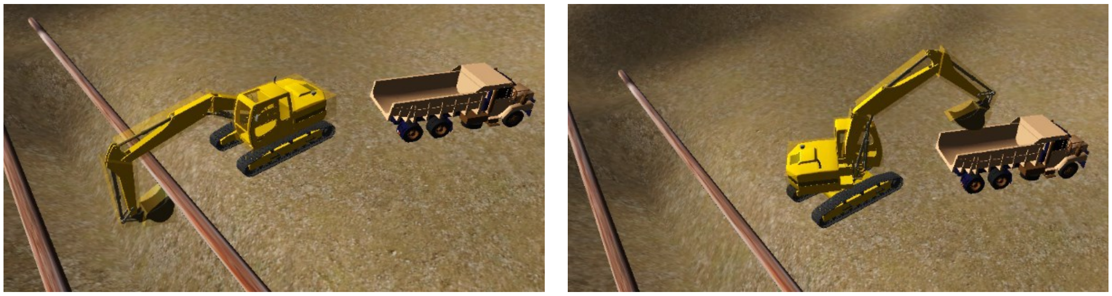
Figure 4-3 Generation and usage of QR codes in a virtual construction site (Fuzor, 2019)

4.2.3 Game engine

4.2.3.1 Unity 3D

Unity (2019) can be used to produce both 2D and 3D games. Scripting is a crucial ingredient in all types of games, even the simplest game engines. Unity3D supports two types of scripting languages: C# and JavaScript. Articulated construction equipment and processes can be animated by the game engine using scripts. Unity allows users to see how both the construction equipment as a whole and its components are moving and accomplishing complex repetitive tasks on the construction site. Figure 4-4 shows the functions of an excavator while earth digging and dumping in a truck.

Furthermore, this program is identified as one of the most well-known VR tools. Users can interface with computer-simulated surroundings through VR technology. Built-in physics engines of Unity control the physical behavior of objects, such as gravity, collisions, and wind effects. Additionally, Unity3D has the terrain following feature, which ensures that the equipment moves on the terrain based on its characteristics (e.g. elevation and slope).



(a) Earth digging (b) Dumping in a truck

Figure 4-4 Digging and dumping motions of an excavator animated in Unity3D (Langari, 2015)

Tridify Convert is a new unity plugin that allows developers to import 3D BIM models to Unity (Tridify Convert, 2019). Figure 4-5 compares the attributes of a structural component (rafter) in Revit before importing to Unity as an IFC file and in Unity properties.

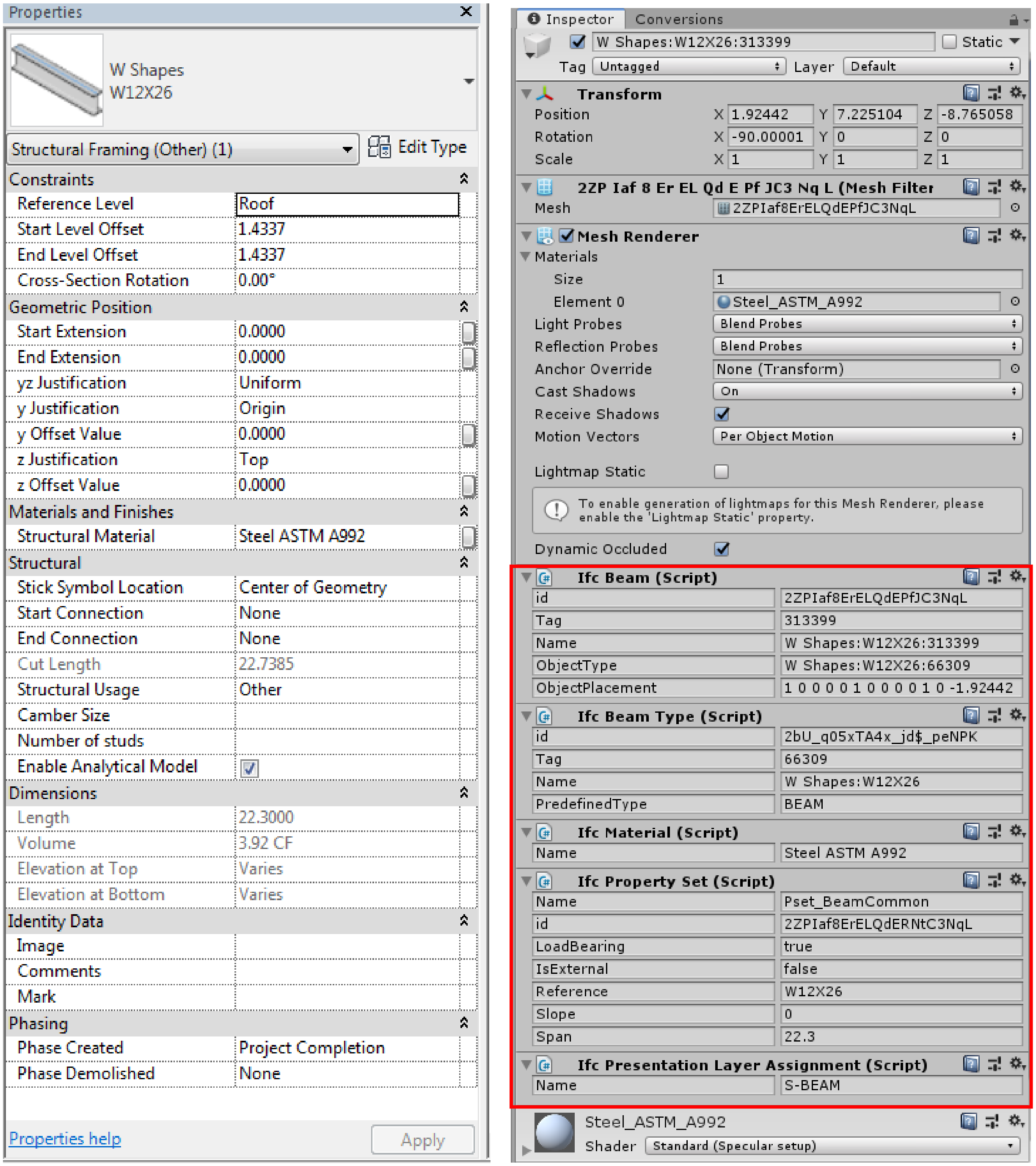


Figure 4-5 Attributes of a component in Revit (left) and Unity (right)

4.2.4 Other applications

4.2.4.1 Lift planning applications

3D Lift Plan (2019) has a library of cranes containing over nine hundred cranes and load charts. It finds the most appropriate crane based on the following characteristics: dimensions and weight of the object to be lifted, and the location and size of obstacles. Figure 4-6 shows a type of crane available in the platform library and the information about its load.

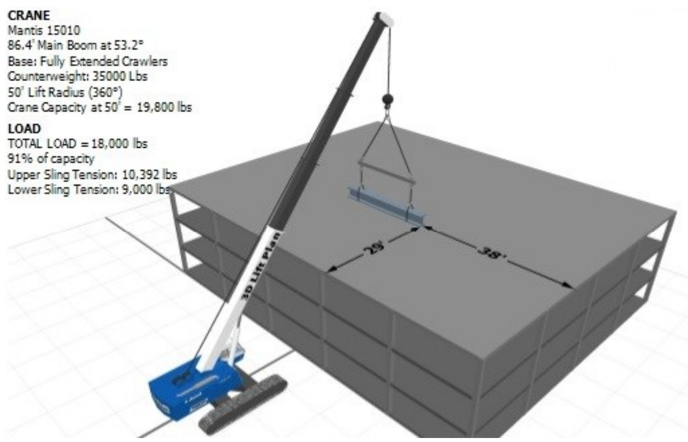


Figure 4-6 A specific crawler crane in the library of 3D Lift Plan (2019)

4.2.4.2 Equipment training simulators

There are different types of equipment training simulators, such as Vortex simulators (CM Labs Simulations, 2019). These simulators model complex construction equipment performance considering all conditions available on the real site, such as terrain characteristics, clash occurrences, and laws of physics. They prepare trainers to operate heavy equipment based on the available conditions of worksites, make better decisions in tough conditions, and operate equipment more accurately and safely.

Table 4-1 Comparison between purposed platforms

Requirements		3D Animation		4D BIM			Game engine	Equipment training simulators
		3DS Max	Lumion	Synchro	Navisworks	Fuzor	Unity	CM Labs
BIM- Supported		×	×	✓	✓	✓	✓	×
Equipment Library		×	×	×	×	✓	×	✓
Determining DOF		✓	×	×	×	✓	✓	✓
Path and motion planning	Simultaneously Moving Parts	✓	Possible by imported animation	×	×	✓	✓	✓
	Path Planning (Relocation)	✓	✓	✓	✓	✓	✓	✓
High 4D LOD	Simultaneously Moving Parts and Equipment	✓	Possible by imported animation	×	×	✓	✓	✓
	Complex Repetitive Tasks	×	×	×	×	Can be done manually	Possible by programming	×
Collision Avoidance		×	×	✓	✓	✓	Possible by programming	✓
Others	Setting Speed of Movements	✓	Possible in path planning	Possible in path planning	Possible in path planning	✓	Possible by programming and non-programming	✓
	Time Scale (Days vs. Minutes)	×	Activities can be set in sequence but the time frame is not available	✓ Minutes/days	✓ Minutes/days	✓ Minutes/days	Possible by programming	✓
	Physics (Gravity, Wind, etc.)	×	×	×	×	Ability to turn on and off gravity/collision	✓	✓
	Terrain Following	×	×	×	×	–	✓	✓
	Dynamic Work Spaces	✓	Possible by imported animation	Only static work-space	×	Import FBX & 3DS	✓	×

4.3 Visualizing articulated equipment and its workspace using 3D animation software

Figure 4-7 shows the steps for generating an animation of articulated construction equipment with a dynamic workspace based on the proposed method in Section 3.3 (category of animation software and basic 4D BIM tools). 3DS Max and Lumion (3D animation tools) and Synchro (4D BIM platform) are used to animate and visualize equipment movements and its workspace. A boom lift (Cherry picker) with the workspace for each of its components are animated and visualized in accordance with the following steps. Based on the complexity of the equipment components' shape, workspaces can be directly created in 3DS Max. However, the compound workspaces can be easily drawn in Synchro and then imported into 3D platforms. The detailed process for modeling articulated equipment and its workspace is explained in the following sections.

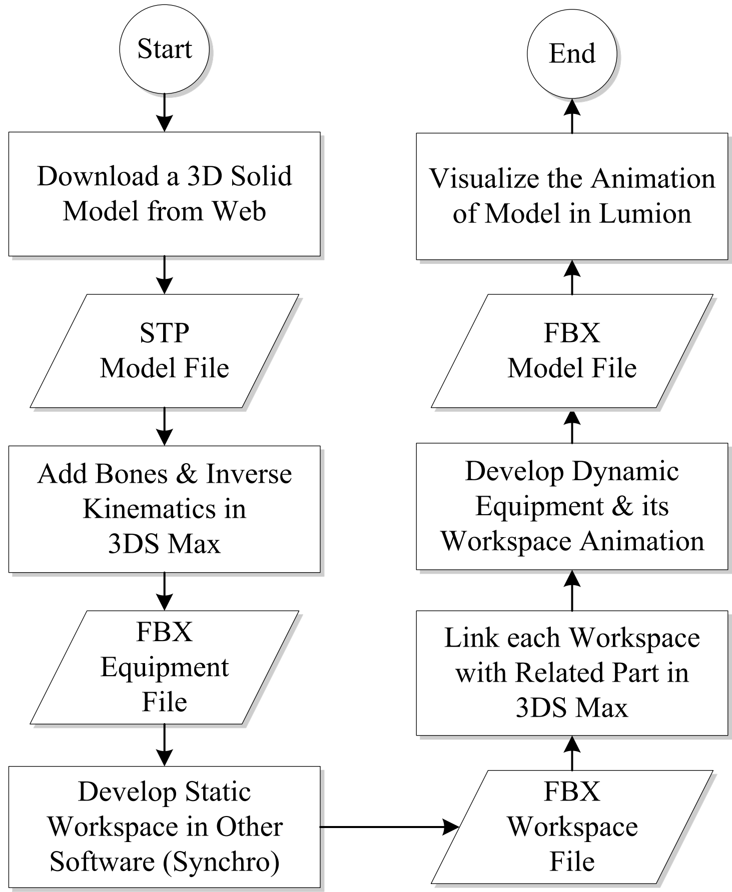
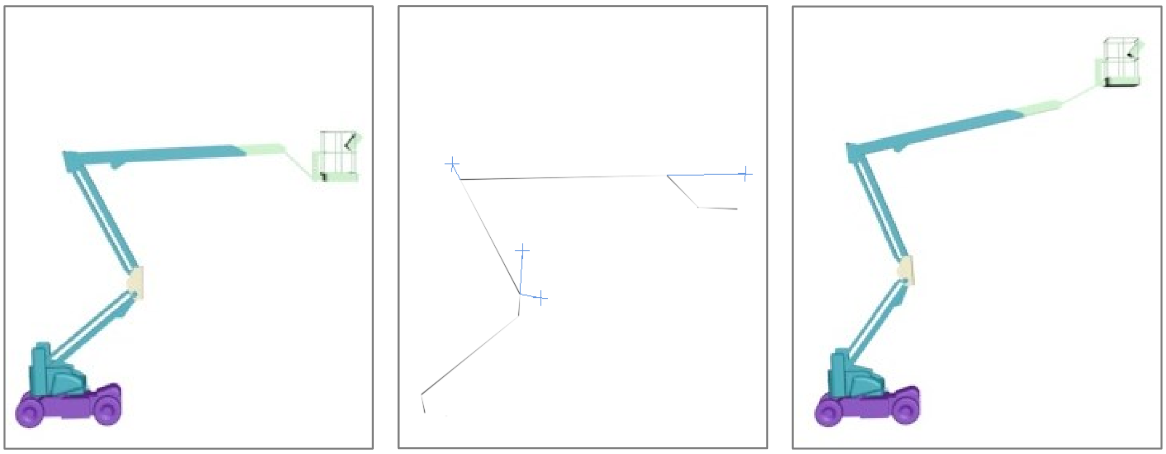


Figure 4-7 Flowchart of creating articulated equipment and its workspace

4.3.1 Animating equipment movements

As shown in Figure 4-8(a), a 3D solid model was downloaded and imported into 3DS Max in STP format. To make kinematics equipment, bones and IK Chains were added to the model Figure 4-8(b) shows several bones created and linked with the equipment components such as arms and bucket so that the boom lift's components are rotated and translated when the relevant bones are moved (Figure 4-8(c)). The model becomes articulated when the created bones are linked with each other by IK Solvers.

There are four types of IK solvers in 3DS Max, including HI Solver, HD Solver, IK Limb Solver, and Spline IK Solver. In this case, HI Solver was utilized because it provides the creation of multiple chains in the pecking order. To add this feature, the bone which decides the IK start was selected. Then, HI solver was selected from IK Solver (in the animation menu) and the part which determines the IK end is selected. This process is repeated to make the whole equipment articulated.



(a) (b) (c)

Figure 4-8 (a) Solid 3D model (GrabCAD, 2019), (b) Creation of bones and IK Chains, (c) Kinematics model of the boom lift

4.3.2 Generating dynamic equipment workspace

Figure 4-9 shows an option in Synchro software, called *create workspace*, which makes the creation of equipment workspace simple by drawing the lines of the workspaces boundary and then extruding them. The kinematics boom lift was imported into Synchro Software to create static workspaces for different equipment parts, including: (1) Arms: for each arm, a specific workspace was considered based on the position of the equipment; (2) Bucket: a workspace for the bucket was created with regard to both the buckets' size and the worker standing in it and doing his/her job; and (3) Main body: a distinctive workspace was allocated to the equipment's main body to move and rotate safely.

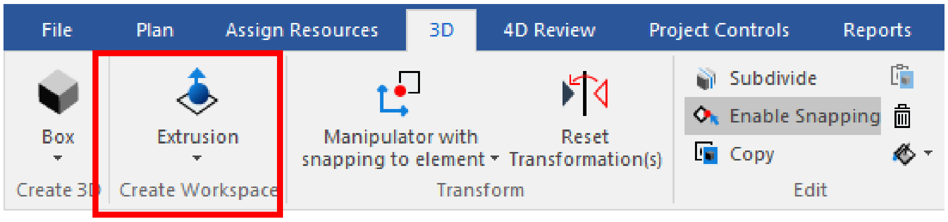


Figure 4-9 Create workspace tab in synchro software

To generate dynamic equipment workspace, the solid workspace model was imported into 3DS Max again before linking each generated workspace with the related part. When IK chain moved, both the assigned components and workspaces attached to them move simultaneously. This led to the generation of the dynamic workflow of the equipment. Subsequently, the animation of equipment model and the building model (1st floor of EV building), in which the equipment is operated, were imported into Lumion, as shown in Figure 4-10. This software was chosen because of its visualization capabilities and its user friendly environment.

(a) T1 (b) T2 (c) T3

Figure 4-10 Several frames of animated boom lift and its workspace in Lumion

4.4 First Case Study: Modeling and scheduling the construction progress in 4D BIM

The spatio-temporal conflicts in construction sites can be reduced when movements of construction equipment and workers are simulated and scheduled at high 4D- LOD in BIM (e.g. the swing movement of the boom of a crane). In the first case study, a steel structure was modeled with consideration of equipment and workers activities, and material allocation from the beginning to the end of the project. Based on the comparison in Table 4-1, Fuzor platform was selected to model and schedule equipment activities.

4.4.1 General Information

Figure 4-11 shows snapshots of the construction of a steel framed church erected in Bonita, California by Pascal Steel Buildings (2019). This is a construction company located in California, specialized in erecting industrial steel and steel farm buildings.

(a) (b)

Figure 4-11 Snapshots of the construction of steel framed church (2019)

This structure was modeled with some simplifications. The model has 23 components, including 6 columns, 4 eave struts, 3 rafters, and 10 roof purlins. The dimensions of building width, bay spacing, and eave height were assumed 22 m, 10 m, and 8 m, respectively. The names of the components are depicted in Figure 4-11.

From the structural point of view, two columns should be erected before installing the eave strut above them. For example, after placing C1 and C2 at their locations, E1 will be installed by the workers. C3, C4, and E2 will be assembled in the same order. For the next steps, Rafter 1 and Rafter 2 can be installed. Then, roof purlins are fixed at their locations after assembling the columns, eave struts, and rafters.

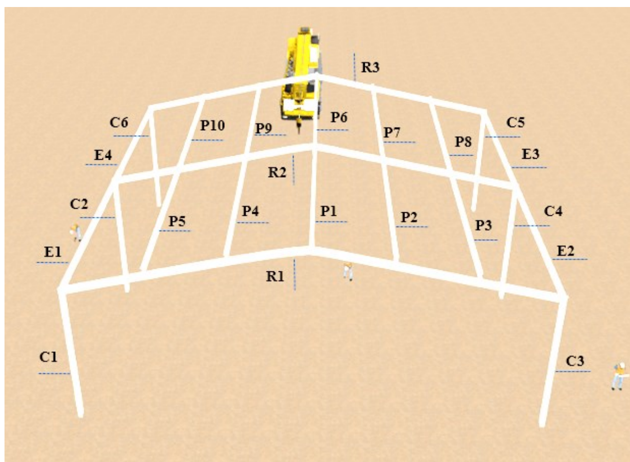


Figure 4-12 The names of the structure components

4.4.2 Resource allocation and animating the equipment tasks

As shown in Figure 4-17, the structure model was modeled in a 3D BIM software (Revit) before importing into Fuzor to add construction equipment and workers. For starting the simulation of the construction process, an area was allocated to resources on site (pieces of equipment and building components). The staging task was created in 4D Simulation in Fuzor and the components of the structure were linked to the created staging task through *add selection* (Figure 4-13). Then, the components of the structure (columns, eave struts, rafters, and roof purlin) were automatically collected in one place to be picked up by the crawler crane, as shown in Figure 4-14.

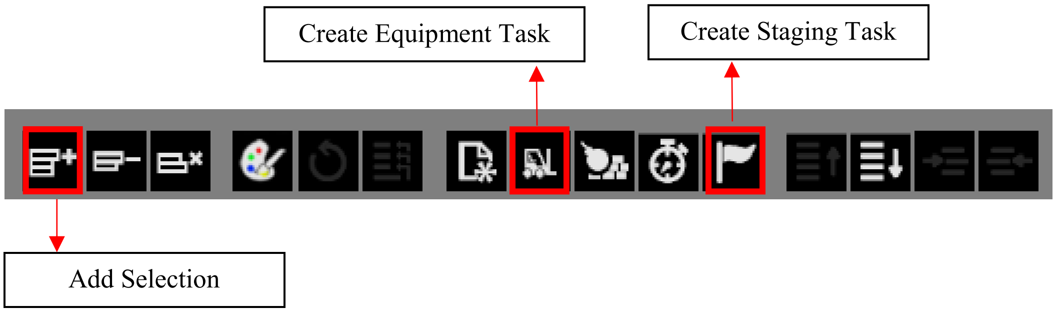


Figure 4-13 4D Simulation tabs in Fuzor

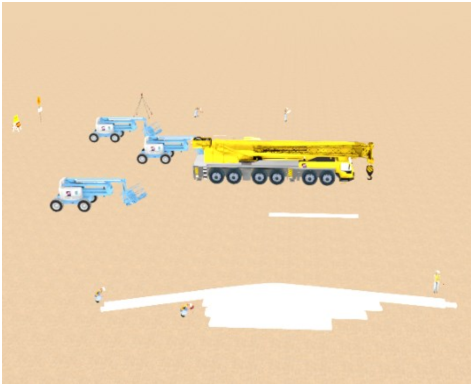


Figure 4-14 Resource allocation

Simultaneously, a crane was selected from the equipment library (Figure 4-15). After importing the desired type of crane, an equipment task was created in the 4D simulation. Through *add selection*, the imported equipment was linked to the created equipment task (Figure 4-13).

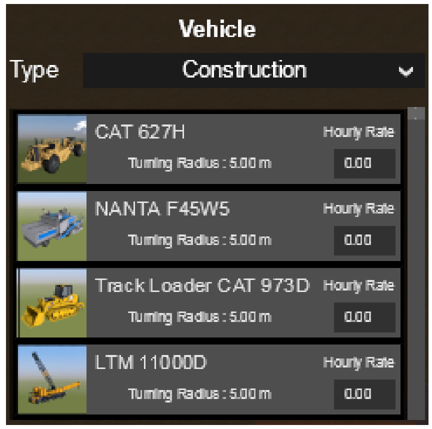


Figure 4-15 Equipment library

All of the equipment movements were broken down to the micro-tasks for improving the visualization accuracy. For simulating equipment at high LOD, several frames were assigned for each equipment (crane and boom lifts), as shown in Figure 4-16. Each frame represents a micro-task; the group of these frames visualizes the behavior of equipment throughout the project.

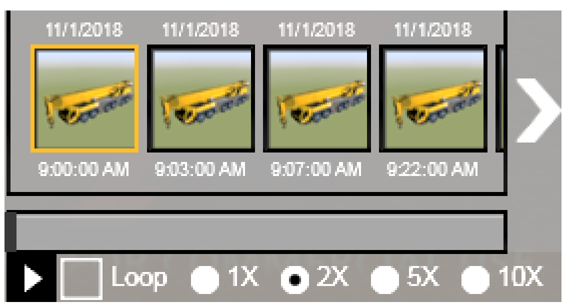


Figure 4-16 Micro-tasks of the simulated crane

In the first case study, a crawler crane (LTM 1300) was animated to move the 23 components from the origin at the staging area to the actual locations they should be assembled based on the BIM model. The first component for installation was found at the staging area. Then, the jib, trolley, and hook of the crane were adjusted to grab this component from its location. The crane parts moved to release the component at the destination based on the BIM model. This process was repeated until all structural components were installed. Subsequently, a specific time was allocated to each task (this part is explained in Section 4.4.3) and a collision test was run to find the potential safety hazards (Figure 4-17).

Other pieces of equipment (boom lifts) were also animated to visualize the construction activities along with the crane operations. Three boom lifts were used for assembling the steel components. They were animated and scheduled based on their tasks.

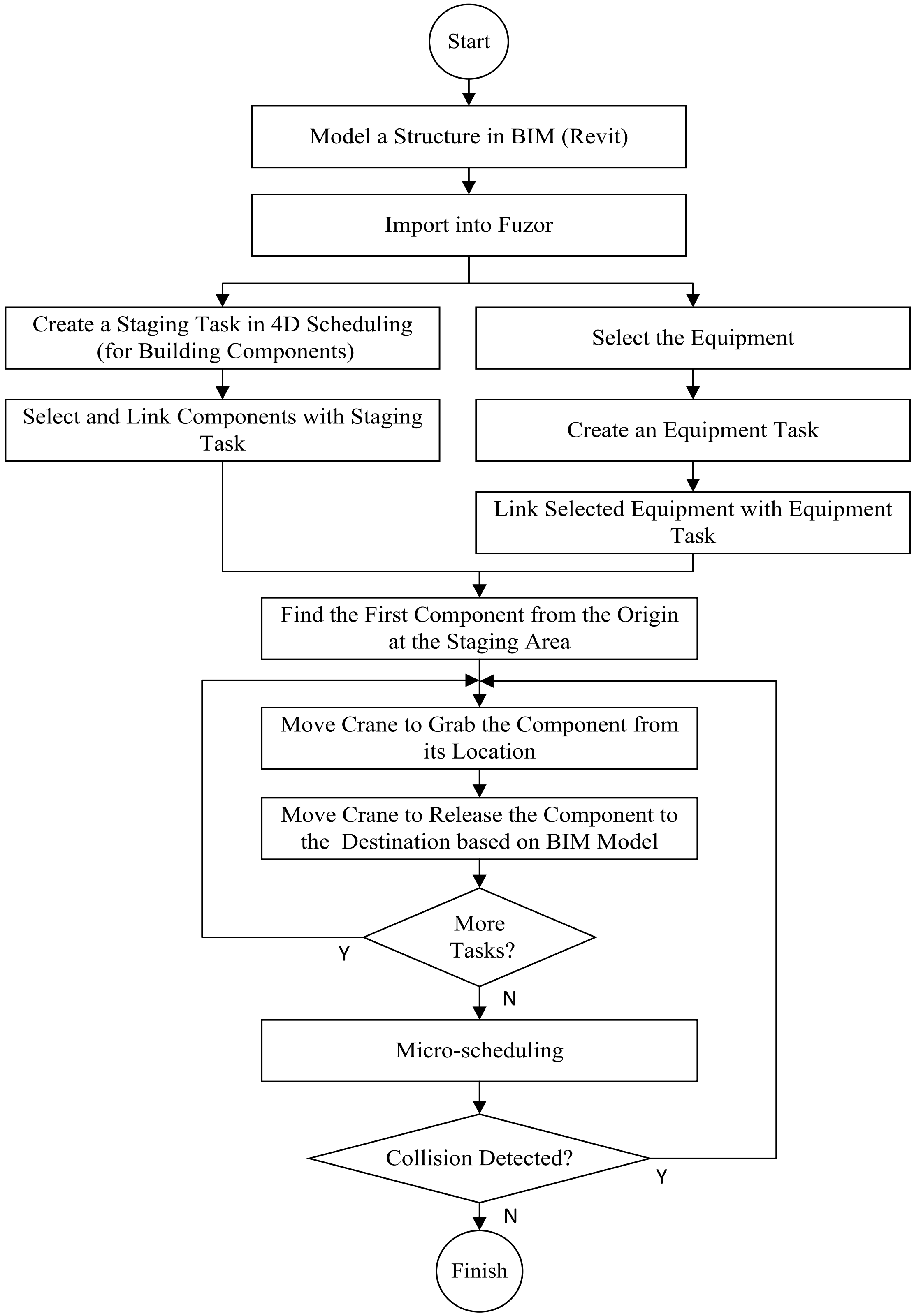


Figure 4-17 Flowchart of animating crane movements

4.4.3 Scheduling

4.4.3.1 Scheduling equipment movements at the micro-level

Each movement of the equipment needs a specific time based on the planned tasks. Before micro-scheduling, overall scheduling should be determined for each piece of equipment and workers, in which the start and finish time are specified, as shown in Table 4-2. The minimum duration which can be selected in this part is an hour, while minutes and seconds can be stated for each task duration later.

Table 4-2 Scheduling in 4D simulation

No.	Name of object	Duration	Planned start	Planned end
1	Staging task	3 days	11/1/2018	11/3/2018
2	LTM 1300 (crane)	3 days	11/1/2018	11/3/2018
3	Boom lift 1	3 days	11/1/2018	11/3/2018
4	Boom lift 2	3 days	11/1/2018	11/3/2018
5	Boom lift 3	3 days	11/1/2018	11/3/2018
6	Worker on Boom lift 1	3 day	11/1/2018	11/3/2018
7	Worker on Boom lift 2	2 day	11/1/2018	11/2/2018
8	Worker on Boom lift 3	2 day	11/2/2018	11/3/2018

It was assumed that the structure erected within 3 days, from 11/1/2018 to 11/3/2018 and the working hours started from 9 AM and finished at 5 PM. However, equipment and workers do not work all the time and they are ideling for some time. Table 4-3 shows that each component was scheduled in detail to be rigged, moved and assembled in an hour. After swinging to the staging area (7 min), the crane was operated to rig the component with the aid of the workers during 15 min. In the next step, the crane picked up and moved the component to the final location in accordance with the BIM model in 8 min. Then, 30 min were allocated for assembling the component by the workers standing on the boom lifts. In addition, workers were scheduled at the site to do other tasks. For instance, a worker standing on the boom lift assembles several components within 6 hours.

Table 4-3 Detailed schedule of equipment movements

	Component	Date	Duration	Swing to the staging area (7 min)	Rigging (15 min)	Swing to the final location (8 min)	Assembling (30 min)
	C1	11/1/2018	1 Hour	09:00-09:07 AM	09:07-09:22 AM	09:22-09:30 AM	09:30-10:00 AM
	C2	11/1/2018	1 Hour	10:00-10:07 AM	10:07-10:22 AM	10:22-10:30 AM	10:30-11:00 AM
	E1	11/1/2018	1 Hour	11:00 -11:07 AM	11:07-11:22 AM	11:22-11:30 AM	11:30-12:00 AM
	C3	11/1/2018	1 Hour	12:00 -12:07 PM	12:07-12:22 PM	12:22-12:30 PM	12:30-01:00 AM
	C4	11/1/2018	1 Hour	01:00 -01:07 PM	01:07-01:22 PM	01:22-01:30 PM	01:30-02:00 PM
	E2	11/1/2018	1 Hour	02:00 -02:07 PM	02:07-02:22 PM	02:22-02:30 PM	02:30-03:00 PM
	R1	11/1/2018	1 Hour	03:00 -03:07 PM	03:07-03:22 PM	03:22-03:30 PM	03:30-04:00 PM
	R2	11/1/2018	1 Hour	04:00 -04:07 PM	04:07-04:22 PM	04:22-04:30 PM	04:30-05:00 PM
	C5	11/2/2018	1 Hour	09:00 -09:07 AM	09:07-09:22 AM	09:22-09:30 AM	09:30-10:00 AM
	C6	11/2/2018	1 Hour	10:00 -10:07 AM	10:07-10:22 AM	10:22-10:30 AM	10:30-11:00 AM
	E3	11/2/2018	1 Hour	11:00 -11:07 AM	11:07-11:22 AM	11:22-11:30 AM	11:30-12:00 AM
	E4	11/2/2018	1 Hour	12:00 -12:07 PM	12:07-12:22 PM	12:22-12:30 PM	12:30-01:00 PM
	R3	11/2/2018	1 Hours	01:00 -01:07 PM	01:07-01:22 PM	01:22-01:30 PM	01:30-02:00 PM
	P1	11/2/2018	1 Hour	02:00 -02:07 PM	02:07-02:22 PM	02:22-02:30 PM	02:30-03:00 PM
	P2	11/2/2018	1 Hour	03:00 -03:07 PM	03:07-03:22 PM	03:22-03:30 PM	03:30-04:00 PM
	P3	11/2/2018	1 Hour	04:00 -04:07 PM	04:07-04:22 PM	04:22-04:30 PM	04:30-05:00 PM
	P4	11/3/2018	1 Hour	09:00 -09:07 AM	09:07-09:22 AM	09:22-09:30 AM	09:30-10:00 AM
	P5	11/3/2018	1 Hour	10:00 -10:07 AM	10:07-10:22 AM	10:22-10:30 AM	10:30-11:00 AM
	P6	11/3/2018	1 Hour	11:00 -11:07 AM	11:07-11:22 AM	11:22-11:30 AM	11:30-12:00 AM
	P7	11/3/2018	1 Hour	12:00 -12:07 PM	12:07-12:22 PM	12:22-12:30 PM	12:30-01:00 PM
	P8	11/3/2018	1 Hour	01:00 -01:07 PM	01:07-01:22 PM	01:22-01:30 PM	01:30-02:00 PM
	P9	11/3/2018	1 Hour	02:00 -02:07 PM	02:07-02:22 PM	02:22-02:30 PM	02:30-03:00 PM
	P10	11/3/2018	1 Hour	03:00 -03:07 PM	03:07-03:22 PM	03:22-03:30 PM	03:30-04:00 PM
Total	**23**	**3 Days**	**23 h**	**2 h & 41 min (161 min)**	**5 h & 45 min (345 min)**	**3 h & 4 min (184 min)**	**11 h & 30 min (690 min)**

4.4.3.2 The linkage between micro-schedule and micro-tasks

In order to model the structure at high 4D-LOD, resulting in full analysis of equipment activities, equipment tasks should be linked to the detailed schedule of these tasks. In the first case study, the crane was animated to rig, move and assemble the 23 components. 7 frames were allocated for tasks of rigging, moving, and assembling each structural component in an hour. Out of 7 frames, one frame was allocated for rigging (15 min) and another one for assembling (30 min), since the crane parts did not move during the time of these tasks. Moreover, two frames were apportioned for the task of swinging to the staging area (7 min) and three frames for the task of swinging to the final location (8 min). In general, the crane was animated to rig, move, and assemble 23 components through 151 frames (7 × 23).

Figure 4-18 shows the sequence of simulating the construction tasks with animated workers and articulated equipment in 4D. This figure depicts the result of applying the micro-schedule for each equipment task and the time at which different components were assembled.

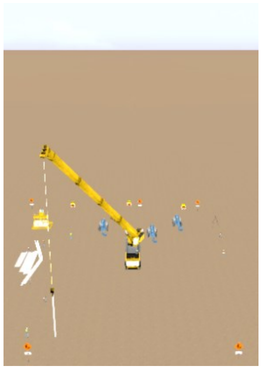
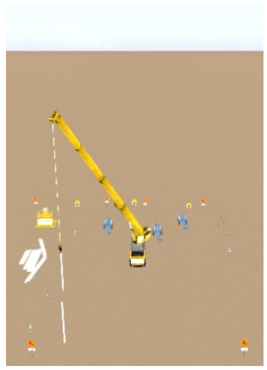
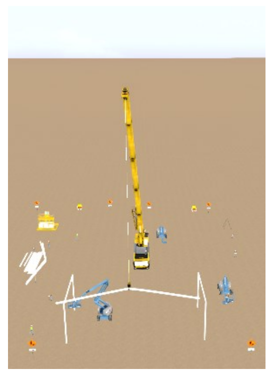
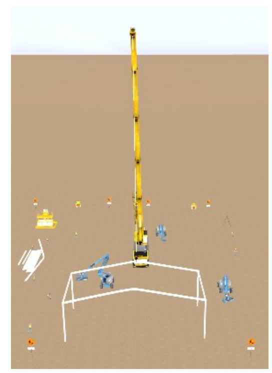
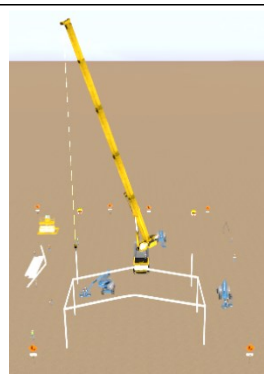
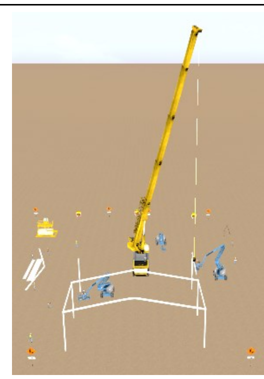
 C1 Date: 11/1/2018 Time: 09:30-10:00 AM	 C2 Date: 11/1/2018 Time:10:30-11:00 AM	 E1 Date: 11/1/2018 Time:11:30-12:00 AM	 C3 Date: 11/1/2018 Time:12:30-01:00 AM
 C4 Date: 11/1/2018 Time:01:30-02:00 PM	 E2 Date: 11/1/2018 Time:02:30-03:00 PM	 R1 Date: 11/1/2018 Time:03:30-04:00 PM	 R2 Date: 11/1/2018 Time:04:30-05:00 PM
 C5 Date: 11/2/2018 Time: 09:30-10:00 AM	 C6 Date: 11/2/2018 Time:10:30-11:00 AM	 E3 Date: 11/2/2018 Time:11:30-12:00 AM	 E4 Date: 11/2/2018 Time:12:30-01:00 PM

Figure 4 18 The sequential steps of erecting the structure in 4D and assembling time

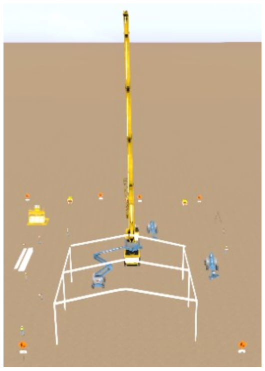
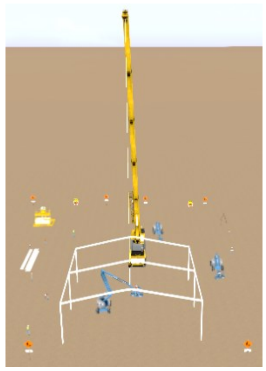
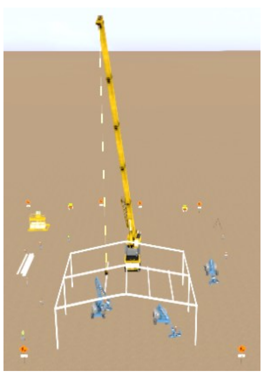
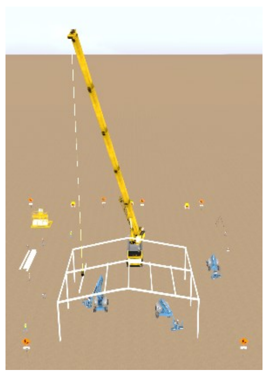
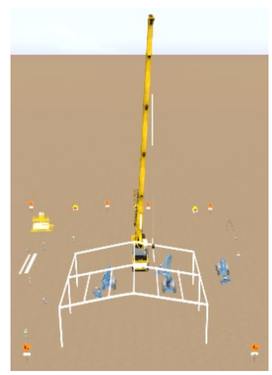
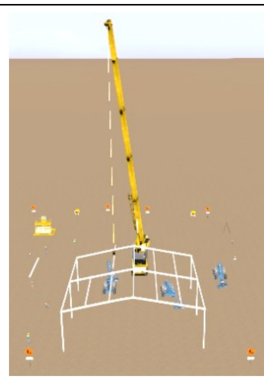
 R3 Date: 11/2/2018 Time:01:30-02:00 PM	 P1 Date: 11/2/2018 Time:02:30-03:00 PM	 P2 Date: 11/2/2018 Time:03:30-04:00 PM	 P3 Date: 11/2/2018 Time:04:30-05:00 PM
 P4 Date: 11/3/2018 Time:09:30-10:00 AM	 P5 Date: 11/3/2018 Time:10:30-11:00 AM	 P6 Date: 11/3/2018 Time:11:30-12:00 AM	 P7 Date: 11/3/2018 Time:12:30-01:00 PM
 P8 Date: 11/3/2018 Time:01:30-02:00 PM	 P9 Date: 11/3/2018 Time:02:30-03:00 PM	 P10 Date: 11/3/2018 Time:03:30-04:00 PM	

Figure 4-18 The sequential steps of erecting the structure in 4D and assembling time (continued)

4.5 Second Case Study: Visualizing equipment operations at a congested site

Due to the lack of space for workers and equipment in congested sites to do their activities, the probability of conflicts increases and the work progresses slowly resulting in poor performance and low productivity. Furthermore, several activities can be carried out in parallel and detailed scheduling plays an important role. As a result, when workers and equipment should perform their tasks at a congested site in limited time, project managers should pay special attention to the spatio-temporal conflicts by using 4D simulation of construction activities at high LOD.

Based on the general information discussed in Section 4.4.1, the second case study is similar to the first one with the following modifications: (1) the site is occupied with more pieces of equipment and workers; (2) the project is erected in a shorter period of time (1 day); and (3) some barriers are added which restrict the usage of some areas of the site.

4.5.1 Resource allocation and animating the equipment activities and workers' activities

In the second case study, two cranes were operated simultaneously (Figure 4-19). The structure components for each crane were collected at two pre-defined staging areas by repeating the steps discussed in Section 4.4.2.

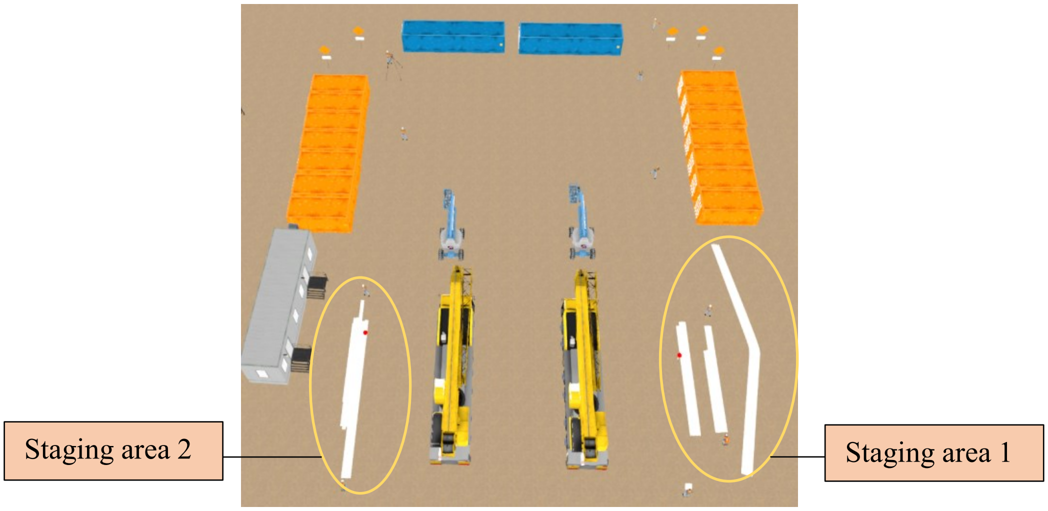


Figure 4-19 Allocating structure components

Two crawler cranes (LTM 1300) were selected from the equipment library and animated to move the 23 structure components from the origin at the staging area to their actual locations in the BIM model. The activities for rigging, moving and assembling of the components were divided between the pieces of equipment. Micro-tasks were defined for each piece of equipment separately and these tasks were visualized sequentially. Crane 1 and Crane 2 were assigned to erect the following components (in order):

Crane 1: C6, C2, E4, C1, E1, R1, R2, R3, P1, P4, P5, P9, P10

Crane 2: C5, C4, E3, C3, E2, P3, P2, P8, P7, P6

The time which each component took to be rigged, moved and installed is explained in the next section.

Additionally, two boom lifts were selected to assemble and fix the components (eave struts, rafters, and roof purlins) at their locations with the aid of workers standing on the buckets. These boom lifts were operated to assemble the following components (in order):

Boom lift 1: E4, E1, R1, R2, R3, P1, P4, P5, P9, P10

Boom lift 2: E3, E2, P3, P2, P8, P7, P6

When the crane brought a component to its final location, a worker standing on the boom lift was ready to install that component. For example, Crane 1 moved component E4 to its predefined position; Then, the worker on Boom lift 1 installed this component (Figure 4-20).

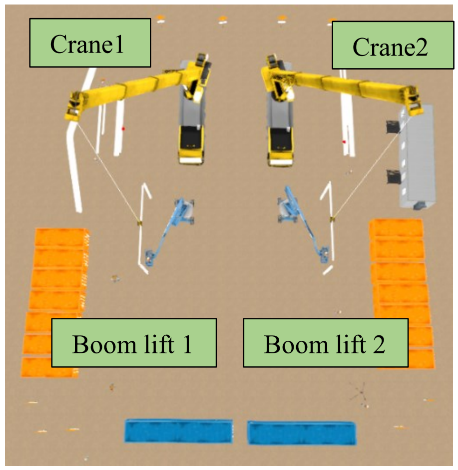


Figure 4-20 Assembling two struts

Furthermore, in the congested construction sites, several workers may work in a congested space and they interrupt each other. Therefore, it is important to determine their activities and working hours in detail in the planning stage. When workers and the equipment operators know each other's tasks and the corresponding time, accidents can be reduced. For instance, Figure 4-21 shows two workers working at the same time in a narrow space. One of the workers is working on the bucket of the boom lift and the other is assembling the rafter while sitting on the strut and wearing a safety harness.

Figure 4-21 Workers' activities in a narrow space

4.5.2 Scheduling

4.5.2.1 Specifying tasks and scheduling equipment at the micro-level

Table 4-4 shows general scheduling including the working hours of workers and pieces of equipment (2 cranes and 2 boom lifts). Similar to the first case study, the movements of equipment were broken down to the micro-tasks, and specific durations (micro-schedule) were considered for these tasks (Figure 4-16). Based on the complexity of the activity, the number of micro-tasks can change so that the time allocated for each task can be flexible.

Cranes and boom lifts were modeled to erect the structure in one day (11/1/2018), from 6 AM to 7 PM (13 hours). Each component of the structure was scheduled in detail to be rigged, moved and assembled in an hour, as shown in Table 4-5.

Table 4-4 Scheduling in 4D simulation (Case study 2)

No.	Name of object	Duration	Planned start	Planned end
1	Staging task 1	1 day	11/1/2018	11/1/2018
2	Staging task 2	1 day	11/1/2018	11/1/2018
3	Crane 1 (LTM 1300)	1 day	11/1/2018	11/1/2018
4	Crane 2 (LTM 1300)	1 day	11/1/2018	11/1/2018
5	Boom lift 1	1 day	11/1/2018	11/1/2018
6	Boom lift 2	1 day	11/1/2018	11/1/2018
7	Worker on Boom lift 1	1 day	11/1/2018	11/1/2018
8	Worker on Boom lift 2	1 day	11/1/2018	11/1/2018
9	Worker (s)	1 day	11/1/2018	11/1/2018

Table 4-5 Micro-scheduling of the equipment activities (Case study 2)

	Component	Equipment	Duration	Swing to the staging area (7 min)	Rigging (15 min)	Swing to the final location (8 min)	Assembling (30 min)
	C6	Crane 1	1 Hour	06:00-06:07 AM	06:07-06:22 AM	06:22-06:30 AM	06:30-07:00 AM
	C5	Crane 2					
	C2	Crane 1	1 Hour	07:00-07:07 AM	07:07-07:22 AM	07:22-07:30 AM	07:30-08:00 AM
	C4	Crane 2					
	E4	Crane 1	1 Hour	08:00-08:07 AM	08:07-08:22 AM	08:22-08:30 AM	08:30-09:00 AM
	E3	Crane 2					
	C1	Crane 1	1 Hour	09:00-09:07 AM	09:07-09:22 AM	09:22-09:30 AM	09:30-10:00 AM
	C3	Crane 2					
	E1	Crane 1	1 Hour	10:00-10:07 AM	10:07-10:22 AM	10:22-10:30 AM	10:30-11:00 AM
	E2	Crane 2					
	R1	Crane 1	1 Hour	11:00-11:07 AM	11:07-11:22 AM	11:22-11:30 AM	11:30-12:00 AM
	R2	Crane 1	1 Hour	12:00-12:07 PM	12:07-12:22 PM	12:22-12:30 PM	12:30-01:00 PM
	R3	Crane 1	1 Hour	01:00-01:07 PM	01:07-01:22 PM	01:22-01:30 PM	01:30-02:00 PM
	P1	Crane 1	1 Hour	02:00-02:07 PM	02:07-02:22 PM	02:22-02:30 PM	02:30-03:00 PM
	P3	Crane 2					
	P4	Crane 1	1 Hour	03:00-03:07 PM	03:07-03:22 PM	03:22-03:30 PM	03:30-04:00 PM
	P2	Crane 2					
	P5	Crane 1	1 Hour	04:00-04:07 PM	04:07-04:22 PM	04:22-04:30 PM	04:30-05:00 PM
	P8	Crane 2					
	P9	Crane 1	1 Hour	05:00-05:07 PM	05:07-05:22 PM	05:22-05:30 PM	05:30-06:00 PM
	P7	Crane 2					
	P10	Crane 1	1 Hour	06:00-06:07 PM	06:07-06:22 PM	06:22-06:30 PM	06:30-07:00 PM
	P6	Crane 2					
Total	**23**	**2 Cranes**	**13 h**	**1 h & 31 min (91 min)**	**3 h & 15 min (19 5 min)**	**1 h & 44 min (104 min)**	**6 h & 30 min (390 min)**

4.5.2.2 The linkage between micro-schedule and micro-tasks

As mentioned in Section 4.4.3.2, each component was modeled to be rigged, moved, and installed using 7 frames during 60 min. Some screenshots from the construction progress and the time at which different components were assembled are shown in Figure 4-22.

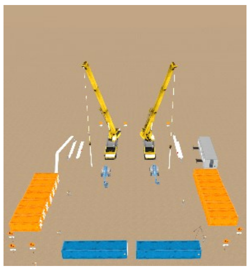
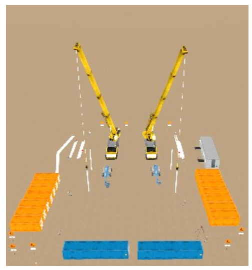
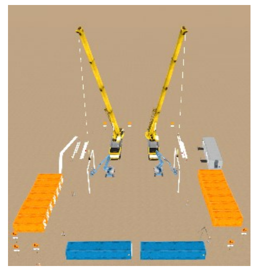
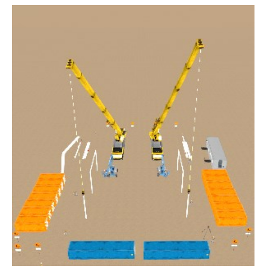
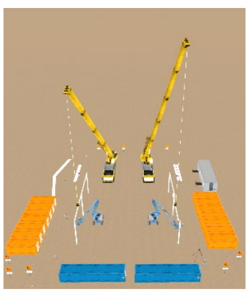
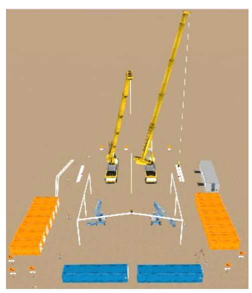
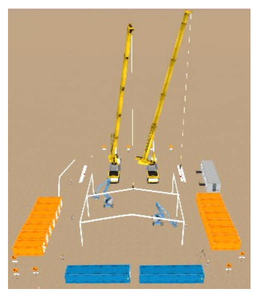
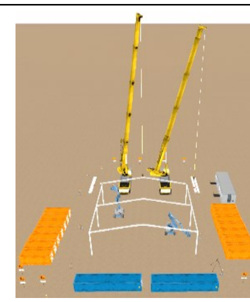
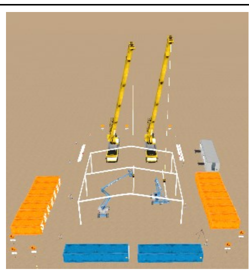
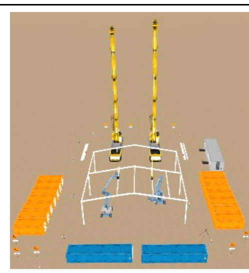
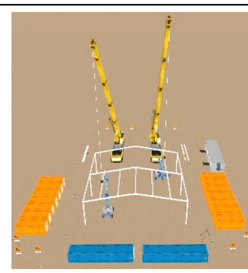
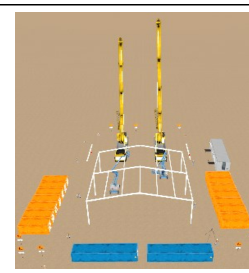
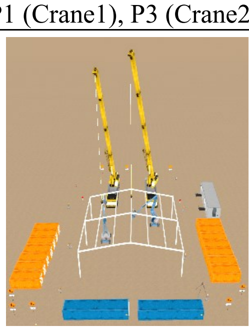
 Time: 06:30-07:00 AM C6 (Crane1), C5 (Crane2)	 Time: 07:30-08:00 AM C2 (Crane1), C4 (Crane2)	 Time:08:30-09:00 AM E4 (Crane1), E3 (Crane2)	 Time: 09:30-10:00 AM C1 (Crane1), C3 (Crane2)
 Time: 10:30-11:00 AM E1 (Crane1), E2 (Crane2)	 Time: 11:30-12:00 AM R1 (Crane1)	 Time: 12:30-01:00 PM R2 (Crane1)	 Time: 01:30-02:00 PM R3 (Crane 1)
 Time: 02:30-03:00 PM P1 (Crane1), P3 (Crane2)	 Time: 03:30-04:00 PM P4 (Crane1), P2 (Crane2)	 Time: 04:30-05:00 PM P5 (Crane1), P8 (Crane2)	 Time: 05:30-06:00 PM P9 (Crane1), P7 (Crane2)
 Time: 06:30-07:00 PM P10 (Crane1), P6 (Crane2)			

Figure 4-22 The sequential steps for modeling the structure in 4D (assembling time)

4.5.2.3 Detecting potential conflicts

Resource management is a critical point leading to a reduction in the number of conflicts between objects when tasks and schedules of construction equipment and workers are defined in detail. After animating and visualizing the construction process, a collision test was run to check potential hazards. The following conflicts could be found (1) between different pieces of equipment, (2) between workers standing on the boom lift and structure components, (3) between equipment and components, (4) between workers and equipment, and (5) between equipment parts and other surfaces like the terrain. Figure 4-23 shows a detected conflict error and a sample of conflict between pieces of equipment during the modeling of the case study that solved by the author.

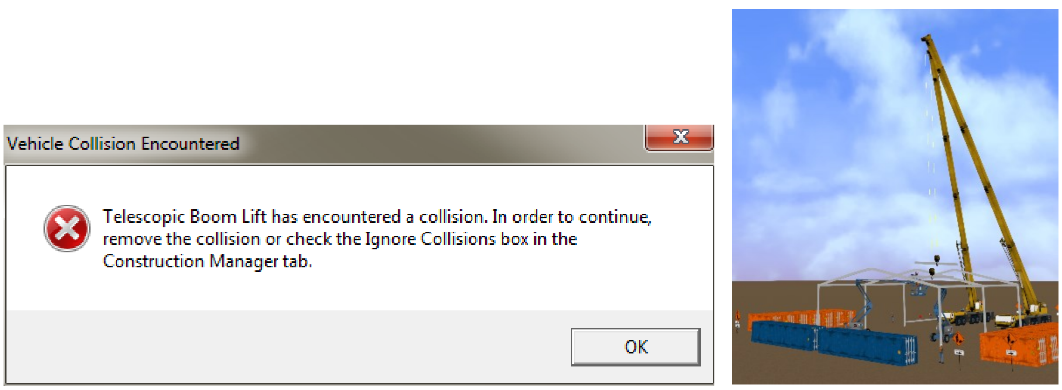


Figure 4-23 (a) The error message of conflict detection, (b) Conflicts between two cranes

Based on requirements identified for modeling construction equipment in 3.2.1, capabilities of different software tools were compared (Table 4-1) and Fuzor was selected for developing 4D context. Fuzor satisfied the following requirements for modeling equipment activities: BIM compatibility, equipment library, ability to determine multiple DOFs, simultaneously moving parts, path planning (relocation), modeling at high 4D-LOD, collision avoidance, and other requirements (e.g. setting specific speed for each equipment movement). It should be noted that these features can be manually applied in the software environment. Furthermore, this tool allows the linkage between BIM model and equipment that is going to erect the structure. Components are picked from the staging area and are moved to the destination based on the BIM model. However, this is more applicable in big projects in which the safety issues and spatio-temporal conflicts could have major impacts (e.g. large-scale capital projects). If any mistakes occur during the erection of large and congested projects, it is costly and dangerous. As a result, detailed simulation and scheduling of these projects play an important role in improving safety and productivity.

On the other hand, Fuzor has some limitations and needs to be improved (Appendix B). For example, it does not support the creation of compound and dynamic workspaces and only simple box spaces can be generated.

4.6 Construction safety training in 3D/4D virtual reality

4.6.1 Development of the case scenarios in a virtual construction site

After developing the 4D construction site, the designed safety scenarios for training presented in Section3.4.1 were added to the 4D model. The hazards were added to the model presented in Section 4.4 for the training phase, and the 4D model developed in Section 4.5 was used to make the testing more challenging. Next, twenty students from the Department of Building, Civil, and Environmental Engineering at the Concordia University were selected to train about PPE- and equipment-related hazards.

The important role of PPE (e.g. hard hats, gloves, safety harnesses, and reflective clothing) and the identification of equipment-related dangers in improving on-site safety were explained to students based on safety regulations and guidelines (OSHA). This process was accompanied by a photo representation; the required pieces of protective equipment for construction workers and requisite measures for preventing accidents with equipment were represented and explained through conventional methods in ten minutes. Next, the instructions for using Oculus Rift as a VR tool were given to students (Appendix C). The seven educational scenarios explained in Section 3.4.1 were introduced to students while they were navigating in the virtual construction site. They visualized and experienced PPE-related hazards in the 3D and 4D virtual environments. In addition, equipment-oriented conflicts were designated in 4D VR. This step took approximately 10 minutes to be completed.

In the next step, the capabilities of students for recognizing hazards were tested (average score: 6/7). This assessment ensures that the learners have the capability of applying their safety knowledge to the real construction site. Figure 4-24 shows an example of the hazard inspection process, at which a learner navigates in the virtual construction site and visualizes a welder who does not wear safety gloves. The worker without suitable PPE is marked and the relevant message is added by using touch controllers (pressing Trigger and moving the hand).

Figure 4-24 Hazard identification in VR

4.6.2 Evaluation result

The evaluation questions and responses of students are shown in Table 4-6. This assessment provided general insight about the role of VR training in improving safety knowledge of students, though statistical significance cannot be considered because of the small number of participators.

Table 4-6 Results of the questionnaire about the safety learning experience

Criteria	Questions	Mean			
		Training methods	Conventional	3D VR	4D VR
Visualization	1. The hazards were represented realistically.		1.95	3.75	4.65
Safety recognition	2. The training improved your safety knowledge.		2.6	4.1	4.85
Memory response	3. You remember what you have experienced clearly.		2.6	4.1	4.7
Attractiveness	4. You are interested in experiencing similar training sometimes in the future.		1.8	4.05	4.75
	5. You suggest others (your friends) to have similar training.		2.15	4.25	4.95
		Mean	1.97	4.15	4.85
Safety knowledge (Equipment)	6. Visualizing the equipment operations in specific training method had impact on improving your safety knowledge.		1.6	3.4	4.95

Notes: 1 = Strongly disagree; 2 = Disagree; 3 = Neutral; 4 = Agree; 5 = Strongly agree

Based on the findings, 4D VR is more effective than 3D VR and traditional training methods, as shown in Figure 4-25. Students felt more comfortable to use 4D VR for learning purposes since they found an opportunity to develop their safety recognition capabilities. Based on students' feedbacks, the hazards at the 4D virtual construction site were represented more realistically compared with 3D and conventional methods. They also mentioned that the interactive and engagement characteristics of the VR content are clear in their memory. Most of students did not try VR training and were eager to experience new training methods. In addition, they believed that visualizing the equipment activities in 4D VR had positive impact on improving their safety knowledge. However, 3D VR and traditional training do not provide students with full recognition of equipment-related hazards.

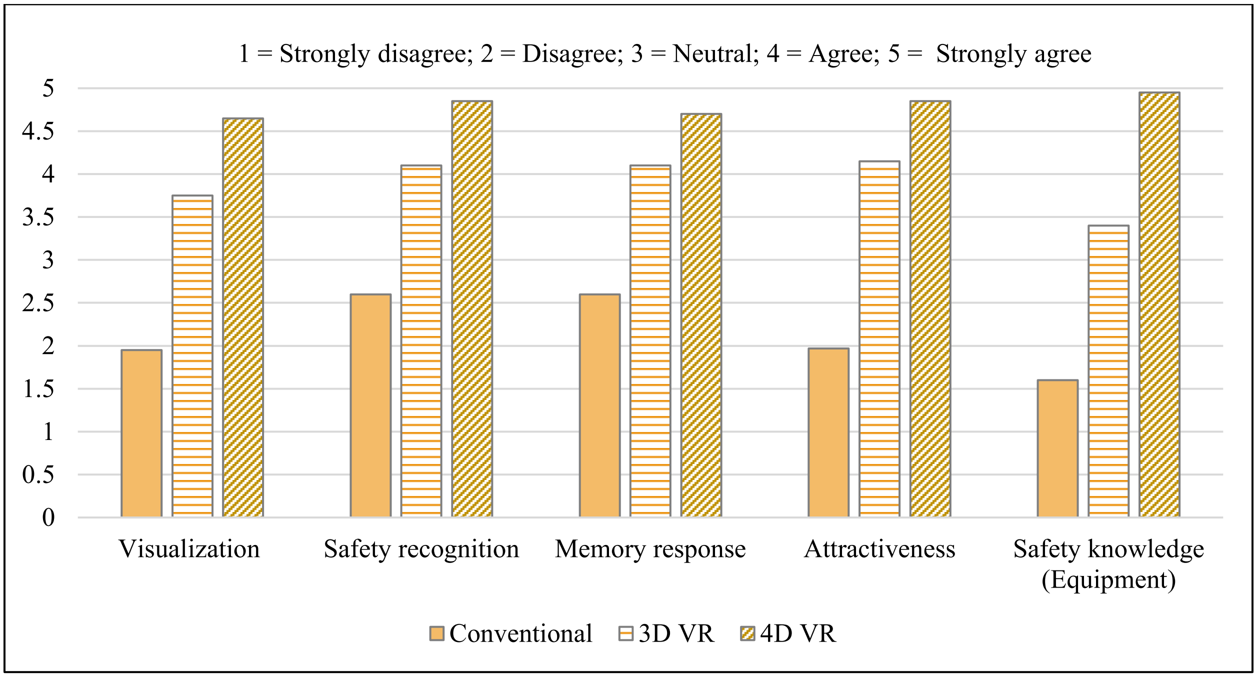


Figure 4-25 The evaluation result

4.7 Summary and conclusions

Case studies, capabilities and limitations of the existing tools regarding modeling equipment operations, and construction safety training in VR form this chapter. The chapter starts with an equipment-oriented comparison between 3D/4D tools and game engines based on the requirements discussed in Chapter 3. They were tested and evaluated in terms of detecting equipment and workspace conflicts, simultaneously moving equipment components, animating complex repetitive tasks, visualizing dynamic workspaces, etc. Section 4.3 presented the applicability of the proposed method using a piece of equipment and its workspace which were visualized dynamically in 3D animation software.

A simplified structure was modeled in Revit before importing into Fuzor software to animate and schedule the erection progress. In Section 4.4, cranes and three boom lifts were animated and the equipment movements were broken down to the micro-tasks to show the activities accurately. Furthermore, a specific time was defined for each related task to be able to appropriately schedule the equipment cycle time and the entire project time. Some challenges were applied to the second model (Section 4.5) to convey the importance of visualizing and scheduling the equipment movements and the worker's activities in congested sites for improving the safety, productivity, and constructability. More pieces of equipment worked simultaneously in the construction site to show how several pieces of equipment can safely perform their tasks in a limited space with accurate scheduling.

In Section 4.6, construction students were trained and tested to identify some safety issues in the 3D/4D virtual environments. To gain a general view of their experience, an assessment was carried out at the end of work. This evaluation tried to compare the effectiveness of traditional, 3D VR, and 4D VR training methods in the safety training of students. The results showed that 4D VR helps construction students improve their safety recognition and specifically equipment-oriented hazard recognition.

CHAPTER 5 CONCLUSIONS AND FUTURE WORK

5.1 Summary of research

BIM can be used in animating and scheduling equipment activities at the micro-level and the results can be used in VR safety training. In this thesis, first, relevant research works in the areas of 3D/4D applications in the construction industry, visualization of equipment activities, equipment workspace generation, and the usage of VR in the safety training were reviewed. Then, the main requirements for modeling construction equipment activities at high LOD were defined in Chapter 3. In addition, a method was proposed to generate articulated pieces of equipment and dynamic equipment workspace in different commercial tools.

From another point of view, construction students and the next generation of workers are in need of experiential VR training methods to enhance their safety knowledge because traditional training methods have several limitations. This study proposed an approach to improve students'safety knowledge through 4D VR, which represents hazards on the construction site as they happen in the real world (e.g. the hazard of a worker walking under a crane when its components are moving).

The strengths and limitations of several tools in terms of visualizing, animating, and simulating equipment-related characteristics were analyzed in Chapter 4. Fuzor VDC was used as a 4D BIM platform to visualize and schedule the erection of a steel structure by cranes and boom lifts. Two case studies with different conditions were carried at a high level of detail; in the first case study, the erection activities were animated and scheduled in three days, although in the second more pieces of equipment were used to finish the work in one day. Also, workers' activities on the construction site were visualized.

According to recent research works, training students with VR technology is more promissing than traditional methods. Therefore, some field hazard samples resulting from not wearing appropriate PPE by workers were provided in VR. On the other hand, accidents occur between equipment and workers since they have not trained properly on how to work safely with different pieces of equipment. A 4D virtual environment with some hazards was provided to enhance and test the safety knowledge of students. Then, a questionnaire was prepared and the results were presented in different areas including visualization, safety recognition, memory response, attractiveness, and recognition.

5.2 Research contributions and conclusions

The contributions of this research are as follows:

(1) Requirements that tools should satisfy for animating and simulating construction equipment activities are defined and the capabilities of tools in terms of animating and visualizing the equipment activities are analyzed and compared; (2) A method is proposed in which different pieces of construction equipment can be animated through external modeling, programming, and manually in an advanced BIM software. In addition, dynamic equipment workspaces are generated based on the equipment activities; and (3) A framework for safety knowledge training is proposed that uses 4D VR for improving hazard identification of construction students.

In addition, the followings represent the conclusions of this research:

(1) When equipment tasks are visualized and scheduled at micro-level in 4D BIM, the conflicts can be detected in advance and the cycle time of equipment can be determined, leading to the improvement of safety, productivity, and constructability in construction sites; (2) VR safety

training improves hazard recognition of construction students since they can experience risky conditions in virtual construction sites; and (3) The capability of students in identifying equipment-related hazards would improve when they experience safety risks applied in 4D VR.

5.3 Limitation and future works

Different BIM and non-BIM tools were utilized to visualize the construction progress. 3D platforms (3DS Max) and game engines (Unity 3D) allow users to make the equipment articulated, although they are not BIM-based and the modeling process is time consuming. It should be mentioned that 3D BIM and CAD models with attached BIM data can be converted into Unity through a new plugin (Tridify).

On the other hand, several 4D BIM tools, such as Navisworks and Synchro, provide basic functions for animating equipment movements. However, these applications have the following limitations: (1) lack of a library of construction equipment; (2) time-consuming process for modeling articulated equipment; (3) limited capabilities for animating the equipment movements; (4) lack of ability to schedule equipment activities at micro-level; (5) difficulties for generating dynamic workspaces; and (6) not supporting laws of physics and terrain following. Moreover, equipment training simulators such as Vortex simulator can model the operations of heavy construction equipment at a high LOD, although they are prepared for training purposes.

Fuzor VDC was used in this research as a new generation of VDC tools to animate and schedule construction activities and equipment operations at the micro-level. However, this process was done manually and mobile cranes were modeled to move and assemble prefabricated components.

From the training point of view, most research works have utilized 3D VR technology for training the workers, operators, inspectors, etc. However, 4D virtual environments can be used to inform them about hazard that may threat their lives during the construction sequences and equipment operations.

This research has achieved its objectives, although there are areas of research that can be taken into consideration in future work:

(1) Construction equipment operations can be simulated automatically for large construction projects by using programming.
(2) A more complete collection of hazard scenarios in the 4D VR/AR environment can be designed and a larger group of users can test and evaluate its efficiency.
(3) 4D AR and VR technologies can be integrated with mobile platforms to improve the collaboration between the construction project team members such as field inspectors and project managers.

REFERENCES

3D Lift Plan. (2019). “Crane lift planning software.” <http://www.3dliftplan.com/default.aspx>.

AIA. (2017). “Level of development specification guide LOD Spec 2017 Guide.”

Akhavian, R., and Behzadan, A. H. (2015). “Construction equipment activity recognition for simulation input modeling using mobile sensors and machine learning classifiers.” *Advanced Engineering Informatics*, Elsevier Ltd, 29(4), 867-877.

Akinci, B., and Fischer, M. (2000). “4-D Workplanner: A prototype system for automated generation of construction spaces and analysis of time-space conflicts.” *Computing in Civil and Building Engineering*, American Society of Civil Engineers, Reston, VA, 740-747.

Akinci, B., Fischer, M., and Kunz, J. (2002a). “Automated generation of work spaces required by construction activities.” *Journal of Construction Engineering and Management*, 128(4), 306-315.

Akinci, B., Fischer, M., Kunz, J., and Levitt, R. (2002b). “Representing work spaces generically in construction method models.” *Journal of Construction Engineering and Management*, 128(4), 296-305.

AndersOrum. (2015). “Games - Vehicle Physics Simulation- Unity Forum.” <https://forum.unity.com/threads/vehicle-physics-simulation-update-20-feb-17-terrain-editor-preview-1.324085/>.

Anumba, C. J., and Wang, X. (2012). “Mobile and pervasive computing in construction.” An introduction, *Wiley publishing*, 1-10.

Autodesk. (2019a). “What’s new in 3DS Max 2019 | 3D modelling & rendering features.” *Autodesk*, <https://www.autodesk.co.uk/products/3ds-max/features>.

Autodesk. (2019b). “Features for Navisworks Manage and Navisworks Simulate.” <https://www.autodesk.com/products/navisworks/features>.

Behzadan, A. H., Aziz, Z., Anumba, C. J., and Kamat, V. R. (2008). “Ubiquitous location tracking for context-specific information delivery on construction sites.” *Automation in Construction*, 17(6), 737-748.

Behzadan, A. H., and Kamat, V. R. (2007). “Georeferenced registration of construction graphics in mobile outdoor augmented reality.” *Journal of Computing in Civil Engineering*, 21(4), 247–258.

BuildingSMART. (2018). “buildingSMART - The home of BIM.” <https://www.buildingsmart.org/>.

Burke, M. J., Sarpy, S. A., Smith-crowe, K., Chan-serafin, S., Salvador, R. O., and Islam, G. (2006). “Relative effectiveness of worker safety and health training methods.” *American Journal of Public Health*, 96(2), 315-324.

Carmigniani, J., Furht, B., Anisetti, M., Ceravolo, P., Damiani, E., and Ivkovic, M. (2011). “Augmented reality technologies, systems and applications.” *Multimedia Tools and Applications*, 51(1), 341-377.

Caudell, T. P., and Mizell, D. W. (1992). “Augmented reality: an application of heads-up display technology to manual manufacturing processes.” *Proceedings of the Twenty-Fifth Hawaii International Conference on System Sciences*, IEEE, vol. 2, 659-669.

Cheng, T., and Teizer, J. (2013). “Real-time resource location data collection and visualization technology for construction safety and activity monitoring applications.” *Automation in Construction*, Elsevier B.V., 34, 3-15.

Chi, H. L., Kang, S. C., and Wang, X. (2013). “Research trends and opportunities of augmented reality applications in architecture, engineering, and construction.” *Automation in Construction*, Elsevier B.V., 33, 116-122.

Choi, B., Lee, H.-S., Park, M., Cho, Y. K., and Kim, H. (2014). “Framework for work-space planning using four-dimensional BIM in construction projects.” *Journal of Construction Engineering and Management*, 140(9), 04014041.

CM Labs simulations. (2019). “Simulators and simulation software.” <https://www.cm-labs.com/>.

Digging & Rigging, Inc. (2019). “Crane Hauling Photos.”<http://www.digrig.com/gallery.html>.

Dunston, P. S., Asce, A. M., and Wang, X. (2005). “Mixed reality-based visualization interfaces for architecture , engineering , and construction industry.” *Journal of Construction Engineering and Management*, 131(12), 1301-1309.

ESI Group. (2018). “ESI showcases smart virtual prototyping at CES and ESI Group.” <https://www.esi-group.com/company/press/news-releases/esi-showcases-smart-virtual-prototyping-ces-2018>.

Fischer, M., and Kam, C. (2002). “PM4D final report.” *CIFE, Stanford University*, USA, 1-49.

Fuzor. (2019). <https://www.kalloctech.com/>.

Gikas, J., and Grant, M. M. (2013). “Mobile computing devices in higher education : Student perspectives on learning with cellphones , smartphones & social media.” *The Internet and Higher Education*, Elsevier Inc., 19, 18-26.

Golparvar-Fard, M., Peña-Mora, F., Savarese, S. (2009). “A 4-dimensional augmented reality model for automating construction progress monitoring data collection, processing and communication." *Journal of Information Technology in Construction (ITcon),* Vol. 14, 129-153.

GrabCAD. (2019). "3D CAD model collection | GrabCAD community library." <https://grabcad.com/library?page=1&time=all_time&sort=recent&query=wc>.

Gradientspace. (2019). "Simplex touch controls." <http://www.gradientspace.com/simplex-touch-controls/>.

Gu, N., Singh, V., and Wang, X. (2010). "Applying augmented reality for data interaction and collaboration in BIM." *15th International Conference on Computer Aided Architectural Design Research in Asia (CAADRIA)*, 511-520.

Guevremont, M., and Hammad, A. (2019). "Defining levels of development for 4D simulation of major capital construction projects." *Advances in Informatics and Computing in Civil and Construction Engineering*, Springer International Publishing, Cham, 77-83.

Hammad, A., Setayeshgar, S., Zhang, C., and Asen, Y. (2012). "Automatic generation of dynamic virtual fences as part of BIM-based prevention program for construction safety." *Proceedings Title: Proceedings of the 2012 Winter Simulation Conference (WSC)*, IEEE, 1-10.

Hartmann, T., Gao, J., and Fischer, M. (2008). "Areas of application for 3D and 4D models on construction projects." *Journal of Construction Engineering and Management*, 134(10), 776-785.

Heesom, D., and Mahdjoubi, L. (2004). "Trends of 4D CAD applications for construction planning." *Construction Management and Economics*, 22(2), 171-182.

IfcResource. (2019). <http://www.buildingsmart-tech.org/ifc/IFC2x3/TC1/html/ifckernel/lexical/ifcresource.htm>.

Kamat, V. R., and Martinez, J. C. (2001). "Visualizing simulated construction operations in 3D." *Journal of Computing in Civil Engineering*, 15(4), 329-337.

Kamat, V. R., and Martinez, J. C. (2005). "Dynamic 3D visualization of articulated construction equipment." *Journal of Computing in Civil Engineering*, 19(4), 356-368.

Keneman, A. (National L. U., and Waller, R. (Montana S. U. B. (2016). "Augmented reality in the classroom." *Literacy Practice & Research*, 41(3), 5-8.

Kim, C., Kim, H., Park, T., and Kim, M. K. (2011). "Applicability of 4D CAD in civil engineering construction: Case study of a cable-stayed bridge project." *Journal of Computing in Civil Engineering*, 25(1), 98-107.

Koo, B., and Fischer, M. (2000). “Feasibility study of 4D CAD in commercial construction.” *Journal of Construction Engineering and Management*, 126(4), 251-260.

Langari, M. (2015). “Enhanced path planning method for improving safety and productivity of excavation operations.” *Master thesis, Concordia University*, 2015.

Le, Q. T., Pedro, A., Lim, C. R., Park, H. T., Park, C. S., and Kim, H. K. (2015). “A framework for using mobile based virtual reality and augmented reality for experiential construction safety education.” *International Journal of Engineering Education*, 31(3), 713-725.

Li, M. (2010). “Applications of virtual reality technology in construction industry.” *International Conference on Computer Engineering and Technology,* IEEE, 4, V4-223-V4-227.

Li, X., Yi, W., Chi, H. L., Wang, X., and Chan, A. P. C. (2018). “A critical review of virtual and augmented reality (VR/AR) applications in construction safety.” *Automation in Construction*, Elsevier, 86, 150-162.

Liebherr. (2019). “Technical data Hydraulic crawler crane, HS 855 HD.”

Lin, K. Y., Son, J. W., and Rojas, E. M. (2011). “A pilot study of a 3D game environment for construction safety education.” *Electronic Journal of Information Technology in Construction*, Vol. 16, 69-83.

Lin, T. J., Duh, H. B. L., Li, N., Wang, H. Y., and Tsai, C. C. (2013). “An investigation of learners’ collaborative knowledge construction performances and behavior patterns in an augmented reality simulation system.” *Computers and Education*, Elsevier Ltd, 68, 314-321.

Lucas, J., Tech, V., Thabet, W., Tech, V., Worlikar, P., and Tech, V. (2008). “A VR-based training program for conveyor belt safety.” *Journal of Information Technology in Construction*, Vol. 13, 381-407.

Lumion. (2019).“Beautiful renders within reach.” <https://lumion.com/>.

Mandal, S. (2013). “Brief introduction of virtual reality and its challenges.” *International Journal of Scientific & Engineering Research*, 4(4), 304-309.

Mazuryk, T., and Gervautz, M. (1996). “Virtual reality in the real world - history , applications, technology, future.” *Institute of Computer Graphics Vienna University of Technology*, Austria.

Mital, A., and Karwowski, W. (1991). “Workspace, equipment and tool design.” *Elsevier Science Ltd*.

National BIM Standard (NBIMS) project committee. (2016). “About the national BIM standard-United States®” *National Institute of Building Sciences*,

<https://www.nationalbimstandard.org/about>.

Oculus. (2019). <https://www.oculus.com/>.

OSHA. (2017). “Commonly used statistics, occupational safety and health administration.” *Occupational Safety and Health Administration*, <https://www.osha.gov/oshstats/commonstats.html>.

Pascal Steel. (2019). “Metal buildings and steel structures.”. <https://pascalsteel.com/>.

PlayStation. (2019). “VR Over 200 games and counting.” <https://www.playstation.com/en-us/explore/playstation-vr/>.

Pradhananga, N., and Teizer, J. (2013). “Automatic spatio-temporal analysis of construction site equipment operations using GPS data.” *Automation in Construction*, Elsevier B.V., 29, 107-122.

Rezazadeh, I. M., Wang, X., Firoozabadi, M., and Hashemi Golpayegani, M. R. (2011). “Using affective human-machine interface to increase the operation performance in virtual construction crane training system: A novel approach.” *Automation in Construction*, Elsevier B.V., 20(3), 289-298.

Sacks, R., Perlman, A., and Barak, R. (2013). “Construction safety training using immersive virtual reality construction safety training using immersive virtual reality.” *Construction Management and Economics,* Vol. 31, 1005–1017.

Salman Azhar, Khalfan, M., and Maqsood, T. (2015). “Building information modelling (BIM): now and beyond.” *Construction Economics and Building*, 12(4), 15-28.

Samsung gear VR with controller. “The official Samsung Galaxy site.” (2019). <https://www.samsung.com/global/galaxy/gear-vr/>.

Shang, Z., and Shen, Z. (2016). “A framework for a site safety assessment model using statistical 4D BIM-based spatial-temporal collision detection. ” *Construction Research Congress*, American Society of Civil Engineers, Reston, VA, 2187-2196.

Stephenson, H. L. (2007). “PS.04 scheduling management: Classifications vs levels.” *AACE, International Transactions*, (18), 1-9.

Sutherland, I. E., and E., I. (1968). “A head-mounted three dimensional display.” *Proceedings of the Fall Joint Computer Conference, AFIPS ’68 (Fall, part I)*, ACM Press, New York, USA, 757.

Synchro software. (2019). “4D construction project management software.” <https://www.synchroltd.com/products-2/synchro-pro/>.

Tantisevi, K., and Akinci, B. (2007). “Automated generation of workspace requirements of mobile crane operations to support conflict detection.” *Automation in Construction*, 16(3), 262-276.

Thomas, B., Close, B., Donoghue, J., Squires, J., Bondi, P. De, Morris, M., and Piekarski, W. (2000). “ARQuake: An outdoor/indoor ar first person application.” *Proceedings of the International Symposium on Wearable Computers*, 139-146.

Tommaso, L., and Paolis, D. (1994). “Virtual and augmented reality applications.” *Department of Engineering for Innovation University of Salento*, Lecce, Italy.

Trebbe, M., Hartmann, T., and Dorée, A. (2015). “4D CAD models to support the coordination of construction activities between contractors.” *Automation in Construction*, Elsevier B.V., 49(PA), 83-91.

Tridify convert. (2019). “3D BIM; CAD models to Unity with BIM data attached.” <https://www.tridify.com/convert/>.

Unity. (2019). <https://unity3d.com/>.

Vahdatikhaki, F., and Hammad, A. (2015). “Dynamic equipment workspace generation for improving earthwork safety using real-time location system.” *Advanced Engineering Informatics*, Elsevier Ltd, 29(3), 459-471.

Vahdatikhaki, F., Hammad, A., olde Scholtenhuis, L., Miller, S., and Makarov, D. (2017). “Data-driven scenario generation for enhanced realism of equipment training simulators.” *6th CSCE/CRC International Construction Specialty Conference,* Vancouver, Canada

Vahdatikhaki, F., Hammad, A., and Siddiqui, H. (2015). “Optimization-based excavator pose estimation using real-time location systems.” *Automation in Construction*, Elsevier B.V., 56, 76-92.

VIVE^{TM} . (2019). “VIVE virtual reality system.” <https://www.vive.com/us/product/vive-virtual-reality-system/>.

Wang, H. J., Zhang, J. P., Chau, K. W., and Anson, M. (2004a). “4D dynamic management for construction planning and resource utilization.” *Automation in Construction*, 13(5 SPEC. ISS.), 575-589.

Wang, X., Dunston, P. S., and Skiniewski, M. (2004b). “Mixed reality technology applications in construction equipment operator training.” *Proceedings of the 21st International Symposium on Automation and Robotics in Construction (ISARC)*, 21-25.

Wang, X., and Dunston, P. S. (2007). “Design, strategies, and issues towards an augmented reality-based construction training platform.” *Electronic Journal of Information Technology in Construction*, 363-380.

Wang, X., and Love, P. E. D. (2012). "BIM + AR: Onsite information sharing and communication via advanced visualization." *Proceedings of the 16th International Conference on Computer Supported Cooperative Work in Design, CSCWD 2012*, IEEE, 850-855.

Wang, X., Love, P. E. D., Kim, M. J., Park, C. S., Sing, C. P., and Hou, L. (2013). "A conceptual framework for integrating building information modeling with augmented reality." *Automation in Construction*, Elsevier B.V., 34, 37-44.

Wang, X., Truijens, M., Hou, L., Wang, Y., and Zhou, Y. (2014). "Integrating augmented reality with building information modeling: onsite construction process controlling for liquefied natural gas industry." *Automation in Construction*, Elsevier B.V., 40, 96-105.

Whyte, J., Bouchlaghem, N., Thorpe, A., and McCaffer, R. (2000). "From CAD to virtual reality: Modelling approaches, data exchange and interactive 3D building design tools." *Automation in Construction*, 10(1), 43-45.

Zhang, S., Lee, J., Venugopal, M., Teizer, J., and Eastman, C. (2011). "Integrating BIM and safety: an automated rule-based checking system for safety planning and simulation." *CIB W99 Conference*, 1-13.

Zhang, S., Teizer, J., Lee, J. K., Eastman, C. M., and Venugopal, M. (2013). "Building Information Modeling (BIM) and safety: automatic safety checking of construction models and schedules." *Automation in Construction*, Elsevier B.V., 29, 183-195.

Zhang, S., Teizer, J., Pradhananga, N., and Eastman, C. M. (2015). "Workforce location tracking to model, visualize and analyze workspace requirements in building information models for construction safety planning." *Automation in Construction*, Elsevier B.V., 60, 74-86.

Zhou, Y., Ding, L., Wang, X., Truijens, M., and Luo, H. (2015). "Applicability of 4D modeling for resource allocation in mega liquefied natural gas plant construction." *Automation in Construction*, Elsevier B.V., 50(C), 50-63.

APPENDIX A - DOFS FOR SOME PIECES OF EQUIPMENT

Table A-1 The DOFs for some pieces of equipment available in Fuzor Library

Equipment		Rotations	Translations	Description
Excavators	Compact (Wheel) Excavator	4 (6)	1	
	Backhoe	7	1	
	Demolition Excavator	6	1	
	Electric Rope Shovel	5	1	
	Loader	3	1	
Lifts	Fork Lift	1	2	
	Scissor Man Lift	0	3	
Cranes	Tower Crane	1	2+2	The length of two translations (T3, T4) are adjustable (Figure A-8(b))
	Luffer Crane	2	1+1	The length of T2 is adjustable (Figure A-9(b))
	Crawler Crane	2	2+1	The length of T2 is adjustable (Figure A-10(b))
	Roof Crane	2	1	
Others	Road roller	1 or 2	1	
	Bulldozer	2 (3)	1	The lights of Bulldozer can be rotated
	Hydrofraise	3	3	

Excavators:

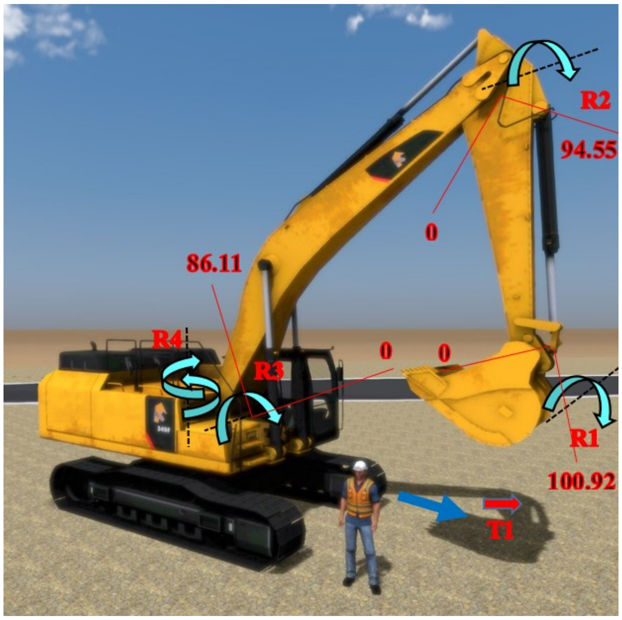


Figure A-1 Compact Excavator

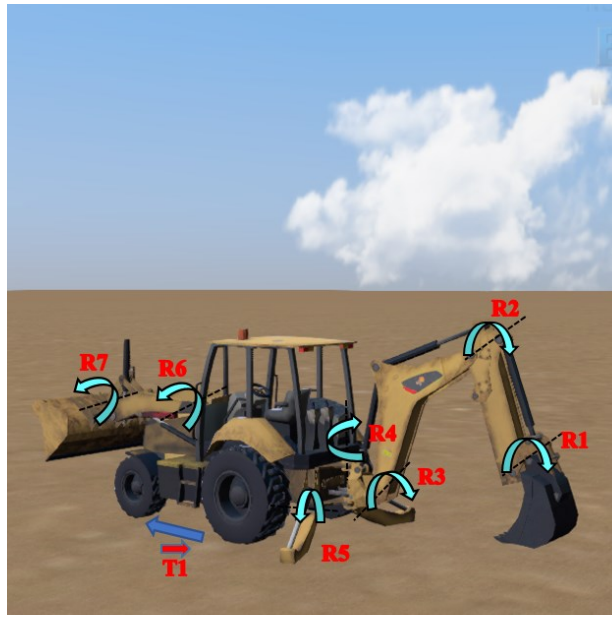


Figure A-2 Backhoe

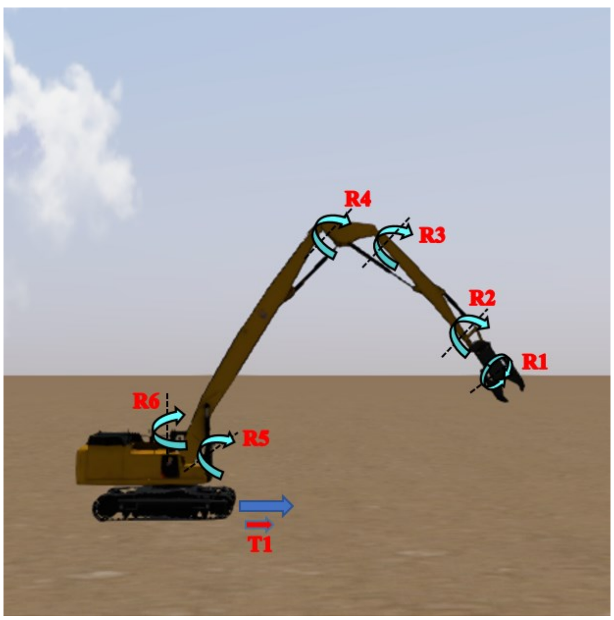


Figure A-3 Demolition Excavator

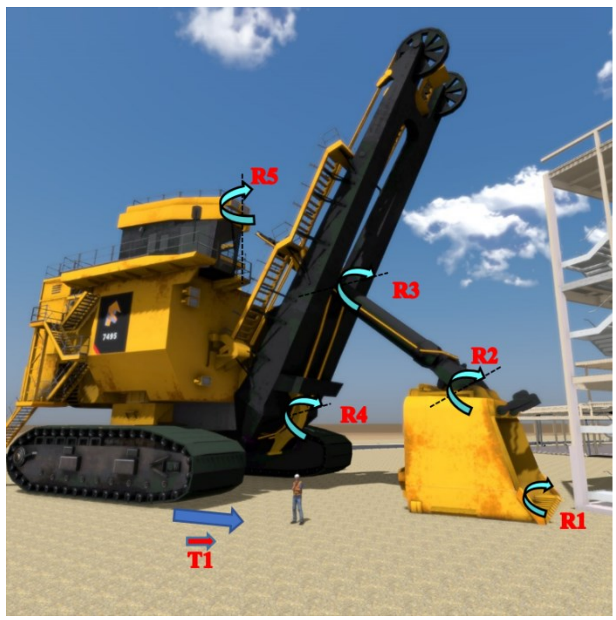


Figure A-4 Electric Rope Shovel

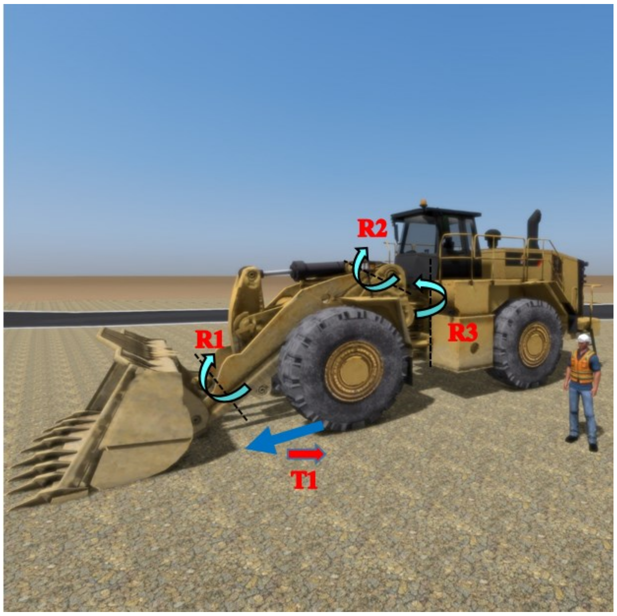


Figure A-5 Loader

Lifts:

Figure A-6 Fork Lift

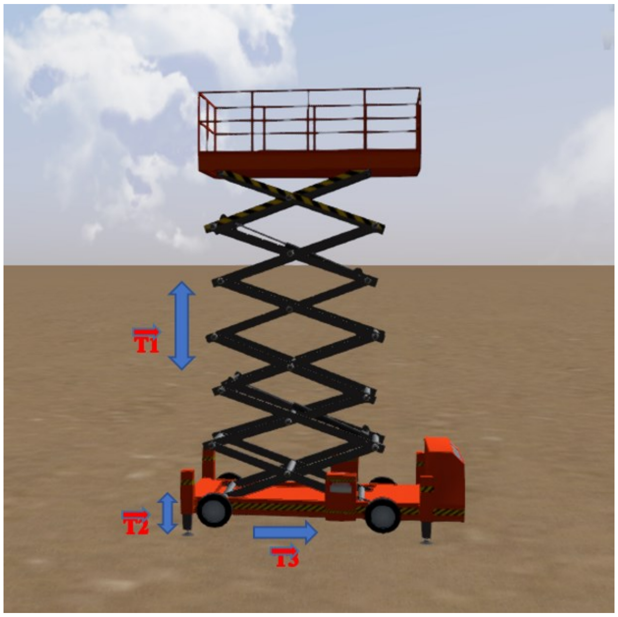
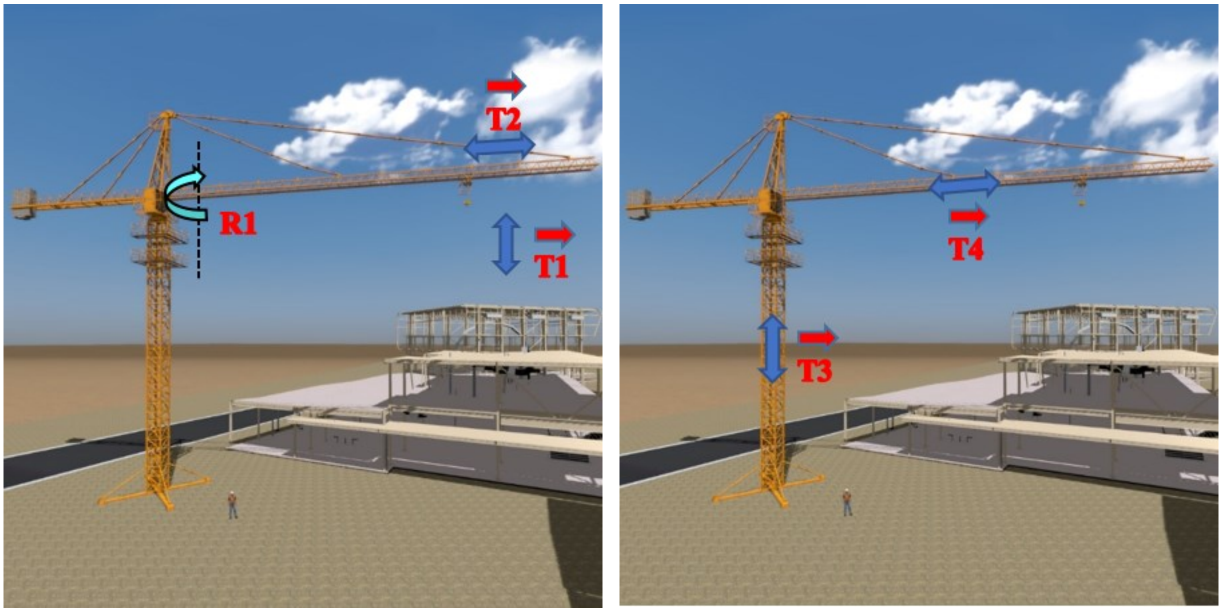


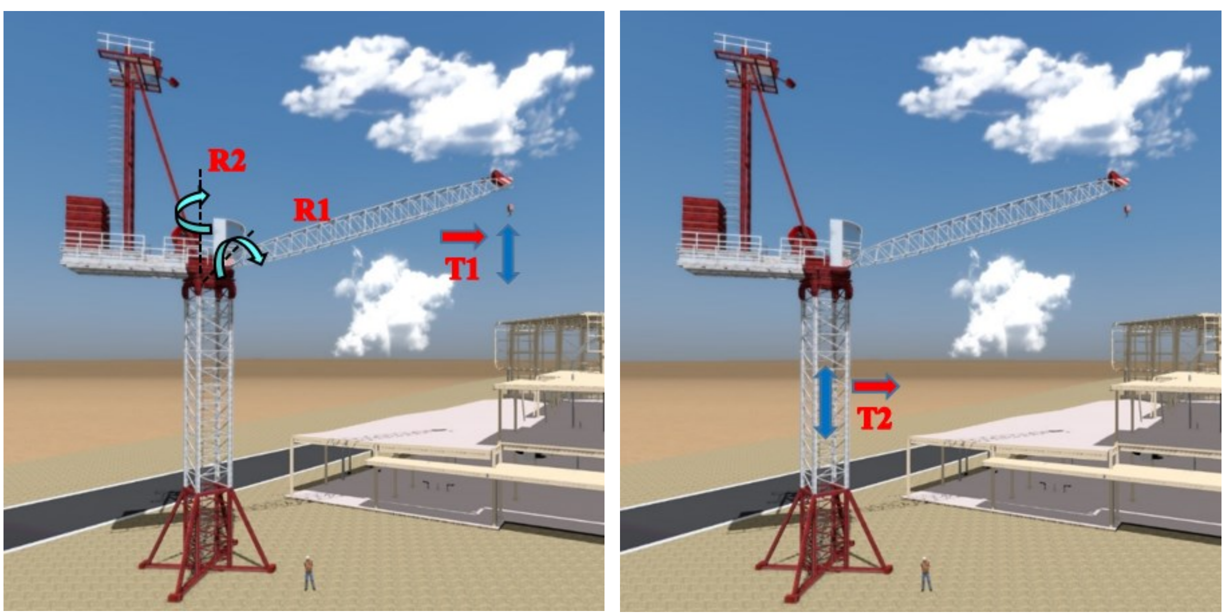
Figure A-7 Scissor Man Lift

Cranes:



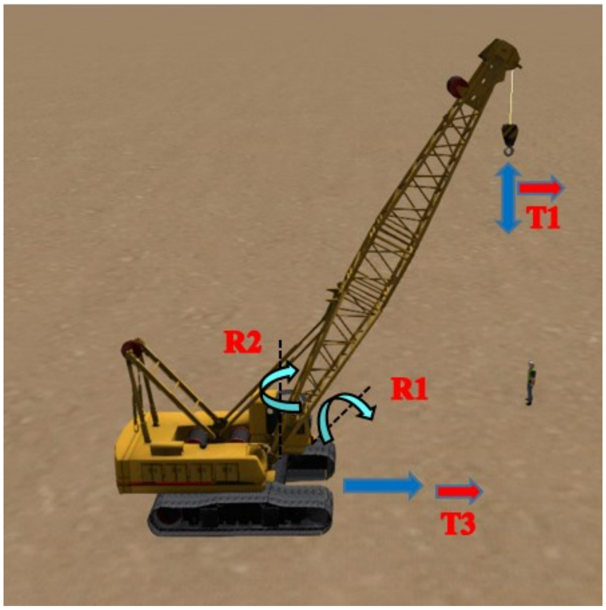
(a) (b) Adjustments of configuration

Figure A-8 Tower Crane

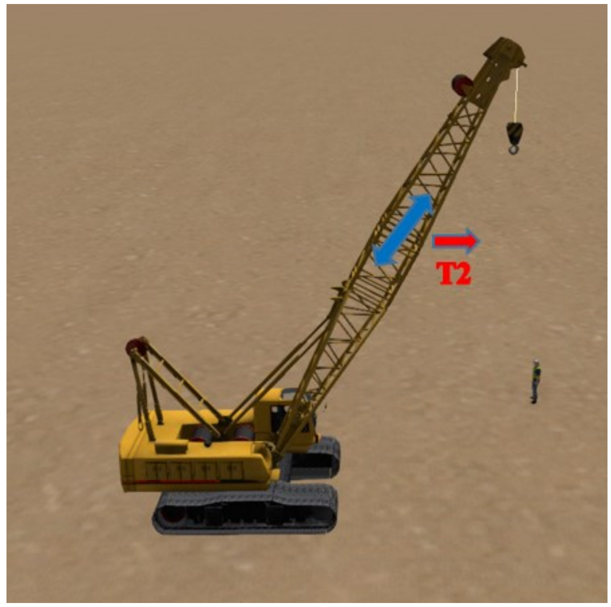


(a) (b) Adjustments of configuration

Figure A-9 Luffer Crane



(a)



(b) Adjustments of configuration

Figure A-10 Crawler Crane

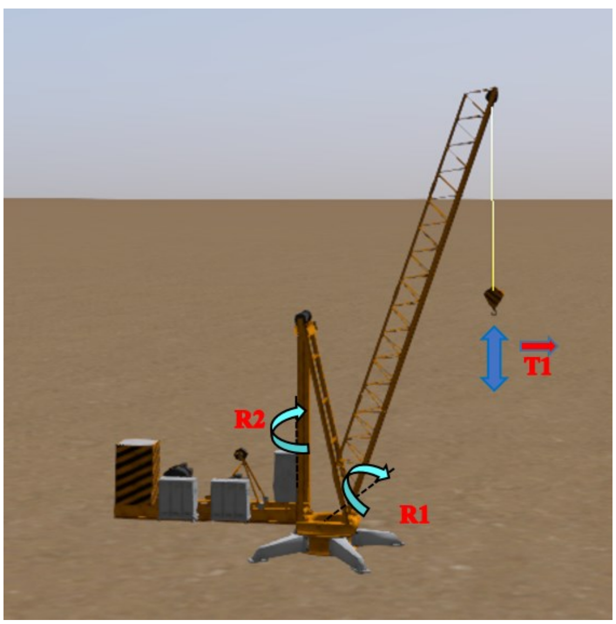


Figure A-11 Roof Crane

Others:

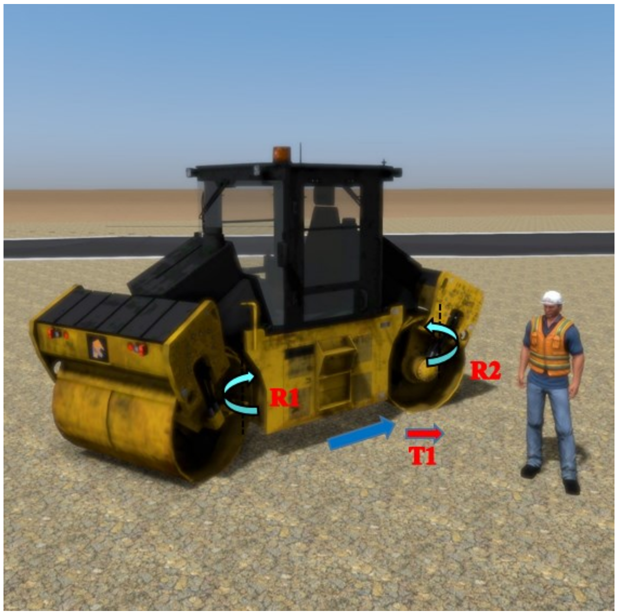


Figure A-12 Road Roller

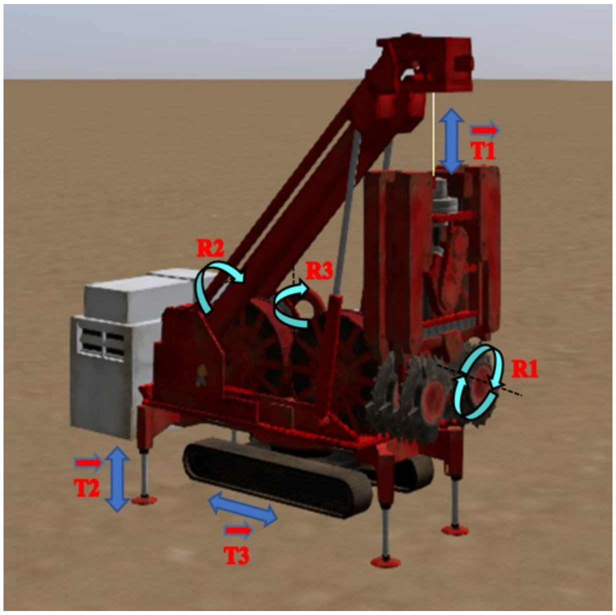


Figure A-13 Bulldozer

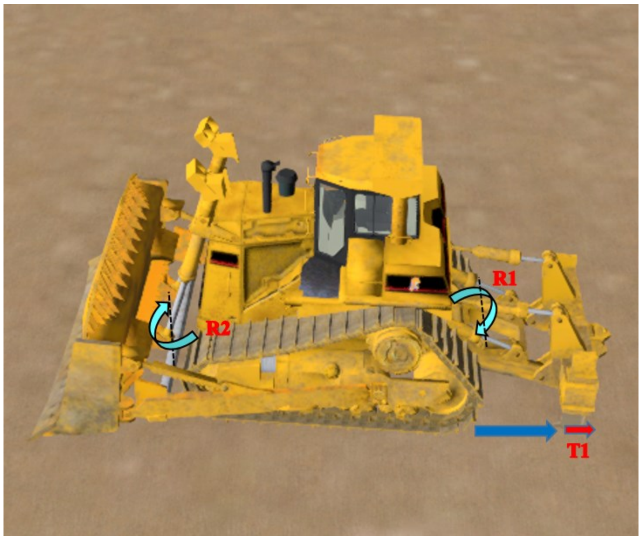


Figure A-14 Hydrofraise

Table A-2 The range of DOFs for the category of excavators

Components	The type of DOFs		Name	The range of DOFs (Unit: degrees)
	Rotation	Translation		
Compact Excavator				
Bucket	✓		R1	0-100.92
Stick	✓		R2	0-94.55
Boom	✓		R3	0-86.11
Cab	✓		R4	0-360
Track mounting		✓	T1	
Backhoe				
Bucket (hoe)	✓		R1	0-110.59
Stick (hoe)	✓		R2	0-95.83
Boom (hoe)	✓		R3	0-65.49
Swing Frame	✓		R4	0-165
Stabilizer Legs	✓		R5	0-87.33
Boom (loader)	✓		R6	0-46.86
Bucket (loader)	✓		R7	0-98.67
Wheels (loader)		✓	T1	
Demolition Excavator				
Demolition Pulveriser 1	✓		R1	0-21.19
End Arm	✓		R2	0-100.19
Extension Boom	✓		R3	0-95.14
Mid Arm	✓		R4	0-89.82
Base Boom	✓		R5	0-63.89
Cab	✓		R6	0-360
Crawler Track		✓	T1	
Electric Rope Shovel				
Dipper teeth 3	✓		R1	0-106.83
Dipper 1	✓		R2	0-106.96
Stick 2	✓		R3	0-105
Boom	✓		R4	0-72
Operator Cab	✓		R5	0-360
Crawler Track		✓	T1	
Loader				
Bucket	✓		R1	0-84.25
Boom	✓		R2	0-66
Wheels	✓		R3	0-32
Wheels		✓	T1	

Table A-3 The range of DOFs for the category of lifts

Components	The type of DOFs		Name	The range of DOFs (Unit: degrees, meter)
	Rotation	Translation		
Fork Lift				
Mast	✓		R1	0-32
Forks		✓	T1	0-2.70
Wheels		✓	T2	
Scissor Lift				
Scissor Arms		✓	T1	0-3.68
Stabilizers		✓	T2	0-0.26
Wheels		✓	T3	

Table A-4 The range of DOFs for the category of cranes

Components	The type of DOFs		Name	The range of DOFs (Unit: degrees, meter)
	Rotation	Translatio n		
Tower Crane (different models)				
Hook		✓	T1	0-50 for one segment
Trolley		✓	T2	0-18.68
Jib (Boom)	✓		R1	0-360
Adjustments of Configuration (Tower crane)				
Tower		✓	T3	
Jib (Boom)		✓	T4	
Luffer Crane (different models)				
Hook		✓	T1	0-150 for one segment
Jib (Boom)	✓		R1	0-105
Counter Jib	✓		R2	0-360
Adjustments of Configuration (Luffer crane)				
Jib (Boom)		✓	T2	
Crawler Crane				
Hook		✓	T1	0-31.89 for one segment
Boom	✓		R1	0-90
Cab	✓		R2	0-360
Track mounting		✓	T3	
Adjustments of Configuration (Crawler crane)				
Boom		✓	T2	
Roof Crane				
Hook		✓	T1	0-150
Boom	✓		R1	0-78.56
Counterweight	✓		R2	0-360

Table A-5 The range of DOFs for the road roller, bulldozer, and hydrofraise

Components	The type of DOFs		Name	The range of DOFs (Unit: degrees)
	Rotation	Translation		
Road Roller				
Rolling Drum 1	✓		R1	0-44
Rolling Drum 2	✓		R2	0-44
(Translation)		✓	T1	
Bulldozer				
Ripper	✓		R1	0-52.70
Blade	✓		R2	0-11.52
Track		✓	T1	
Hydrofraise				
Cutter wheels 1	✓		R1	0-360
Boom	✓		R2	0-31
Base Carrier	✓		R3	0-360
Guiding Frame 1		✓	T1	0-33.07
Stabilizer/ Outrigger		✓	T2	0-0.69
Track		✓	T3	

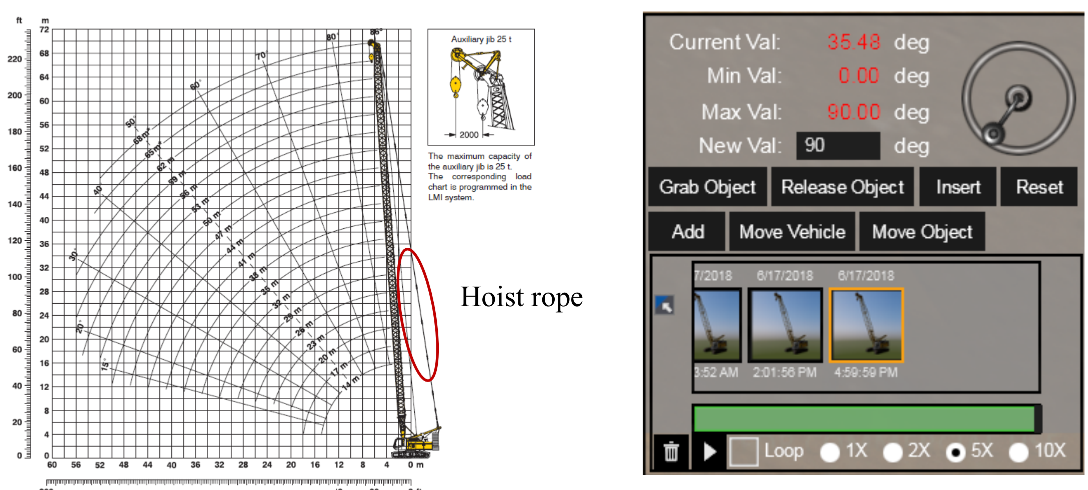
APPENDIX B - EQUIPMENT SIMULATION IN FUZOR SOFTWARE

A crane (HS855 HD) is chosen as an example in the Fuzor library. The following limitations and strengths have been found during working with the software:

Limitations

1) Some equipment characteristics, which are represented in the software, are not in accordance with the real equipment features. These are some examples:

- From the visualization point of view, the crane available in the software library lacks the hoist rope, while this type of crane possesses this rope in the real world (Figure B-1(a)). In addition, a crane that can lift a load with two or more hooking points does not exist in the library.
- In specification (Liebherr- HS 855 HD, 2019), the maximum value at which boom rotates vertically is 86°, while this value is represented 90° in Fuzor, as shown in Figure B-1(b).



(a) In practice (b) In Fuzor software

Figure B-1 The range at which boom rotates vertically

- The available cranes in the software library lack rigging rope, although different types of cranes with this rope exist in the real world.

(a) In practice (Digging & Rigging, Inc., 2019) (b) Fuzor software

Figure B-2 Difference between equipment and equipment in the software library

2) Each piece of equipment is restricted by some constraints in its performance. However, vehicles can move in each direction without any constraint in the software environment.

3) As Figure B-3 shows, equipment components are not named accurately in the software environment. However, each part has a specific name, as shown in Table B-1.

Figure B-3 The names of crane components in Fuzor

Table B-1 Names of crane components

Name of crane components	Name of components in Fuzor
Hook	Hook
Boom	Arm
Cab	Rote
Track mounting	

4) The load capacity and load chart are not considered in Fuzor. On the other hand, in 3D Lift Plan, the load capacity and load chart are taken into consideration.

Strengths

(1) The length of equipment components, such as boom crane, can be increased and decreased through *add segments.*

(2) The length, width, and height of equipment can be changed based on the desired purpose of the user and project.

APPENDIX C - INSTRUCTION OF USING FUZOR VR

The Oculus Rift, as a VR technology, consists of different parts such as the headset, touch controllers, sensors, and remote. Touch controllers allow users to interact in VR by their hands. The button names of Oculus touch controllers are shown in Figure C-1.

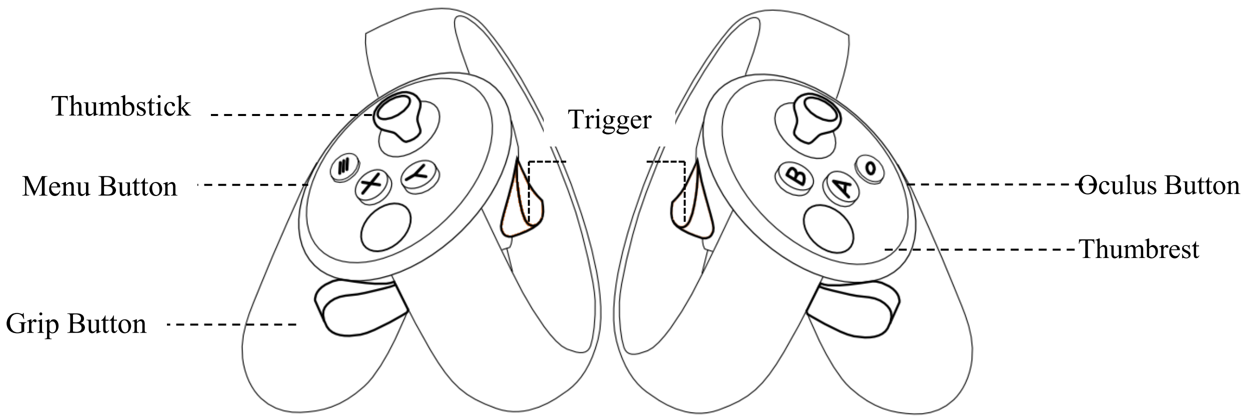
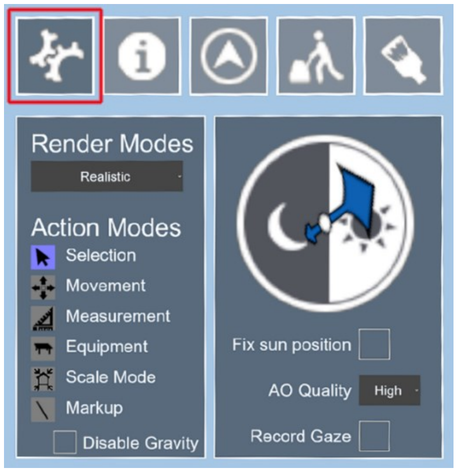


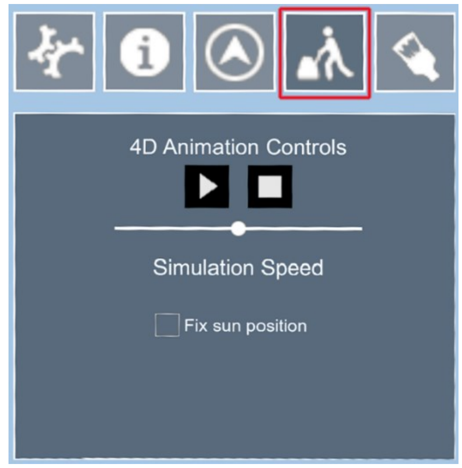
Figure C-1 Oculus touch controllers (Gradientspace, 2019)

The users of Fuzor can interact and navigate in the virtual model of their project by selecting the VR mode on the software main tab. By selecting the Menu button on the left side touch controller, Fuzor VR Menu will appear that consists of Render Modes, Element Properties, Level/ Saved Views, 4D Animation Controls, and Creation Mode. These options can be selected by pressing the Trigger and changed by using the right side Thumbstick.

As Figure C-2 (a) shows, there are different options including equipment selection, measurement, scale mode, markup, and movement in the render modes. Element properties shows BIM information for each object. Additionally, users can jump into different levels and saved views. 4D simulation can be played with the desired speed in the 4D animation controls, as shown in Figure C-2 (b). Furthermore, basic shapes, ducts, and pipes can be created in the creation mode.



(a)



(b)

Figure C-2 Different options in Fuzor VR menu (a) Render modes, and (b) 4D animation controls

APPENDIX D - OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION (OSHA) STANDARDS

OSHA PPE Standards

Standard Number: 1926.28 (Personal protective equipment):

1926.28(a) The employer is responsible for requiring the wearing of appropriate personal protective equipment in all operations where there is an exposure to hazardous conditions or where this part indicates the need for using such equipment to reduce the hazards to the employees.

1926.95 (Criteria for personal protective equipment):

1926.95(a) Protective equipment, including personal protective equipment for eyes, face, head, and extremities, protective clothing, respiratory devices, and protective shields and barriers, shall be provided, used, and maintained in a sanitary and reliable condition wherever it is necessary by reason of hazards of processes or environment, chemical hazards, radiological hazards, or mechanical irritants encountered in a manner capable of causing injury or impairment in the function of any part of the body through absorption, inhalation or physical contact.

1926.100 (Head protection):

1926.100(a) Employees working in areas where there is a possible danger of head injury from impact, or from falling or flying objects, or from electrical shock and burns, shall be protected by protective helmets.

Standard Number: 1910.135 (Head protection):

1910.135(a)(1) The employer shall ensure that each affected employee wears a protective helmet when working in areas where there is a potential for injury to the head from falling objects.

1910.135(a)(2) The employer shall ensure that a protective helmet designed to reduce electrical shock hazard is worn by each such affected employee when near exposed electrical conductors which could contact the head.

1910.138 (Hand protection):

1910.138(a) General requirements. Employers shall select and require employees to use appropriate hand protection when employees' hands are exposed to hazards such as those from skin absorption of harmful substances; severe cuts or lacerations; severe abrasions; punctures; chemical burns; thermal burns; and harmful temperature extremes.

1910.138(b) Employers shall base the selection of the appropriate hand protection on an evaluation of the performance characteristics of the hand protection relative to the task(s) to be performed, conditions present, duration of use, and the hazards and potential hazards identified.

1926.760 (Fall protection (steel erection)):

1926.760(a)(1) Each employee engaged in a steel erection activity who is on a walking/working surface with an unprotected side or edge more than 15 feet (4.6 m) above a lower level shall be protected from fall hazards by guardrail systems, safety net systems, personal fall arrest systems, positioning device systems or fall restraint systems.

Safety and Health Regulations for Construction

1926.1425 (Cranes & Derricks in Construction):

1926.1425(d) Receiving a load. Only employees needed to receive a load are permitted to be within the fall zone when a load is being landed.

1926.1425(e) During a tilt-up or tilt-down operation:

(1) No employee must be directly under the load.

1926.453 (Aerial lifts):

1926.453(b)(2)(iv) Employees shall always stand firmly on the floor of the basket, and shall not sit or climb on the edge of the basket or use planks, ladders, or other devices for a work position.

1926.453(b)(2)(v) A body belt shall be worn and a lanyard attached to the boom or basket when working from an aerial lift.

1926.1424 (Cranes & Derricks in Construction, work area control):

1926.1424(a)(3)(i) Before an employee goes to a location in the hazard area that is out of view of the operator, the employee (or someone instructed by the employee) must ensure that the operator is informed that he/she is going to that location.

1926.1424(b) Where any part of a crane/derrick is within the working radius of another crane/derrick, the controlling entity must institute a system to coordinate operations. If there is no controlling entity, the employer or employers, must institute such a system.

APPENDIX E - EVALUATION RESULT OF TRAINIG IN VR

Table E-1 Students' responses to questions

Students	Question 1			Question 2			Question 3		
	Conventional	3D VR	4D VR	Conventional	3D VR	4D VR	Conventional	3D VR	4D VR
1	4	4	5	2	3	5	2	3	5
2	1	3	5	2	3	5	1	5	5
3	2	4	5	2	4	5	2	3	5
4	2	3	4	3	4	5	3	5	5
5	1	3	5	2	4	5	1	4	5
6	2	4	5	2	5	5	4	5	5
7	3	4	4	4	5	5	3	5	4
8	1	4	5	2	5	5	2	5	5
9	2	4	4	3	4	5	2	4	5
10	3	4	5	3	4	5	4	4	5
11	1	4	5	2	4	4	2	3	5
12	3	4	5	4	5	5	5	5	5
13	1	4	5	1	4	5	1	2	3
14	2	4	5	2	3	5	3	4	5
15	3	4	4	4	4	4	3	4	4
16	2	3	4	3	4	5	3	5	5
17	2	4	5	2	4	5	3	4	4
18	1	3	4	4	5	5	1	3	4
19	1	4	5	2	4	4	3	5	5
20	2	4	4	3	4	5	4	4	5
Mean	1.95	3.75	4.65	2.6	4.1	4.85	2.6	4.1	4.7

Table E-1 Students' responses to questions (continued)

Students	Question 4			Question 5			Question 6		
	Conventional	3D VR	4D VR	Conventional	3D VR	4D VR	Conventional	3D VR	4D VR
1	1	4	5	1	4	5	1	3	4
2	1	4	5	1	5	5	1	4	5
3	2	3	5	1	3	5	1	4	5
4	1	4	5	2	5	5	1	4	5
5	1	3	5	1	4	5	1	2	5
6	2	5	5	2	4	5	3	4	5
7	3	5	5	2	5	5	3	5	5
8	1	4	5	2	5	5	1	2	5
9	2	5	5	3	5	5	2	4	5
10	2	3	5	1	4	5	2	4	5
11	2	5	5	2	3	5	1	2	5
12	3	5	5	3	5	5	2	3	5
13	1	1	1	5	5	5	2	3	5
14	1	5	5	2	4	5	1	2	5
15	4	5	5	4	4	4	3	4	5
16	2	4	5	2	4	5	2	4	5
17	2	5	5	1	3	5	1	3	5
18	2	4	5	3	4	5	2	4	5
19	1	4	4	2	5	5	1	3	5
20	2	3	5	3	4	5	1	4	5
Mean	1.8	4.05	4.75	2.15	4.25	4.95	1.6	3.4	4.95