December 2019

Examining the Effectiveness of a 4D Schedule and a Virtual Reality Model on a Modular Project: UNLV Solar Decathlon Case

Rajarshi Ghimire

EXAMINING THE EFFECTIVENESS OF A 4D SCHEDULE AND A VIRTUAL REALITY MODEL ON A MODULAR PROJECT: UNLV SOLAR DECATHLON CASE

By

Rajarshi Ghimire

Bachelor of Engineering - Civil Engineering
Tribhuvan University
2016

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science in Engineering – Civil and Environmental Engineering

Department of Civil and Environmental Engineering and Construction
Howard R. Hughes College of Engineering
The Graduate College

University of Nevada, Las Vegas

December 2019

UNLV | GRADUATE COLLEGE

Thesis Approval

The Graduate College
The University of Nevada, Las Vegas

November 13, 2019

This thesis prepared by

Rajarshi Ghimire

entitled

Examining the Effectiveness of a 4D Schedule and a Virtual Reality Model on a Modular Project: UNLV Solar Decathlon Case

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Engineering – Civil and Environmental Engineering
Department of Civil and Environmental Engineering and Construction

Jin Ouk Choi, Ph.D.
Examination Committee Chair

Moses Karakouzian, Ph.D.
Examination Committee Member

Jee Woong Park, Ph.D.
Examination Committee Member

Eric Weber, M. Arch
Graduate College Faculty Representative

Kathryn Hausbeck Korgan, Ph.D.
Graduate College Dean

ABSTRACT

Examining the Effectiveness of a 4D Schedule and a Virtual Reality Model on a Modular Project: UNLV Solar Decathlon Case

By Rajarshi Ghimire

The use of a 4D schedule as technological advancement has brought significant improvement to the planning and execution of construction projects, through visualizing stepwise construction progress, following a sequence of pre-planned activities, and finalizing a baseline schedule with necessary changes. Moreover, the application of virtual reality (VR) to create interactive 3D models of a planned structure has made it possible to make a detailed planning of any construction project. Because of these benefits, the use of 4D schedules and VR in the construction industry has increased drastically, leading to improved planning and execution. However, past studies have given little attention to the applications of such technologies on modular projects. Therefore, this study attempts to analyze the benefits and effectiveness of combining and utilizing a 4D schedule along with VR on modular projects. This study is based on an actual modular house that is currently being executed, in 2019, at the University of Nevada, Las Vegas, for the Solar Decathlon 2020 competition.

In this study, a 4D schedule was developed by combining a developed 3D model with a project schedule. Additionally, the 4D model in Revit was converted to VR using the Revit plugin - Enscape™. This study used VR model visualization followed by a questionnaire survey that included 31 participants (students). The survey questionnaires were used to compare the effectiveness of the developed 4D schedule and VR model with a 2D drawing and project schedule. The survey was divided into two parts: the first part required participants to schedule the assembly sequence of the models with the help of a 2D drawing and project schedule once, and then again with the 4D schedule and VR; the second part contained comparisons of a 2D drawing and project schedule with a 4D schedule and VR on six different topics. Results showed that in all six topics, participants agreed that a 4D schedule and VR were more effective than a 2D drawing and project schedule; however, from the open-ended questions provided to the participants at the end, it was noted that for a first-time user, 4D scheduling and VR are difficult to use. Additionally, responses on ten direct comparison topics further showed the benefits of the 4D schedule and VR. Further, the survey results show that the use of a 4D schedule and VR, with proper training, is more effective in the construction planning and execution of modular projects. These findings suggest that the implementation of 4D and VR technologies would enhance the fabrication and assembly of modules in the modular construction industry. Thus, this study encouraged the practitioners and educators in the modular construction industry to use a 4D schedule and VR, based on its success with students.

ACKNOWLEDGMENTS

I am very grateful to my advisor, Dr. Jin Ouk Choi, who has guided me through my graduate studies. His comments, suggestions, guidance, and encouragement were very helpful while completing my research.

I am also thankful to my thesis committee members, Dr. JeeWoong Park, Dr. Moses Karakouzian, and Professor Eric Weber, for their insightful comments and feedback. My gratitude is due to all my faculty, friends, and seniors for their support throughout this research.

I would also like to thank my friends from the Design Built Studio in the School of Architecture, who prepared the 2D drawing for the UNLV Solar Decathlon house. I would like to thank my friend Jin-Yeol Lee for his help during the preparation of the 4D schedule and the Virtual Reality model. I would also like to thank all survey participants during this study. I would like to thank the Office of Information Technology at UNLV for providing the student licenses for the software, Autodesk Revit 2020, Navisworks Manage 2020, and MS Project 2019, used in this study. I would also like to thank the Enscape™ team for providing me the student license to the Enscape™ plugin used in Autodesk Revit 2020 to convert the Revit model to a VR model.

I would like to acknowledge my friend Rabin Subedi for reviewing and suggesting edits on the graphics during data analysis. I would also like to deeply acknowledge my friends Ali Khodabandelu and Sayan Sakhakarmi for reading my thesis and providing valuable comments and suggestions.

I am what I am today because of my parents Rishi Ram Ghimire and Kalpana Neupane Ghimire. I am extremely thankful to them, as well as my sister, for their continued support, love, and inspiration throughout my graduate studies.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

Acronym	**Description**
2D	Two Dimensional
3D	Three Dimensional
4D	Four Dimensional (3D + Schedule)
AR	Augmented Reality
VR	Virtual Reality
4D/VR	4D and Virtual Reality
UNLV	University of Nevada, Las Vegas

CHAPTER 1: INTRODUCTION

1.1 Background

Modularization is a construction process in which some parts, or the whole of the work on a job-site, are moved to fabrication shops (Tatum, Vanegas, & Williams, 1987; O'Connor, O'Brien, & Choi, 2015). The modules created in fabrication shops are then transported to the job site and assembled there. A large number of studies have been done over the years to realize the advantages that can be gained from modularization; research has also addressed the difficulties and tendencies in the application of modularization (Haas, O'Connor, Tucker, Eickmann, & Fagerlund, 2000; Song, Fagerlund, Haas, Tatum, & Vanegas, 2005; Tatum, Vanegas, & Williams, 1987). Several studies claim that the effective utilization of modularization decreases the overall cost, duration, and number of accidents on construction projects, while reducing construction waste and noise, and improving safety, quality, productivity, and environmental performance (Haas et al., 2000; O'Connor, O'Brien, & Choi, 2016; Song et al., 2005; Tatum et al., 1987). Despite all of the benefits of modularization, on-site storage areas, and transportation/logistics are the major barriers to its application (Choi, Chen, & Kim, 2017). These challenges necessitate effective planning and scheduling to ensure the efficient transportation of modules to an assembly site and their proper storage.

Scheduling is the process of integrating a logical sequence related to how a construction project will be completed during a specific time frame (Hinze, 2011). 2D drawings and scheduling with the critical path method (CPM) have been used as the primary means of planning and scheduling in the construction industry. However, the planners and stakeholders are not able to correctly visualize a project using such 2D drawings and schedules (L. Wang, 2007). The complexity associated with huge buildings makes visualization from 2D drawings more difficult, which leads to misunderstandings in the construction sequence planning, along with spatial conflicts (L. Wang, 2007). With the employment of recent advances in technology, the construction industry is trying to go beyond traditional methods to solve these issues. The use of Building Information Modeling (BIM) has led to improved understanding, higher quality, better coordination, and more efficient management through 3D visualization. The visualized 3D models can show a better physical reality in construction operation simulation with a plethora of information (Tech, Hall, & Tech, 2001).

4D scheduling is the integration of 3D models with a construction schedule, which enables the visualization of a simulation of the construction/fabrication sequence of the project, from the beginning to the end (Changyoon Kim, Kim, & Kim, 2013; Trebbe, Hartmann, & Dorée, 2015). Previous difficulties, such as those that arise in space during the construction process, along with work sequence bugs, are mitigated by the use of a 4D schedule (Heigermoser, García de Soto, Abbott, & Chua, 2019). 4D schedules have been prominently used for improved understanding (Changyoon Kim et al., 2013), project coordination (Changyoon Kim et al., 2013), structural safety analysis (Zhang & Hu, 2011), risk mitigation strategies (Sloot, Heutink, & Voordijk, 2019), site management (Ma, Shen, & Zhang, 2005), and construction planning and progress control (Taghaddos, Eslami, Hermann, AbouRizk, & Mohamed, 2019). Despite its various benefits and applications, 4D scheduling has yet to find its application in modular construction.

VR is a computer-generated interactive environment, which makes users feel like they are in the environment itself (Kinateder et al., 2014). VR has been simultaneously used with different forms of BIM to attain more benefits from advanced scheduling technology (Ding, Liu, Liao, & Zhang, 2019). VR has been used for construction safety training (Sacks, Perlman, &

Barak, 2013); the simulation of high altitudes to determine emotional and mental fatigue (Xing et al., 2019) instead of physical mock-ups, which are not economical (Kumar, Hedrick, Wiacek, & Messner, 2011); visualizing the behavior of an excavator (Feng et al., 2019); and assessing the scenarios that are dangerous to a real person. Using VR, planners and designers can perceive a building better by observing the inside of the building before the start of its construction (Rüppel & Schatz, 2011). The construction industry has gained many benefits from using the BIM technology along with VR, which have helped in planning, design, construction, and project management (Changyoon Kim et al., 2013; H. J. Wang, Zhang, Chau, & Anson, 2004), as well as in construction education (L. Wang, 2007).

However, the use of these technologies in modular construction and construction education has been limited, so this study attempts to evaluate those issues. The case study presented in this study is the 2020 UNLV Solar Decathlon House, and the students involved in the competition are those who were asked the survey questions.

1.2 Research Objective and Scope

The goal of this study is a higher level of 4D schedule and VR applications in modular construction, which, in turn, enhances the application of modular methods in the construction industry. In order to achieve this goal, this research examined the effectiveness of using a 4D schedule and VR in modular construction, in comparison with a 2D drawing and project schedule, by conducting a questionnaire survey with students at UNLV. This study intends to assist practitioners and educators in the modular construction industry by first examining this technology with university students.

This study is based on the concept of the UNLV Solar Decathlon house, which is a single-story building. The house will be competing in the Solar Decathlon 2020, organized by the U.S.

Department of Energy and supported by the National Renewable Energy Laboratory (NREL). The Solar Decathlon has two competition challenges including the Design Challenge and Build Challenge, where collegiate teams contest against each other ("Solar Decathlon: About Solar Decathlon," 2018). The Solar Decathlon Build Challenge, during which ten teams compete against each other, is conducted every other year. The participating teams focus on their house's efficient energy usage, as well as applying cutting edge technologies in their modular houses ("Solar Decathlon: About Solar Decathlon," 2018). While the design and construction are completed in advance, the competition will be held from June 25th to July 5th, 2020, on the National Mall in Washington DC (U.S. Department of Energy, 2019). During the competition, the teams will be evaluated on the following ten subjects (U.S. Department of Energy, 2019):

a. Energy Performance
b. Engineering
c. Financial Feasibility & Affordability
d. Resilience
e. Architecture
f. Operations
g. Market Potential
h. Comfort & Environmental Quality
i. Innovation
j. Presentation

The modular house is made at a fabrication shop, Ahern Construction in Las Vegas, which will be then transported to the National Mall in Washinton DC (job site). The modular house will be mounted over a temporary foundation for the competition at the National Mall, where it will compete with nine other universities from around the world. After the competition, the modular house will be brought back to Las Vegas and placed over a permanent foundation.

Fig. 1: 3D Rendering of UNLV Solar Decathlon House

The modular house, Figure 1, was in the design and initial phases during the course of this study. Specifically, for this study, the fabrication and assembly of this house were modified to represent a modular house, composed of 10 different modules. Therefore, the fabrication and assembly followed in this research are not aligned with the actual fabrication of the Solar Decathlon house. The 4D Schedule and VR model were developed for the house to reflect the assembly sequence of the modules. The students involved in the Solar Decathlon competition from UNLV, along with Fall 2019 students enrolled in CEM 453/653 (Construction Scheduling and Resource Optimization), participated in this study.

Initially, the study aimed to conduct the research by dividing the participants into two groups, in which one would be tested with 2D drawings and a project schedule, and the other with a 4D schedule and VR. However, due to time and resource limitations, the same participants were tested with both approaches. Moreover, as participants saw the same information with 2D drawings and schedule once, and again with 4D schedule and VR, the schedule sequence might have been impacted, and there is a higher chance that participants performed better in the second task.

1.3 Thesis Structure

This study is structured over four chapters, excluding the introduction, references, and appendices. Chapter two showcases the present body of knowledge, where the papers discussing the application of 4D and VR in general, as well as in modularization, have been summarized. In the next chapter (three), the research methodology is explained with details about the study: a case study of the UNLV Solar Decathlon house, which is the subject for the survey, survey questionnaire formation, survey conduction, and data analysis, along with a description of the survey participants. Chapter four clarifies the findings of this study. Finally, chapter five contains conclusions and recommendations.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

An extensive literature review was done to obtain a proper basis of the current body of knowledge. Major journal papers and conference proceedings from recent years that discussed the technological evolution in construction were the primary focus of the literature review. Articles from journals including Automation in Construction, Computing in Civil Engineering, and the Journal of Construction Engineering Management, as well as conference proceedings including the International Symposium on Automation and Robotics in Construction (ISARC) and the ASCE International Conference on Computing in Civil Engineering (I3CE) were reviewed. As the intention was to cover the extensive recent growth in the use of new technologies, papers from 2015 to 2019 are highlighted.

2.2 Modularization

Modularization is a construction process in which a section of construction work is moved to a fabrication shop (Tatum et al., 1987). Though its modern definition and application were at their peak in the mid-twentieth century, it can be seen that modularization was applied ages before, in Egyptian pyramids and Greek temples (Azhar, Lukkad, & Ahmad, 2012). Tatum et al. (1987) studied prefabrication, preassembly, modularization, and offsite fabrication (PPMOF), and highlighted their usefulness in the construction industry. They focused on determining the driving factors that lead to high use of PPMOF in both industrial and building construction projects. Those factors consisted of site access and condition, contractor capabilities, benefits of fabrication, scheduling benefits, total cost reduction potential, design needs, and standardization (Tatum et al., 1987). A research study on prefabrication and preassembly by Haas et al., (2000) to determine their impacts on the construction workforce, calculated the relative weights of the drivers, advantages, impediments. Further, they determined the effects of technology on prefabrication and preassembly. The primary drivers for using those techniques were found to be labor, cost, and schedule. The advantages were determined to be improved safety and lower salary, while skill remained the same. Moreover, Haas et al. (2000) claimed that prefabrication and preassembly can reduce time, as well as decrease the duration of the supply chain while leading to better productivity.

Song et al. (2005) generated a strategic decision tool to examine the usefulness of PPMOF for industrial project factors that influence decisions on using PPMOF. They concluded that for the successful implementation of PPMOF, systematic analysis and early decision making were required. Furthermore, they contended that PPMOF had become more viable with recent advances in design and IT.

Later, O'Connor, O'Brien, & Choi, (2014) identified 21 critical success factors (CSFs) for the effective implementation of modularization in the construction industry. The authors did similar research about additional steps, termed as CSFs enablers, which aid in the accomplishment of CSFs in modular construction projects (O'Connor et al., 2014). Further, a study on design standardization strategies by the same authors evaluated the advantages and disadvantages of combining modularization with standardization (O'Connor et al., 2015). Moreover, O'Connor et al. (2016) studied the changes that needed to be made in planning and execution for modular projects from stick-built projects in order to achieve a higher level of modularization in the construction industry. Additionally, the impact of each individual or group of modularization CSFs related to the cost and schedule success of modular construction projects was studied by the authors, which confirmed the CSFs' effects (Choi, O'Connor, & Kim, 2016).

Furthermore, a study was conducted by Choi et al. (2017) on the advantages, as well as the difficulties, of using modularization in an urban environment. The study identified improved quality, improved site operations, reductions in duration, increments on productivity, and lower costs as the primary advantages, while on-site storage area, logistics, and distance from fabrication shop to jobsite were identified as difficulties for using modularization.

2.3 4D Scheduling

4D scheduling is the combination of a construction schedule and a 3D model to simulate the construction process (Changyoon Kim et al., 2013; Trebbe et al., 2015). An initial study on 4D scheduling was done by Retik, Warszawski, & Banai, (1990), who explored the potential of using computer graphics in scheduling. Chau, Anson, & Zhang (2004) studied 4D visualization in the field of construction project management and concluded that it can be used for planning and managing daily activities, as well as the sites. Hence, they determined the usefulness of computer graphics for a construction management team.

Further, Chau, Anson, & Zhang (2005) developed a 4DSMM software, which included the management of resources and sites. This software was developed in the early years of the application of 4D, as the software that has been in use in recent years like Navisworks, Synchro and Revit software were not available. Additionally, the developed 4DSMM software was then used by a warehouse building in Hongkong and the authors found that it was a good tool for communication and collaboration between construction stakeholders, namely the owner and site managers (Chau, Anson, & De Saram, 2005). However, the authors were concerned about the large amount of data involved in the software, which lead to slow processing time. The authors believed that advancements in computer technology would solve the problem of slow data processing. The same authors further developed a new information system by adding a resource management system to the existing system and named it 4DSMM+ (H. J. Wang et al., 2004). Integrating site layout management to the system, the authors further developed software called 4D-ISPS, which was more concentrated in on-site planning (Ma et al., 2005).

The usefulness of 4D CAD in each phase of a project, starting from planning to operation and maintenance, was studied by Mahalingam, Kashyap, and Mahajan (2010), who identified its application in communicating between project stakeholders, tracking progress for contractors and subcontractors, and examining the constructability of a project by looking at the conflicts. Later, Zhang and Hu (2011) continued their previous study of 4DSMM by adding geometric information and time information to the existing system to analyze safety during the construction phase. Moreover, 3D sensing technology was combined and compared with 4D BIM for construction progress measurement (Turkan, Bosche, Haas, & Haas, 2012). Similar research was done to track construction progress, in which reliable remote sensing systems were used by Changwan Kim, Kim, and Son, (2013). Further, in their research on construction progress tracking, researchers (Kim et al., 2013) used image-processing-based construction monitoring, whose main advantage was improved communication.

A 4D schedule was used in railway renovation in the Netherlands, where new structures (both temporary and permanent) had to be aligned with the prevalent structures, which was assisted through conflict management on the schedule and space using 4D in each phase of the project (Trebbe et al., 2015). Furthermore, other researchers (Olde, Scholtenhuis, Hartmann, & Dorée, 2016) added ethnographic action research to 4D CAD in multiple project cases to support underground utility projects, which helped in conflict management, while laying down new structures. In another study, researchers (Kassem, Dawood, & Chavada, 2015) identified and solved logistics problems, along with temporal and spatial conflicts in workspace management, using a 4D tool. In a further study, researchers applied 4D BIM tools in a billion-euro canal lock expansion project in The Netherlands to reduce and solve project risks in planning phases (Sloot et al., 2019). Additionally, an inverse photogrammetry approach was used with 4D BIM by (Braun & Borrmann, 2019) for automatically naming construction pictures.

2.4 Virtual Reality (VR)

Sherman and Craig (2002) explained that immersive virtual environments (IVEs) are rich multisensory computer simulations that can afford the feeling of being mentally immersed or present in the simulations, i.e., — a virtual world. Additionally, VR has been described as a computer-generated interactive environment, which makes users feel like being in the environment itself (Kinateder et al., 2014). Along with 4D schedules for simulation, VR has also been used for more realistic visualization. Woksepp and Olofsson (2008) studied the usefulness and dependability of VR in construction planning and design. The VR was tested on construction personnel and the direct visualization they had. The respondents indicated that it could be beneficial for unknown tasks. Further, they found that VR reduced misinterpretation in the planning and design phase, as it gave multiple perspectives to the planning team while increasing the overall understanding of the construction process.

Additional research on VR was conducted by Rüppel and Schatz (2011), who used virtual reality for fire evacuation with the application of BIM-based serious games. As cost and space limitations lead to difficulties in creating physical mock-ups of a building, VR was also used for design review applications for healthcare facilities (Kumar et al., 2011). Sacks et al. (2013) claimed that the application of VR in safety training would be more effective, as personnel would remember and assess the risk involved more than with conventional methods. Another study (M. J. Kim, Wang, Love, Li, & Kang, 2013) summarized recent studies in VR and found that a lower number of participants could be involved in research related to VR and that the realism of the VR environment would worsen if substandard designs were used for VR. VR was further used to examine real-life evacuation scenarios, such as emergency situations in tunnels and hotels (Kinateder et al., 2014; Kobes, Helsloot, De Vries, & Post, 2010; Marsh et al., 2012).

In similar research related to virtual reality, a study (Kasireddy, Zou, Akinci, & Rosenberry, 2016) examined and compared various virtual reality environments for assisting construction virtual activities. Others (Du, Zou, Shi, & Zhao, 2018) studied a means for the automatic update of BIM data to a VR model using a Cloud-based BIM metadata interpretation and communication method. However, they found that the conversion of BIM data to VR is a slow process, which is restricting the construction industry to have higher use of VR. A paper that analyzed the ongoing trends in the UK construction industry noted that VR has been used for comprehending hazards in remote locations (Woodhead, Stephenson, & Morrey, 2018). BIM and VR were used in combination in China in the renovation of a shopping center in order to help the workforce understand the design and construction process; it was found that this increased work efficiency and reduced design alterations and reworks (Ding et al., 2019). In another study, Feng et al. (2019) used a VR environment to improve tracking accuracy, safety, and operation time in a human-excavator cooperative system. VR was also used to improve the safety performance of high-altitude environment workers by simulating their behaviors (Xing et al., 2019).

2.5 Summary of Literature Review

From the literature review, it can be concluded that 4D schedules and VR have been used during various phases of projects starting from planning, designing, and construction to operation and maintenance. Besides the construction domain, VR has also been used for safety and fire evacuation analyses. Both tools have been found to be strong for the communication and collaboration of stakeholders involved in a project. Furthermore, these tools are found to be helpful in conflict management, as well as site and logistics management and schedule risk reduction. Despite their profound importance, 4D schedules and VR have hardly been applied in the modular construction industry. Modular construction is more dependent on modules than any other activities, so proper schedule and logistics management are paramount for modular construction. This research studies the use of a 4D schedule and VR in a modular project so that it can help in transportation and logistics management of modules, as well as construction education of modularization.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 General Research Outline

This study examines the effectiveness of a 4D schedule and VR through six major steps. The first among the six was defining the objective and the scope of the study, which was discussed in chapter one; this was followed by an in-depth literature review, presented in chapter two. As the research was based on 2D drawings and a project schedule, along with a 4D schedule and VR model of the UNLV Solar Decathlon House, software such as MS Project 2019, Autodesk Revit 2020 (with Enscape™ plugin), and Autodesk Navisworks 2020 were used for the model development. The model development was the first step in data collection, which was followed by the VR model visualization using Oculus Rift S (a VR headset), and then a survey questionnaire was completed by the participants. The data collection completed after the survey is further described in this chapter, along with the model development. After the collection of sufficient data, the next step was analyzing the data, which is discussed in chapter four. Based on the data analysis, the conclusion and recommendations are presented in chapter five. The research methodology flowchart is presented in Figure 2.

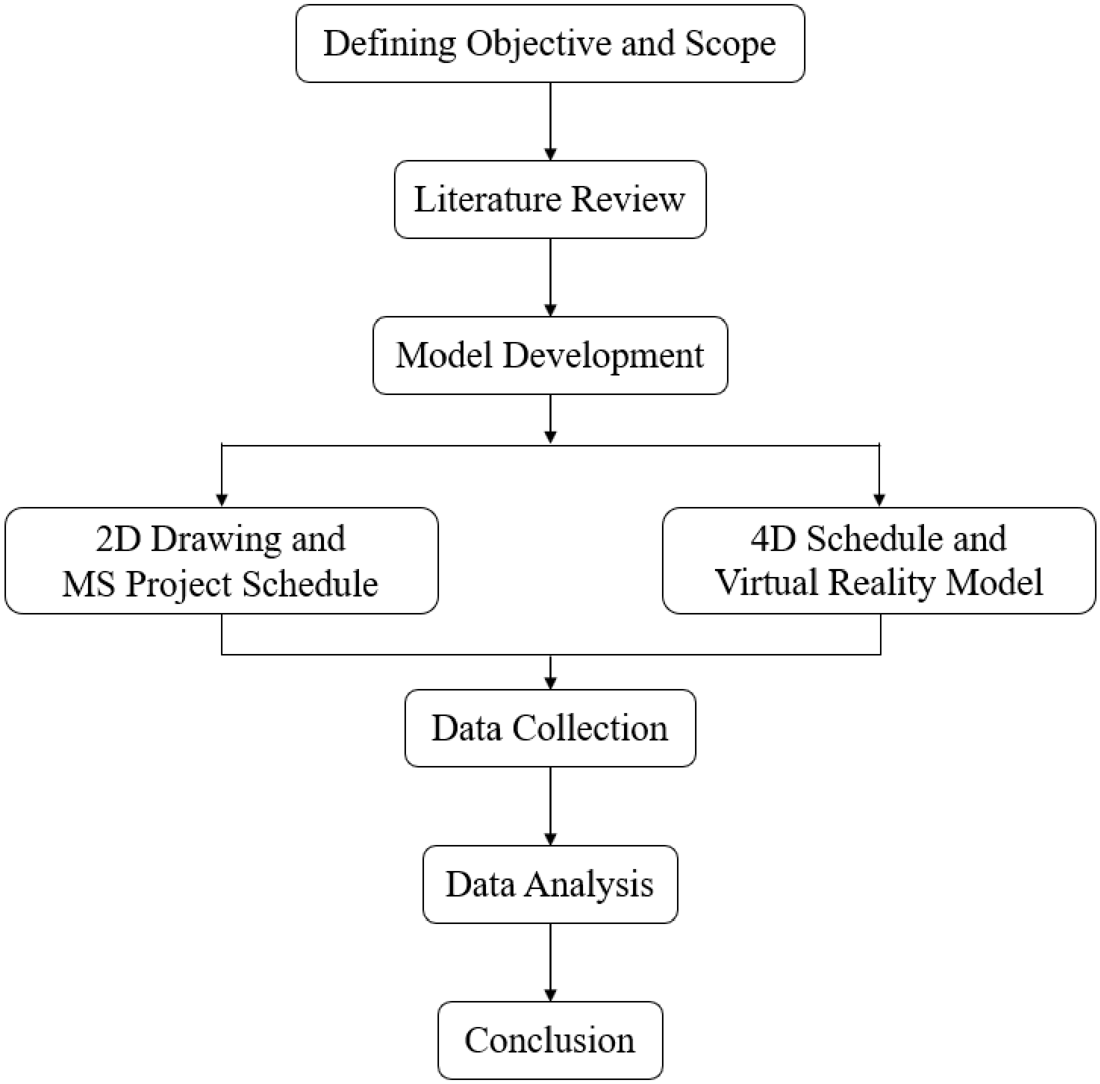


Fig. 2: Research Methodology Flowchart

3.2 Model Development

The major challenge in this study was to develop a 4D schedule and a VR model of the UNLV Solar Decathlon House using 2D drawings. The AutoCAD 2D drawings for the model were available from the School of Architecture (UNLV), which were used to develop the project schedule, using MS Project. The details of the 4D schedule and VR model development are discussed in the following sections:

3.2.1 4D Schedule

A 4D schedule is the combination of a 3D model and a project schedule. Initially, the 3D model was developed in Autodesk Revit 2020, and the construction schedule was developed in MS Project 2019, both considering the stick-built method using the available 2D drawings. The UNLV solar decathlon house is a modular house, which is to be fabricated in Las Vegas and transported to Washington DC. The house consists of 10 modules, namely: Mechanical Room Module, Bathroom Module, Bedroom Module, Courtyard Module, Kitchen Module, East Wall Module, West Wall Module, Front Wall Module, Back Wall Module, and Four 500 Galloon Storage Tank Module. Then, the project schedule was updated to clearly depict the fabrication, as well as the assembly sequences of the modules. The 3D model was also modified so that it can clearly show the progress of each module in fabrication and assembly. The updated schedule and the 3D model were combined using Autodesk Navisworks Manage 2020. Figure 3 shows the 4D schedule preparation in Autodesk Navisworks Manage 2020.

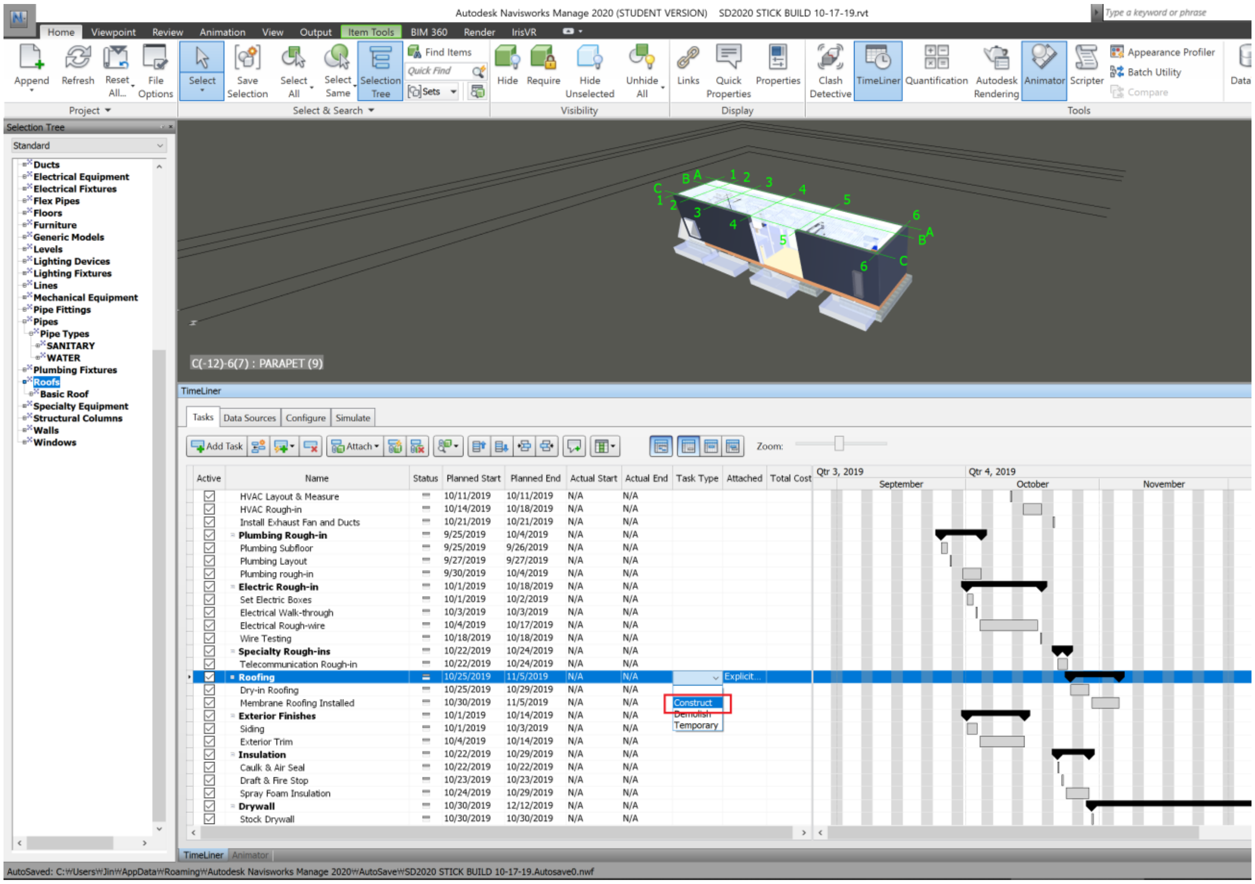


Fig. 3: Schedule Activities Linked with the Tasks in the 3D Model Using Autodesk Navisworks Manage 2020

The task type of each activity in the schedule with the corresponding task in the 3D model was changed to “construct” so that it would show the progress within each activity in the simulation. Figure 4 shows a simulation in Autodesk Navisworks Manage 2020.

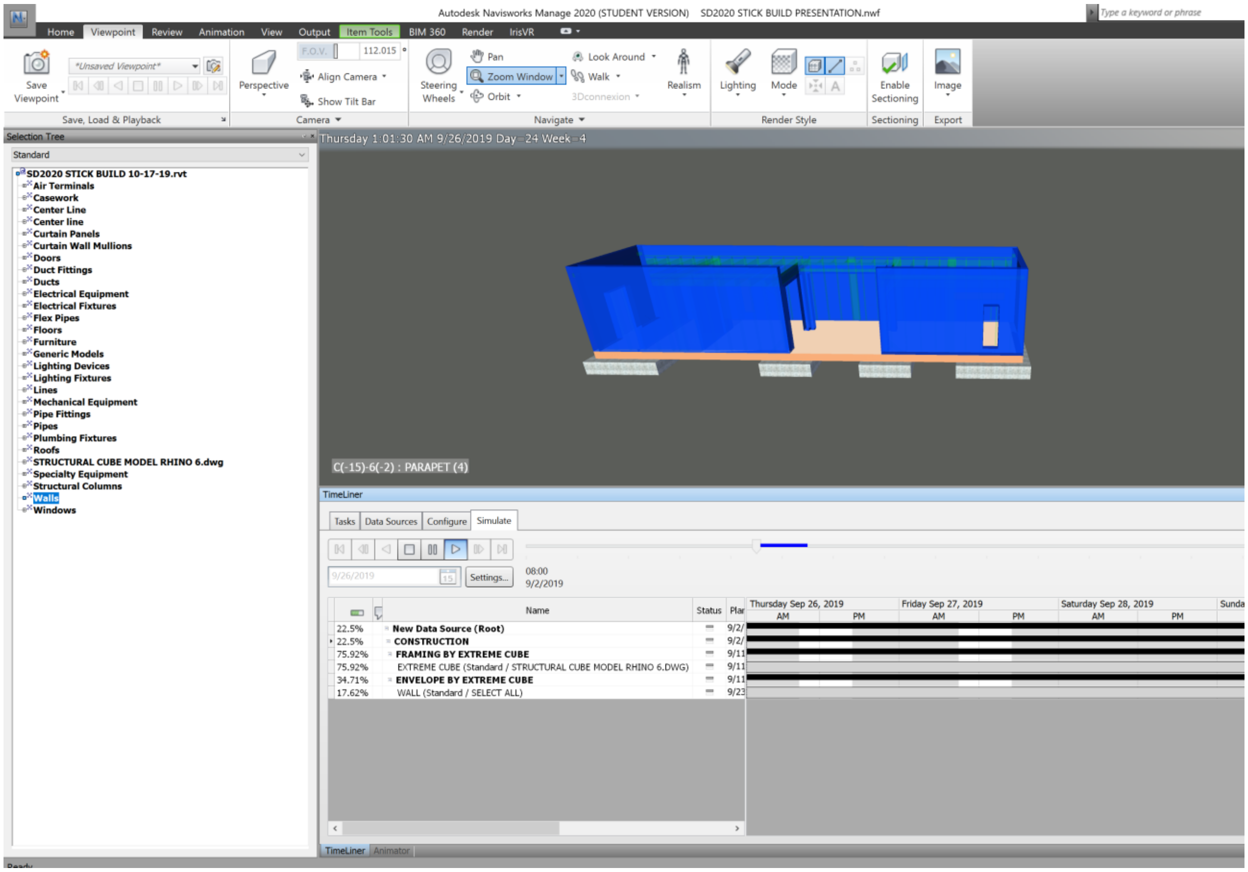
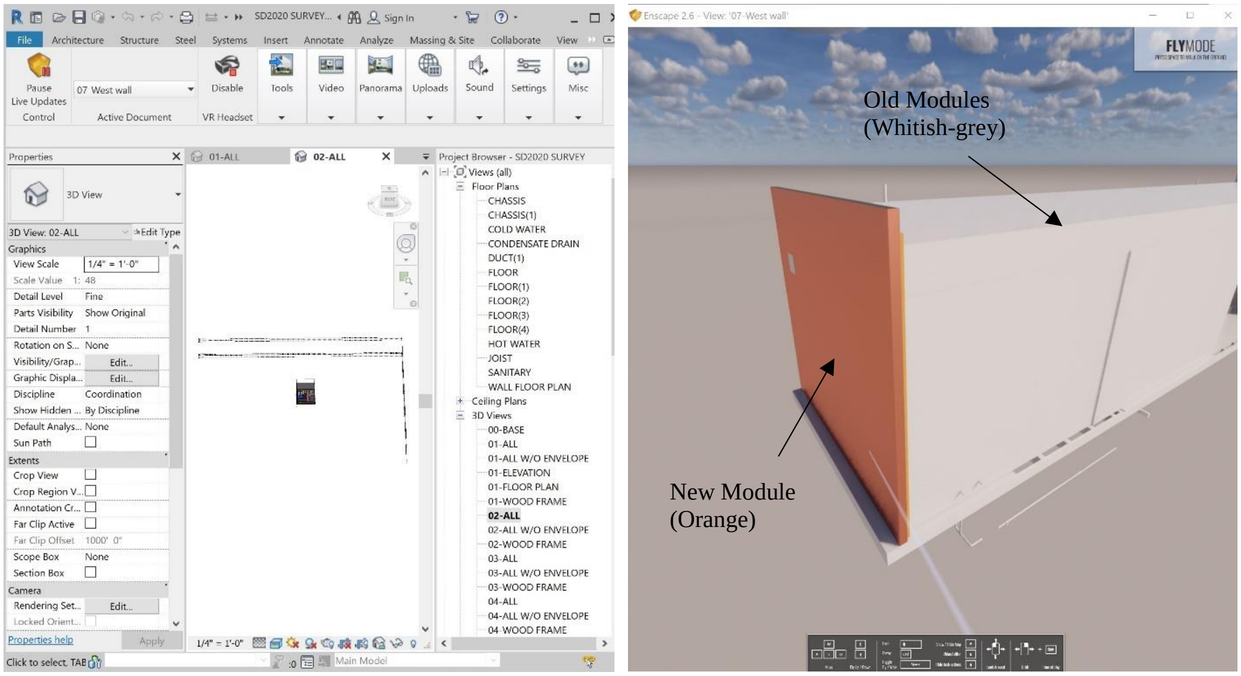


Fig. 4: Simulation in Autodesk Navisworks Manage 2020

3.2.2 Virtual Reality Model

The next step in the model development was to convert the 4D schedule into a VR model. However, the 4D schedule developed in Autodesk Navisworks 2020 could not be exported to the VR model, nor does the Revit software have the capability to link the 3D model and construction schedule. Therefore, to simulate the assembly sequence, each module was assigned to “Phase” in the Autodesk Revit 2020. Such assignments of phases to each module allowed the visualization of the assembly sequence of the ten modules. By using the phase filter, the changes occurring in the assembly sequence could be easily shown.

In the Revit, the segregation of module-assembly sequencing was presented with different colors, so that the users were aware of the model assembly sequence. The modules that were already assembled took the whitish-grey color, while the new modules were shown in the original color. When a useable model was developed in the Revit, the next step was to transform the Revit model to a VR model, for which the Enscape™ plugin in Revit was used. Figure 5 shows the transformation. Figure 5 (a) shows a phase of a module in Revit. Figure 5 (b) shows the different colors for new and old modules.



a) Autodesk Revit 2020 Window b) Enscape™ Window

Fig. 5: Transformation of a Revit model to a VR model

For the visualization of the VR, Oculus Rift S was used. The details that were provided to the students for the introduction of Oculus Rift S and for how to navigate the device are attached in Appendix I. Figure 6 shows the Enscape™ window as it was seen on the computer screen when the VR was shown to participants.

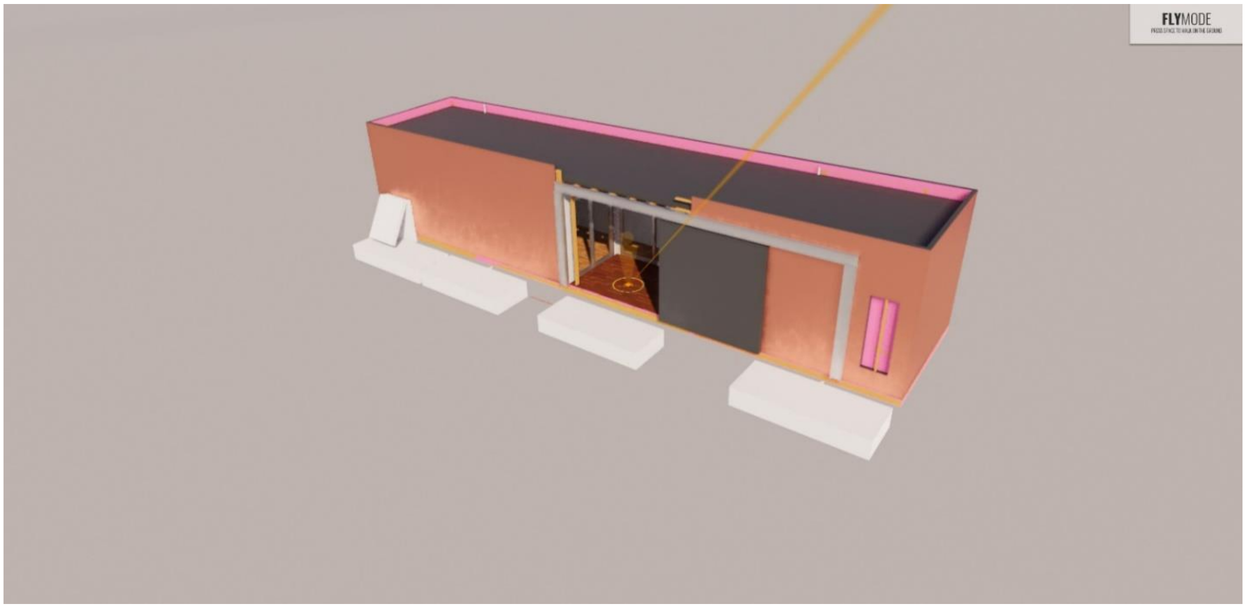


Fig. 6: UNLV Solar Decathlon House Model as in Enscape™ in the Computer Screen

3.3 Data Collection

3.3.1 Survey Design

The survey questionnaire was generated so that it could easily examine the 2D drawing and project schedule against the 4D schedule and VR model. The first part of the survey consisted of the definitions of modular construction, 4D schedule, and VR. This was followed by questions that ask the participants about their general information: academic year, industry experience, scheduling experience, familiarity with 4D schedule and VR, and familiarity with modular construction. After the information about themselves, participants were separately asked to schedule the assembly sequence of the ten modules of the UNLV modular house with the help of 2D drawings and a project schedule provided to them. Likewise, they were next asked to schedule the assembly sequence after visualization with 4D/VR. Additionally, the following topics related to the traditional approach and 4D/VR were examined during the survey:

- Easy to visualize
- No need to call a designer for further information
- Design errors can be easily located
- Easy to use
- Felt confident
- Effective

The six comparison topics were described to participants as follows, in order to mitigate their chances of confusion:

- **Easy to visualize**: Information can be easily seen.
- **No need to call a designer for further information**: Everything has been understood from the drawing, so no further contacts made.
- **Design errors can be easily located**: Looking around the available resources, design errors are easily located.
- **Easy to use:** Users can easily use the given materials.
- **Felt confident**: Confirm that you picked up the correct information.
- **Effective**: Construction activities could be smoothly carried out using the given means without any mistakes.

Furthermore, responses on 10 more comparison statements were asked for examining 4D/VR over traditional methods:

- It was clearer to understand the fabrication sequence with the 4D schedule and VR.
- VR immersion helps in better understanding the interior and exterior of the fabrication process.
- VR helps in more easily locating design errors than 2D drawings.
- I had difficulties in understanding the traditional schedule and drawings without using 4D and VR technologies.
- I feel more knowledgeable about the details of the modules after using the 4D schedule and VR, so there is no need to contact the designer for design information.
- I felt more confident using the 4D schedule and VR over the traditional approach.
- A 4D schedule provides easier communication with team members and stakeholders during the construction and planning phases, than does traditional 2D drawings.
- 4D/VR is helpful in examining the developed project schedule.
- 4D/VR assists in finding places where efficiency improvement can be made during the planning phase.
- I found the 4D schedule and VR more effective than 2D schedules and drawings in the fabrication of the modular house.

Participants were given four open-ended questions at the end of the survey in which they were asked the following questions:

- What did you like about the 4D Schedule and VR?

- What difficulties did you find during the use of the 4D schedule and VR?
- Please list the design errors you found in the VR model.
- Please provide further comments if you have any.

3.3.2 Data Collection with Virtual Reality Visualization

The majority of the participants in the survey were students enrolled in the CEM453/653 (Construction Scheduling and Resource Optimization) class in the Fall 2019 semester, which lead to a major portion of the study being done in two lab sessions of the class. Eighteen students were divided into two groups of nine students each. In a three-hour lab (180 minutes), each of nine participants was allocated 15 minutes of VR, with five minutes spared for logistics and resetting the visualization. Further, 13 students who were not enrolled in CEM 453/653, but who are students in the Department of Civil and Environmental Engineering at UNLV participated in the survey.

Two days before the VR visualization, a handout with an introduction of the Oculus Rift S (which is attached in Appendix B) was provided to the participants to make sure that they were familiar with the VR headset. Further, the researcher demonstrated how to use the VR headset to the participants. After equipping a participant with a VR headset, each participant was given two minutes to become accustomed to the navigation. There were three primary navigators: the thumbstick on both controllers (left and right) and a primary index trigger on the right hand. The use of the thumbstick on the left-hand controller was for navigating on the horizontal plane, and the use of the thumbstick on the right-hand controller was for navigating on the vertical plane. Moreover, the primary index trigger controller on the right hand was used to move around the space; the user has to point to a location where they want to move and then press the trigger for the space movement. Figure 7 shows the VR model visualization of participants during the study.

Fig. 7: VR model visualization

The Oculus Rift S was connected to a Lenovo ThinkPad P53 Mobile Workstation using the Type C to Display port adaptor. The Revit model was exported to VR using the in Enscape™ plugin in the Autodesk Revit 2020. The ten modules were segregated using phases in the Revit. The participants were shown the VR visualizations of the modules one after the other, as they were in the assembly sequence in the VR headset. The Mechanical Room module was the first in the sequence of assembly, so it came first and was followed by the Bathroom Module. The participants were able to easily identify each recently-added module, as it was presented in its original color, while the older modules had a whitish-grey color.

3.4 Data Analysis

The data collected during the survey, before and after the VR model visualization, were digitized into a spreadsheet with Microsoft Excel 2019. The digital data were then analyzed and summarized using descriptive analyses. The analyses were carried out for all the survey questions.

CHAPTER 4: DATA ANALYSIS AND RESULTS

4.1 Introduction

The primary motive of this study was to examine the effectiveness of a 4D schedule and VR over a traditional schedule and 2D drawings. The participants were asked to complete the assembly sequence of the modules using the traditional approach first and then using the VR model the next time. The participants were asked six questions about their experiences with both methods on a five-point Likert scale. Further, they were asked to compare the methods in 10 questions, which were again on the Likert scale. In the data analysis, the 2D drawings and schedule will be known as the traditional approach, while the acronym 4D/VR will be used for the 4D schedule and virtual reality. The findings of the study are described and analyzed in this chapter.

4.2 Characteristics of Survey Participants

4.2.1 Education Level

The survey participants were students enrolled in various specializations in the Department of Civil and Environmental Engineering and Construction, with the majority from Dr. Jin Ouk Choi’s CEM453/653 Construction Scheduling and Resource Optimization class. The total number of participants, who were either undergraduate or graduate students, was 31. None of the participants were freshmen or sophomores. Three were juniors, 13 were seniors, and 15 were graduate students. Figure 8 shows the detailed division of participants’ academic years.

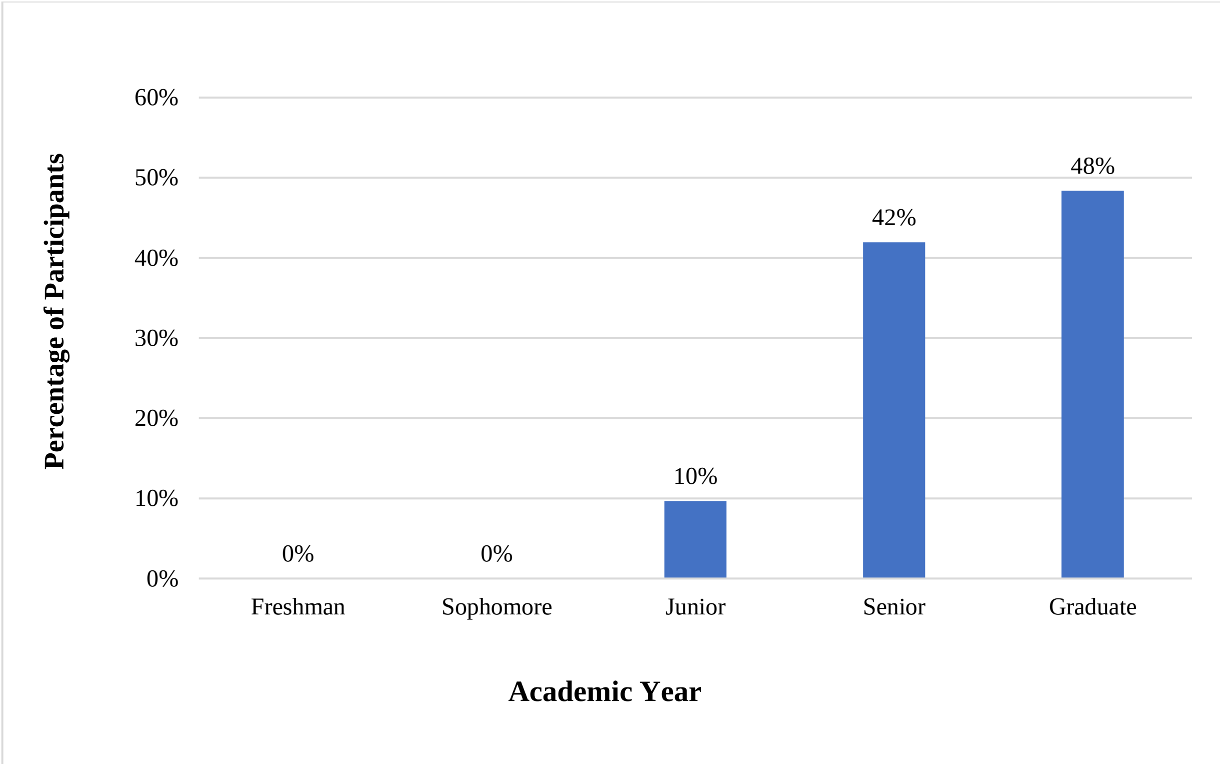


Fig. 8: Education Levels of Participants

4.2.2 Industry Experience

The industry experience of each participant was noted. Seven participants had less than a year of industry experience, while five, seven, four, and eight had a year, two years, three years, and more than three years of industry experience, respectively. The details of the participants' industry experiences are shown in Figure 9.

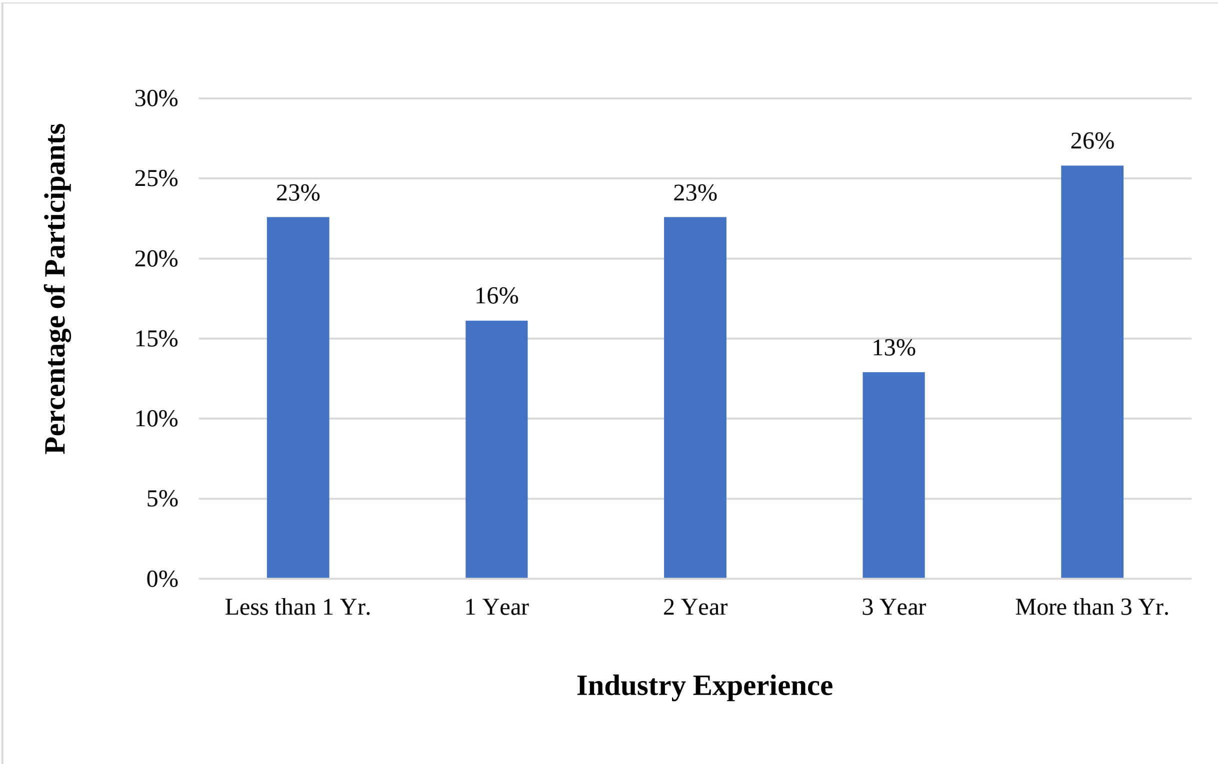


Fig. 9: Industry Experience of Participants

4.2.3 Scheduling Experience

The participants were further asked about their expertise in scheduling in construction. Thirteen participants mentioned they had less than a year experience, 13 had a year of experience, four had two years of experience, and one had more than three years of experience. Figure 10 shows further details.

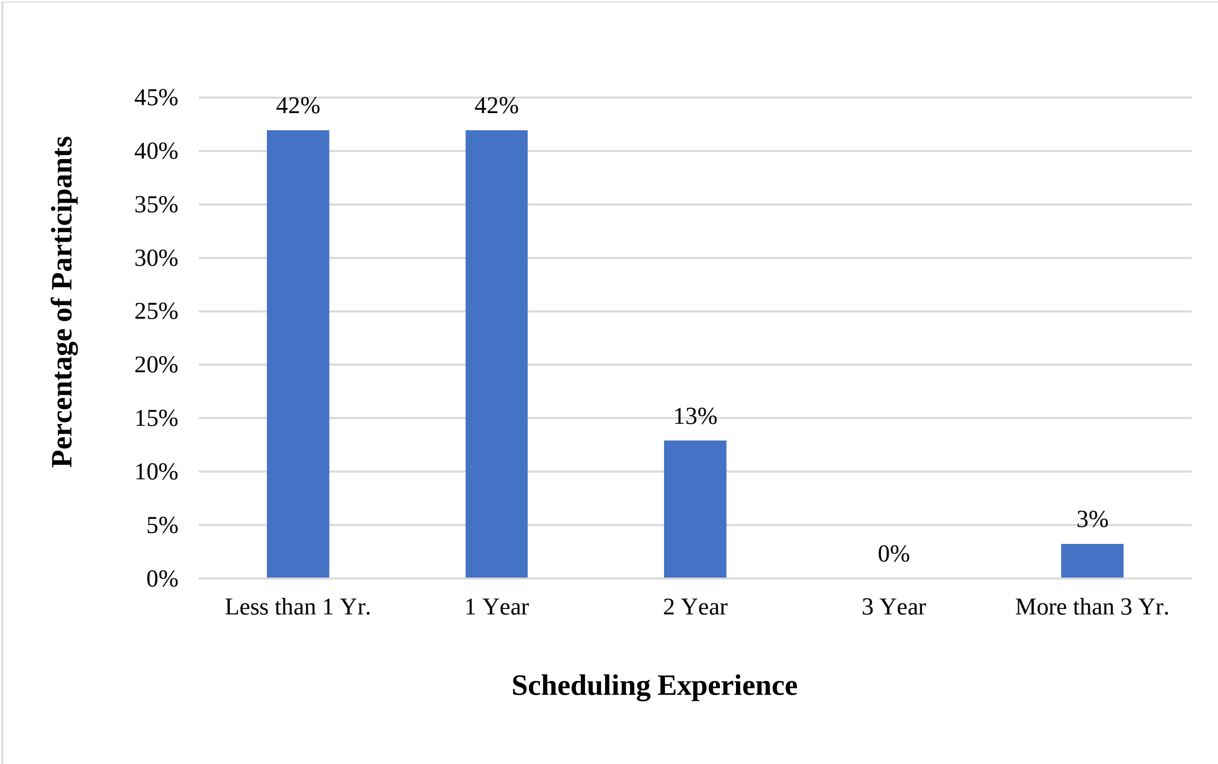


Fig. 10: Scheduling Experience of the Participants

4.2.4 Familiarity with Modularization

The participants were questioned about their familiarity with modularization or modular construction. Based on the responses, it was observed that only one participant was very familiar, whereas 15 participants were familiar, and 15 were not familiar with modularization. Figure 11 shows further details.

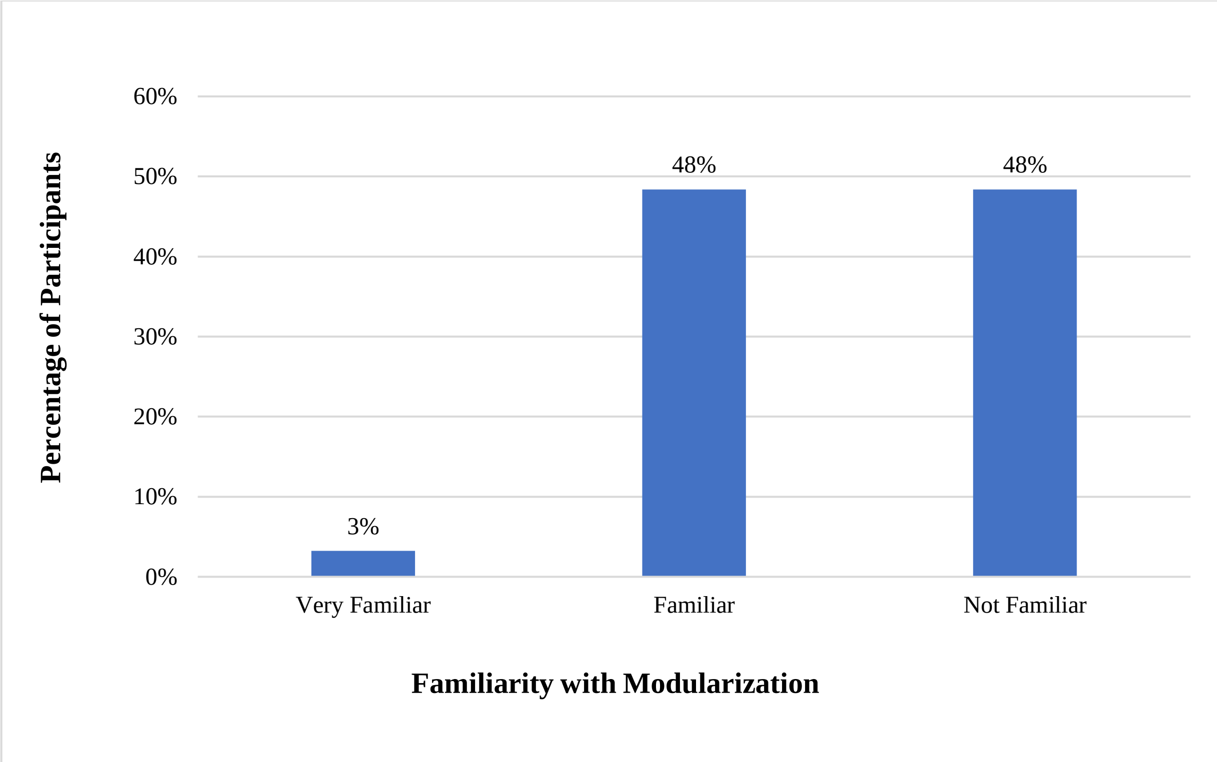


Fig. 11: Familiarity with Modularization

4.2.5 Familiarity with 4D Schedule and VR

The next inquiry was about the familiarity of participants with a 4D schedule and VR. None of the participants were very familiar, whereas six participants were familiar, and 25 participants were not familiar with a 4D schedule and VR. Figure 12 shows further details.

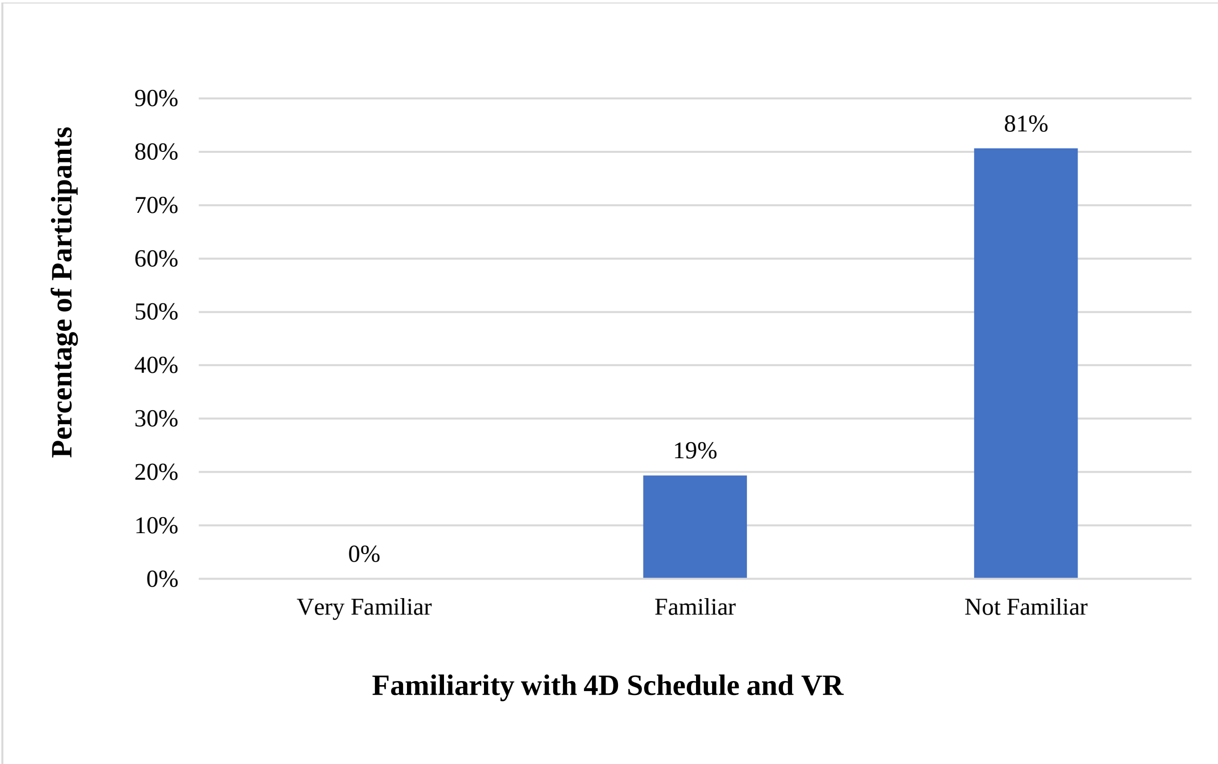


Fig. 12: Familiarity with 4D Schedule and VR

4.2.6 Time Taken by Each Participant on VR Model Visualization

The participants were provided enough time so that they could navigate in all directions on the module, both inside and outside. Figure 7 shows the time taken by each participant during the VR model visualization.

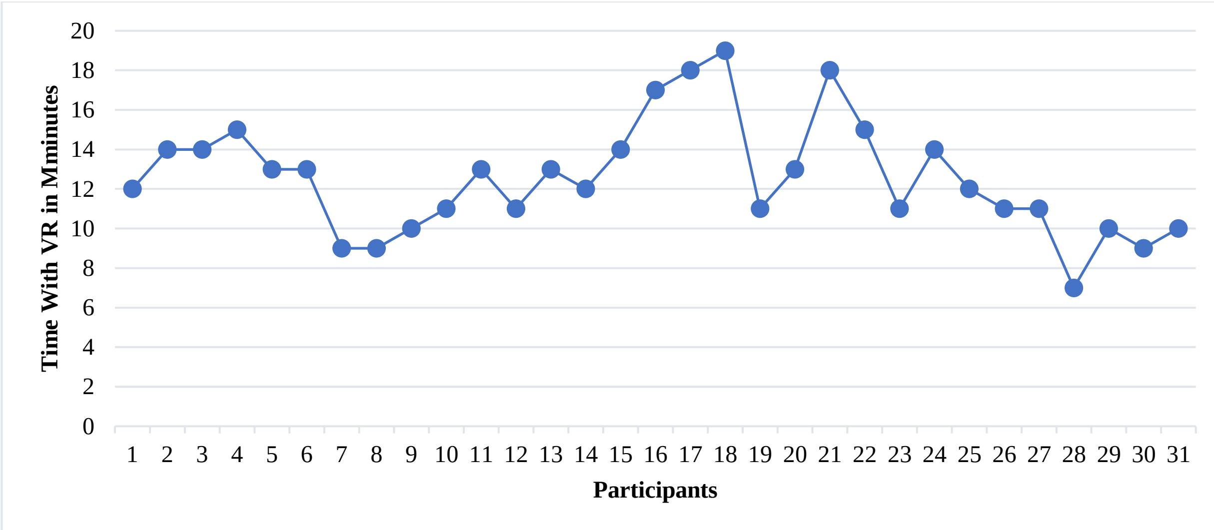


Fig. 13: Time Taken by Each Participant during VR Model Visualization

The minimum time taken by a participant was seven minutes, while the maximum time was 19 minutes, and the average was 12.55 minutes. It can be clearly seen that a learning curve of participants varies tremendously when getting used to new technology.

4.3 Participants' Performance on Module Assembly Sequence (Traditional Vs. 4D/VR Approach)

The participants were provided 2D drawings containing a section of each module and project schedule developed in MS project. Then they were asked to assemble the ten modules that were in the survey using the traditional approach. The assembly sequence they created was then compared to the one provided to them. Thirteen participants completed the sequence correctly, and 18 participants completed it incorrectly. Conversely, when asked to do the same task of sequencing assembly after the visualization with 4D/VR, which had the same assembly sequence, 24 out of 31 participants sequenced the assembly correctly. Five among the seven who had the wrong sequence assembly had just one activity sequenced incorrectly. Figure 14 shows the details of the participants' performances.

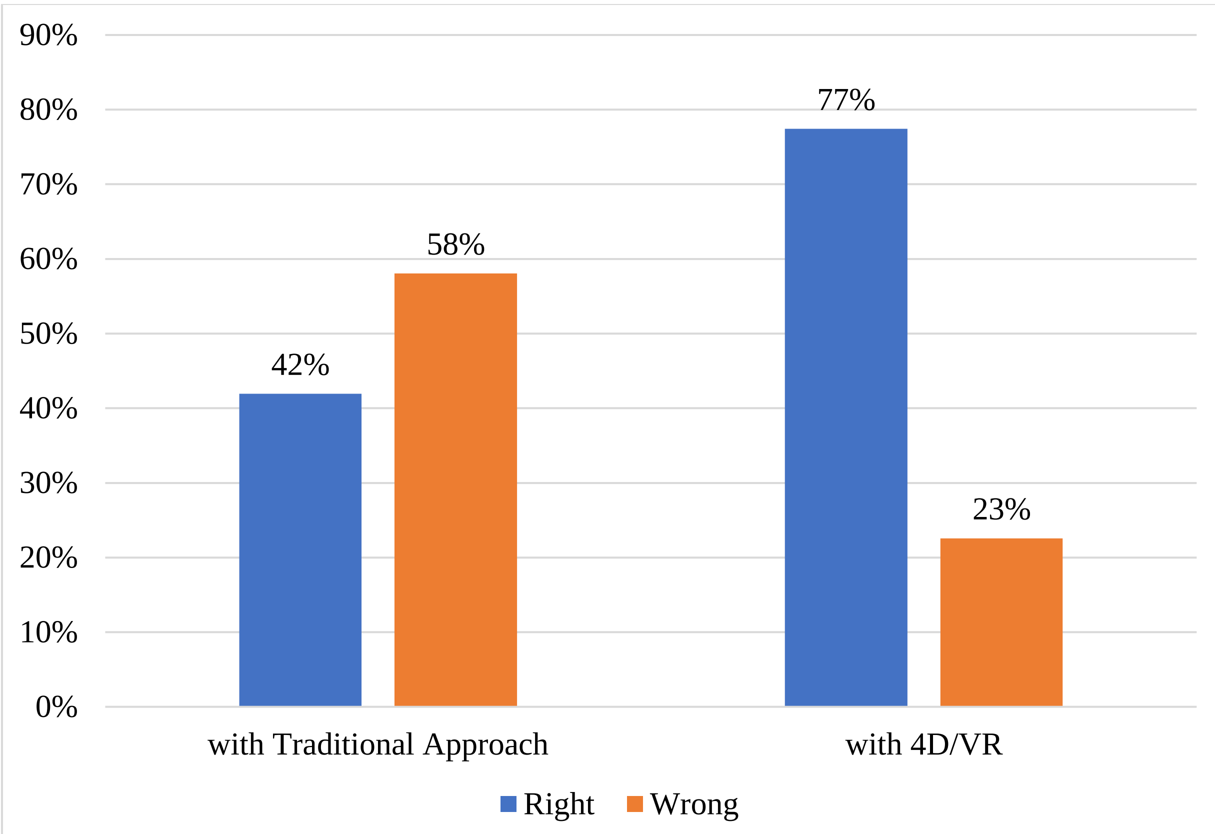


Fig. 14: Assembly Sequence of the Modules with Traditional Approach and 4D/VR

4.4 Participants' Responses Over 4D Schedule and VR vs. 2D Drawing and Traditional Schedule

4.4.1 Easy to Visualize

The participants were asked about the ease of visualization for the two approaches independently. The responses for the traditional approach were collected after the participants were asked to complete the assembly sequence using the 2D drawings and schedule. Based on the answers, only seven participants strongly agreed, 13 agreed, eight were neutral, and three disagreed that it was easy to visualize using the traditional approach. None of the participants strongly disagreed on the ease of visualization.

The same question was repeated after the use of the 4D/VR, and all of the participants at least agreed that it was easy to visualize with the use of 4D/VR; in fact, 26 among all participants strongly agreed. The overall responses from the two cases are shown in Figure 15.

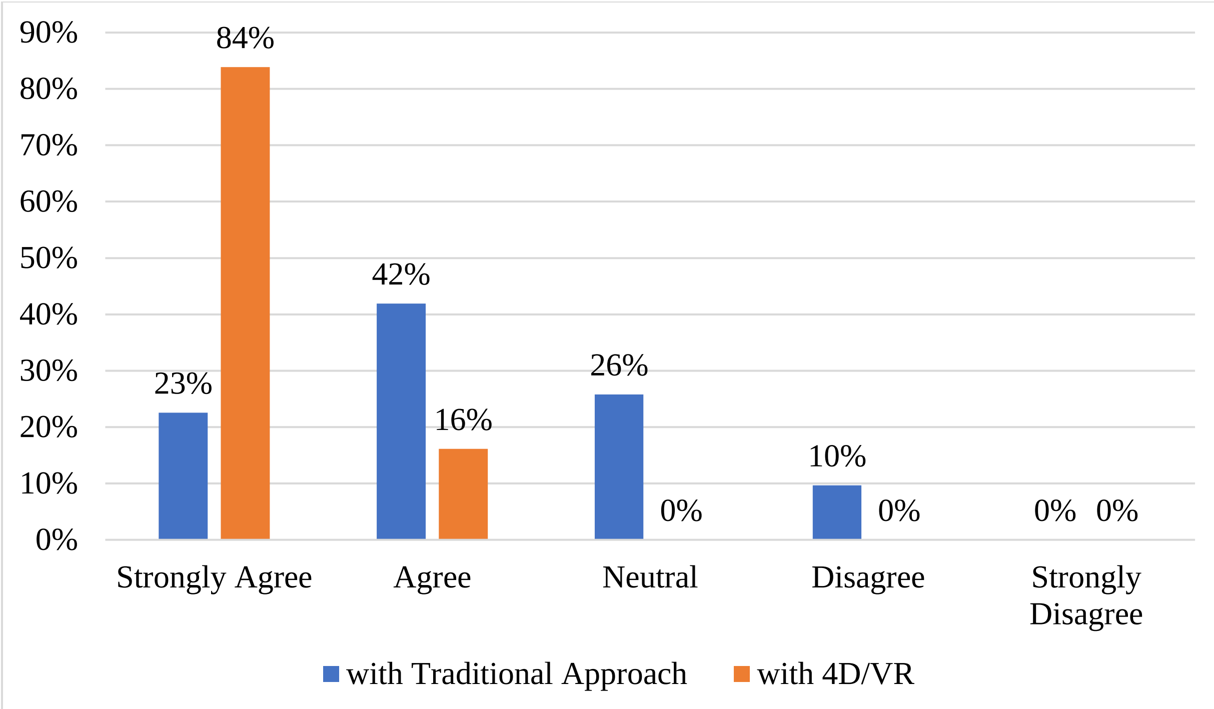


Fig. 15: Participants' Responses on Easy to Visualize for Traditional Approach and 4D/VR

The summary of the results that showcase independent responses on the 4D/VR and traditional approach is presented in Table 1.

Table 1: Summary of the Responses on Easy to Visualize

Response	Traditional Approach	4D/VR
Strongly Agree	23%	84%
Agree	42%	16%
Neutral	26%	0%
Disagree	10%	0%
Strongly Disagree	0%	0%

It can be noted that both approaches were easy to visualize for participants, moreover, all the participants at least agreed that it was easier to visualize the construction plans and schedule with 4D/VR than with the traditional approach.

4.4.2 No Need to Call a Designer for Further Information

The participants were asked whether they would need to call the designer for further information on both approaches, separately. In the case of the traditional approach, five participants strongly agreed that they did not need to communicate with the designer for further information while nine participants agreed. However, six and three participants disagreed and strongly disagreed, respectively, that they did not need to call the designer.

Similarly, the participants were questioned on the same parameter once they used 4D/VR. Twelve of them strongly agreed that they did not need to contact the designer for further information, while seven agreed. Details of the responses are shown in Figure 16.

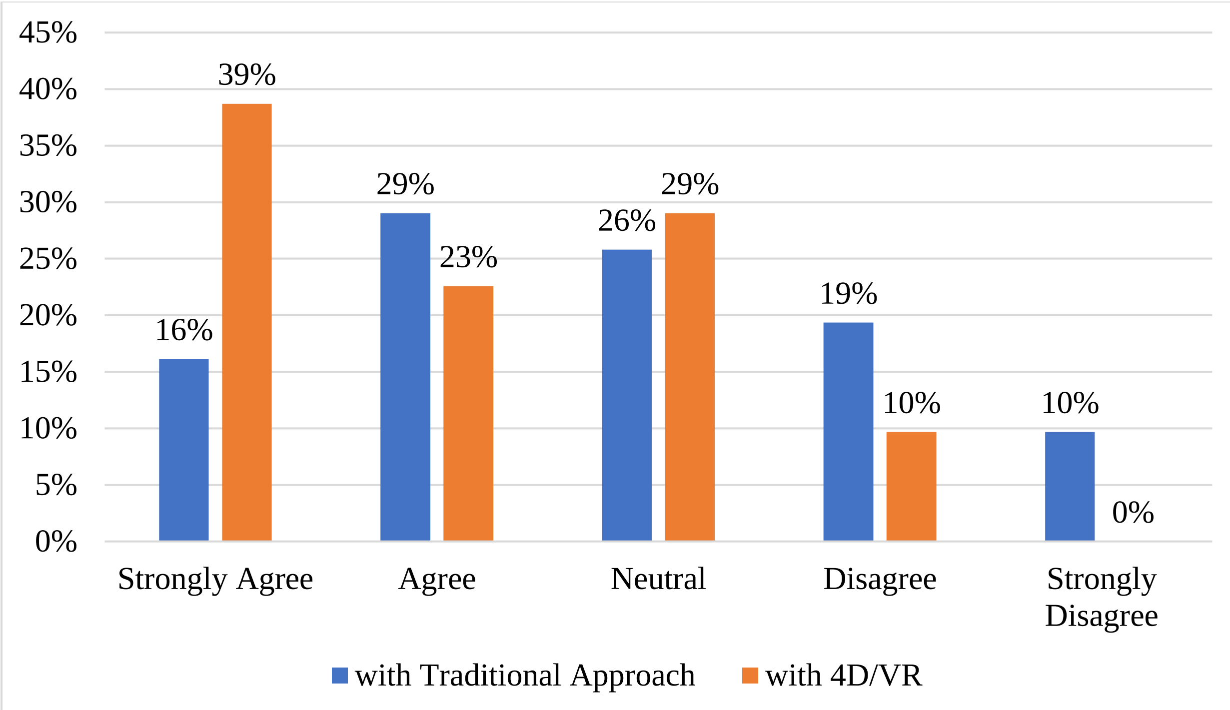


Fig. 16: Participants' Responses on No Need to Call Designer for Further Information for Traditional Approach and 4D/VR

Based on these responses to the two approaches independently, it was noted that nine participants had at least disagreed that with the traditional approach that there was no need to call the designer for further information. The summary of the responses from the participants related to the question of no need to call the designer is presented in Table 2.

Table 2: Summary of the Responses on No Need to Call the Designer for Further Information

Response	Traditional Approach	4D/VR
Strongly Agree	16%	39%
Agree	29%	23%
Neutral	26%	29%
Disagree	19%	10%
Strongly Disagree	10%	0%

It can be noted that with 4D/VR, there is a lesser need to call the designer for further information than with the traditional approach.

4.4.3 Design Errors Can be Easily Located

The participants were asked whether design errors could be easily located on both approaches, separately. In the case of the traditional approach, three participants strongly agreed that design errors could be easily located, while seven agreed. However, ten and seven participants disagreed and strongly disagreed with that claim, respectively. Similarly, the participants were questioned on the same claim once they had used the 4D/VR. It was noted that 16 of them strongly agreed that design errors could be easily located, while 13 agreed, and one participant disagreed with the claim for 4D/VR. Details of the responses are shown in Figure 17.

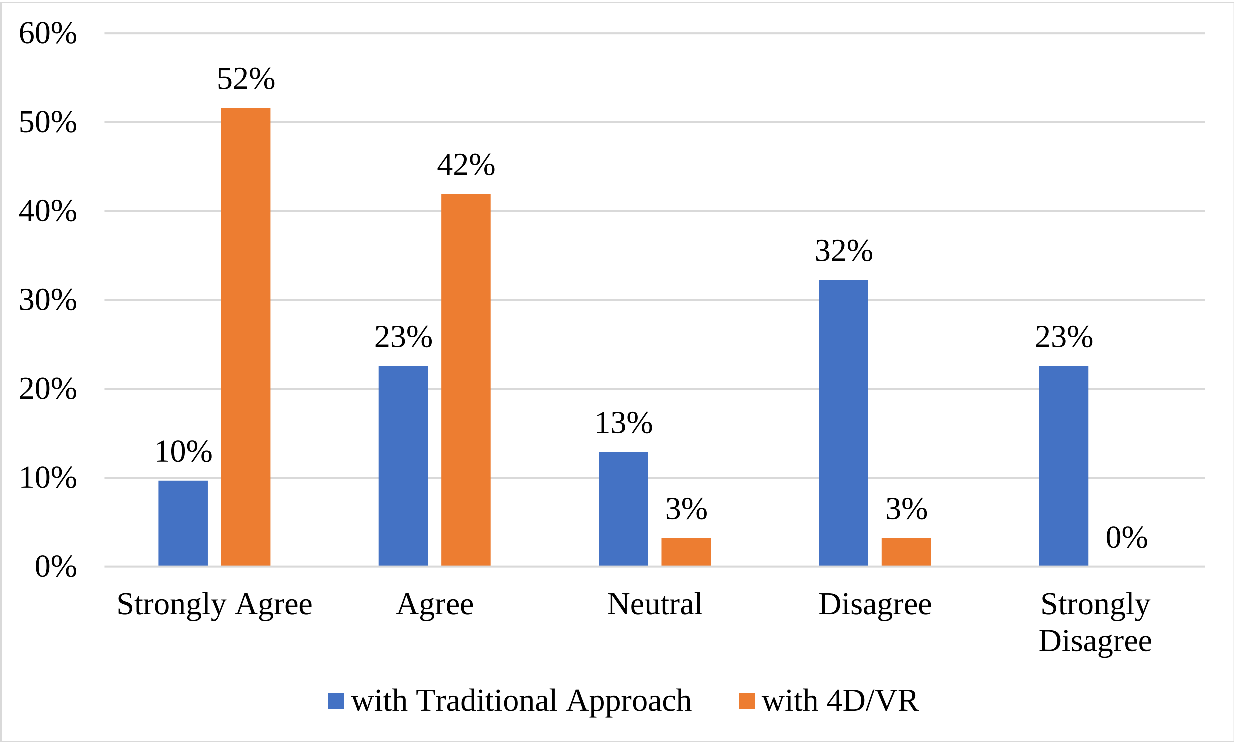


Fig. 17: Participants' Responses on Design Errors Can be Easily Located for Traditional Approach and 4D/VR

From the summary of the results, it is clear that design errors can be more easily located with 4D/VR, compared to the traditional approach. The summary of the results is presented in Table 3.

Table 3: Summary of the Responses on Design Errors Can be Easily Located

Response	Traditional Approach	4D/VR
Strongly Agree	10%	52%
Agree	23%	42%
Neutral	13%	3%
Disagree	32%	3%
Strongly Disagree	23%	0%

4.4.4 Easy to Use

The participants were asked whether it was easy to use both approaches, separately. In the case of the traditional approach, seven participants strongly agreed that the traditional approach was easy to use, while 11 agreed. However, six and two participants disagreed and strongly disagreed with that claim, respectively.

Similarly, the participants were questioned on the same claim once they had used the 4D/VR. Sixteen of them strongly agreed that the 4D/VR was easy to use, while 11 agreed, and two participants disagreed with the claim for the 4D/VR. Details of the responses are shown in Figure 18.

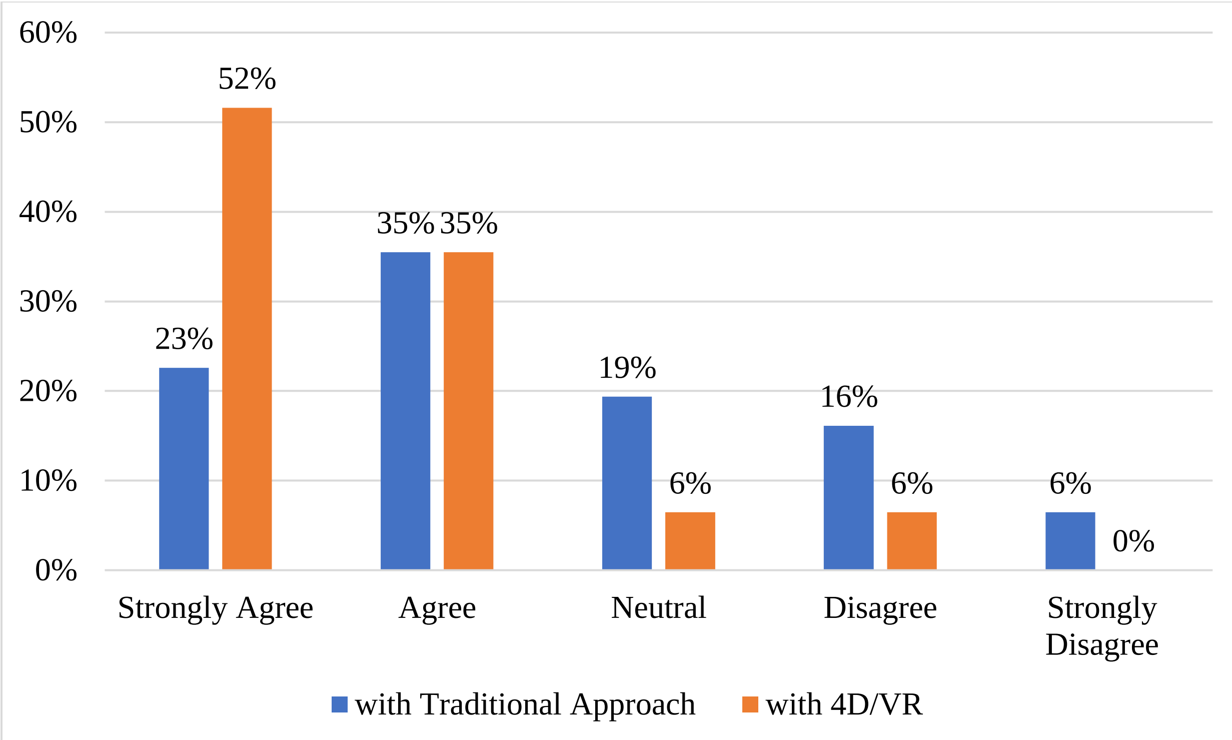


Fig. 18: Participants Responses on Easy to Use for Traditional Approach and 4D/VR

Based on these responses to the two approaches independently, it was noted that some participants disagreed that both approaches were easy to use. The response summary from the participants related to the question about the approaches being easy to use is presented in Table 4.

Table 4: Summary of the Responses on Easy to Use

Response	Traditional Approach	4D/VR
Strongly Agree	23%	52%
Agree	35%	35%
Neutral	19%	6%
Disagree	16%	6%
Strongly Disagree	6%	0%

4.4.5 Felt Confident

The participants were asked whether they felt confident using the two approaches, separately. In the case of the traditional approach, six participants strongly agreed that they felt confident using the traditional approach, while seven agreed. However, 12 participants were neutral, three participants disagreed, and three more strongly disagreed with that claim.

Similarly, the participants were questioned on the same claim once they had used the 4D/VR. Seventeen of them strongly agreed that they felt confident using the 4D/VR, while 11 agreed. Two participants were neutral to the claim for 4D/VR, and one participant strongly disagreed. Details of the responses are shown in Figure 19.

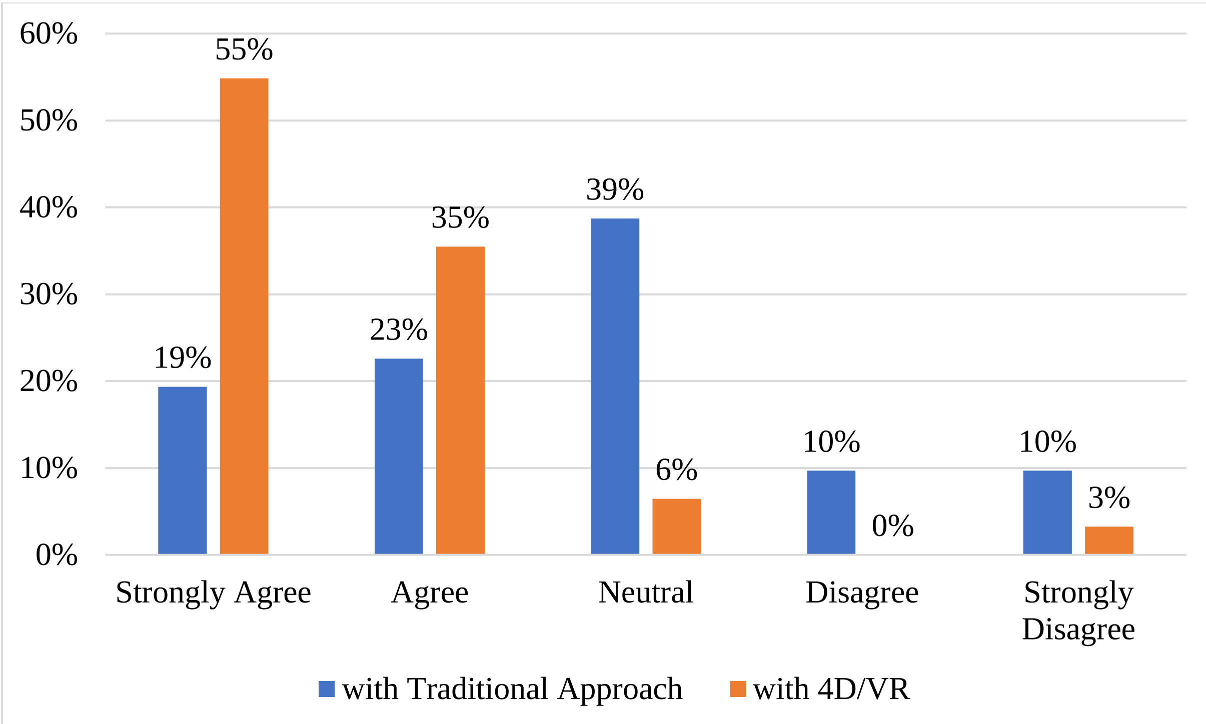


Fig. 19: Participants Responses on Felt Confident for Traditional Approach and 4D/VR

The responses from the participants clearly show that the confidence of choosing correct information is higher with 4D/VR than with the traditional approach. The summary of the results is shown in Table 5.

Table 5: Summary of the Responses on Felt Confident

Response	2D Drawing and Schedule	4D schedule and VR
Strongly Agree	19%	55%
Agree	23%	35%
Neutral	39%	6%
Disagree	10%	0%
Strongly Disagree	10%	3%

4.4.6 Effective

Further, the participants were asked about their views on which of the two approaches was more effective. In the case of the traditional approach, five participants strongly agreed that the traditional approach was effective, while nine agreed. Eleven participants were neutral on whether the traditional approach was effective, whereas three participants and another three participants disagreed and strongly disagreed with that claim, respectively.

Similarly, the participants were questioned on the same claim once they used 4D/VR. Twenty of them strongly agreed that the 4D/VR was effective, while eight agreed. Two participants were neutral, while one strongly disagreed that the 4D/VR was effective. Details of the responses are shown in Figure 20.

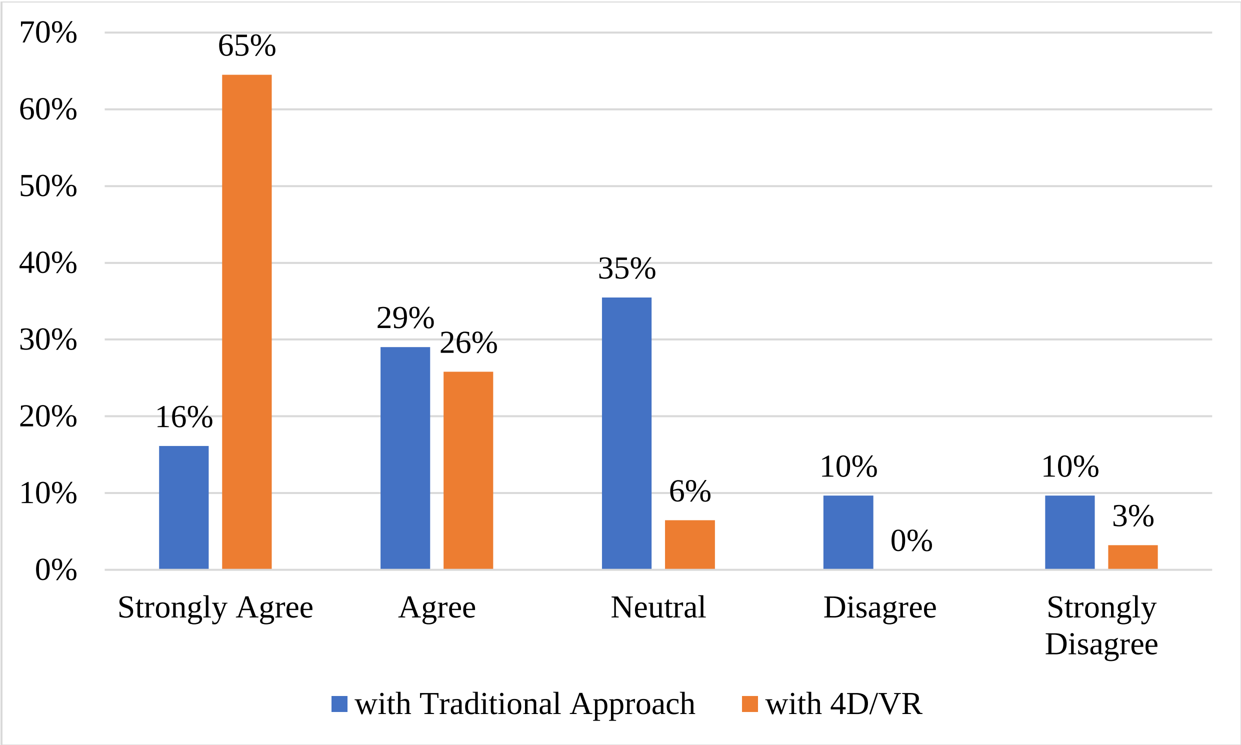


Fig. 20: Participants Responses on Effective for Traditional Approach and 4D/VR

The responses from the participants clearly show that they found the 4D/VR more effective than the traditional approach, as agreed upon by 74% of the participants. The summary of the results is shown in Table 6.

Table 6: Summary of the Responses on Effective

Response	2D Drawing and Schedule	4D schedule and VR
Strongly Agree	16%	65%
Agree	29%	26%
Neutral	35%	26%
Disagree	10%	0%
Strongly Disagree	10%	3%

4.5 Direct Comparison of 4D Schedule and VR with 2D Drawing and Project Schedule

4.5.1 Clearer with 4D Schedule and VR to Understand the Fabrication Sequence

The participants were asked if it was clearer to understand the fabrication sequence with 4D/VR. It was observed that 16 participants strongly agreed, and 11 participants agreed that it was clearer to understand using the 4D/VR. Figure 21 shows the details of the responses.

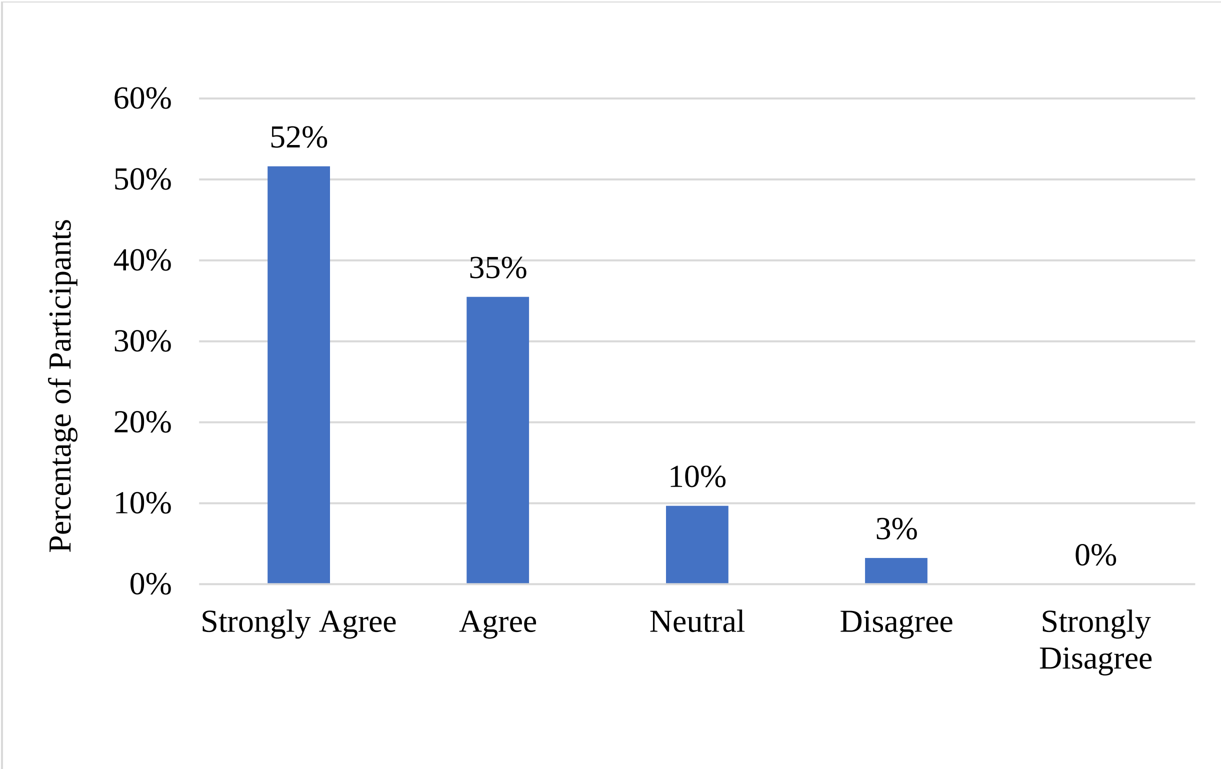


Fig. 21: It Was Clearer with 4D/VR to Understand the Fabrication Sequence

4.5.2 Easy to Locate Design Errors While Using VR than Just Looking at 2D Drawings

The participants were asked if design errors could be more easily located using VR than by looking at 2D drawings. Fifteen strongly agreed and 13 agreed with the claim. One participant's response was neutral, and one participant disagreed that design errors could be more easily located with the 4D/VR than with the traditional approach. The details of the responses are shown in Figure 22.

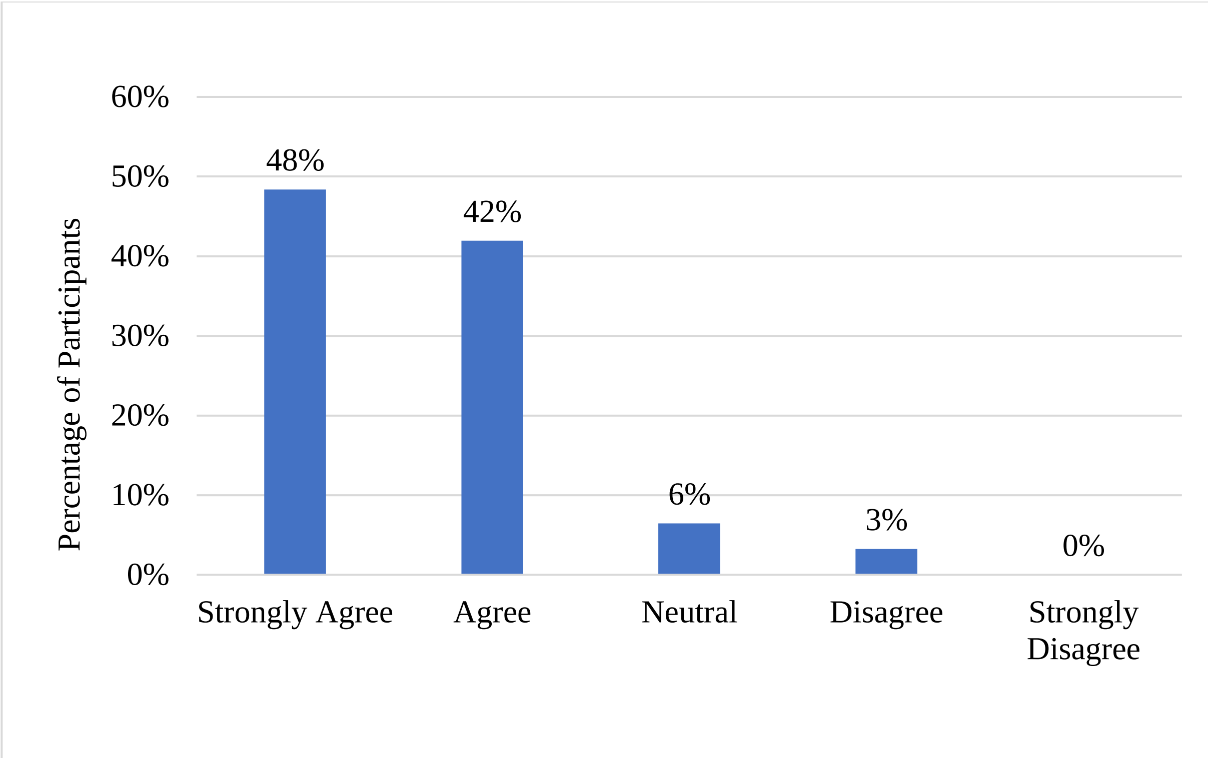


Fig. 22: Design Errors Can be More Easily Located with the Use of VR than with 2D Drawings and the Traditional Approach

4.5.3 Better Understanding of the Interior and Exterior of the Fabrication Process with VR

The participants were asked whether the VR immersion helped them to understand the fabrication and assembly processes. Twenty-one of the participants strongly agreed that VR immersion helped them with developing a better understanding of the fabrication process, whereas nine participants agreed, while one was neutral. None of the participants disagreed with the statement. The details of the responses are shown in Figure 23.

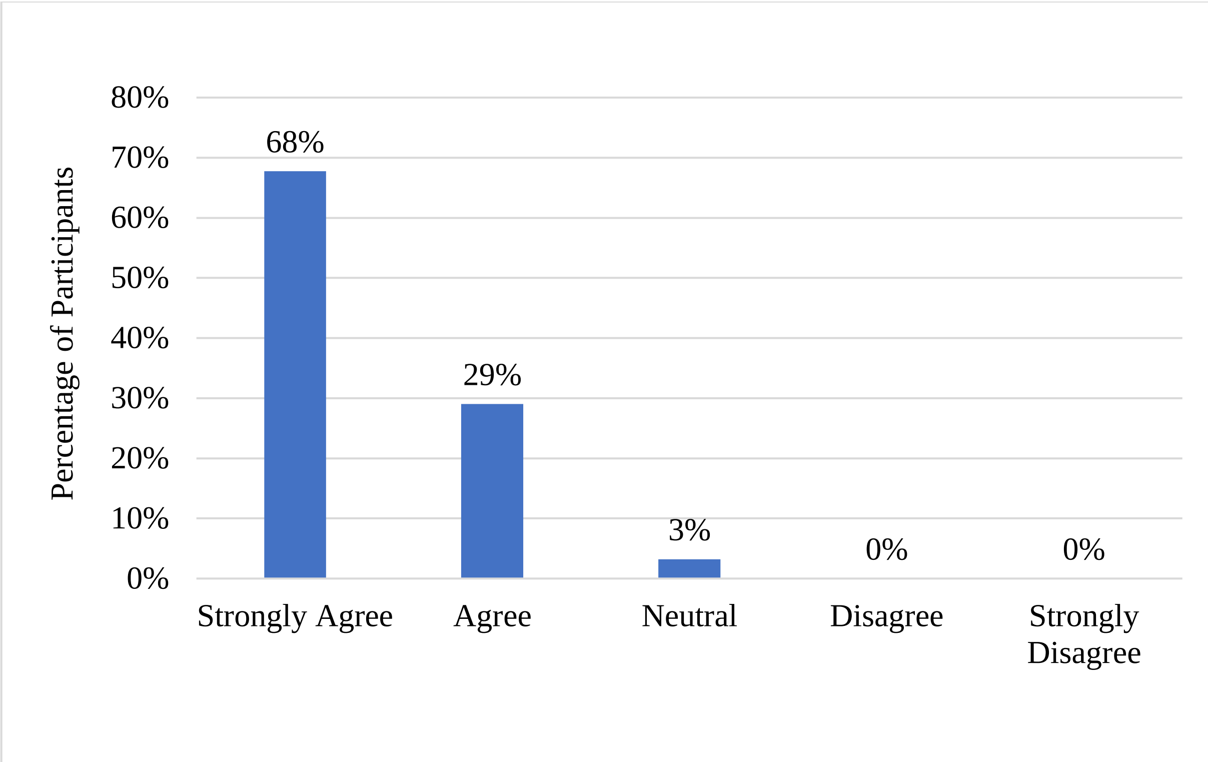


Fig. 23: VR Immersion Helps in Better Understanding the Interior and Exterior of the Fabrication Process

4.5.4 Difficulties in Understanding the Traditional Schedules and Drawings Without Using 4D and VR

The participants were asked if they have difficulties in understanding the traditional schedules and drawings without using 4D/VR. Three of them strongly agreed and eight of them agreed with the claim. Seven participants' responses were neutral, while 11 and two participants disagreed and strongly disagreed, respectively, that they had difficulties in understanding the traditional schedules and drawings without using 4D/VR. The details of the responses are shown in Figure 24.

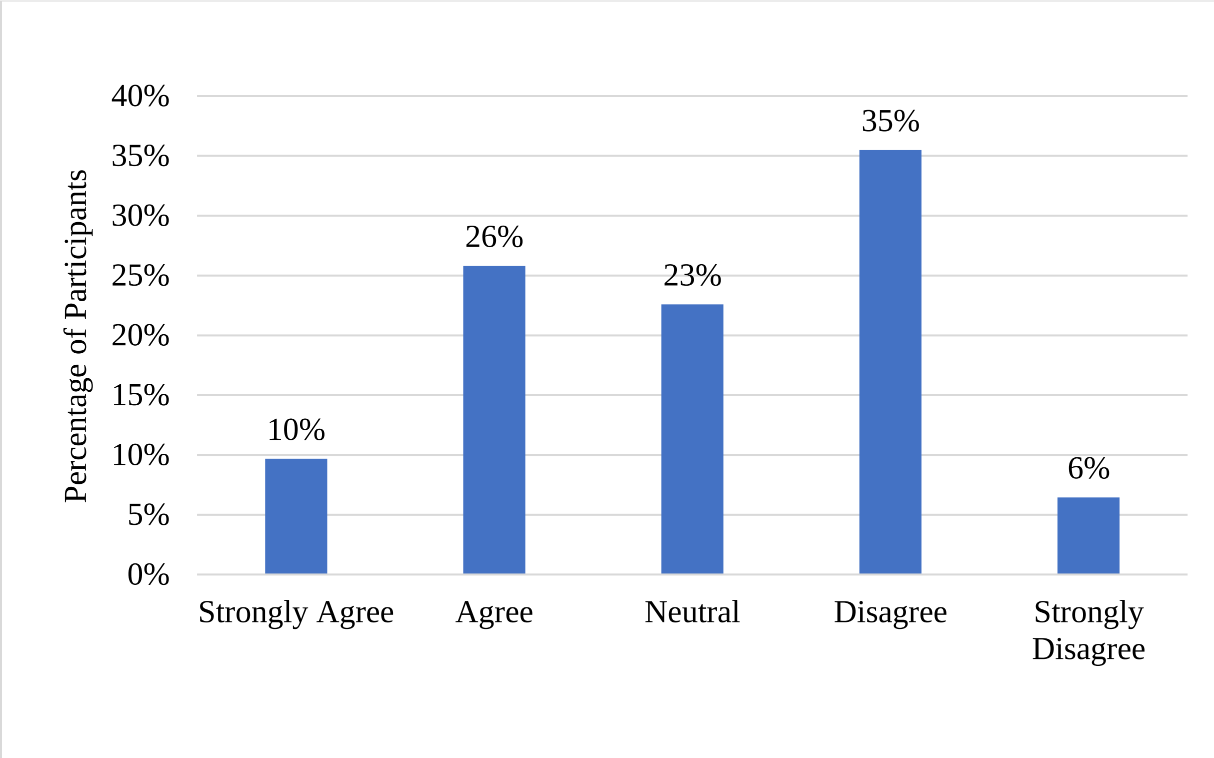


Fig. 24: Difficulties in Understanding Traditional Schedule and Drawings Without 4D/VR

4.5.5 Clarity of Design Information Using 4D/VR

The participants were asked if there was a lesser need or no need to call the designer for further information with the 4D/VR, in comparison with the traditional approach. Seven of them strongly agreed, and ten of them agreed with the claim. Seven of the participants' responses were neutral, and six participants disagreed, while one participant strongly disagreed that there was lesser need to call the designer for further information with 4D/VR than with the traditional approach. The details of the responses are shown in Figure 25.

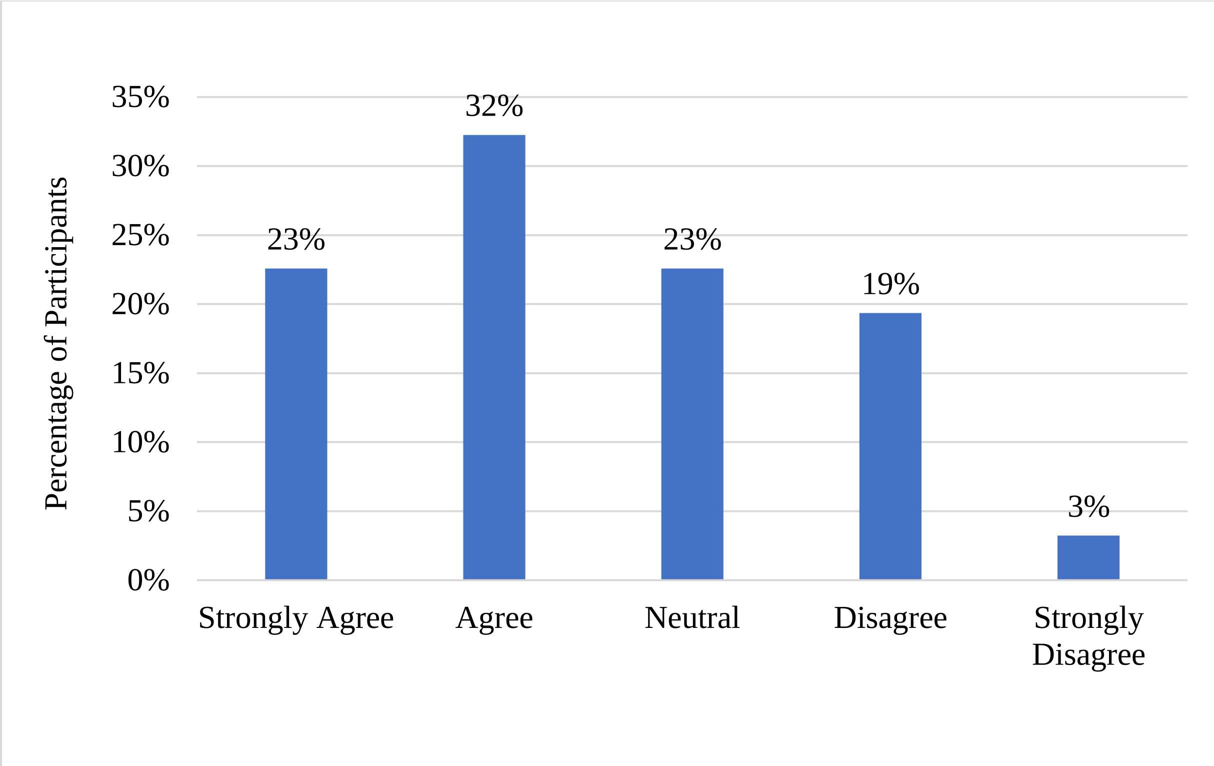


Fig. 25: There is No or Lesser Need to Call Designer for Further Information with the Use of 4D/VR than the Traditional Approach

4.5.6 Confidence in Using 4D Schedule and VR over Traditional Approach

The participants were asked if they felt more confident using the 4D/VR than the traditional approach. Seven of them strongly agreed, and 14 of them agreed with the claim. Seven participants' responses were neutral, while two participants and one participant disagreed and strongly disagreed, respectively, that they felt more confident while using the 4D/VR than the traditional approach. The details of the responses are shown in Figure 26.

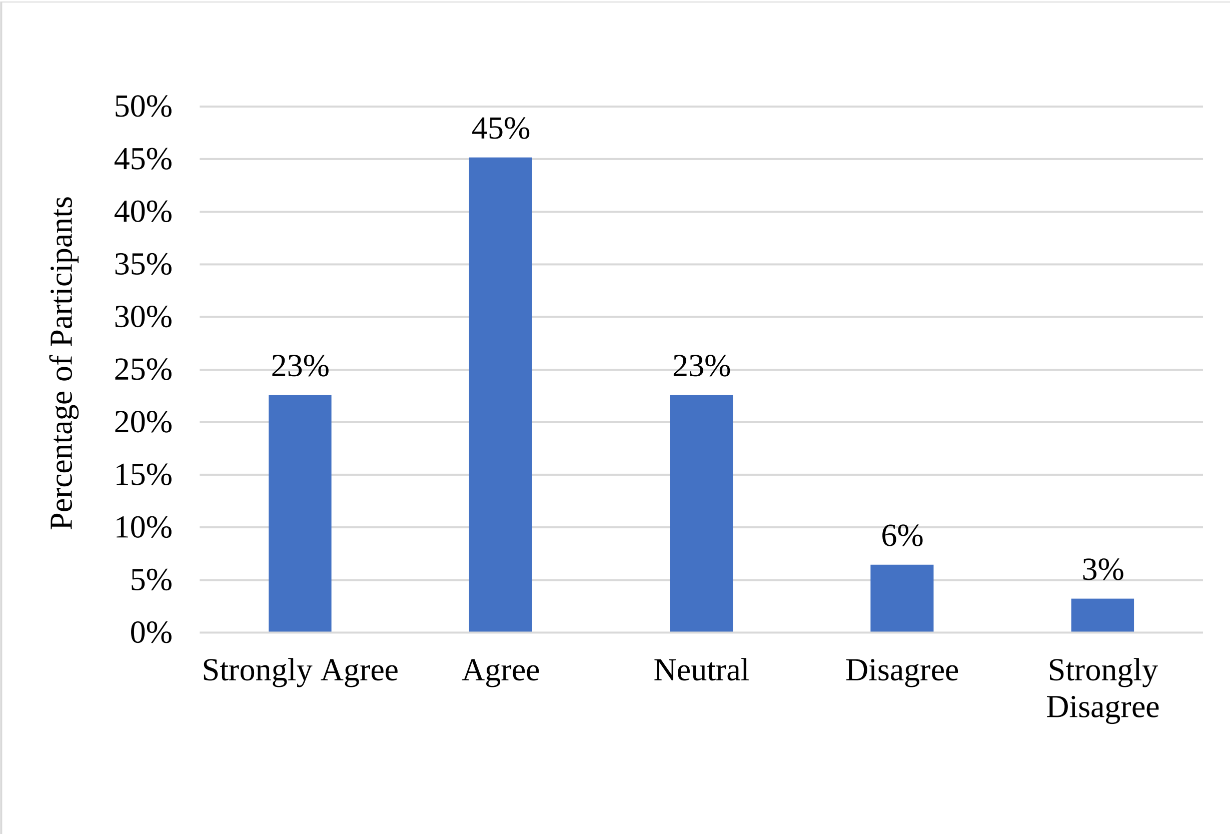


Fig. 26: Felt More Confident with the Use of 4D/VR than Traditional Approaches

4.5.7 Communication with Team Members and Stakeholders During the Planning Phases for 4D Schedules and Traditional 2D Drawings

The participants were asked to compare 4D with 2D for the scope of communication. Seventeen participants strongly agreed that a 4D schedule was a better tool for communication, while 13 agreed to the statement, and one stood neutral to the claim. None of the participants disagreed with the claim. The details of the responses are shown in Figure 27.

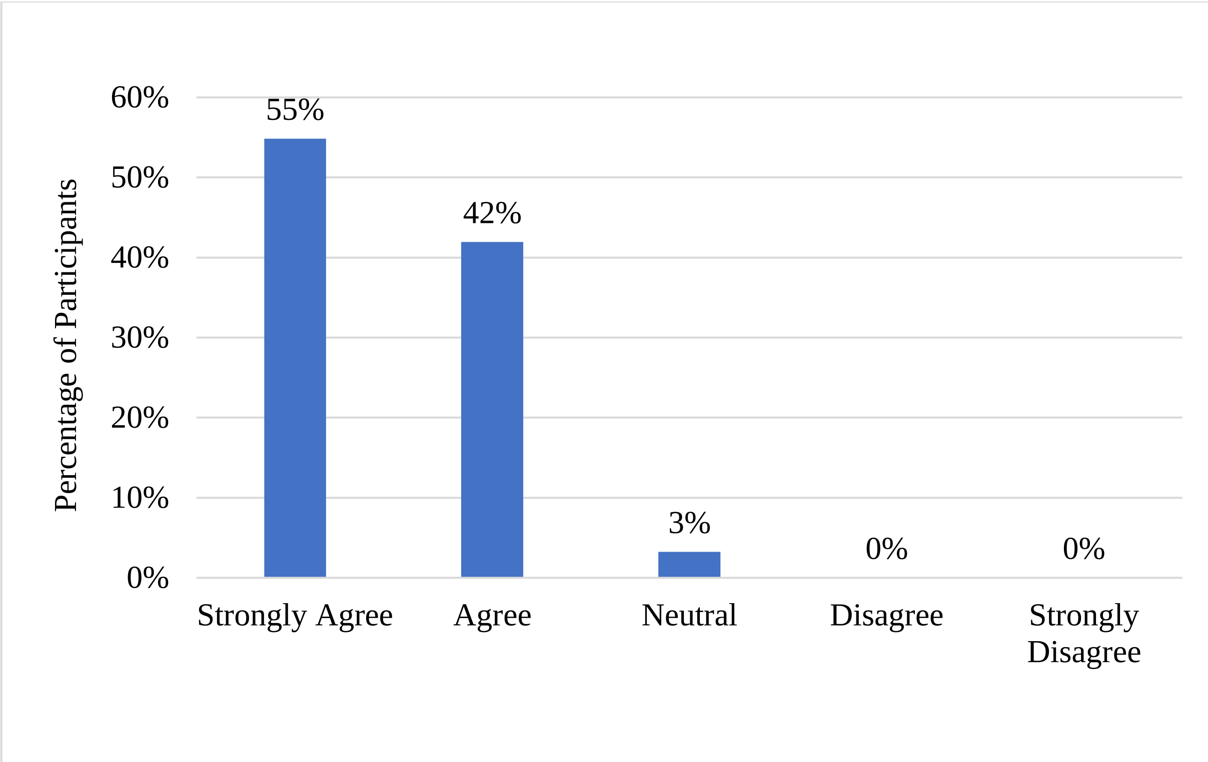


Fig. 27: 4D Schedule Provides Easier Communication with Team Members and Stakeholders

4.5.8 Helpfulness of 4D/VR in Examining the Schedule Developed

The participants were asked if they found 4D/VR helpful in examining the developed construction schedule developed. Thirteen participants strongly agreed, 13 agreed, and three were neutral, while one each disagreed and strongly disagreed with the claim. The details of their responses are shown in Figure 28.

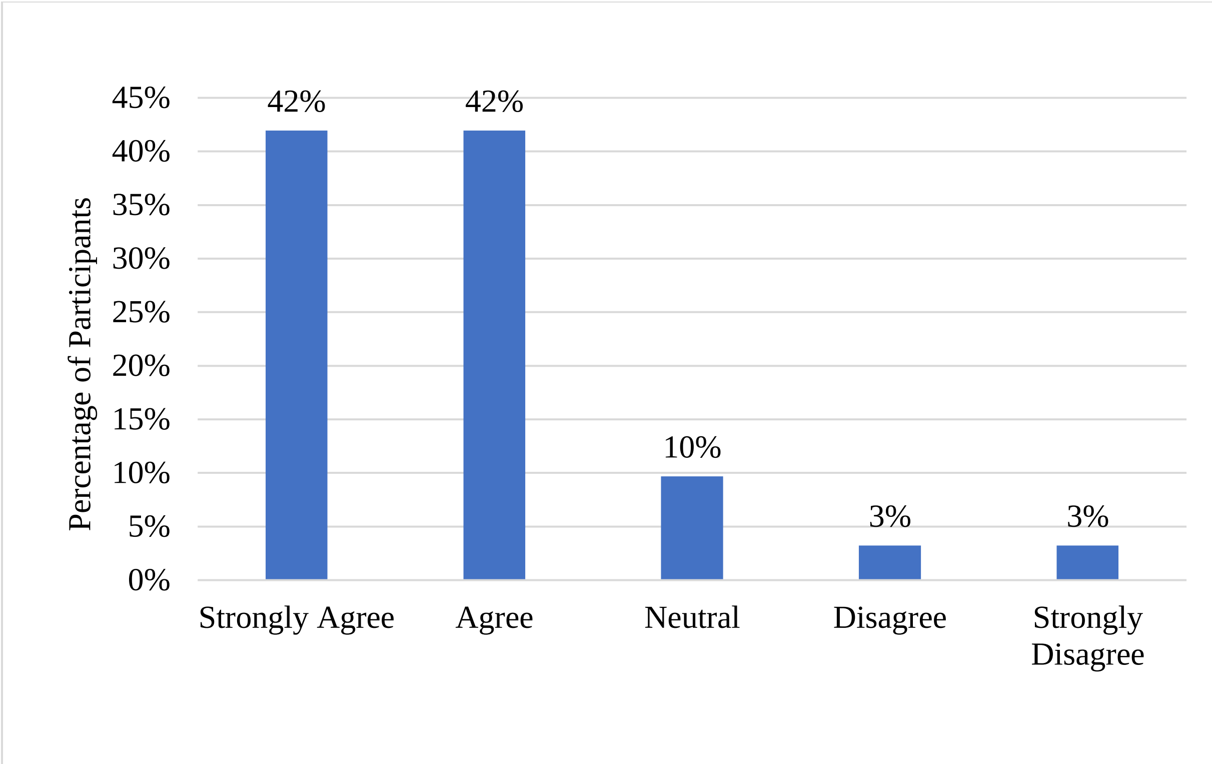


Fig. 28: 4D/VR Were Helpful in Examining the Schedule Developed

4.5.9 Assistance in Locating Areas for Efficiency Improvement During Planning Phase Using 4D/VR

The participants were asked whether the application of 4D/VR improved efficiency during the planning phase. Fourteen participants strongly agreed that 4D/VR can assist in finding efficiency improvement. Fourteen more participants agreed with the statement, while two were neutral, and one participant strongly disagreed with the claim. The details of their responses are shown in Figure 29.

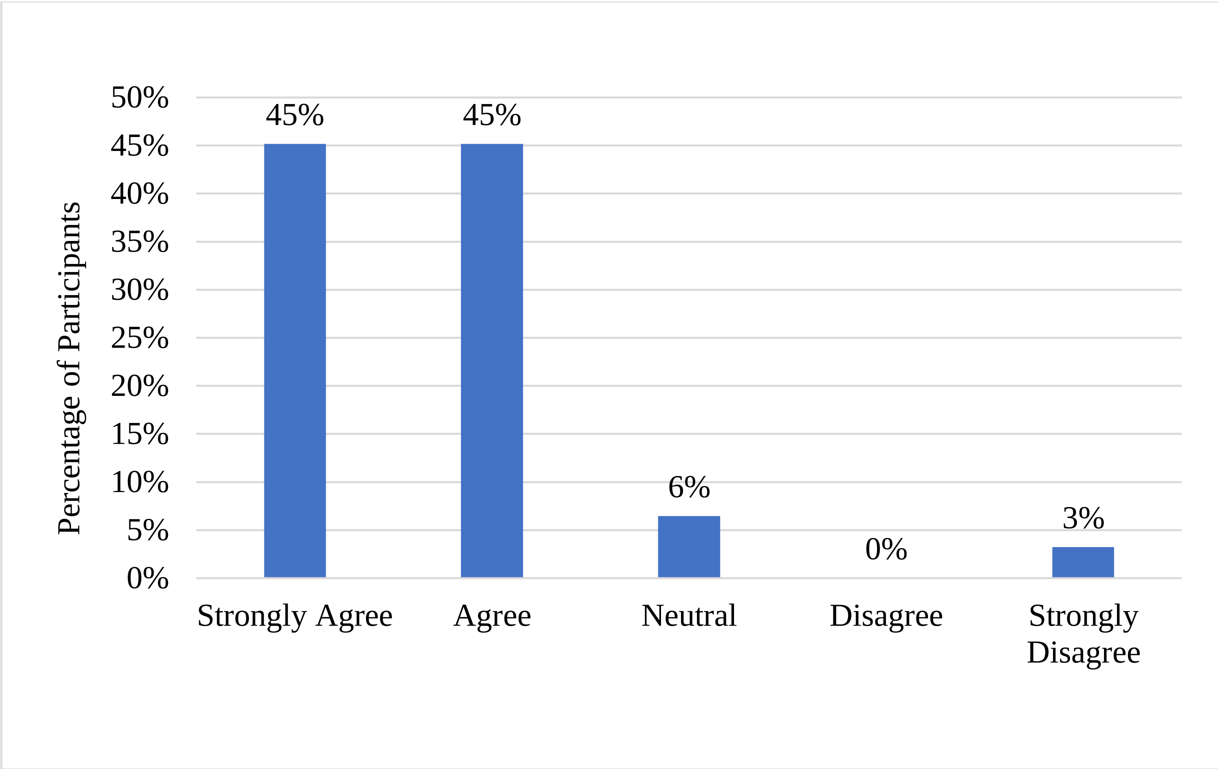


Fig. 29: 4D/VR Assist in Finding Places Where Efficiency Improvement Can Be Made During Planning Phase

4.5.10 Effectiveness of 4D/VR Over Traditional Approach

The participants were asked if they found 4D/VR more effective than the traditional approach. Fifteen of them strongly agreed and eight of them agreed with the claim. Six participants were neutral, while one participant and another participant, respectively, disagreed and strongly disagreed that they found the 4D/VR more effective than the traditional approach. The details of the responses are shown in Figure 30.

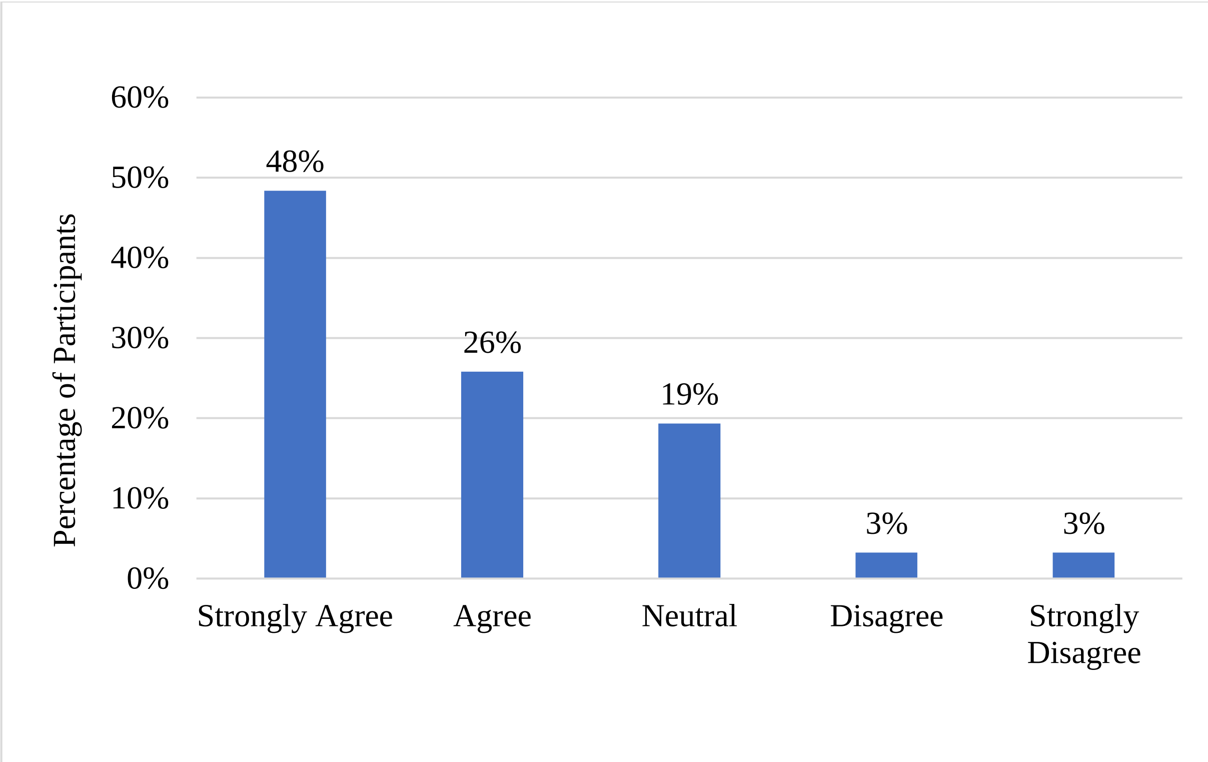


Fig. 30: 4D/VR is More Effective than Traditional Approaches

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study focused on examining the effectiveness of a 4D schedule and VR on a modular project. For this purpose, this study adopted the design of the UNLV Solar Decathlon house that is being built for the 2020 competition. The house consists of 10 modules and based on that, a project schedule, 3D model, 4D schedule, and VR model were developed for this study. Then a questionnaire survey was conducted with the university students involved in the project in order to study the differences between the 4D/VR and traditional approaches (2D drawing and project schedule). There were 31 participants from the Department of Civil and Environmental Engineering and Construction at UNLV, most of whom were either seniors or graduate students. It was recorded that the participants were not very familiar with 4D/VR or modularization. However, the participants had a couple of years of industry experience, as well as scheduling experience. During the survey, the participants spent seven to 19 minutes (with an average of 12.55 minutes) experiencing the VR model visualization.

During the survey, initially, the participants were provided 2D drawings and a project schedule and were asked to schedule an assembly sequence of the ten modules. In the survey response, it was noted that only 42% of the participants scheduled the assembly sequence correctly, as compared to the project schedule provided to them. However, 77% of the participants correctly scheduled the assembly sequence after visualization with 4D/VR, and the incorrect responses showed that 19% of the participants had only one incorrect assembly. Besides scheduling the assembly sequences, the participants were asked for Likert scale responses on six topics that were used to examine the effectiveness of the two approaches. In the case of the traditional approach, at least one-third of the participants agreed on those six topics, whereas in the case of 4D/VR at least 60% of participants agreed on each of the topics.

Further, the participants were asked to compare the 4D/VR with the traditional approach. It was observed that at least 33% of the participants agreed on each of the six topics used for comparing the effectiveness of 4D/VR over the traditional approach. In comparison, more than 60% of participants had positive responses about using 4D/VR; considering only the summary, all of the participants found 4D/VR more effective than the traditional approach. Additionally, four-fifths of the participants responded positively on: clearer to understand the fabrication with the 4D schedule and VR; easier to locate design errors using VR, rather than looking at 2D drawings; impact 4D/VR has on communication between stakeholders of a project; finding places for efficiency improvement during project planning phases; and examining project schedule. A bit more than half of the participants agreed that there is a lesser need, or no need to contact a designer for further information while using 4D/VR, than when using the traditional approach. More than two-thirds of the participants felt more confident with 4D/VR than the traditional approach. Almost all of the respondents agreed that VR immersion helped them to better understand the fabrication and assembly processes through interactive model visualization. Nearly half of the participants disagreed that they had difficulties in understanding the traditional schedules and drawings without using 4D/VR. From the responses, it was noted that the participants were used to traditional approach; however, they found 4D/VR, which they were not familiar with, more effective, as shown by their 70% positive response.

Based on these findings, it was concluded that 4D/VR is more effective than the traditional approach for modular projects when examined with students. However, as most of the participants were not familiar with 4D/VR, the participants had difficulty in handling the VR headset. Therefore, it is important that the intended users are familiar with VR for its effective use, so it is necessary to train users for the proper handling of VR.

5.2 Discussion

4D schedules and VR have been used in various trades in recent years (Ding et al., 2019; Heigermoser et al., 2019; Changyoon Kim et al., 2013; Sloot et al., 2019; Taghaddos et al., 2019; H. J. Wang et al., 2004; L. Wang, 2007). Their advancement in the construction industry is also notable. However, they have not been used significantly in modular projects. This study tried to overcome the rarity of the use of 4D/VR in modular projects, as demonstrated by the unfamiliarity of most of the survey participants in this study. This unfamiliarity resulted in the varying amounts of time they required to manage the VR headset to visualize the VR model. However, the participants were able to locate multiple design errors in the model presented to them, once they were familiar with using VR. This demonstrates that the effectiveness of VR improves significantly when the participants are familiar with VR.

Further, more than half of the participants either felt dizzy, motion sickness or stress to their eyes during VR model visualization. A response from one of the participants was “I got really dizzy. I find that this will be a problem for owners not used to it. It would be harder for much bigger building.” Thus, this issue with users feeling dizzy needs to be resolved for the widespread use of VR in construction.

Based on the participants’ responses, 4D/VR was found to be an excellent method for presenting construction plans and designs to an owner, as this method provides real-world interactive experience to users. Moreover, users would have a better visualization of the planned structures with a walkthrough on a jobsite using VR before the actual construction begins. The views expressed by the participants emphasized that the application of VR would be valuable for understanding the conceptual design of a project and seeing its overview. Further, the participants highlighted that VR would also assist in identifying any design errors.

5.3 Contribution to Practice

This study provided a better understanding to the practitioners about the advantages and disadvantages of a 4D schedule and VR in the modular project through testing with students. It encourages the use of a 4D schedule and VR in the planning and execution of modular construction projects.

5.4 Contribution to Body of Knowledge

This study examined the effectiveness of using a 4D schedule and VR in the modular construction industry, through research conducted with university students.

5.5 Recommendations

The UNLV Solar Decathlon House used in this study was a one-story building, so it is recommended that future studies be conducted on larger modular projects, with the consideration of different parameters. The participants in this study were university students; hence, it is suggested to conduct future studies with industry professionals to validate the effectiveness of the 4D schedule and VR in the modular construction industry. Further, the same group of students was used in the case of each approach, so it is recommended that future studies have different groups of participants for each approach. Moreover, the majority of the participants in this study felt dizzy while using VR. Thus, it is suggested to conduct studies to determine how to eliminate the dizziness factor when using the VR, so that its application for extended durations would be practicable. Furthermore, it is also recommended to conduct a study on whether dizziness has been a problem with the use of VR in other research areas, in addition to its application in the modular construction industry.

APPENDIX A: SURVEY QUESTIONNAIRE

Testing 4D schedule and VR

Some Definitions:

Modularization is a construction process where a part of or whole of work on jobsite is moved to fabrication shops. The modules created in fabrication shops are then transported to the job site and assembled there.

4D (four dimensional) scheduling is the integration of 3D (three dimensional) models with construction schedule which enables the visualization of simulation of the construction/fabrication sequence of the project from beginning to end.

Virtual Reality (VR) is a computer-generated interactive environment which makes users feel like being in the environment itself.

Set 1.

Name: ____

Please answer the following questions.

1. Which academic year you are in?

a.	b.	c.	d.	e.
Freshman	Sophomore	Junior	Senior	Graduate

2. What is your industry experience?

a.	b.	c.	d.	e.
Less than 1 year	1 year	2 years	3 years	More

3. How much years of scheduling experience do you have?

a.	b.	c.	d.	e.
Less than 1 year	1 year	2 years	3 years	More

4. How familiar you are with modular construction methods.

a.	b.	c.
Very Familiar	Familiar	Not familiar

5. How familiar are you with 4D and Virtual Reality model?

a.	b.	c.
Very Familiar	Familiar	Not familiar

Set 2

Please schedule the following modules in their assembly sequence using the 2D drawings and given project schedule.

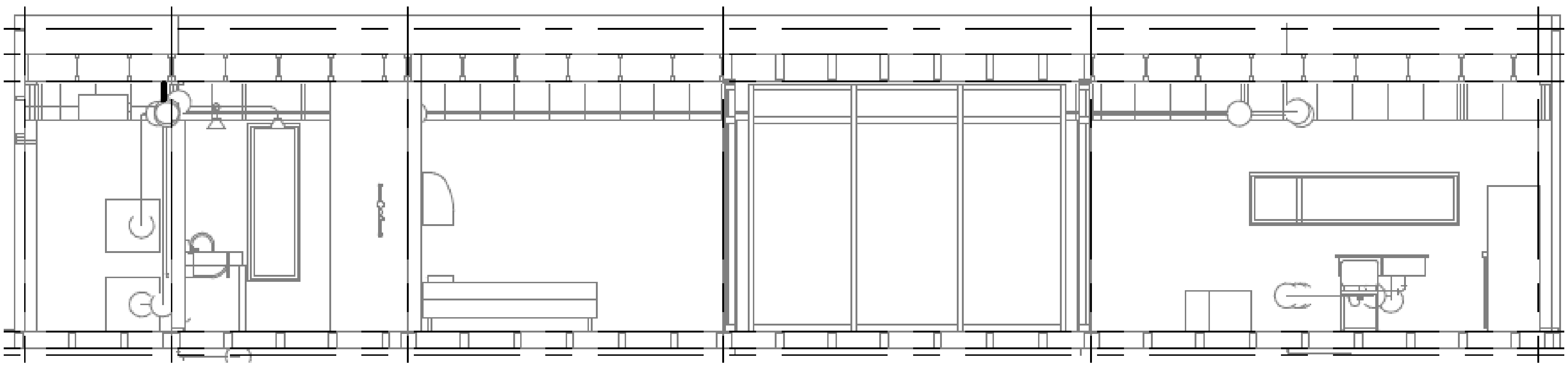
Sequence no.	Name of module (A/B/C……)
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

The modules names are

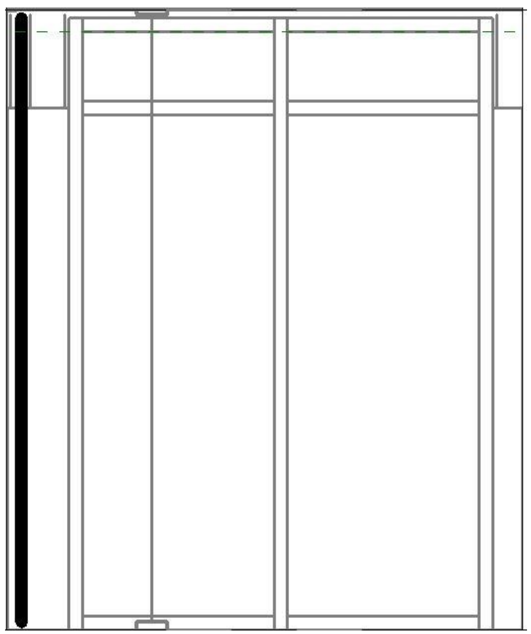
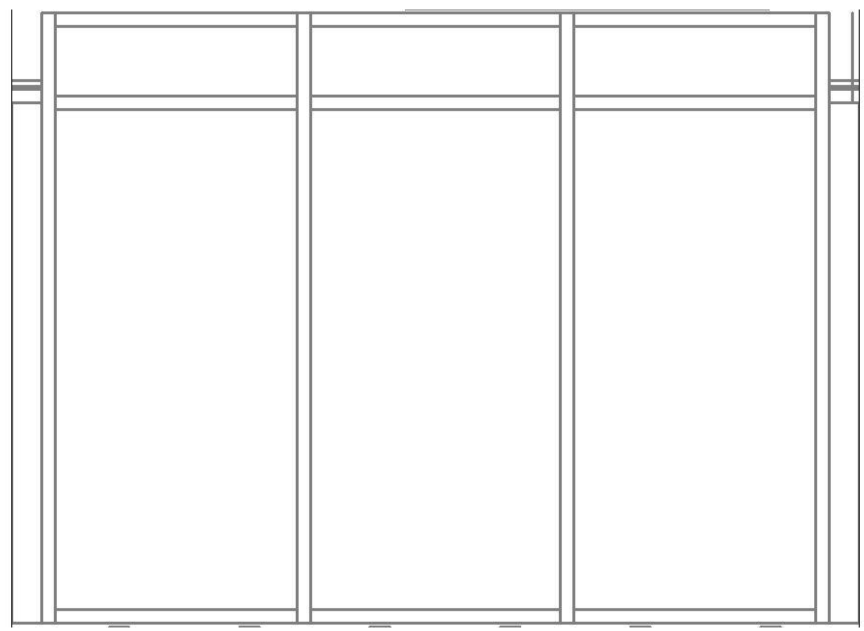
A. Courtyard Module
B. Back Side Wall Module
C. Mechanical Room Module
D. East Side Wall Module
E. Kitchen Module
F. Bathroom Module
G. Front Wall Module
H. Bedroom Module
I. West Wall Module
J. Four 500-gallon storage tank modules

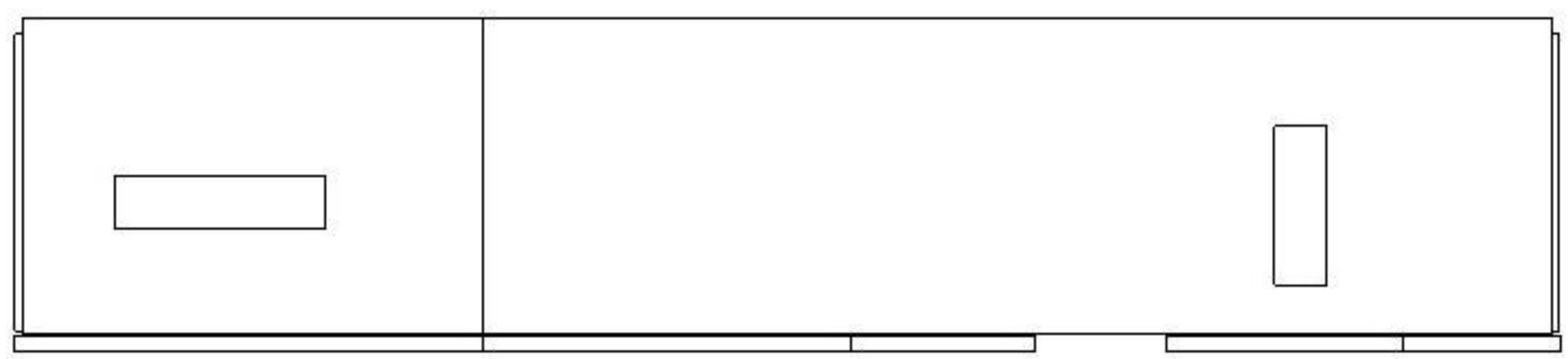
Set 2.

This is the sectional view of modular house after completion.

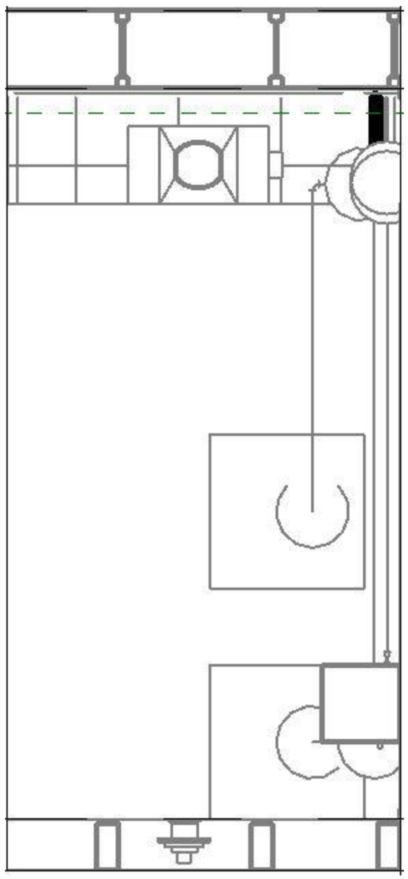
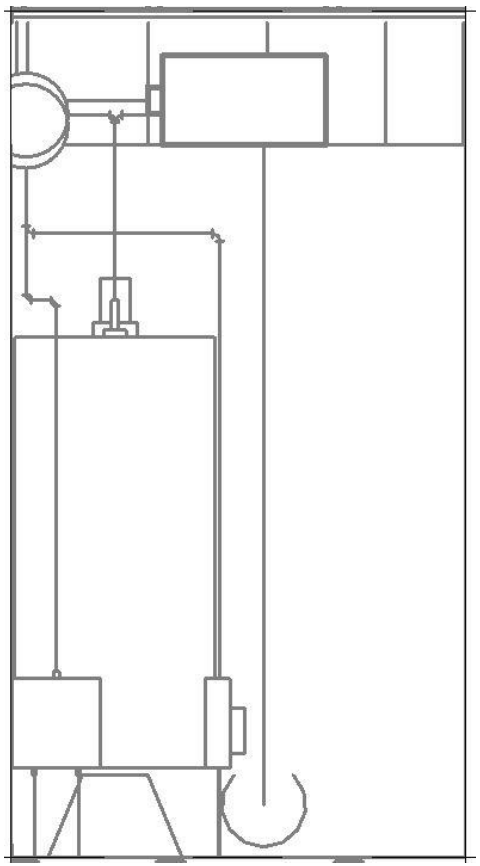


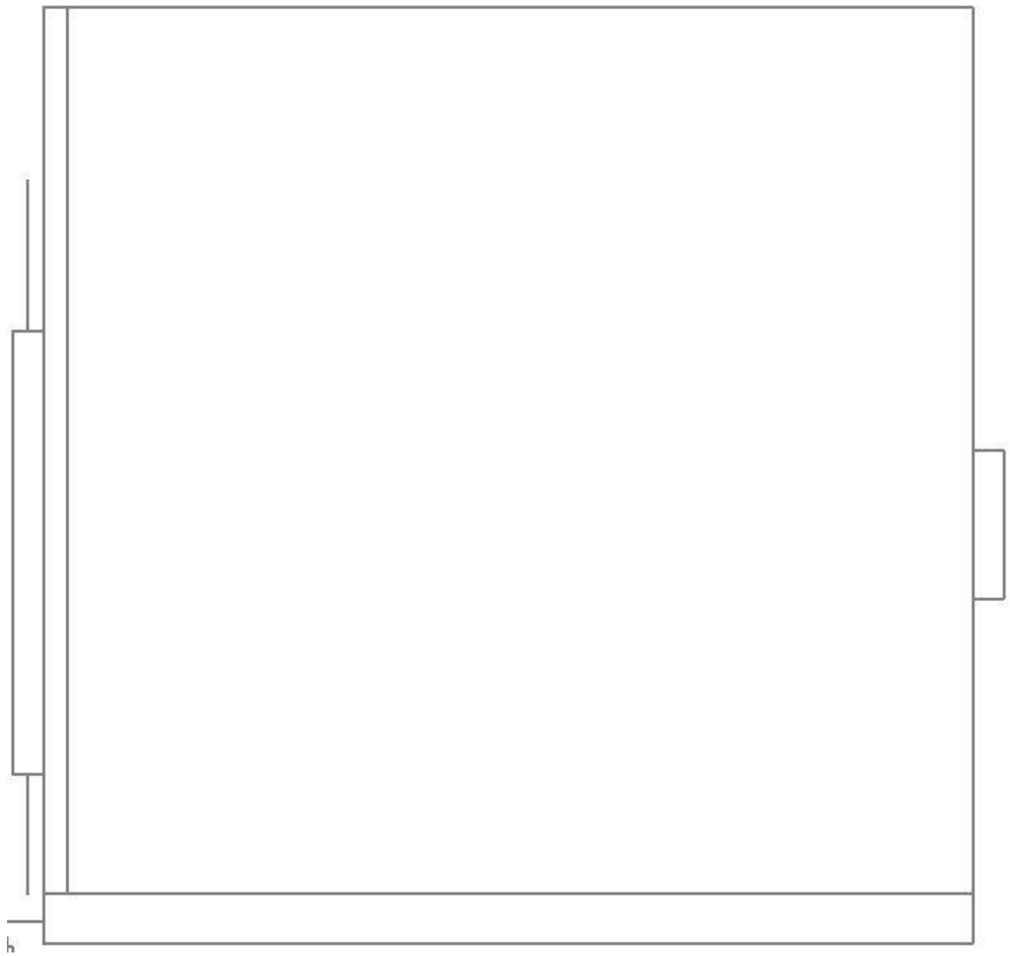
Please schedule the following modules in their assembly sequence. Modules have views of their interior elevation to make visualization easier. The drawings are not in scale.

	
A. Courtyard Module	**Details** This module also consists of front entrance to the building.

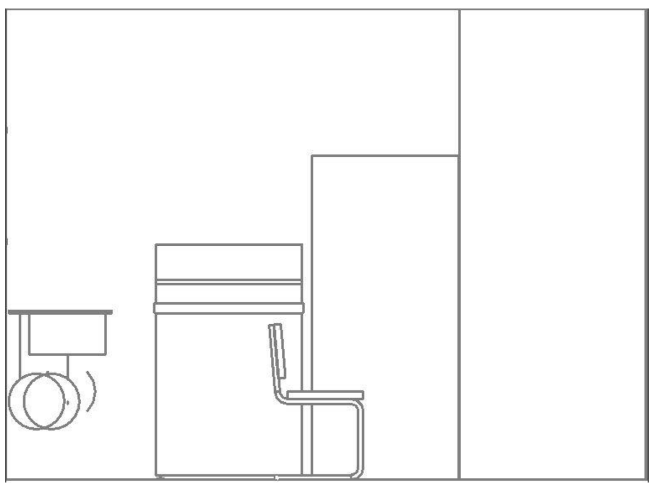
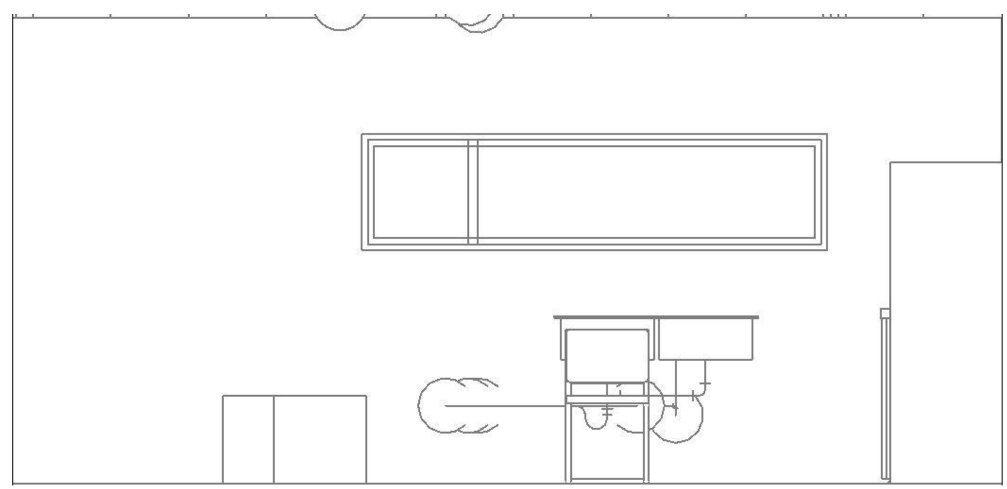


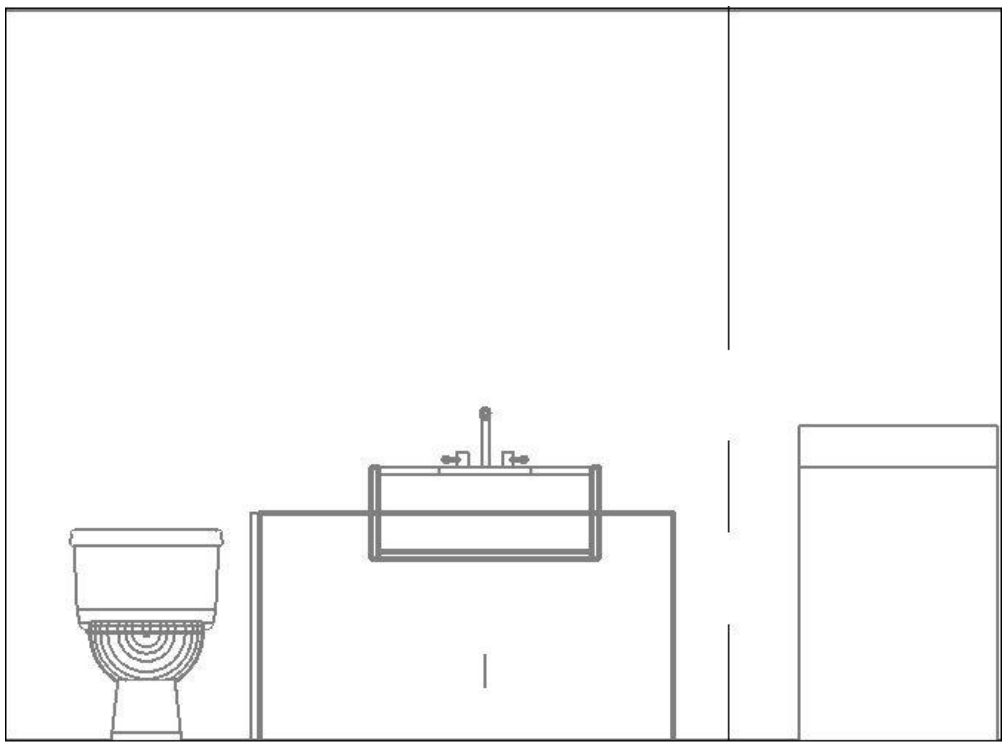
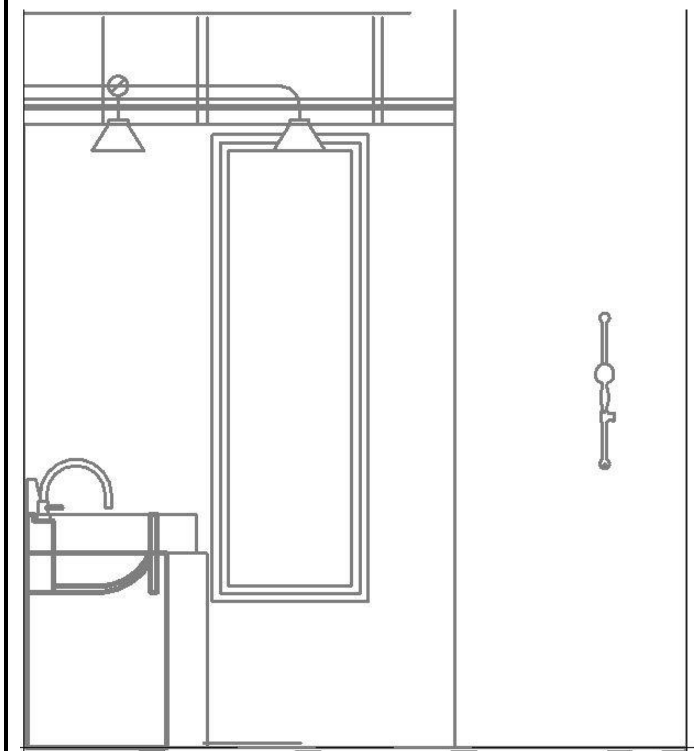
B. Back Side Wall module	**Details** This module consists of wall envelope of back side.

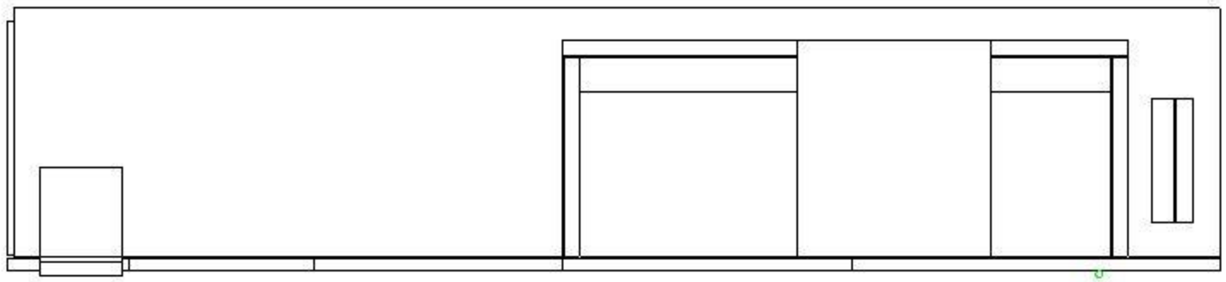
	
C. Mechanical Room Module	**Details** This module is a mechanical room module located in the west side of building.



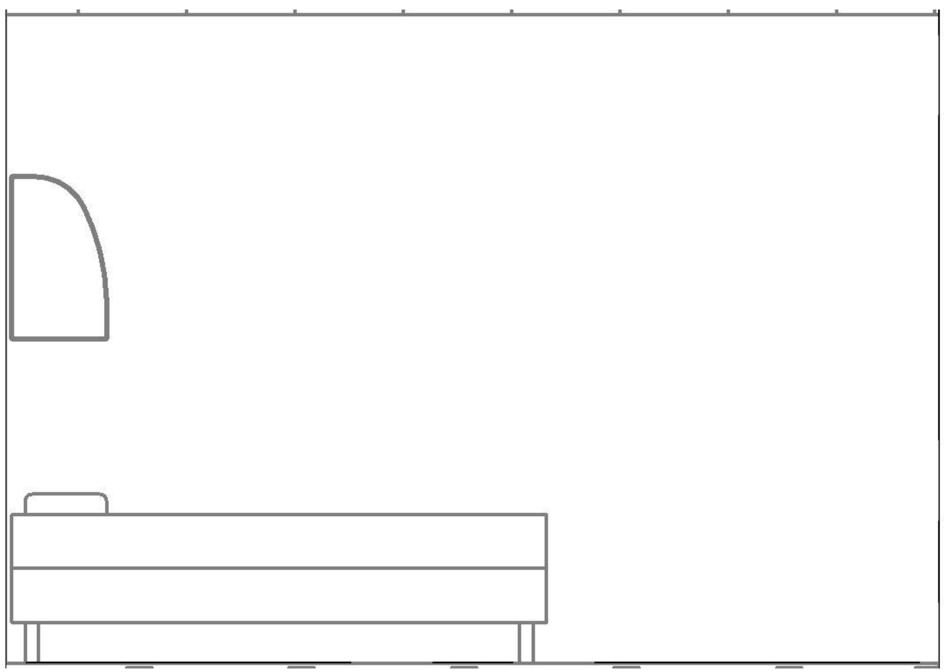
D. East Side Wall Module	Details This module consists of wall envelope for the east side of the building.

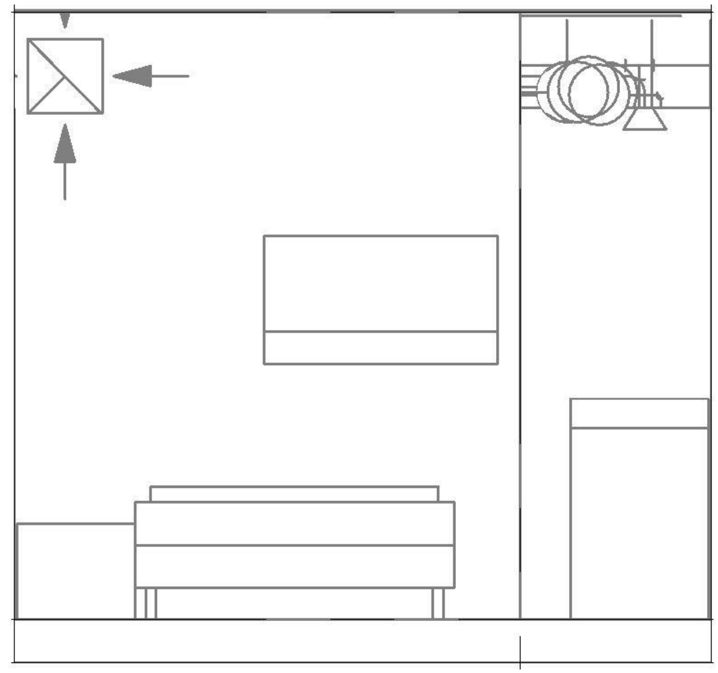
	
E. Kitchen Module	**Details** This module is the kitchen room located in the east side of building.

	
F. Bathroom Module	**Details** Bathroom module consists of bathroom and restroom.

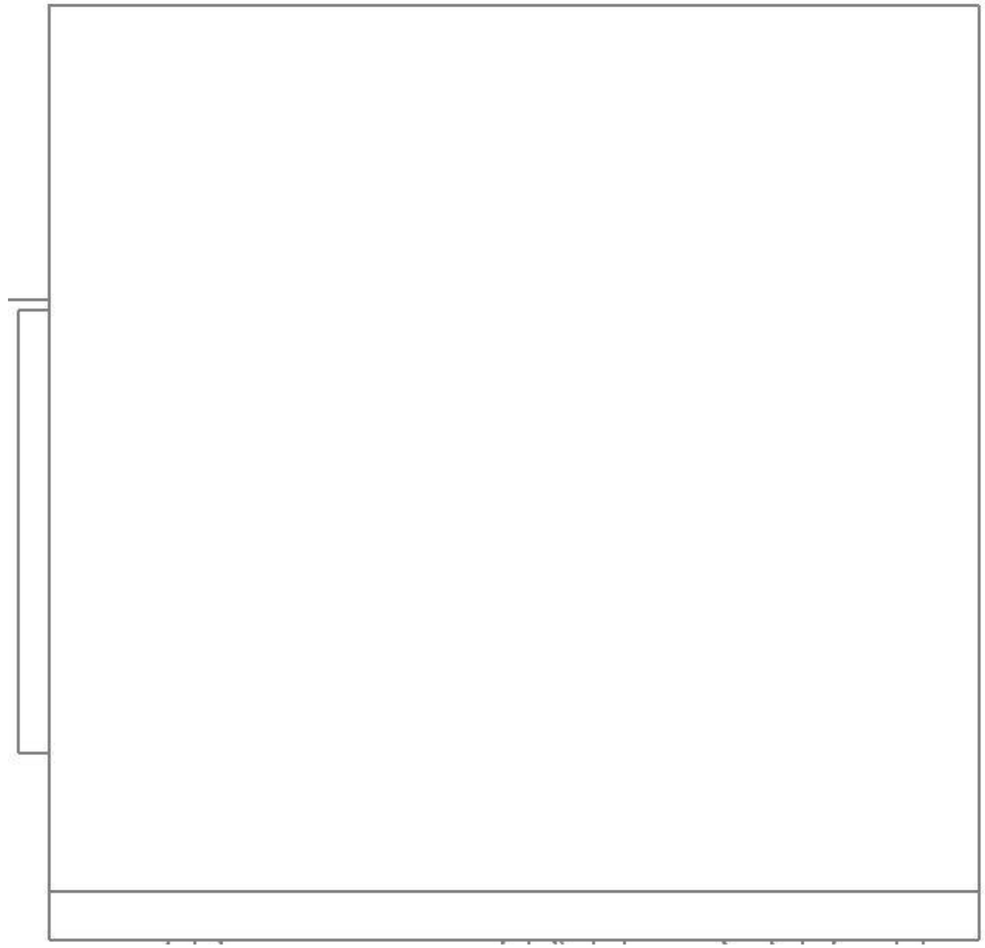


G. Front Wall Module	**Details** This is the front wall envelope module located in the front side of the building.

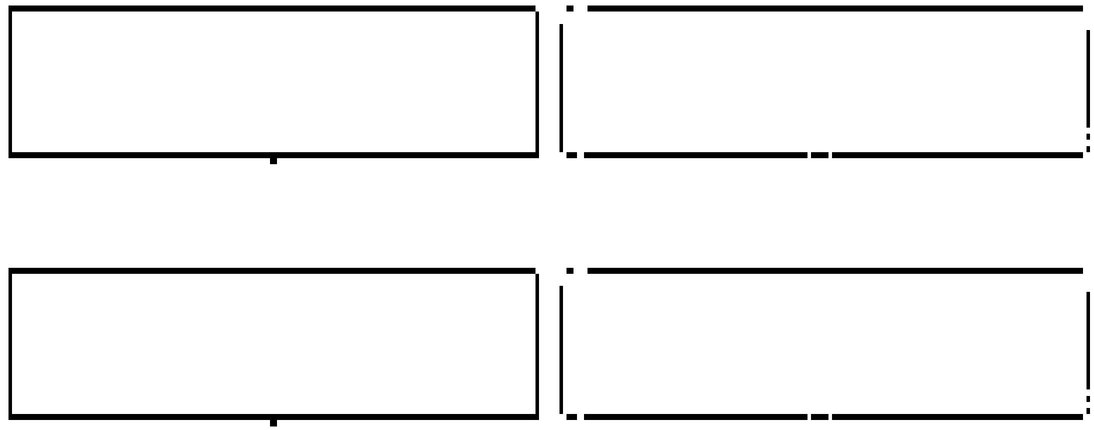




H. Bedroom Module	**Details** Bedroom module contains just the bedroom.



I. West Wall Module	**Details**
	This is the wall envelope in the west side of the building.



J. Four 500-gallon storage tank module	**Details** These are four separate modules of 500-gallon capacity water tank, which are considered as one.

Set 3.

Please select the appropriate options.

i> 2D drawing and project schedule.

Measures	**Strongly agree**	**Agree**	**Neutral**	**Disagree**	**Strongly disagree**
Easy to visualize					
No need to call designer for further information					
Design errors can be easily located					
Easy to use					
Felt confident					
Effective					

Easy to visualize: Information can be easily seen.

No need to call designer for further information: everything has been understood from the drawing, so no further contacts made.

Design errors can be easily located: looking around the available resources design errors are easily located.

Easy to use: intended user can easily use the given materials.

Felt confident: confirm that you picked up the correct information.

Effective: construction activities could be smoothly carried out using the given means without any mistakes.

After VR

ii> Please schedule the following modules in their assembly sequence.

Sequence no.	Name of module (A/B/C……)
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

The modules names are

A. Courtyard Module
B. Back Side Wall Module
C. Mechanical Room Module
D. East Side Wall Module
E. Kitchen Module
F. Bathroom Module
G. Front Wall Module
H. Bedroom Module
I. West Wall Module
J. Four 500-gallon storage tank modules

iii> 4D schedule & VR

Measures	**Strongly agree**	**Agree**	**Neutral**	**Disagree**	**Strongly disagree**
Easy to visualize					
No need to call designer for further information					
Design errors can be easily located					
Easy to use					
Felt confident					
Effective					

Easy to visualize: Information can be easily seen.

No need to call designer for further information: everything has been understood from the drawing, so no further contacts made.

Design errors can be easily located: looking around the available resources design errors are easily located.

Easy to use: intended user can easily use the given materials.

Felt confident: confirm that you picked up the correct information.

Effective: construction activities could be smoothly carried out using the given means without any mistakes.

Comparison of 4D schedule and VR with Traditional Schedule and 2D Drawings.

1. It was clearer with 4D module and VR to understand the fabrication sequence.

a.	b.	c.	d.	e.
Strongly agree	Agree	Neutral	Disagree	Strongly disagree

2. I could easily locate design errors while using VR than just looking at 2D drawings

a.	b.	c.	d.	e.
Strongly agree	Agree	Neutral	Disagree	Strongly disagree

3. VR immersion helps in better understanding of the interior and exterior of the fabrication process.

a.	b.	c.	d.	e.
Strongly agree	Agree	Neutral	Disagree	Strongly disagree

4. I have difficulties in understanding the traditional schedules and drawings without using 4D and VR technologies.

a.	b.	c.	d.	e.
Strongly agree	Agree	Neutral	Disagree	Strongly disagree

5. I feel more knowledgeable about the details of the modules so there is no need to contact designer for design information after using 4D schedule and VR.

a.	b.	c.	d.	e.
Strongly agree	Agree	Neutral	Disagree	Strongly disagree

6. I felt more confident using of 4D schedule and VR over traditional approach.

a.	b.	c.	d.	e.
Strongly agree	Agree	Neutral	Disagree	Strongly disagree

7. 4D schedule provides easier communication with team members and stakeholders during the construction and planning phases than traditional 2D drawings.

a.	b.	c.	d.	e.
Strongly agree	Agree	Neutral	Disagree	Strongly disagree

8. The 4D and VR were helpful for examining the schedule we developed.

a.	b.	c.	d.	e.
Strongly agree	Agree	Neutral	Disagree	Strongly disagree

9. The 4D and VR technologies assist in finding places where efficiency improvement can be made during planning phase.

a.	b.	c.	d.	e.
Strongly agree	Agree	Neutral	Disagree	Strongly disagree

10. I found 4D schedule and VR more effective over 2D schedules and drawings in fabrication of the modular house.

a.	b.	c.	d.	e.
Strongly agree	Agree	Neutral	Disagree	Strongly disagree

Questions

1. What did you like about 4D schedule and VR?

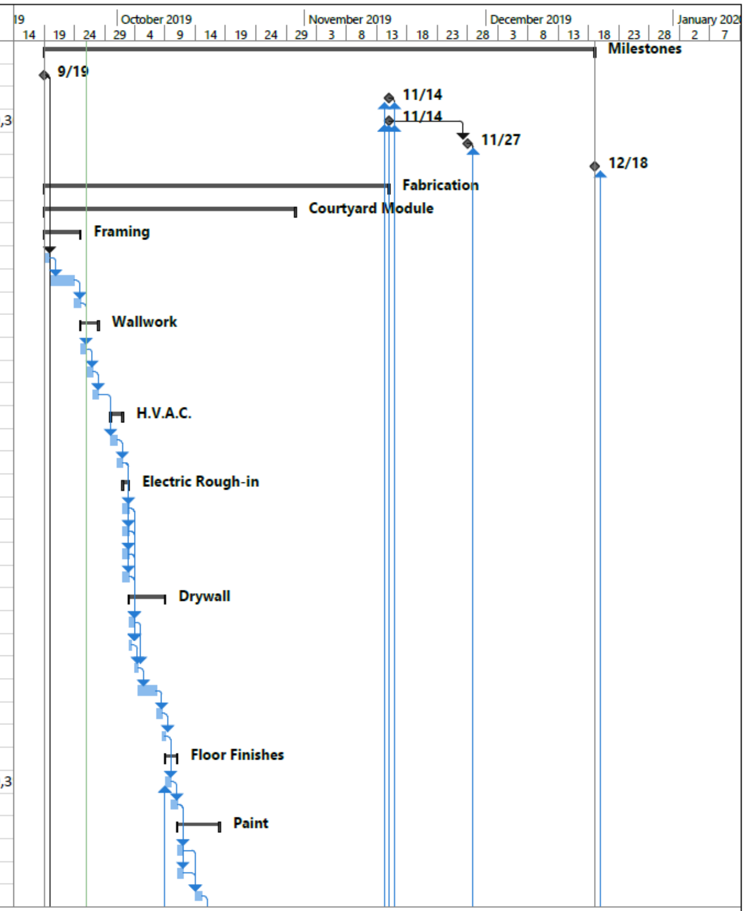
2. What difficulties you found during the use of 4D schedule and VR?

3. Please list the design errors you found in the VR model.

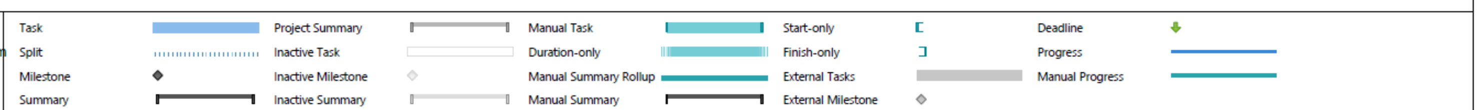
4. Please provide further comments, if you have any.

APPENDIX B: PROJECT SCHEDULE PROVIDED TO THE PARTCIPANTS

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Milestones**	**65 days**	**Thu 9/19/19**	**Wed 12/18/1**	
2		Start of Fabrication	0 days	Thu 9/19/19	Thu 9/19/19	
3		Start of Assembly	0 days	Thu 11/14/19	Thu 11/14/19	128,249
4		End of Fabrication	0 days	Thu 11/14/19	Thu 11/14/19	57,128,187,249,3
5		Substantial Completion	0 days	Wed 11/27/1	Wed 11/27/1	413,4
6		Final Completion	0 days	Wed 12/18/1	Wed 12/18/1	416
7		**Fabrication**	**41 days**	**Thu 9/19/19**	**Thu 11/14/19**	
8		**Courtyard Module**	**29.5 days**	**Thu 9/19/19**	**Wed 10/30/1**	
9		**Framing**	**4 days**	**Thu 9/19/19**	**Tue 9/24/19**	
10		Deck Framing	1 day	Thu 9/19/19	Thu 9/19/19	2
11		Wall Framing	2 days	Fri 9/20/19	Mon 9/23/19	10
12		Install Door	1 day	Tue 9/24/19	Tue 9/24/19	11
13		**Wallwork**	**3 days**	**Wed 9/25/19**	**Fri 9/27/19**	
14		Subfloor	1 day	Wed 9/25/19	Wed 9/25/19	12
15		Exterior Sheathing	1 day	Thu 9/26/19	Thu 9/26/19	14
16		Roof sheathing	1 day	Fri 9/27/19	Fri 9/27/19	15
17		**H.V.A.C.**	**2 days**	**Mon 9/30/19**	**Tue 10/1/19**	
18		HVAC Layout & Measure	1 day	Mon 9/30/19	Mon 9/30/19	16
19		HVAC Rough-in	1 day	Tue 10/1/19	Tue 10/1/19	18
20		**Electric Rough-in**	**1 day**	**Wed 10/2/19**	**Wed 10/2/19**	
21		Set Electric Boxes	1 day	Wed 10/2/19	Wed 10/2/19	19
22		Electrical Walk-through	1 day	Wed 10/2/19	Wed 10/2/19	19
23		Electrical Rough-wire	1 day	Wed 10/2/19	Wed 10/2/19	19
24		Wire Testing	1 day	Wed 10/2/19	Wed 10/2/19	19
25		**Drywall**	**4 days**	**Thu 10/3/19**	**Tue 10/8/19**	
26		Stock Drywall	1 day	Thu 10/3/19	Thu 10/3/19	21,22,23,24
27		Hang Drywall	0.5 days	Thu 10/3/19	Thu 10/3/19	21,22,23,24
28		Remove Scrap Drywall	0.5 days	Fri 10/4/19	Fri 10/4/19	26,27
29		Tape and Finish Drywall	1 day	Fri 10/4/19	Mon 10/7/19	28
30		Sand Drywall	1 day	Mon 10/7/19	Tue 10/8/19	29
31		Drywall Point-up	0.5 days	Tue 10/8/19	Tue 10/8/19	30
32		**Floor Finishes**	**2 days**	**Wed 10/9/19**	**Thu 10/10/19**	
33		Install Prefinished Hardwood Floor	1 day	Wed 10/9/19	Wed 10/9/19	31,323,346,369,3
34		Baseboard	1 day	Thu 10/10/19	Thu 10/10/19	33
35		**Paint**	**5 days**	**Fri 10/11/19**	**Thu 10/17/19**	
36		Prep Drywall for Prime Coat	1 day	Fri 10/11/19	Fri 10/11/19	34
37		Prime Paint Drywall	1 day	Fri 10/11/19	Fri 10/11/19	34
38		Prep Trim for Prime Coat	1 day	Mon 10/14/1	Mon 10/14/1	36,37

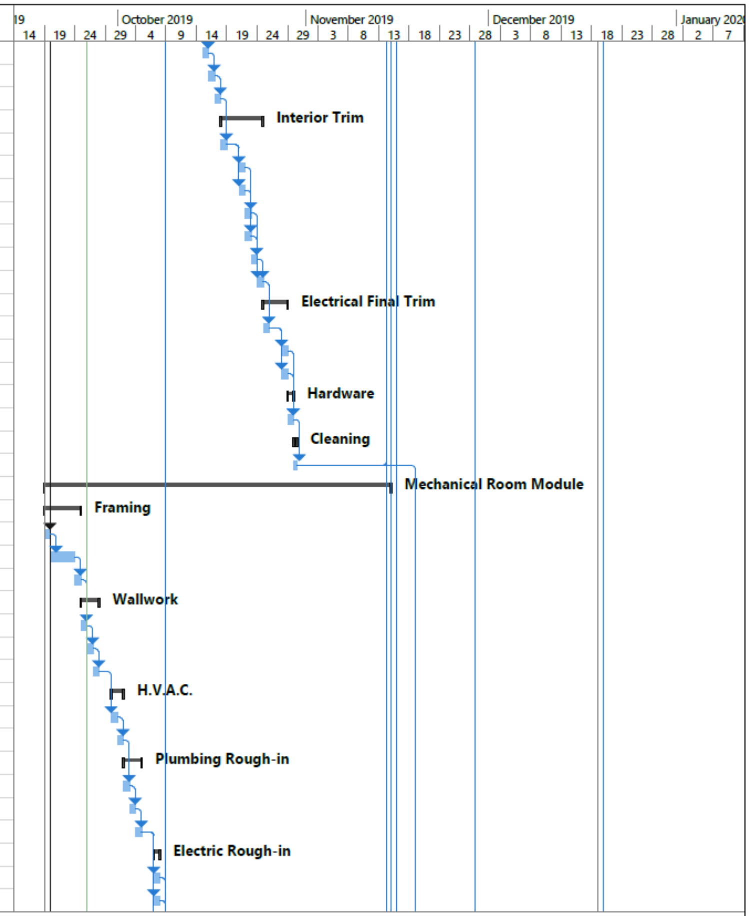


Project: Modular Building Assem
Date: Thu 9/26/19



Page 1

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
39		Prime Trim	1 day	Tue 10/15/19	Tue 10/15/19	38
40		Finish Coat Trim	1 day	Wed 10/16/1	Wed 10/16/1	39
41		Finish Coat Drywall	1 day	Thu 10/17/19	Thu 10/17/19	40
42		**Interior Trim**	**5 days**	**Fri 10/18/19**	**Thu 10/24/19**	
43		Interior Trim Delivery	1 day	Fri 10/18/19	Fri 10/18/19	41
44		Install Interior Doors	1 day	Mon 10/21/1	Mon 10/21/1	43
45		Install Interior Trim	1 day	Mon 10/21/1	Mon 10/21/1	43
46		Install Cabinetry	1 day	Tue 10/22/19	Tue 10/22/19	44
47		Install Appliances	1 day	Tue 10/22/19	Tue 10/22/19	45
48		Sensors, hardware, sofware, controllers, networks	1 day	Wed 10/23/1	Wed 10/23/1	47
49		1st Punch-out Interior Trim	1 day	Thu 10/24/19	Thu 10/24/19	46,48
50		**Electrical Final Trim**	**2 days**	**Fri 10/25/19**	**Mon 10/28/1**	
51		Switch & Plug	1 day	Fri 10/25/19	Fri 10/25/19	49
52		Install Fixtures	1 day	Mon 10/28/1	Mon 10/28/1	51
53		Connect Appliances	1 day	Mon 10/28/1	Mon 10/28/1	51
54		**Hardware**	**1 day**	**Tue 10/29/19**	**Tue 10/29/19**	
55		Door Hardware	1 day	Tue 10/29/19	Tue 10/29/19	52,53
56		**Cleaning**	**0.5 days**	**Wed 10/30/1**	**Wed 10/30/1**	
57		Rough Clean	0.5 days	Wed 10/30/1	Wed 10/30/1	55
58		**Mechanical Room Module**	**41 days**	**Thu 9/19/19**	**Thu 11/14/19**	
59		**Framing**	**4 days**	**Thu 9/19/19**	**Tue 9/24/19**	
60		Deck Framing	1 day	Thu 9/19/19	Thu 9/19/19	2
61		Wall Framing	2 days	Fri 9/20/19	Mon 9/23/19	60
62		Install Door	1 day	Tue 9/24/19	Tue 9/24/19	61
63		**Wallwork**	**3 days**	**Wed 9/25/19**	**Fri 9/27/19**	
64		Subfloor	1 day	Wed 9/25/19	Wed 9/25/19	62
65		Exterior Sheathing	1 day	Thu 9/26/19	Thu 9/26/19	64
66		Roof sheathing	1 day	Fri 9/27/19	Fri 9/27/19	65
67		**H.V.A.C.**	**2 days**	**Mon 9/30/19**	**Tue 10/1/19**	
68		HVAC Layout & Measure	1 day	Mon 9/30/19	Mon 9/30/19	66
69		HVAC Rough-in	1 day	Tue 10/1/19	Tue 10/1/19	68
70		**Plumbing Rough-in**	**3 days**	**Wed 10/2/19**	**Fri 10/4/19**	
71		Plumbing Subfloor	1 day	Wed 10/2/19	Wed 10/2/19	69
72		Plumbing Layout	1 day	Thu 10/3/19	Thu 10/3/19	71
73		Plumbing rough-in	1 day	Fri 10/4/19	Fri 10/4/19	72
74		**Electric Rough-in**	**1 day**	**Mon 10/7/19**	**Mon 10/7/19**	
75		Set Electric Boxes	1 day	Mon 10/7/19	Mon 10/7/19	73
76		Electrical Walk-through	1 day	Mon 10/7/19	Mon 10/7/19	73

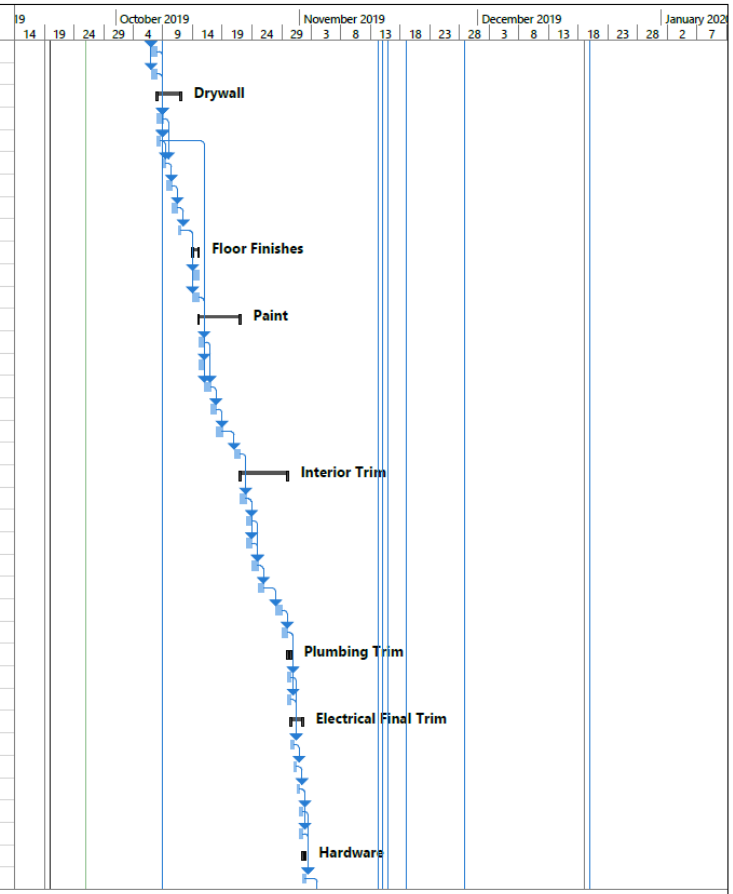


Project: Modular Building Assem
Date: Thu 9/26/19

Task		Project Summary		Manual Task		Start-only		Deadline	
Split		Inactive Task		Duration-only		Finish-only		Progress	
Milestone		Inactive Milestone		Manual Summary Rollup		External Tasks		Manual Progress	
Summary		Inactive Summary		Manual Summary		External Milestone			

Page 2

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
77		Electrical Rough-wire	1 day	Mon 10/7/19	Mon 10/7/19	73
78		Wire Testing	1 day	Mon 10/7/19	Mon 10/7/19	73
79		**Drywall**	**4 days**	**Tue 10/8/19**	**Fri 10/11/19**	
80		Stock Drywall	1 day	Tue 10/8/19	Tue 10/8/19	75,76,77,78
81		Hang Drywall	0.5 days	Tue 10/8/19	Tue 10/8/19	75,76,77,78
82		Remove Scrap Drywall	0.5 days	Wed 10/9/19	Wed 10/9/19	80,81
83		Tape and Finish Drywall	1 day	Wed 10/9/19	Thu 10/10/19	82
84		Sand Drywall	1 day	Thu 10/10/19	Fri 10/11/19	83
85		Drywall Point-up	0.5 days	Fri 10/11/19	Fri 10/11/19	84
86		**Floor Finishes**	**1 day**	**Mon 10/14/1**	**Mon 10/14/1**	
87		Install Prefinished Hardwood Floor	1 day	Mon 10/14/1	Mon 10/14/1	85
88		Baseboard	1 day	Mon 10/14/1	Mon 10/14/1	85
89		**Paint**	**5 days**	**Tue 10/15/19**	**Mon 10/21/1**	
90		Prep Drywall for Prime Coat	1 day	Tue 10/15/19	Tue 10/15/19	88
91		Prime Paint Drywall	1 day	Tue 10/15/19	Tue 10/15/19	88
92		Prep Trim for Prime Coat	1 day	Wed 10/16/1	Wed 10/16/1	90,81
93		Prime Trim	1 day	Thu 10/17/19	Thu 10/17/19	92
94		Finish Coat Trim	1 day	Fri 10/18/19	Fri 10/18/19	93
95		Finish Coat Drywall	1 day	Mon 10/21/1	Mon 10/21/1	94
96		**Interior Trim**	**6 days**	**Tue 10/22/19**	**Tue 10/29/19**	
97		Interior Trim Delivery	1 day	Tue 10/22/19	Tue 10/22/19	95
98		Install Interior Doors	1 day	Wed 10/23/1	Wed 10/23/1	97
99		Install Interior Trim	1 day	Wed 10/23/1	Wed 10/23/1	97
100		Install Cabinetry	1 day	Thu 10/24/19	Thu 10/24/19	98,99
101		Install Appliances	1 day	Fri 10/25/19	Fri 10/25/19	100
102		Sensors, hardware, sofware, controllers, networks	1 day	Mon 10/28/1	Mon 10/28/1	101
103		1st Punch-out Interior Trim	1 day	Tue 10/29/19	Tue 10/29/19	102
104		**Plumbing Trim**	**0.5 days**	**Wed 10/30/1**	**Wed 10/30/1**	
105		Set Fixtures	0.5 days	Wed 10/30/1	Wed 10/30/1	103
106		Connect Appliances	0.5 days	Wed 10/30/1	Wed 10/30/1	103
107		**Electrical Final Trim**	**2 days**	**Wed 10/30/1**	**Fri 11/1/19**	
108		Switch & Plug	0.5 days	Wed 10/30/1	Wed 10/30/1	105,106
109		Install Fixtures	0.5 days	Thu 10/31/19	Thu 10/31/19	108
110		Connect Appliances	0.5 days	Thu 10/31/19	Thu 10/31/19	109
111		Install Electric Service Panel	0.5 days	Fri 11/1/19	Fri 11/1/19	110
112		Install PV Invertor And Battery	0.5 days	Fri 11/1/19	Fri 11/1/19	110
113		**Hardware**	**0.5 days**	**Fri 11/1/19**	**Fri 11/1/19**	
114		Door Hardware	0.5 days	Fri 11/1/19	Fri 11/1/19	111,112

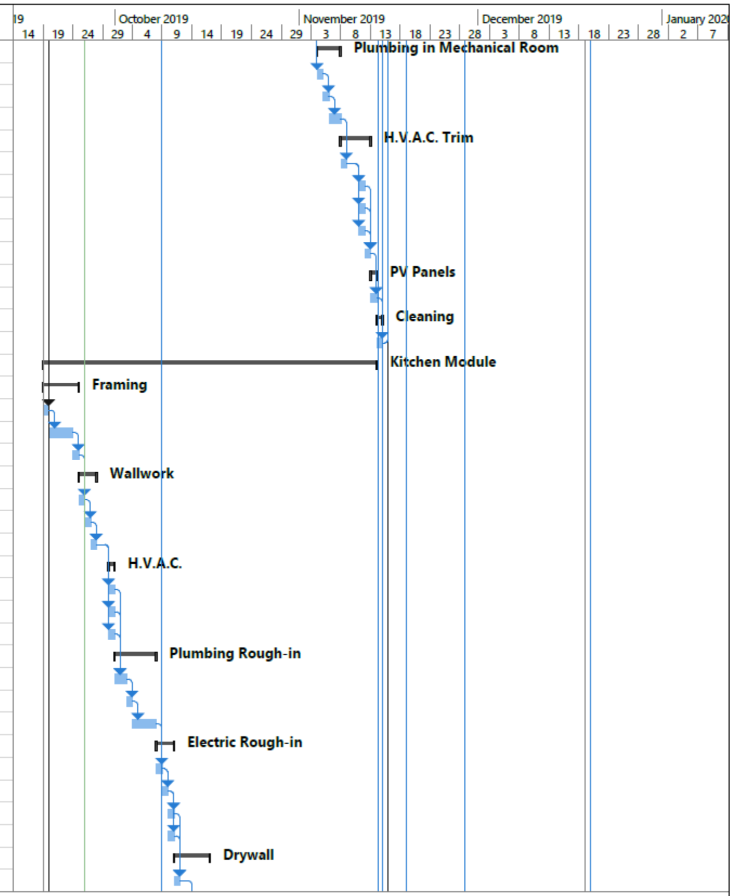


Project: Modular Building Assem
Date: Thu 9/26/19

Task	Project Summary	Manual Task	Start-only	Deadline
Split	Inactive Task	Duration-only	Finish-only	Progress
Milestone	Inactive Milestone	Manual Summary Rollup	External Tasks	Manual Progress
Summary	Inactive Summary	Manual Summary	External Milestone	

Page 3

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
115		**Plumbing in Mechanical Room**	**4 days**	**Mon 11/4/19**	**Thu 11/7/19**	
116		Install Tanks	1 day	Mon 11/4/19	Mon 11/4/19	114
117		Install Solar Collectors	1 day	Tue 11/5/19	Tue 11/5/19	116
118		Install radiant manifold	2 days	Wed 11/6/19	Thu 11/7/19	117
119		**H.V.A.C. Trim**	**3 days**	**Fri 11/8/19**	**Tue 11/12/19**	
120		Install Grills & Registers for Paint	1 day	Fri 11/8/19	Fri 11/8/19	118
121		Set Outdoor Units	1 day	Mon 11/11/19	Mon 11/11/19	120
122		HVAC Set Indoor Units	1 day	Mon 11/11/19	Mon 11/11/19	120
123		Connect Pipes	1 day	Mon 11/11/19	Mon 11/11/19	120
124		Set PCM Pelnum	1 day	Tue 11/12/19	Tue 11/12/19	121,122,123
125		**PV Panels**	**1 day**	**Wed 11/13/19**	**Wed 11/13/19**	
126		PV Panels Installing and Raking	1 day	Wed 11/13/19	Wed 11/13/19	124
127		**Cleaning**	**1 day**	**Thu 11/14/19**	**Thu 11/14/19**	
128		Rough Clean	1 day	Thu 11/14/19	Thu 11/14/19	126
129		**Kitchen Module**	**40 days**	**Thu 9/19/19**	**Wed 11/13/19**	
130		**Framing**	**4 days**	**Thu 9/19/19**	**Tue 9/24/19**	
131		Deck Framing	1 day	Thu 9/19/19	Thu 9/19/19	2
132		Wall Framing	2 days	Fri 9/20/19	Mon 9/23/19	131
133		Install Door	1 day	Tue 9/24/19	Tue 9/24/19	132
134		**Wallwork**	**3 days**	**Wed 9/25/19**	**Fri 9/27/19**	
135		Subfloor	1 day	Wed 9/25/19	Wed 9/25/19	133
136		Exterior Sheathing	1 day	Thu 9/26/19	Thu 9/26/19	135
137		Roof sheathing	1 day	Fri 9/27/19	Fri 9/27/19	136
138		**H.V.A.C.**	**1 day**	**Mon 9/30/19**	**Mon 9/30/19**	
139		HVAC Layout & Measure	1 day	Mon 9/30/19	Mon 9/30/19	137
140		HVAC Rough-in	1 day	Mon 9/30/19	Mon 9/30/19	137
141		Install Exhaust Fan and Ducts	1 day	Mon 9/30/19	Mon 9/30/19	137
142		**Plumbing Rough-in**	**5 days**	**Tue 10/1/19**	**Mon 10/7/19**	
143		Plumbing Subfloor	2 days	Tue 10/1/19	Wed 10/2/19	139,140,141
144		Plumbing Layout	1 day	Thu 10/3/19	Thu 10/3/19	143
145		Plumbing rough-in	2 days	Fri 10/4/19	Mon 10/7/19	144
146		**Electric Rough-in**	**3 days**	**Tue 10/8/19**	**Thu 10/10/19**	
147		Set Electric Boxes	1 day	Tue 10/8/19	Tue 10/8/19	145
148		Electrical Walk-through	1 day	Wed 10/9/19	Wed 10/9/19	147
149		Electrical Rough-wire	1 day	Thu 10/10/19	Thu 10/10/19	148
150		Wire Testing	1 day	Thu 10/10/19	Thu 10/10/19	148
151		**Drywall**	**4 days**	**Fri 10/11/19**	**Wed 10/16/19**	
152		Stock Drywall	1 day	Fri 10/11/19	Fri 10/11/19	149,150

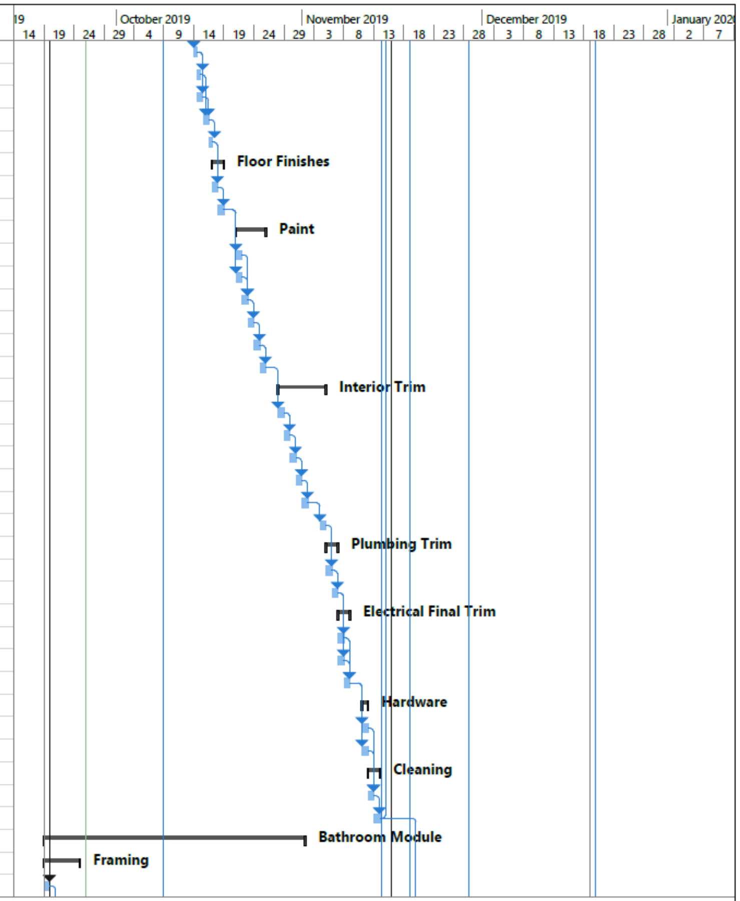


Project: Modular Building Assem
Date: Thu 9/26/19

Task		Project Summary		Manual Task		Start-only		Deadline	
Split		Inactive Task		Duration-only		Finish-only		Progress	
Milestone		Inactive Milestone		Manual Summary Rollup		External Tasks		Manual Progress	
Summary		Inactive Summary		Manual Summary		External Milestone			

Page 4

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
153		Hang Drywall	0.5 days	Mon 10/14/1	Mon 10/14/1	152
154		Remove Scrap Drywall	0.5 days	Mon 10/14/1	Mon 10/14/1	153
155		Tape and Finish Drywall	1 day	Mon 10/14/1	Tue 10/15/19	153
156		Sand Drywall	1 day	Tue 10/15/19	Wed 10/16/1	154,155
157		Drywall Point-up	0.5 days	Wed 10/16/1	Wed 10/16/1	156
158		**Floor Finishes**	**2 days**	**Thu 10/17/19**	**Fri 10/18/19**	
159		Install Prefinished Hardwood Floor	1 day	Thu 10/17/19	Thu 10/17/19	157
160		Baseboard	1 day	Fri 10/18/19	Fri 10/18/19	159
161		**Paint**	**5 days**	**Mon 10/21/1**	**Fri 10/25/19**	
162		Prep Drywall for Prime Coat	1 day	Mon 10/21/1	Mon 10/21/1	160
163		Prime Paint Drywall	1 day	Mon 10/21/1	Mon 10/21/1	160
164		Prep Trim for Prime Coat	1 day	Tue 10/22/19	Tue 10/22/19	162,163
165		Prime Trim	1 day	Wed 10/23/1	Wed 10/23/1	164
166		Finish Coat Trim	1 day	Thu 10/24/19	Thu 10/24/19	165
167		Finish Coat Drywall	1 day	Fri 10/25/19	Fri 10/25/19	166
168		**Interior Trim**	**6 days**	**Mon 10/28/1**	**Mon 11/4/19**	
169		Interior Trim Delivery	1 day	Mon 10/28/1	Mon 10/28/1	167
170		Install Interior Doors	1 day	Tue 10/29/19	Tue 10/29/19	169
171		Install Interior Trim	1 day	Wed 10/30/1	Wed 10/30/1	170
172		Install Cabinetry	1 day	Thu 10/31/19	Thu 10/31/19	171
173		Install Appliances	1 day	Fri 11/1/19	Fri 11/1/19	172
174		1st Punch-out Interior Trim	1 day	Mon 11/4/19	Mon 11/4/19	173
175		**Plumbing Trim**	**2 days**	**Tue 11/5/19**	**Wed 11/6/19**	
176		Set Fixtures	1 day	Tue 11/5/19	Tue 11/5/19	174
177		Connect Appliances	1 day	Wed 11/6/19	Wed 11/6/19	176
178		**Electrical Final Trim**	**2 days**	**Thu 11/7/19**	**Fri 11/8/19**	
179		Switch & Plug	1 day	Thu 11/7/19	Thu 11/7/19	177
180		Install Fixtures	1 day	Thu 11/7/19	Thu 11/7/19	177
181		Connect Appliances	1 day	Fri 11/8/19	Fri 11/8/19	179,180
182		**Hardware**	**1 day**	**Mon 11/11/1**	**Mon 11/11/1**	
183		Door Hardware	1 day	Mon 11/11/1	Mon 11/11/1	181
184		Window Hardware	1 day	Mon 11/11/1	Mon 11/11/1	181
185		**Cleaning**	**2 days**	**Tue 11/12/19**	**Wed 11/13/1**	
186		Windows and door	1 day	Tue 11/12/19	Tue 11/12/19	183,184
187		Rough Clean	1 day	Wed 11/13/1	Wed 11/13/1	186
188		**Bathroom Module**	**31.5 days**	**Thu 9/19/19**	**Fri 11/1/19**	
189		**Framing**	**4 days**	**Thu 9/19/19**	**Tue 9/24/19**	
190		Deck Framing	1 day	Thu 9/19/19	Thu 9/19/19	2

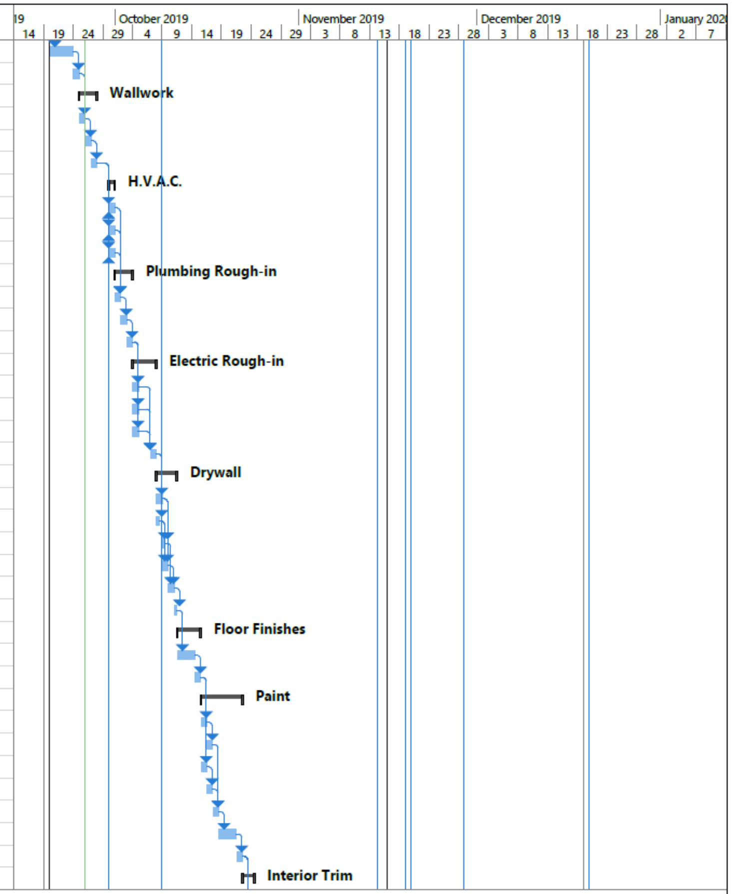


Project: Modular Building Assem
Date: Thu 9/26/19

Task, Split, Milestone, Summary, Project Summary, Inactive Task, Inactive Milestone, Inactive Summary, Manual Task, Duration-only, Manual Summary Rollup, Manual Summary, Start-only, Finish-only, External Tasks, External Milestone, Deadline, Progress, Manual Progress

Page 5

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
191		Wall Framing	2 days	Fri 9/20/19	Mon 9/23/19	190
192		Install Door	1 day	Tue 9/24/19	Tue 9/24/19	191
193		**Wallwork**	**3 days**	**Wed 9/25/19**	**Fri 9/27/19**	
194		Subfloor	1 day	Wed 9/25/19	Wed 9/25/19	192
195		Exterior Sheathing	1 day	Thu 9/26/19	Thu 9/26/19	194
196		Roof sheathing	1 day	Fri 9/27/19	Fri 9/27/19	195
197		**H.V.A.C.**	**1 day**	**Mon 9/30/19**	**Mon 9/30/19**	
198		HVAC Layout & Measure	1 day	Mon 9/30/19	Mon 9/30/19	196,258
199		HVAC Rough-in	1 day	Mon 9/30/19	Mon 9/30/19	196,258
200		Install Exhaust Fan and Ducts	1 day	Mon 9/30/19	Mon 9/30/19	196,258
201		**Plumbing Rough-in**	**3 days**	**Tue 10/1/19**	**Thu 10/3/19**	
202		Plumbing Subfloor	1 day	Tue 10/1/19	Tue 10/1/19	198,199,200
203		Plumbing Layout	1 day	Wed 10/2/19	Wed 10/2/19	202
204		Plumbing rough-in	1 day	Thu 10/3/19	Thu 10/3/19	203
205		**Electric Rough-in**	**2 days**	**Fri 10/4/19**	**Mon 10/7/19**	
206		Set Electric Boxes	1 day	Fri 10/4/19	Fri 10/4/19	204
207		Electrical Walk-through	1 day	Fri 10/4/19	Fri 10/4/19	204
208		Electrical Rough-wire	1 day	Fri 10/4/19	Fri 10/4/19	204
209		Wire Testing	1 day	Mon 10/7/19	Mon 10/7/19	206,207,208
210		**Drywall**	**3.5 days**	**Tue 10/8/19**	**Fri 10/11/19**	
211		Stock Drywall	1 day	Tue 10/8/19	Tue 10/8/19	209
212		Hang Drywall	0.5 days	Tue 10/8/19	Tue 10/8/19	209
213		Remove Scrap Drywall	0.5 days	Wed 10/9/19	Wed 10/9/19	211,212
214		Tape and Finish Drywall	1 day	Wed 10/9/19	Wed 10/9/19	211,212
215		Sand Drywall	1 day	Thu 10/10/19	Thu 10/10/19	213,214
216		Drywall Point-up	0.5 days	Fri 10/11/19	Fri 10/11/19	215
217		**Floor Finishes**	**2 days**	**Fri 10/11/19**	**Tue 10/15/19**	
218		Schluter Systems For Bathroom	1 day	Fri 10/11/19	Mon 10/14/19	216
219		Ceramic Tile	1 day	Mon 10/14/19	Tue 10/15/19	218
220		**Paint**	**5 days**	**Tue 10/15/19**	**Tue 10/22/19**	
221		Prep Drywall for Prime Coat	1 day	Tue 10/15/19	Wed 10/16/19	219
222		Prime Paint Drywall	1 day	Wed 10/16/19	Thu 10/17/19	221
223		Prep Trim for Prime Coat	1 day	Tue 10/15/19	Wed 10/16/19	219
224		Prime Trim	1 day	Wed 10/16/19	Thu 10/17/19	223
225		Finish Coat Trim	1 day	Thu 10/17/19	Fri 10/18/19	222,224
226		Finish Coat Drywall	1 day	Fri 10/18/19	Mon 10/21/19	225
227		Caulk Exterior Windows & Doors	1 day	Mon 10/21/19	Tue 10/22/19	226
228		**Interior Trim**	**2 days**	**Tue 10/22/19**	**Thu 10/24/19**	

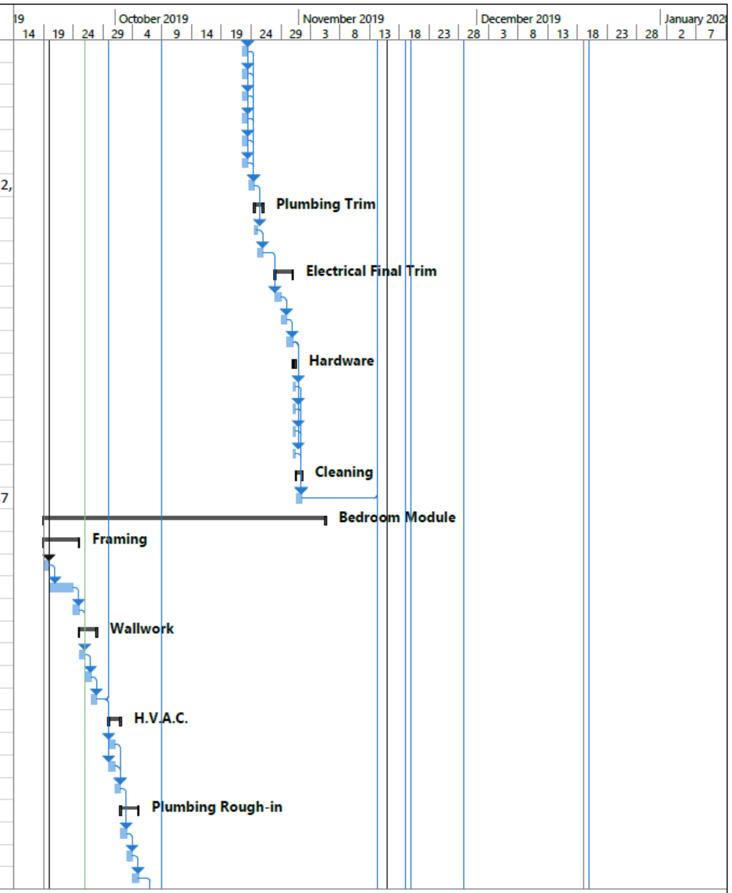


Project: Modular Building Assem
Date: Thu 9/26/19

Task	Project Summary	Manual Task	Start-only	Deadline
Split	Inactive Task	Duration-only	Finish-only	Progress
Milestone	Inactive Milestone	Manual Summary Rollup	External Tasks	Manual Progress
Summary	Inactive Summary	Manual Summary	External Milestone	

Page 6

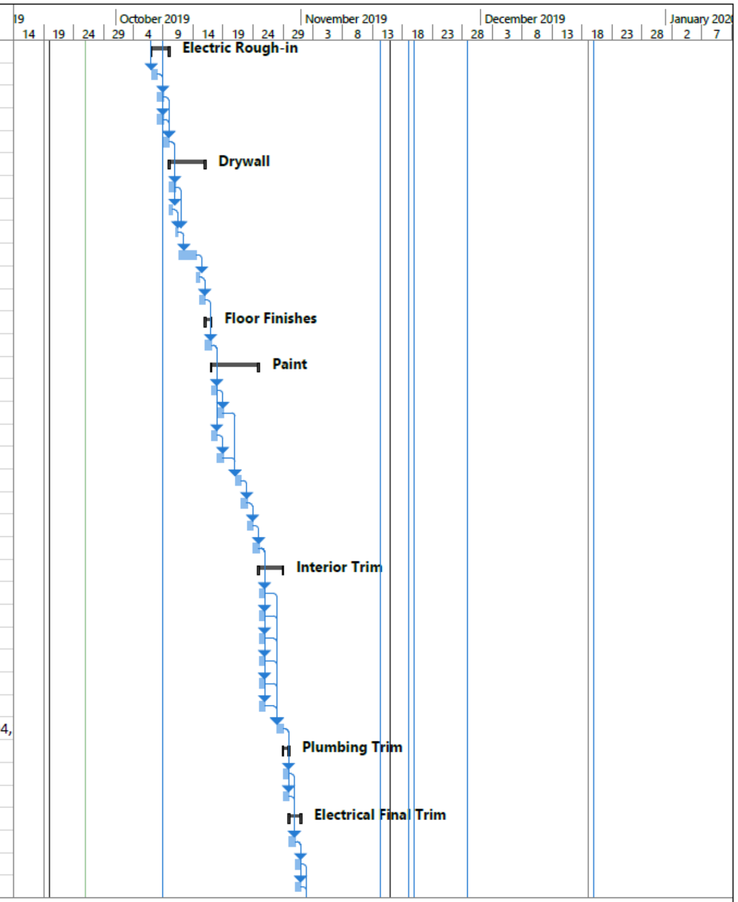
ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
229		Interior Trim Delivery	1 day	Tue 10/22/19	Wed 10/23/1	227
230		Install Interior Doors	1 day	Tue 10/22/19	Wed 10/23/1	227
231		Install Interior Trim	1 day	Tue 10/22/19	Wed 10/23/1	227
232		Install Cabinetry	1 day	Tue 10/22/19	Wed 10/23/1	227
233		Install Appliances	1 day	Tue 10/22/19	Wed 10/23/1	227
234		Sensors, hardware, sofware, controllers, networks	1 day	Tue 10/22/19	Wed 10/23/1	227
235		1st Punch-out Interior Trim	1 day	Wed 10/23/1	Thu 10/24/19	229,230,231,232,
236		**Plumbing Trim**	**1.5 days**	**Thu 10/24/19**	**Fri 10/25/19**	
237		Set Fixtures	0.5 days	Thu 10/24/19	Thu 10/24/19	235
238		Connect Appliances	1 day	Fri 10/25/19	Fri 10/25/19	237
239		**Electrical Final Trim**	**3 days**	**Mon 10/28/1**	**Wed 10/30/1**	
240		Switch & Plug	1 day	Mon 10/28/1	Mon 10/28/1	238
241		Install Fixtures	1 day	Tue 10/29/19	Tue 10/29/19	240
242		Connect Appliances	1 day	Wed 10/30/1	Wed 10/30/1	241
243		**Hardware**	**0.5 days**	**Thu 10/31/19**	**Thu 10/31/19**	
244		Door Hardware	0.5 days	Thu 10/31/19	Thu 10/31/19	242
245		Bath Hardware	0.5 days	Thu 10/31/19	Thu 10/31/19	242
246		Mirrors	0.5 days	Thu 10/31/19	Thu 10/31/19	242
247		Shower Doors	0.5 days	Thu 10/31/19	Thu 10/31/19	242
248		**Cleaning**	**1 day**	**Thu 10/31/19**	**Fri 11/1/19**	
249		Rough Clean	1 day	Thu 10/31/19	Fri 11/1/19	244,245,246,247
250		**Bedroom Module**	**33.5 days**	**Thu 9/19/19**	**Tue 11/5/19**	
251		**Framing**	**4 days**	**Thu 9/19/19**	**Tue 9/24/19**	
252		Deck Framing	1 day	Thu 9/19/19	Thu 9/19/19	2
253		Wall Framing	2 days	Fri 9/20/19	Mon 9/23/19	252
254		Install Door	1 day	Tue 9/24/19	Tue 9/24/19	253
255		**Wallwork**	**3 days**	**Wed 9/25/19**	**Fri 9/27/19**	
256		Subfloor	1 day	Wed 9/25/19	Wed 9/25/19	254
257		Exterior Sheathing	1 day	Thu 9/26/19	Thu 9/26/19	256
258		Roof sheathing	1 day	Fri 9/27/19	Fri 9/27/19	257
259		**H.V.A.C.**	**2 days**	**Mon 9/30/19**	**Tue 10/1/19**	
260		HVAC Layout & Measure	1 day	Mon 9/30/19	Mon 9/30/19	258
261		HVAC Rough-in	1 day	Mon 9/30/19	Mon 9/30/19	258
262		Install Exhaust Fan and Ducts	1 day	Tue 10/1/19	Tue 10/1/19	260,261
263		**Plumbing Rough-in**	**3 days**	**Wed 10/2/19**	**Fri 10/4/19**	
264		Plumbing Subfloor	1 day	Wed 10/2/19	Wed 10/2/19	262
265		Plumbing Layout	1 day	Thu 10/3/19	Thu 10/3/19	264
266		Plumbing rough-in	1 day	Fri 10/4/19	Fri 10/4/19	265



Project: Modular Building Assem
Date: Thu 9/26/19

Task		Project Summary		Manual Task		Start-only		Deadline	
Split		Inactive Task		Duration-only		Finish-only		Progress	
Milestone		Inactive Milestone		Manual Summary Rollup		External Tasks		Manual Progress	
Summary		Inactive Summary		Manual Summary		External Milestone			

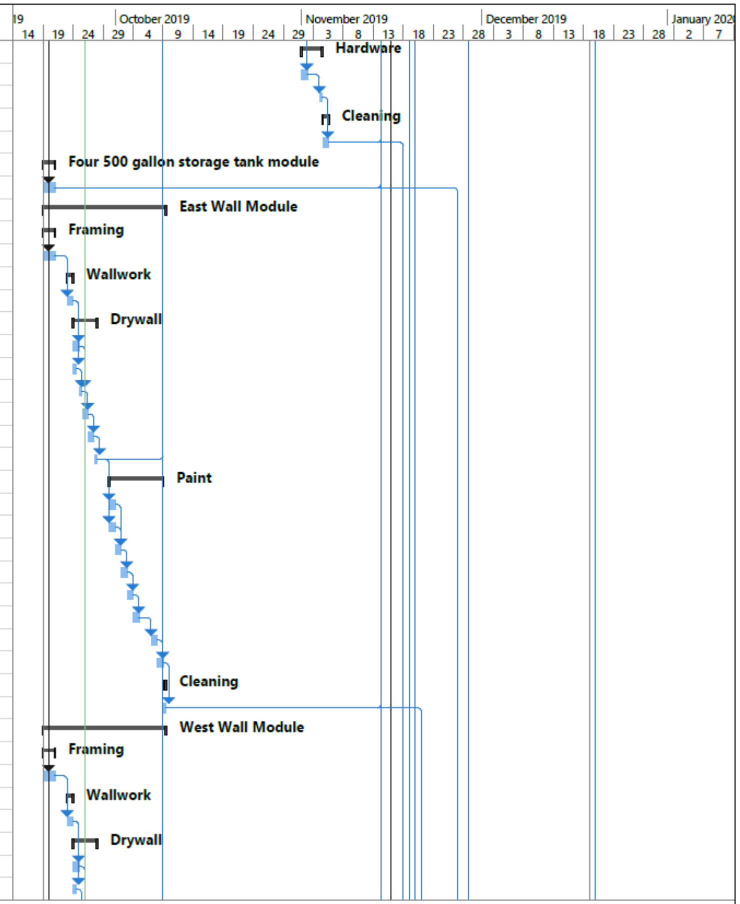
ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
267		**Electric Rough-in**	**3 days**	**Mon 10/7/19**	**Wed 10/9/19**	
268		Set Electric Boxes	1 day	Mon 10/7/19	Mon 10/7/19	266
269		Electrical Walk-through	1 day	Tue 10/8/19	Tue 10/8/19	268
270		Electrical Rough-wire	1 day	Tue 10/8/19	Tue 10/8/19	268
271		Wire Testing	1 day	Wed 10/9/19	Wed 10/9/19	269,270
272		**Drywall**	**4 days**	**Thu 10/10/19**	**Tue 10/15/19**	
273		Stock Drywall	1 day	Thu 10/10/19	Thu 10/10/19	271
274		Hang Drywall	0.5 days	Thu 10/10/19	Thu 10/10/19	271
275		Remove Scrap Drywall	0.5 days	Fri 10/11/19	Fri 10/11/19	273,274
276		Tape and Finish Drywall	1 day	Fri 10/11/19	Mon 10/14/1	275
277		Sand Drywall	0.5 days	Mon 10/14/1	Mon 10/14/1	276
278		Drywall Point-up	1 day	Tue 10/15/19	Tue 10/15/19	277
279		**Floor Finishes**	**1 day**	**Wed 10/16/1**	**Wed 10/16/1**	
280		Install Prefinished Hardwood Floor	1 day	Wed 10/16/1	Wed 10/16/1	278
281		**Paint**	**6 days**	**Thu 10/17/19**	**Thu 10/24/19**	
282		Prep Drywall for Prime Coat	1 day	Thu 10/17/19	Thu 10/17/19	280
283		Prime Paint Drywall	1 day	Fri 10/18/19	Fri 10/18/19	282
284		Prep Trim for Prime Coat	1 day	Thu 10/17/19	Thu 10/17/19	280
285		Prime Trim	1 day	Fri 10/18/19	Fri 10/18/19	284
286		Finish Coat Trim	1 day	Mon 10/21/1	Mon 10/21/1	283,285
287		Finish Coat Drywall	1 day	Tue 10/22/19	Tue 10/22/19	286
288		Caulk Exterior Windows & Doors	1 day	Wed 10/23/1	Wed 10/23/1	287
289		Finish Coat Exterior Trim & Siding	1 day	Thu 10/24/19	Thu 10/24/19	288
290		**Interior Trim**	**2 days**	**Fri 10/25/19**	**Mon 10/28/1**	
291		Interior Trim Delivery	1 day	Fri 10/25/19	Fri 10/25/19	289
292		Install Interior Doors	1 day	Fri 10/25/19	Fri 10/25/19	289
293		Install Interior Trim	1 day	Fri 10/25/19	Fri 10/25/19	289
294		Install Cabinetry	1 day	Fri 10/25/19	Fri 10/25/19	289
295		Install Appliances	1 day	Fri 10/25/19	Fri 10/25/19	289
296		Sensors, hardware, sofware, controllers, networks	1 day	Fri 10/25/19	Fri 10/25/19	289
297		1st Punch-out Interior Trim	1 day	Mon 10/28/1	Mon 10/28/1	291,292,293,294,
298		**Plumbing Trim**	**1 day**	**Tue 10/29/19**	**Tue 10/29/19**	
299		Set Fixtures	1 day	Tue 10/29/19	Tue 10/29/19	297
300		Connect Appliances	1 day	Tue 10/29/19	Tue 10/29/19	297
301		**Electrical Final Trim**	**2 days**	**Wed 10/30/1**	**Thu 10/31/19**	
302		Switch & Plug	1 day	Wed 10/30/1	Wed 10/30/1	299,300
303		Install Fixtures	1 day	Thu 10/31/19	Thu 10/31/19	302
304		Connect Appliances	1 day	Thu 10/31/19	Thu 10/31/19	302



Project: Modular Building Assem
Date: Thu 9/26/19

Task		Project Summary		Manual Task		Start-only		Deadline	
Split		Inactive Task		Duration-only		Finish-only		Progress	
Milestone		Inactive Milestone		Manual Summary Rollup		External Tasks		Manual Progress	
Summary		Inactive Summary		Manual Summary		External Milestone			

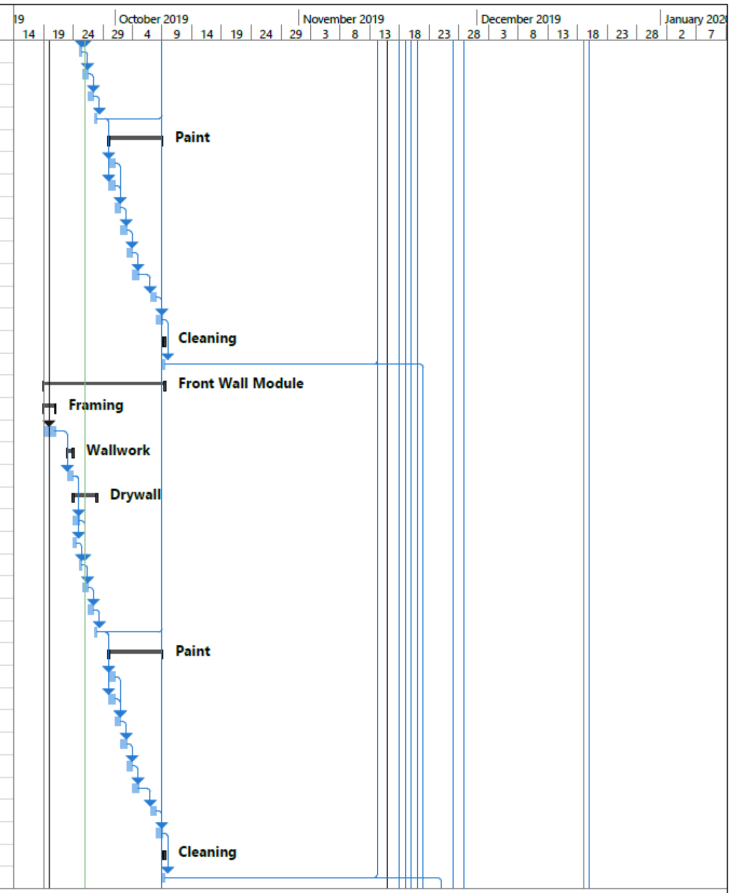
ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
305		**Hardware**	**1.5 days**	**Fri 11/1/19**	**Mon 11/4/19**	
306		Door Hardware	1 day	Fri 11/1/19	Fri 11/1/19	303,304
307		Mirrors	0.5 days	Mon 11/4/19	Mon 11/4/19	306
308		**Cleaning**	**1 day**	**Mon 11/4/19**	**Tue 11/5/19**	
309		Rough Clean	1 day	Mon 11/4/19	Tue 11/5/19	307
310		**Four 500 gallon storage tank module**	**2 days**	**Thu 9/19/19**	**Fri 9/20/19**	
311		Procurement of four 500 gal water tank	2 days	Thu 9/19/19	Fri 9/20/19	2
312		**East Wall Module**	**14.5 days**	**Thu 9/19/19**	**Wed 10/9/19**	
313		**Framing**	**2 days**	**Thu 9/19/19**	**Fri 9/20/19**	
314		Wall Framing	2 days	Thu 9/19/19	Fri 9/20/19	2
315		**Wallwork**	**1 day**	**Mon 9/23/19**	**Mon 9/23/19**	
316		Exterior Sheathing	1 day	Mon 9/23/19	Mon 9/23/19	314
317		**Drywall**	**4 days**	**Tue 9/24/19**	**Fri 9/27/19**	
318		Stock Drywall	1 day	Tue 9/24/19	Tue 9/24/19	316
319		Hang Drywall	0.5 days	Tue 9/24/19	Tue 9/24/19	316
320		Remove Scrap Drywall	0.5 days	Wed 9/25/19	Wed 9/25/19	318,319
321		Tape and Finish Drywall	1 day	Wed 9/25/19	Thu 9/26/19	320
322		Sand Drywall	1 day	Thu 9/26/19	Fri 9/27/19	321
323		Drywall Point-up	0.5 days	Fri 9/27/19	Fri 9/27/19	322
324		**Paint**	**7 days**	**Mon 9/30/19**	**Tue 10/8/19**	
325		Prep Drywall for Prime Coat	1 day	Mon 9/30/19	Mon 9/30/19	323
326		Prime Paint Drywall	1 day	Mon 9/30/19	Mon 9/30/19	323
327		Prep Trim for Prime Coat	1 day	Tue 10/1/19	Tue 10/1/19	325,326
328		Prime Trim	1 day	Wed 10/2/19	Wed 10/2/19	327
329		Finish Coat Trim	1 day	Thu 10/3/19	Thu 10/3/19	328
330		Finish Coat Drywall	1 day	Fri 10/4/19	Fri 10/4/19	329
331		Caulk Exterior Windows & Doors	1 day	Mon 10/7/19	Mon 10/7/19	330
332		Finish Coat Exterior Trim & Siding	1 day	Tue 10/8/19	Tue 10/8/19	331
333		**Cleaning**	**0.5 days**	**Wed 10/9/19**	**Wed 10/9/19**	
334		Rough Clean	0.5 days	Wed 10/9/19	Wed 10/9/19	332
335		**West Wall Module**	**14.5 days**	**Thu 9/19/19**	**Wed 10/9/19**	
336		**Framing**	**2 days**	**Thu 9/19/19**	**Fri 9/20/19**	
337		Wall Framing	2 days	Thu 9/19/19	Fri 9/20/19	2
338		**Wallwork**	**1 day**	**Mon 9/23/19**	**Mon 9/23/19**	
339		Exterior Sheathing	1 day	Mon 9/23/19	Mon 9/23/19	337
340		**Drywall**	**4 days**	**Tue 9/24/19**	**Fri 9/27/19**	
341		Stock Drywall	1 day	Tue 9/24/19	Tue 9/24/19	339
342		Hang Drywall	0.5 days	Tue 9/24/19	Tue 9/24/19	339



Project: Modular Building Assem
Date: Thu 9/26/19

Task		Project Summary		Manual Task		Start-only		Deadline	
Split		Inactive Task		Duration-only		Finish-only		Progress	
Milestone		Inactive Milestone		Manual Summary Rollup		External Tasks		Manual Progress	
Summary		Inactive Summary		Manual Summary		External Milestone			

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
343		Remove Scrap Drywall	0.5 days	Wed 9/25/19	Wed 9/25/19	341,342
344		Tape and Finish Drywall	1 day	Wed 9/25/19	Thu 9/26/19	343
345		Sand Drywall	1 day	Thu 9/26/19	Fri 9/27/19	344
346		Drywall Point-up	0.5 days	Fri 9/27/19	Fri 9/27/19	345
347		**Paint**	**7 days**	**Mon 9/30/19**	**Tue 10/8/19**	
348		Prep Drywall for Prime Coat	1 day	Mon 9/30/19	Mon 9/30/19	346
349		Prime Paint Drywall	1 day	Mon 9/30/19	Mon 9/30/19	346
350		Prep Trim for Prime Coat	1 day	Tue 10/1/19	Tue 10/1/19	348,349
351		Prime Trim	1 day	Wed 10/2/19	Wed 10/2/19	350
352		Finish Coat Trim	1 day	Thu 10/3/19	Thu 10/3/19	351
353		Finish Coat Drywall	1 day	Fri 10/4/19	Fri 10/4/19	352
354		Caulk Exterior Windows & Doors	1 day	Mon 10/7/19	Mon 10/7/19	353
355		Finish Coat Exterior Trim & Siding	1 day	Tue 10/8/19	Tue 10/8/19	354
356		**Cleaning**	**0.5 days**	**Wed 10/9/19**	**Wed 10/9/19**	
357		Rough Clean	0.5 days	Wed 10/9/19	Wed 10/9/19	355
358		**Front Wall Module**	**14.5 days**	**Thu 9/19/19**	**Wed 10/9/19**	
359		**Framing**	**2 days**	**Thu 9/19/19**	**Fri 9/20/19**	
360		Wall Framing	2 days	Thu 9/19/19	Fri 9/20/19	2
361		**Wallwork**	**1 day**	**Mon 9/23/19**	**Mon 9/23/19**	
362		Exterior Sheathing	1 day	Mon 9/23/19	Mon 9/23/19	360
363		**Drywall**	**4 days**	**Tue 9/24/19**	**Fri 9/27/19**	
364		Stock Drywall	1 day	Tue 9/24/19	Tue 9/24/19	362
365		Hang Drywall	0.5 days	Tue 9/24/19	Tue 9/24/19	362
366		Remove Scrap Drywall	0.5 days	Wed 9/25/19	Wed 9/25/19	364,365
367		Tape and Finish Drywall	1 day	Wed 9/25/19	Thu 9/26/19	366
368		Sand Drywall	1 day	Thu 9/26/19	Fri 9/27/19	367
369		Drywall Point-up	0.5 days	Fri 9/27/19	Fri 9/27/19	368
370		**Paint**	**7 days**	**Mon 9/30/19**	**Tue 10/8/19**	
371		Prep Drywall for Prime Coat	1 day	Mon 9/30/19	Mon 9/30/19	369
372		Prime Paint Drywall	1 day	Mon 9/30/19	Mon 9/30/19	369
373		Prep Trim for Prime Coat	1 day	Tue 10/1/19	Tue 10/1/19	371,372
374		Prime Trim	1 day	Wed 10/2/19	Wed 10/2/19	373
375		Finish Coat Trim	1 day	Thu 10/3/19	Thu 10/3/19	374
376		Finish Coat Drywall	1 day	Fri 10/4/19	Fri 10/4/19	375
377		Caulk Exterior Windows & Doors	1 day	Mon 10/7/19	Mon 10/7/19	376
378		Finish Coat Exterior Trim & Siding	1 day	Tue 10/8/19	Tue 10/8/19	377
379		**Cleaning**	**0.5 days**	**Wed 10/9/19**	**Wed 10/9/19**	
380		Rough Clean	0.5 days	Wed 10/9/19	Wed 10/9/19	378

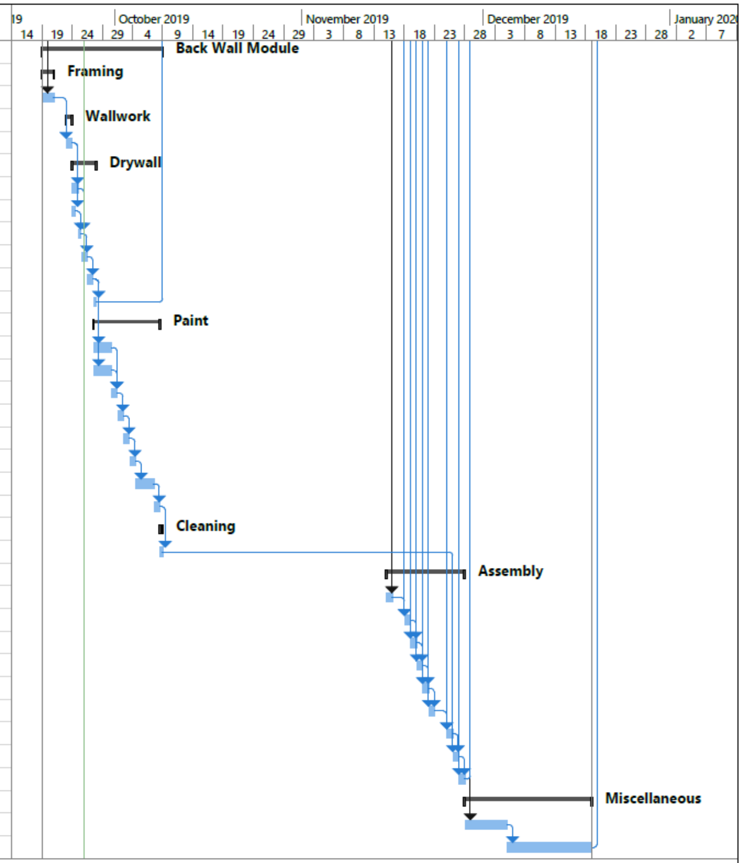


Project: Modular Building Assem
Date: Thu 9/26/19

Task | Split | Milestone | Summary | Project Summary | Inactive Task | Inactive Milestone | Inactive Summary | Manual Task | Duration-only | Manual Summary Rollup | Manual Summary | Start-only | Finish-only | External Tasks | External Milestone | Deadline | Progress | Manual Progress

Page 10

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
381		**Back Wall Module**	**14 days**	**Thu 9/19/19**	**Tue 10/8/19**	
382		**Framing**	**2 days**	**Thu 9/19/19**	**Fri 9/20/19**	
383		Wall Framing	2 days	Thu 9/19/19	Fri 9/20/19	2
384		**Wallwork**	**1 day**	**Mon 9/23/19**	**Mon 9/23/19**	
385		Exterior Sheathing	1 day	Mon 9/23/19	Mon 9/23/19	383
386		**Drywall**	**4 days**	**Tue 9/24/19**	**Fri 9/27/19**	
387		Stock Drywall	1 day	Tue 9/24/19	Tue 9/24/19	385
388		Hang Drywall	0.5 days	Tue 9/24/19	Tue 9/24/19	385
389		Remove Scrap Drywall	0.5 days	Wed 9/25/19	Wed 9/25/19	387,388
390		Tape and Finish Drywall	1 day	Wed 9/25/19	Thu 9/26/19	389
391		Sand Drywall	1 day	Thu 9/26/19	Fri 9/27/19	390
392		Drywall Point-up	0.5 days	Fri 9/27/19	Fri 9/27/19	391
393		**Paint**	**7 days**	**Fri 9/27/19**	**Tue 10/8/19**	
394		Prep Drywall for Prime Coat	1 day	Fri 9/27/19	Mon 9/30/19	391
395		Prime Paint Drywall	1 day	Fri 9/27/19	Mon 9/30/19	391
396		Prep Trim for Prime Coat	1 day	Mon 9/30/19	Tue 10/1/19	394,395
397		Prime Trim	1 day	Tue 10/1/19	Wed 10/2/19	396
398		Finish Coat Trim	1 day	Wed 10/2/19	Thu 10/3/19	397
399		Finish Coat Drywall	1 day	Thu 10/3/19	Fri 10/4/19	398
400		Caulk Exterior Windows & Doors	1 day	Fri 10/4/19	Mon 10/7/19	399
401		Finish Coat Exterior Trim & Siding	1 day	Mon 10/7/19	Tue 10/8/19	400
402		**Cleaning**	**0.5 days**	**Tue 10/8/19**	**Tue 10/8/19**	
403		Rough Clean	0.5 days	Tue 10/8/19	Tue 10/8/19	401
404		**Assembly**	**9 days**	**Fri 11/15/19**	**Wed 11/27/1**	
405		1. Mechincal room module and bathroom module	1 day	Fri 11/15/19	Fri 11/15/19	3
406		2. Adding bedroom module	1 day	Mon 11/18/1	Mon 11/18/1	405,309
407		3. Adding Courtyard module	1 day	Tue 11/19/19	Tue 11/19/19	406,57
408		4. Adding Kitchen	1 day	Wed 11/20/1	Wed 11/20/1	407,187
409		5. Adding East Wall Envelope	1 day	Thu 11/21/19	Thu 11/21/19	408,334
410		6. Adding West Wall Envelope	1 day	Fri 11/22/19	Fri 11/22/19	409,357
411		7. Adding Front Wall Envelope	1 day	Mon 11/25/1	Mon 11/25/1	410,380
412		8. Adding Back Wall Envelope	1 day	Tue 11/26/19	Tue 11/26/19	411,403
413		9. Adding four 500 gallon tank	1 day	Wed 11/27/1	Wed 11/27/1	412,311
414		**Miscellaneous**	**15 days**	**Thu 11/28/19**	**Wed 12/18/1**	
415		Final Clean	5 days	Thu 11/28/19	Wed 12/4/19	5
416		Reserve Days	10 days	Thu 12/5/19	Wed 12/18/1	415



Project: Modular Building Assem
Date: Thu 9/26/19

Task, Split, Milestone, Summary, Project Summary, Inactive Task, Inactive Milestone, Inactive Summary, Manual Task, Duration-only, Manual Summary Rollup, Manual Summary, Start-only, Finish-only, External Tasks, External Milestone, Deadline, Progress, Manual Progress

Page 11

APPENDIX C: OCULUS RIFT S' INTRODUCTION

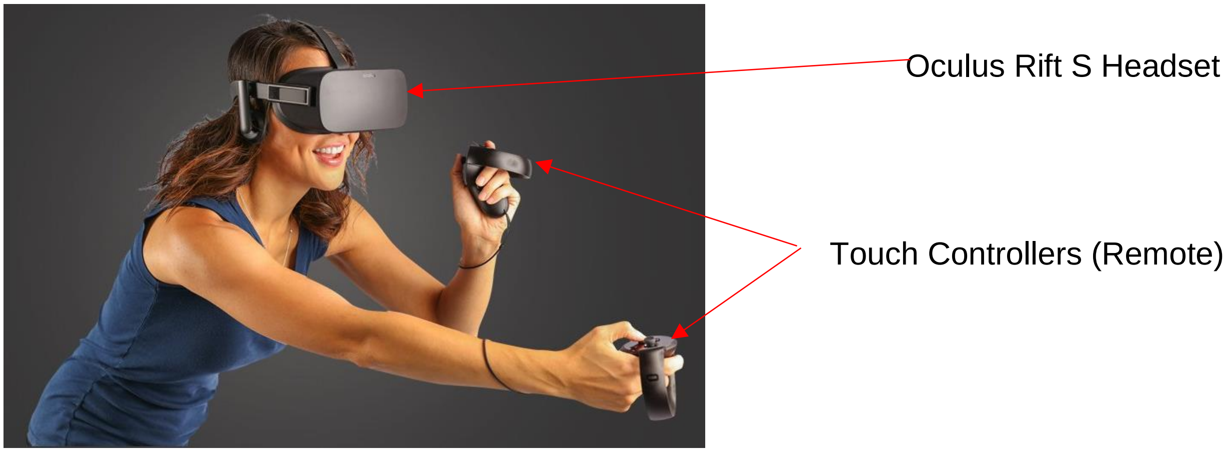
Experiencing Virtual Reality:

UNLV Solar Decathlon Modular House

Oculus Rift S

[Source: https://www.oculus.com/rift-s/?locale=en_US]

Details



[Source: https://images-na.ssl-images-amazon.com/images/I/51EnLfF7o-L._SL1465_.jpg]

Virtual Reality (VR)

“Virtual Reality is an artificial environment that is created with software and presented to the user in such a way that the user suspends belief and accepts it as a real environment. On a computer, virtual reality is primarily experienced through two of the five senses: sight and sound.” [https://whatis.techtarget.com/definition/virtual-reality]

There are various VR devices available in market like Samsung Gear VR, Dell HTC Vive virtual reality system, Sony PlayStation VR, Nintendo Labo VR Kit, Oculus Go, Lenovo Mirage Solo with Daydream, Oculus Rift S, etc.

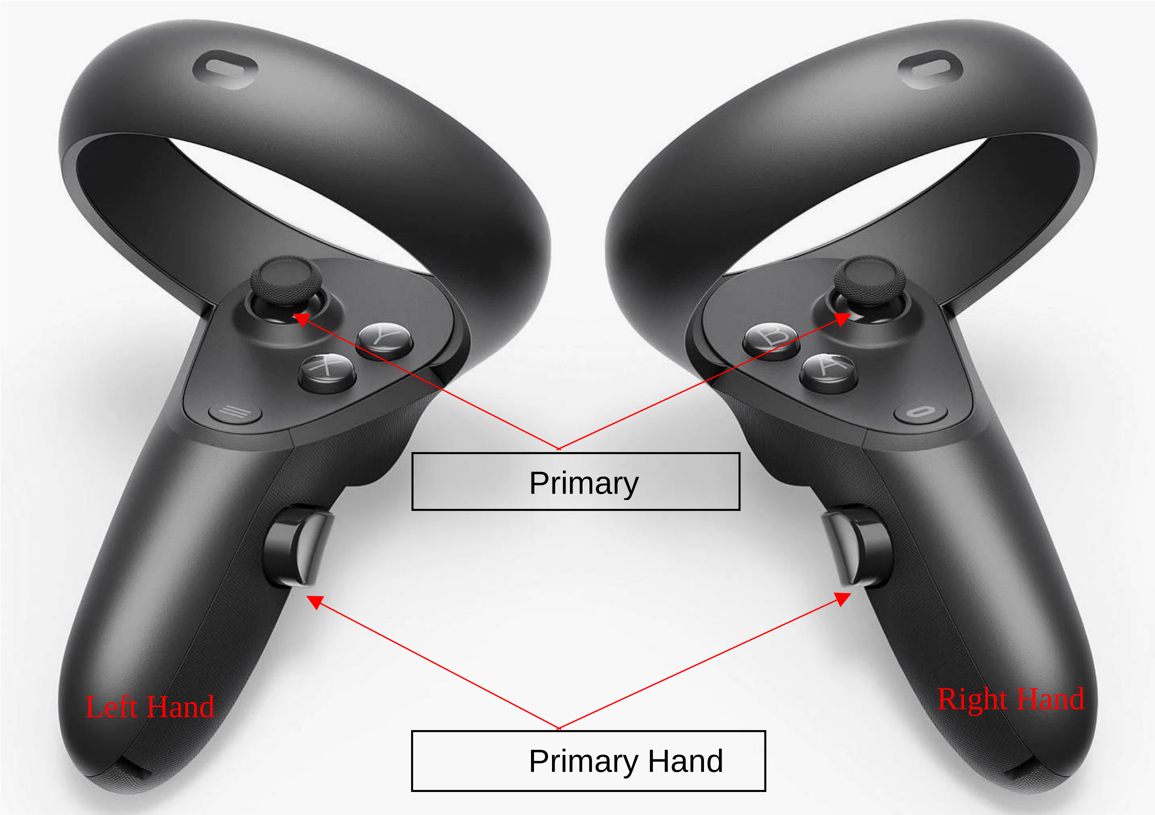
But we will use the one we have right now that is Oculus Rift S,

Our professor Dr. Choi has ‘Oculus Go’ as well.

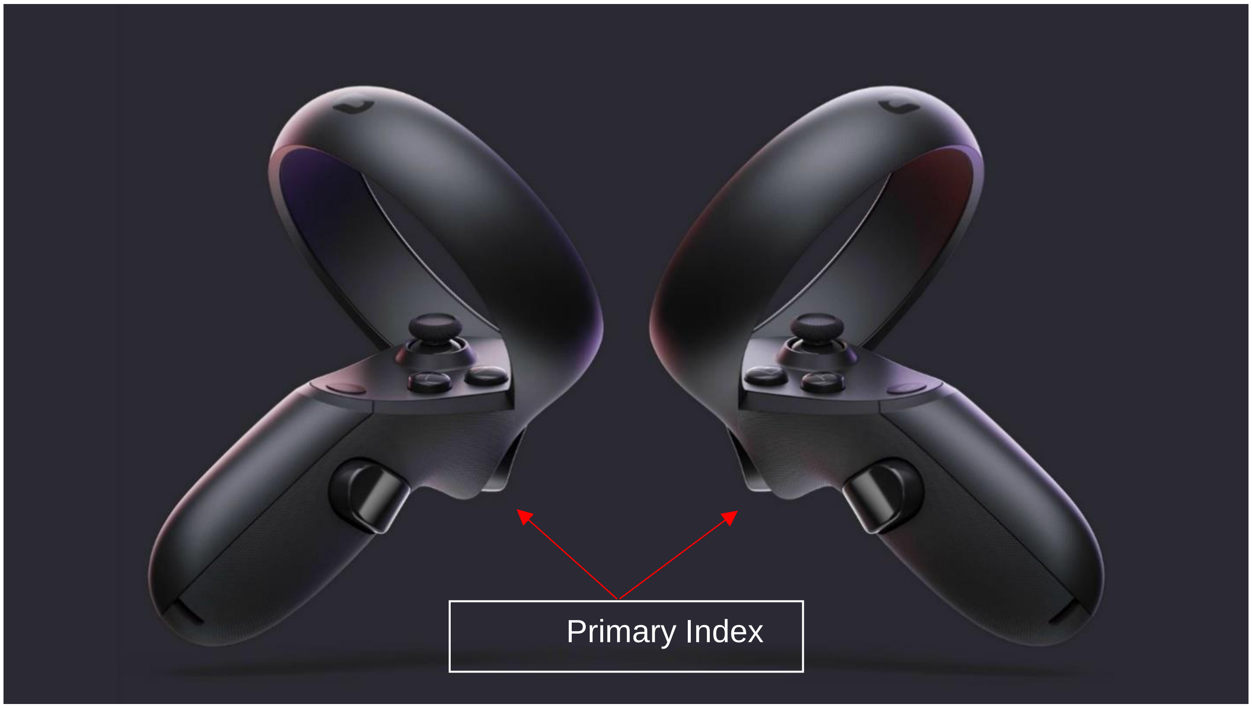
Oculus Rift S primarily consists of two items:

- VR Headset Gear: which you wear and on which you can see things and hear sounds from.
- Two Touch Controllers: which are basically remote controllers which assist with your movement and positioning inside the VR environment.

Components of Touch Controllers and their functions



[Source: https://johnlewis.scene7.com/is/image/JohnLewis/238147805alt3?$rsp-pdp-port-1440$]



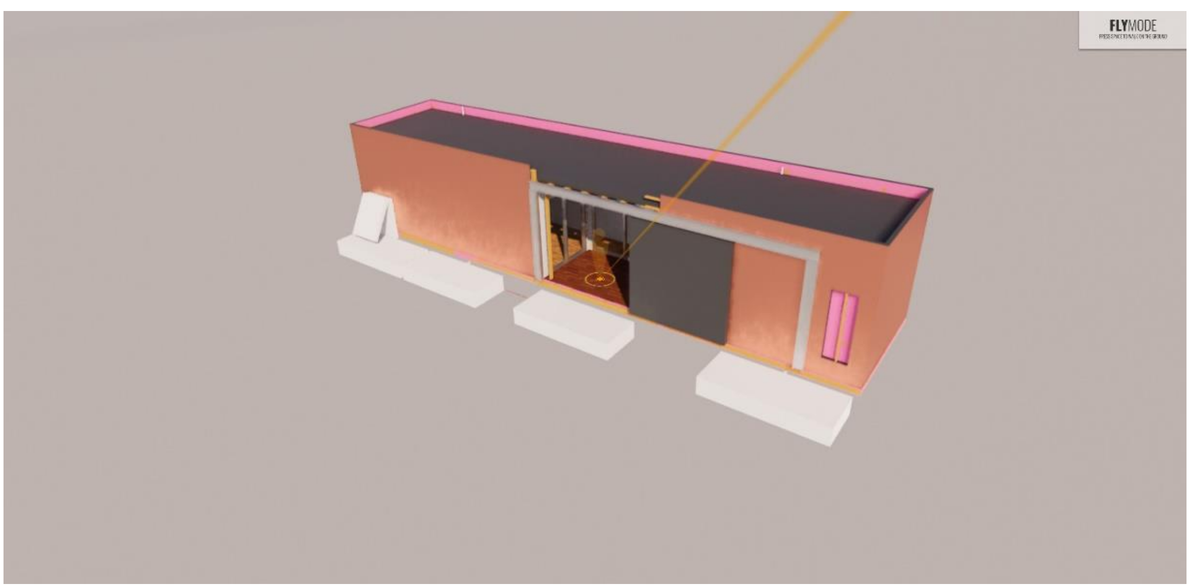
[Source: https://www.roadtovr.com/oculus-quest-touch-controllers-hit-fcc-proceeding-spring-2019-launch/]

Some Instructions

1. You will use only six buttons, three buttons with each hand.
2. Primary Thumbstick helps you move is horizontal and vertical plane.
    - For moving yourself on horizontal plane, you will use thumbstick of left hand. If you want to change your position inside VR environment and move right with reference to building model, you will toggle the thumbstick right. Likewise, toggle left to move yourself left. Same for front and back.

    - For shifting your position is vertical plane i.e. moving up or down with respect to building model in the VR environment you will toggle the thumbstick in right hand. Toggle front for moving yourself up. Toggle backwards to move yourself down.

3. For pointing in the building model use the touch controller of right hand.
4. For moving yourself to a certain location in the building model, point to that location using touch controller of right hand and the press the primary index trigger of same right hand.

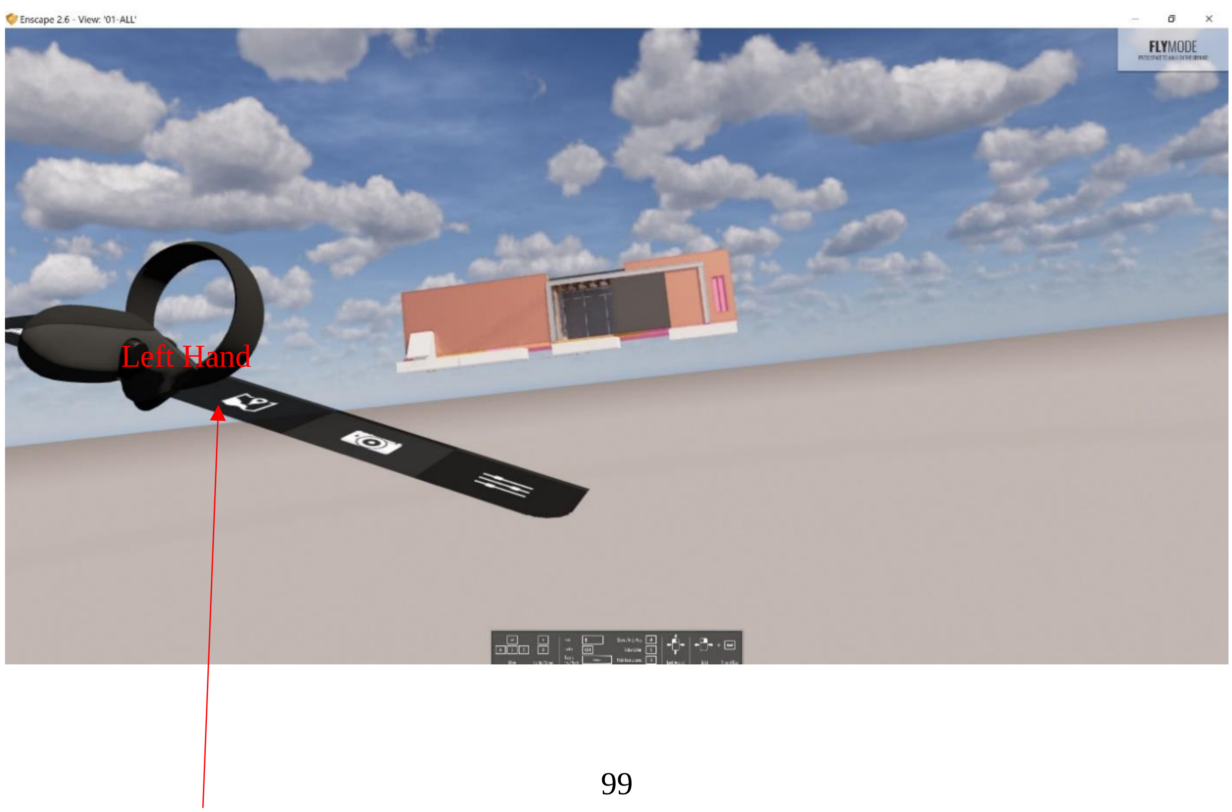


Note: if you just place your finger over the primary index trigger of right hand, you will see human shadow in the location where you pointed.

If you press (not just place, press, a bit harder) the primary index trigger on the right hand once, now you will be present at that location.

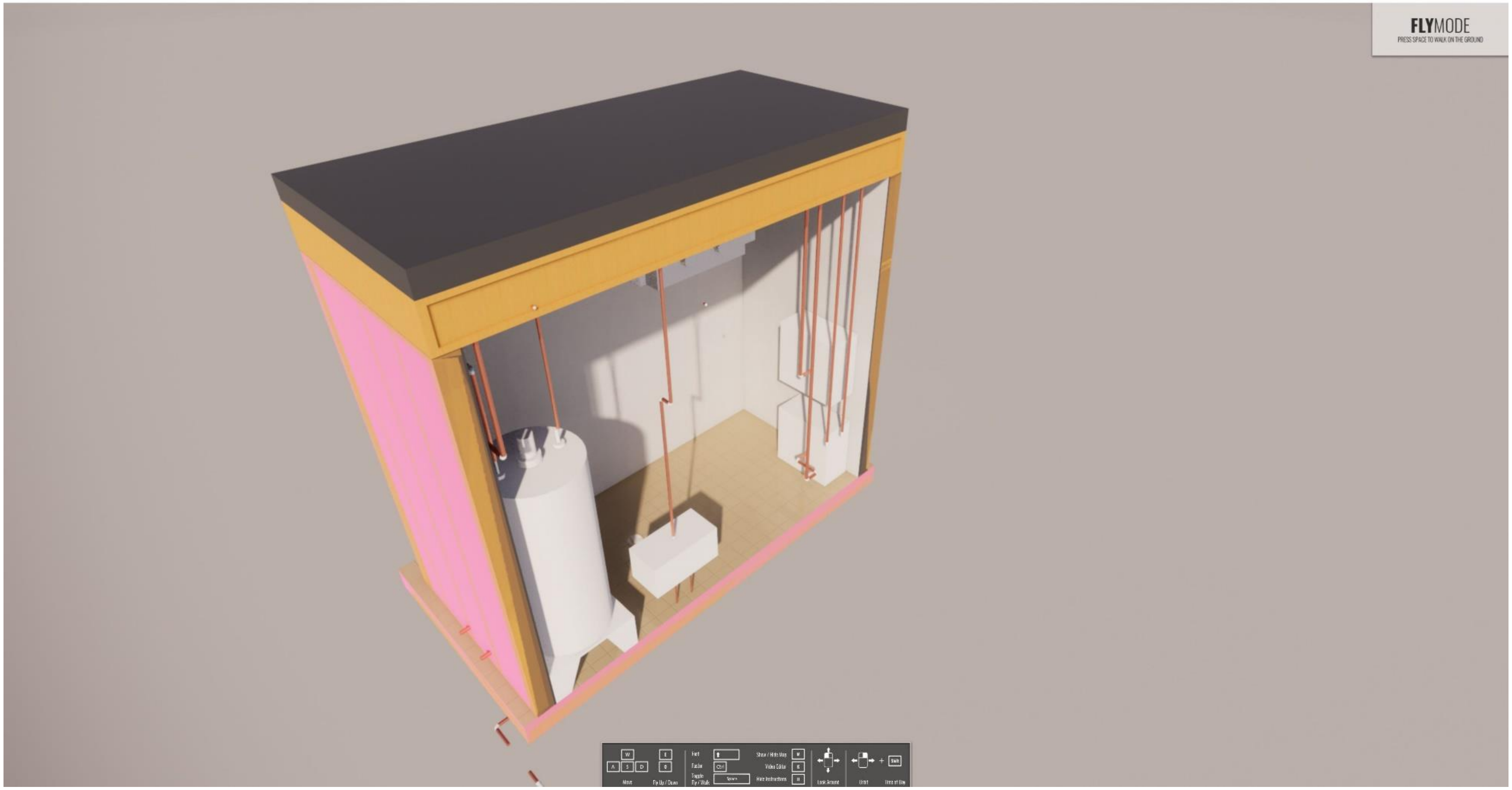
[Source: https://d11zer3aoz69xt.cloudfront.net/media/catalog/product/cache/1/image/1200x/9df78eab33525d08d6e5fb8d27136e95/o/c/oculus_quest_64gb_all_in_one_vr_with_controller_1.jpg]

5. For moving the plane, you are seeing, to left or right (horizonal motion of the vertical plane) or we can say rotating 'what you see' around you, use the primary hand trigger of left hand. Press it, hold it then rotate in the direction you want, either left or right. This way the whole thing that we see rotates around you.

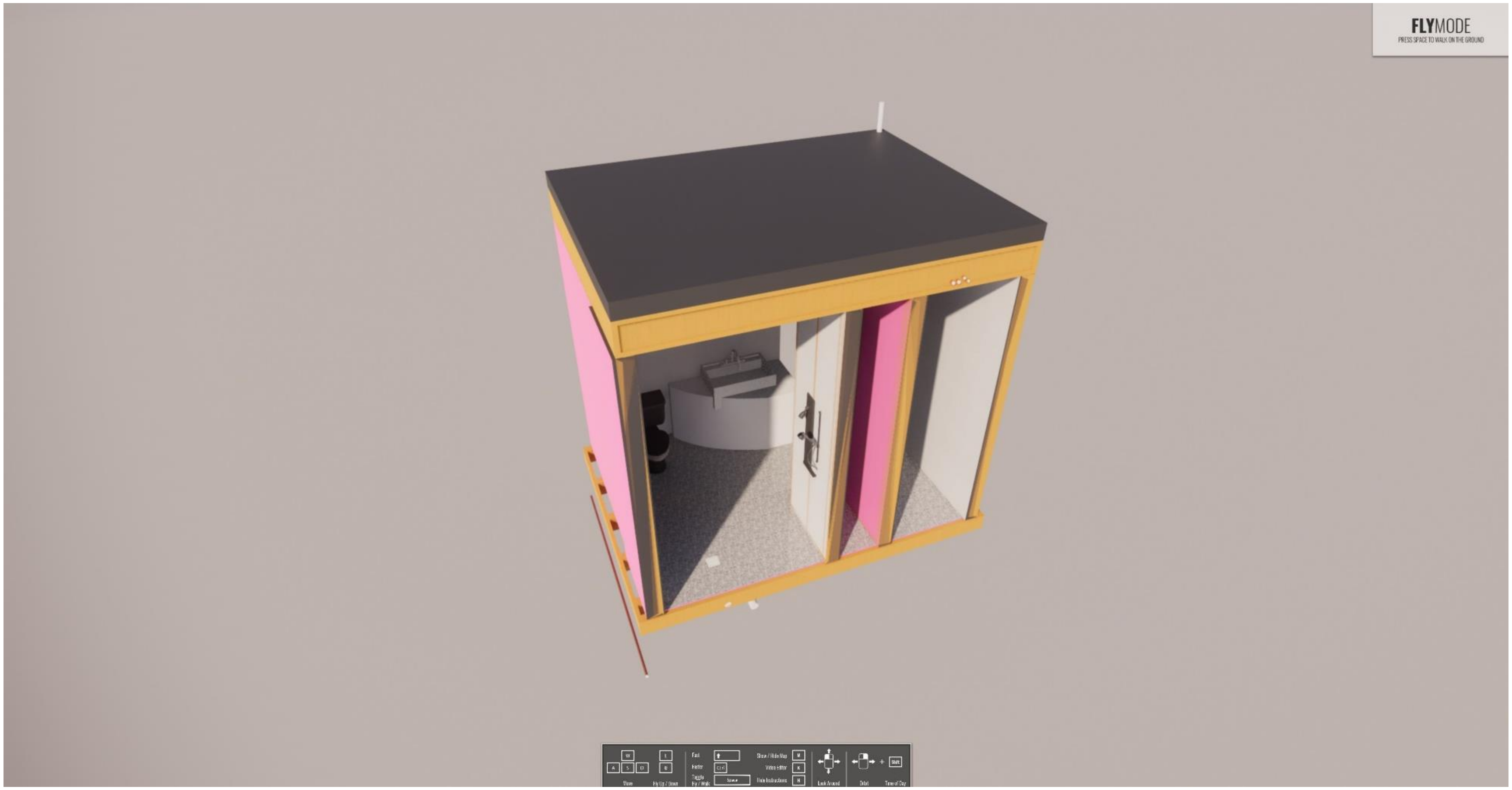


We will have an initial demonstration in the lab.

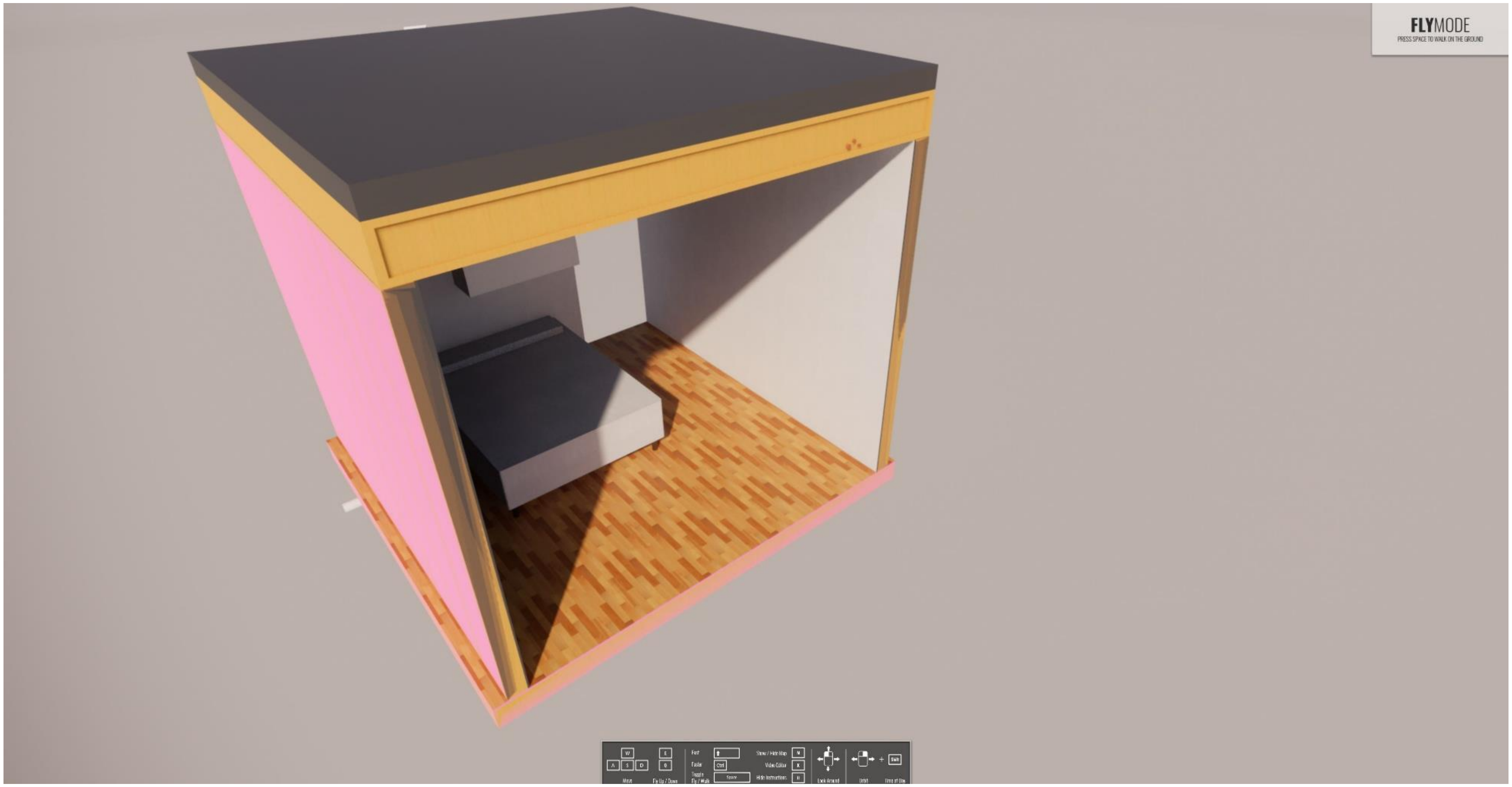
APPENDIX D: ENSCAPE™ SCREEN CAPTURES OF MODULES



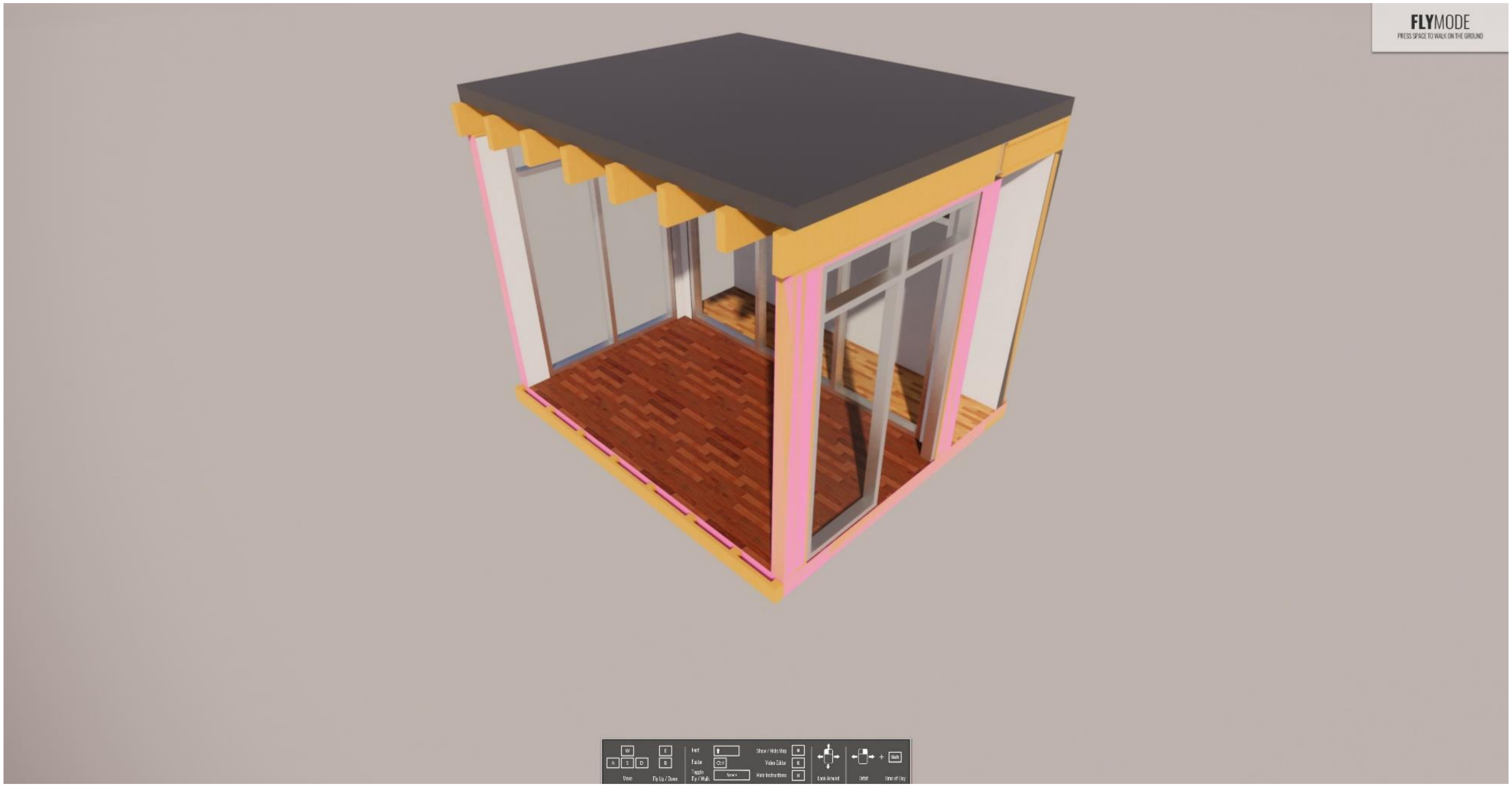
Module 1: Mechanical Room Module



Module 2: Bathroom Module

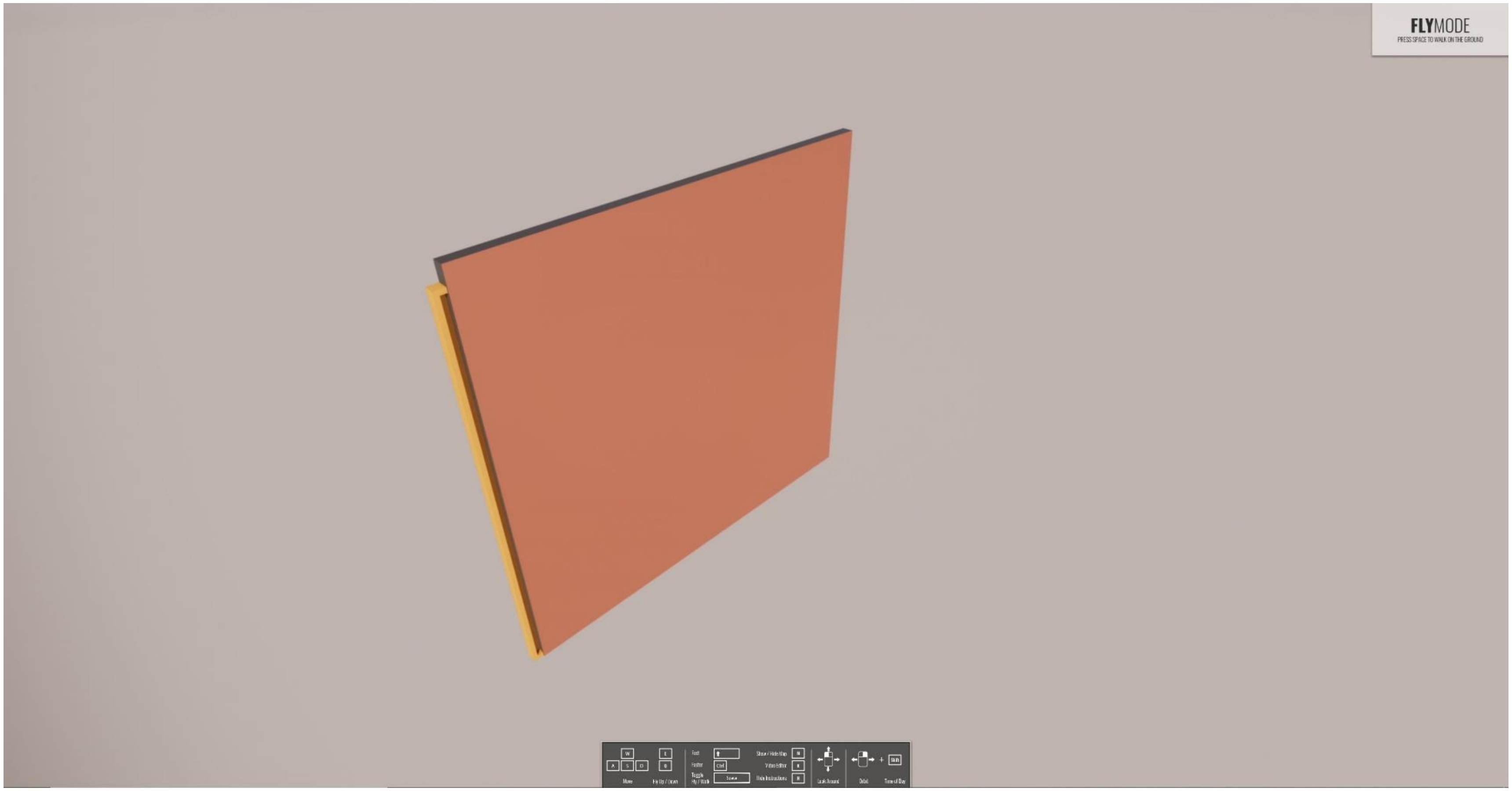


Module 3: Bedroom Module

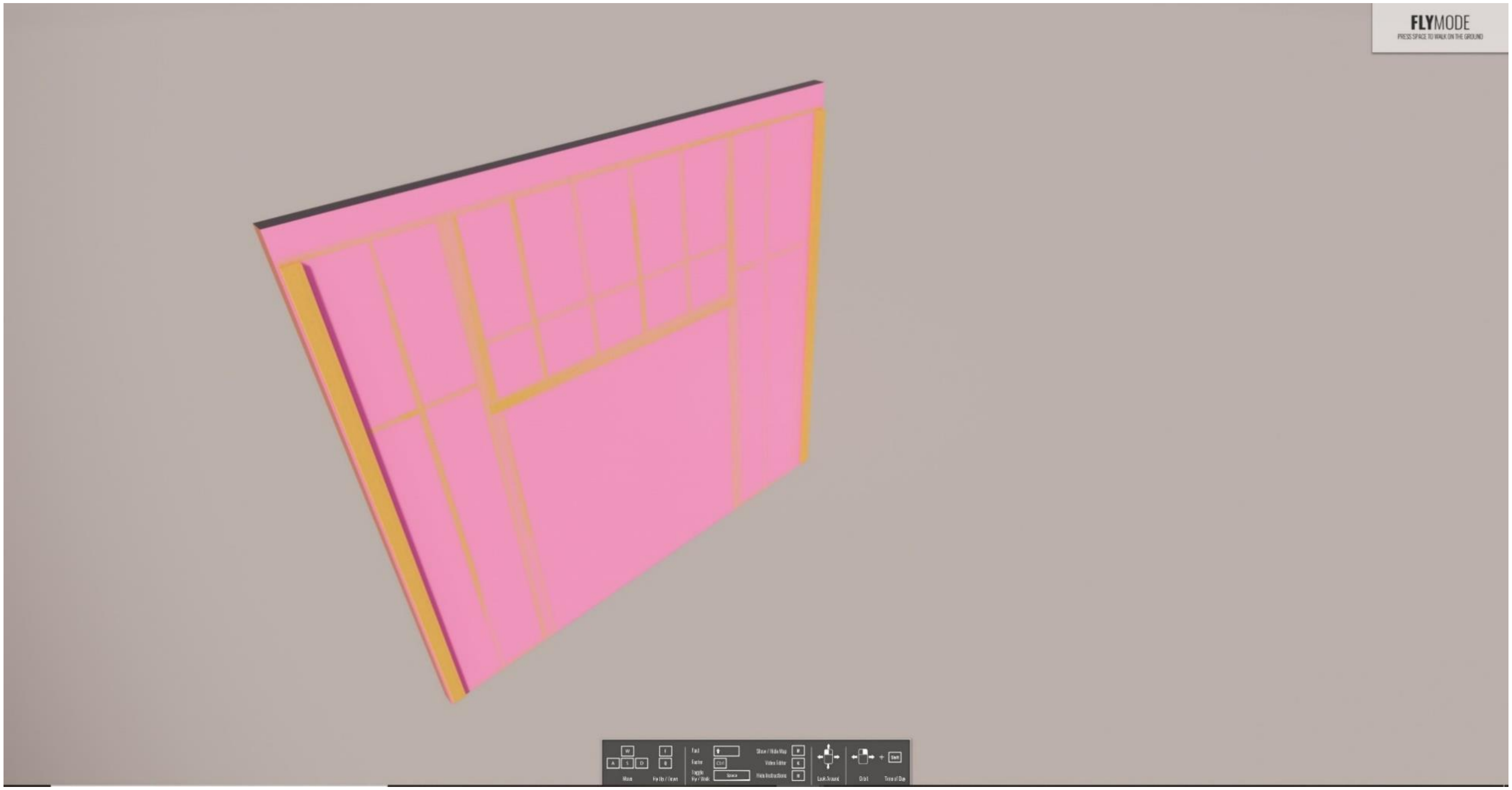


Module 4: Courtyard Module

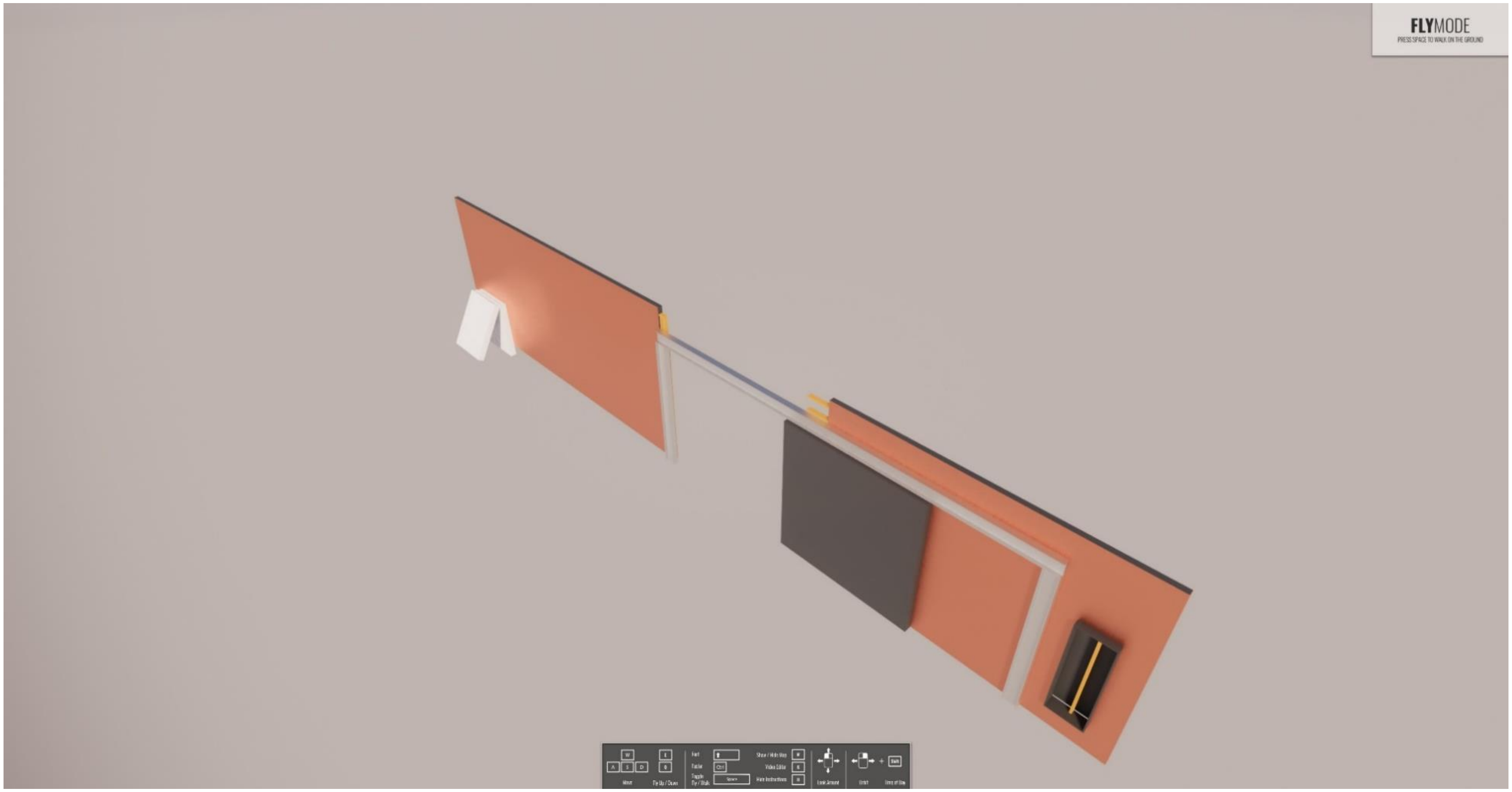
Module 5: Kitchen Module



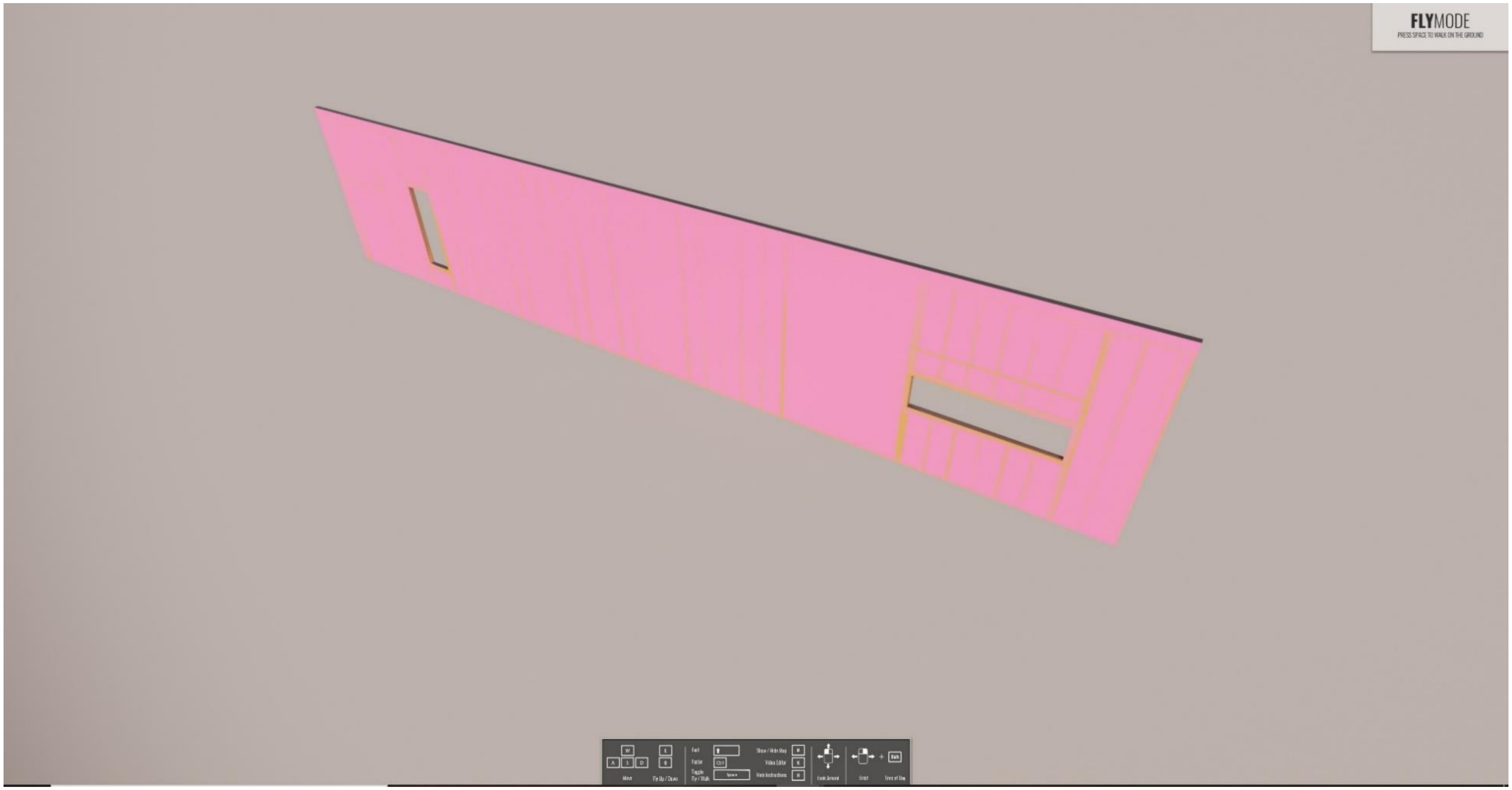
Module 6: East Wall Module



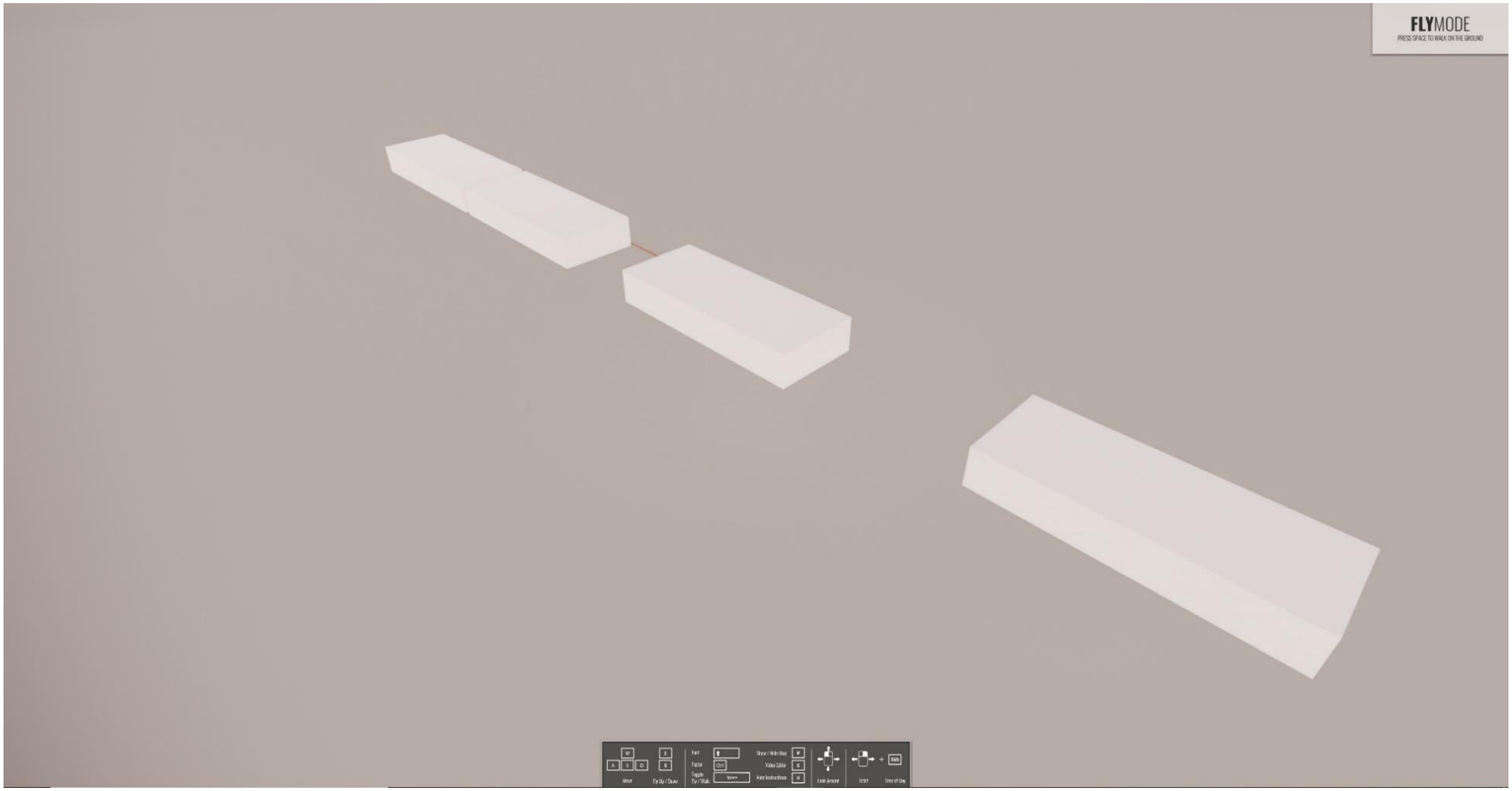
Module 7: West Wall module



Module 8: Front Wall Module



Module 9: Back Wall Module



Module 10: Four 500-Gallon Storage Tank Modules

Modular House after Complete Module Assembly

REFERENCES

Azhar, S., Lukkad, M., & Ahmad, I. (2012). Modular v. stick-built construction: Identification of critical decision-making factors. In *48th Annual Conference of Associated Schools of Construction* (p. 8).

Braun, A., & Borrmann, A. (2019). Combining inverse photogrammetry and BIM for automated labeling of construction site images for machine learning. *Automation in Construction*, *106*, 102879. https://doi.org/10.1016/j.autcon.2019.102879

Chau, K. W., Anson, M., & De Saram, D. D. (2005). 4D dynamic construction management and visualization software: 2. Site trial. *Automation in Construction*, *14*, 525–536. https://doi.org/10.1016/j.autcon.2004.11.005

Chau, K. W., Anson, M., & Zhang, J. P. (2004). Four-dimensional visualization of construction scheduling and site utilization. *Journal of Construction Engineering and Management*, *130*(4), 598–606. https://doi.org/10.1061/(ASCE)0733-9364(2004)130:4(598)

Chau, K. W., Anson, M., & Zhang, J. P. (2005). 4D dynamic construction management and visualization software: 1. Development. *Automation in Construction*, *14*, 512–524. https://doi.org/10.1016/j.autcon.2004.11.002

Choi, J. O., Chen, X. Bin, & Kim, T. W. (2017). Opportunities and challenges of modular methods in dense urban environment. *International Journal of Construction Management*, *19*, 1–13. https://doi.org/10.1080/15623599.2017.1382093

Choi, J. O., O'Connor, J. T., & Kim, T. W. (2016). Recipes for Cost and Schedule Successes in Industrial Modular Projects: Qualitative Comparative Analysis. *Journal of Construction Engineering and Management*, *142*(10). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001171

Ding, Z., Liu, S., Liao, L., & Zhang, L. (2019). A digital construction framework integrating building information modeling and reverse engineering technologies for renovation projects. *Automation in Construction*, *102*, 45–58. https://doi.org/10.1016/j.autcon.2019.02.012

Du, J., Zou, Z., Shi, Y., & Zhao, D. (2018). Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making. *Automation in Construction*, *85*, 51–64. https://doi.org/10.1016/j.autcon.2017.10.009

Feng, H., Yin, C., Li, R., Ma, W., Yu, H., Cao, D., & Zhou, J. (2019). Flexible virtual fixtures for human-excavator cooperative system. *Automation in Construction*, *106*, 102897. https://doi.org/10.1016/j.autcon.2019.102897

Haas, C. T., O'Connor, J. T., Tucker, R. T., Eickmann, J. A., & Fagerlund, W. R. (2000). *Prefabrication and preassembly trends and effects on the construction workforce* (Vol. 14). Center for Construction Industry Studies.

Heigermoser, D., García de Soto, B., Abbott, E. L. S., & Chua, D. K. H. (2019). BIM-based Last Planner System tool for improving construction project management. *Automation in Construction*, *104*, 246–254. https://doi.org/10.1016/j.autcon.2019.03.019

Hinze, J. W. (2011). *Construction planning and scheduling*. Pearson Higher Ed.

Kasireddy, V., Zou, Z., Akinci, B., & Rosenberry, J. (2016). Evaluation and Comparison of Different Virtual Reality Environments towards Supporting Tasks Done on a Virtual Construction Site. In *Construction Research Congress 2016* (pp. 2371–2381).

Kassem, M., Dawood, N., & Chavada, R. (2015). Construction workspace management within an Industry Foundation Class-Compliant 4D tool. *Automation in Construction*, *52*, 42–58. https://doi.org/10.1016/j.autcon.2015.02.008

Kim, Changwan, Kim, C., & Son, H. (2013). Automated construction progress measurement using a 4D building information model and 3D data. *Automation in Construction*, *31*, 75–82. https://doi.org/10.1016/j.autcon.2012.11.041

Kim, Changyoon, Kim, B., & Kim, H. (2013). 4D CAD model updating using image processing-based construction progress monitoring. *Automation in Construction*, *35*, 44–52. https://doi.org/10.1016/j.autcon.2013.03.005

Kim, M. J., Wang, X., Love, P. E. D., Li, H., & Kang, S. C. (2013). Virtual reality for the built environment: A critical review of recent advances. *Journal of Information Technology in Construction*, *18*, 279–305. Retrieved from http://www.itcon.org/2013/14

Kinateder, M., Ronchi, E., Nilsson, D., Kobes, M., Müller, M., Pauli, P., & Mühlberger, A. (2014). Virtual Reality for Fire Evacuation Research. *Proceedings of the 2014 Federated Conference on Computer Science and Information Systems*, *2*, 313–321. https://doi.org/10.15439/2014f94

Kobes, M., Helsloot, I., De Vries, B., & Post, J. (2010). Exit choice, (pre-)movement time and (pre-)evacuation behaviour in hotel fire evacuation - Behavioural analysis and validation of the use of serious gaming in experimental research. *Procedia Engineering*, *3*, 37–51. https://doi.org/10.1016/j.proeng.2010.07.006

Kumar, S., Hedrick, M., Wiacek, C., & Messner, J. I. (2011). Developing an experienced-based design review application for healthcare facilities using a 3D game engine. *Journal of Information Technology in Construction*, *16*, 85–104.

Ma, Z., Shen, Q., & Zhang, J. (2005). Application of 4D for dynamic site layout and management of construction projects. *Automation in Construction*, *14*, 369–381. https://doi.org/10.1016/j.autcon.2004.08.011

Mahalingam, A., Kashyap, R., & Mahajan, C. (2010). An evaluation of the applicability of 4D CAD on construction projects. *Automation in Construction*, *19*, 148–159. https://doi.org/10.1016/j.autcon.2009.11.015

Marsh, K. L., Wilkie, C. T., Luh, P. B., Zhang, Z., Gifford, T., & Olderman, N. (2012). Crowd Guidance in Building Emergencies: Using Virtual Reality Experiments to Confirm Macroscopic Mathematical Modeling of Psychological Variables. *Pedestrian and Evacuation Dynamics 2012*, 197–212. https://doi.org/10.1007/978-3-319-02447-9

O'Connor, J. T., O'Brien, W. J., & Choi, J. O. (2014). Critical success factors and enablers for optimum and maximum industrial modularization. *Journal of Construction Engineering and Management*, *140*(6), 04014012. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000842

O'Connor, J. T., O'Brien, W. J., & Choi, J. O. (2015). Standardization Strategy for Modular Industrial Plants. *Journal of Construction Engineering and Management*, *141*(9), 04015026(10). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001001

O'Connor, J. T., O'Brien, W. J., & Choi, J. O. (2016). Industrial Project Execution Planning: Modularization versus Stick-Built. *Practice Periodical on Structural Design and Construction*, *21*(1), 04015014. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000270

Olde Scholtenhuis, L. L., Hartmann, T., & Dorée, A. G. (2016). 4D CAD Based Method for Supporting Coordination of Urban Subsurface Utility Projects. *Automation in Construction*, *62*, 66–77. https://doi.org/10.1016/j.autcon.2015.10.013

Retik, A., Warszawski, A., & Banai, A. (1990). The use of computer graphics as a scheduling tool. *Building and Environment*, *25*(2), 133–142. https://doi.org/10.1016/0360-1323(90)90025-M

Rüppel, U., & Schatz, K. (2011). Designing a BIM-based serious game for fire safety evacuation simulations. *Advanced Engineering Informatics*, *25*, 600–611. https://doi.org/10.1016/j.aei.2011.08.001

Sacks, R., Perlman, A., & Barak, R. (2013). Construction safety training using immersive virtual reality. *Construction Management and Economics*, *31*(9), 1005–1017. https://doi.org/10.1080/01446193.2013.828844

Sherman, W. R., & Craig, A. B. (2002). *Understanding virtual reality: Interface, application, and design*. Morgan Kaufmann.

Sloot, R. N. F., Heutink, A., & Voordijk, J. T. (2019). Assessing usefulness of 4D BIM tools in risk mitigation strategies. *Automation in Construction*, *106*, 102881. https://doi.org/10.1016/j.autcon.2019.102881

Solar Decathlon: About Solar Decathlon. (2018). Retrieved July 31, 2019, from https://www.solardecathlon.gov/about.html

Song, J., Fagerlund, W. R., Haas, C. T., Tatum, C. B., & Vanegas, J. A. (2005). Considering Prework on Industrial Projects. *Journal of Construction Engineering and Management*, *131*(6), 723–733. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:6(723)

Taghaddos, H., Eslami, A., Hermann, U., AbouRizk, S., & Mohamed, Y. (2019). Auction-based Simulation for Industrial Crane Operations. *Automation in Construction*, *104*, 107–119. https://doi.org/10.1016/j.autcon.2019.03.015

Tatum, C. B., Vanegas, J. A., & Williams, J. M. (1987). *Constructability improvement using prefabrication, preassembly, and modularization*. Bureau of Engineering Research, University of Texas at Austin Austin, TX.

Tech, V., Hall, P., & Tech, V. (2001). VISUALIZING SIMULATED CONSTRUCTION OPERATIONS IN 3D. *JOURNAL OF COMPUTING IN CIVIL ENGINEERING*, *15*(4), 329–337.

Trebbe, M., Hartmann, T., & Dorée, A. (2015). 4D CAD models to support the coordination of construction activities between contractors. *Automation in Construction*, *49*, 83–91. https://doi.org/10.1016/j.autcon.2014.10.002

Turkan, Y., Bosche, F., Haas, C. T., & Haas, R. (2012). Automated progress tracking using 4D schedule and 3D sensing technologies. *Automation in Construction*, *22*, 414–421. https://doi.org/10.1016/j.autcon.2011.10.003

U.S. Department of Energy. (2019). Solar Decathlon Competition Guide 2019-20. Retrieved February 28, 2019, from https://www.solardecathlon.gov/assets/pdfs/sd-competition-guide.pdf

Wang, H. J., Zhang, J. P., Chau, K. W., & Anson, M. (2004). 4D dynamic management for construction planning and resource utilization. *Automation in Construction*, *13*(5), 575–589. https://doi.org/10.1016/j.autcon.2004.04.003

Wang, L. (2007). *Using 4D Modeling To Advance Construction Visualization In Engineering Education*.

Woksepp, S., & Olofsson, T. (2008). Credibility and applicability of virtual reality models in design and construction. *Advanced Engineering Informatics*, *22*, 520–528. https://doi.org/10.1016/j.aei.2008.06.007

Woodhead, R., Stephenson, P., & Morrey, D. (2018). Digital construction: From point solutions to IoT ecosystem. *Automation in Construction*, *93*, 35–46. https://doi.org/10.1016/j.autcon.2018.05.004

Xing, X., Li, H., Li, J., Zhong, B., Luo, H., & Skitmore, M. (2019). A multicomponent and neurophysiological intervention for the emotional and mental states of high-altitude construction workers. *Automation in Construction*, *105*, 102836. https://doi.org/10.1016/j.autcon.2019.102836

Zhang, J. P., & Hu, Z. Z. (2011). BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 2. Development and site trials. *Automation in Construction*, *20*, 167–180. https://doi.org/10.1016/j.autcon.2010.09.014

CURRICULUM VITAE

Rajarshi Ghimire

Email: ghimirerajarshi@gmail.com

Education:

Bachelor of Engineering in Civil Engineering, February 2016

Institute of Engineering, Tribhuvan University, Nepal

Thesis Title:

Examining the Effectiveness of a 4D Schedule and a Virtual Reality Model on a Modular Project: UNLV Solar Decathlon Case

Thesis Examination Committee:

Dr. Jin Ouk Choi (Advisory Committee Chair)

Dr. Moses Karakouzian (Advisory Committee Member)

Dr. JeeWoong Park (Advisory Committee Member)

Professor Eric Weber (Graduate College Representative)