Immersive Visualization Intervention on Pull Planning

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Abstract

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Pull-Planning is considered a brainstorming process conducted by stakeholders in construction projects. It encourages collaboration by making a stakeholder communicate and visualize the work plan for the next few weeks so that other stakeholders are aware of what activity is happening on the jobsite. This allows project stakeholders to carefully plan their work and minimize conflicts that arise from miscommunication during the project. However, as a tool in lean construction, pull planning has a learning curve and some documents may be needed to help stakeholders in completing the process. Throughout the years, several tools may have been used, whether it is a floor plan or a 3-D models, to help the pull plan process.

This study aimed to explore what alternative visualization tool may be possible to be introduced to the pull planning processes. Virtual Reality was considered because the technology has been advanced enough to be implemented economically. Combined with BIM models, the VR was expected to provide the stakeholders an immersive environment in the pull planning process, which should enhance their communication process. The study also looked at how the intervention would help with the learning process to help people with less knowledge on pull planning be able participate in the process.

A prototype and several studies were conducted both on professional and students. It was concluded that professionals were more akin to using a shared screen with the virtual reality screen mirrored in it. Meanwhile, as a learning tool, VR intervention can be implemented on a smaller scale such as a classroom setting with simplified scenarios to help the learning process.

This study results also enforced the notion that the implementation of VR contributed to identification of errors or problem related to the model, which had been suggested by other studies. In the real of pull plan itself, study results indicated the possibility of accelerating the conflict resolution process between stakeholders through the model visualization by having the stakeholders use VR model as a visual aid tool.

In a long term, this study is expected to be a point of departure for other studies that seek to further implement VR/AR/XR in a project beyond using them as a design review tool. With more developed model and hardware, the industry can potentially implement the technology in a more economical way to help stakeholders in the pull planning process

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TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

Chapter 1 - Introduction

1.1 Background

The evolution of the construction industry has manifested increased complexities in recent times. Contemporary techniques and protocols for enhancing the efficacy of both construction planning and execution have been introduced. Certain of these methodologies aim to mitigate the ambiguities in construction projects.

Among these innovative approaches, the Architecture, Engineering, and Construction (AEC) sector has incorporated practices and techniques drawn from disparate industries and disciplines. Lean construction, a methodology derived from the manufacturing sector, has demonstrated its potential to elevate performance and minimize waste generation throughout the construction process (Ghosh et al., 2017a). This approach also attenuates project uncertainties due to the efficient exchange of information among different disciplines. The Last Planner System or Pull Planning encourages the collaboration between project team members to ensure the punctual fulfillment of their responsibilities while encouraging them to collaborate(Ghanem et al., 2022a).

Simultaneously, the most recent leap forward in the construction industry is the virtualization or digital representation of information. This visualization technology is designed to promote the exchange of information between disciplines, ultimately fostering a collaborative ethos among the project stakeholders. Building Information Modeling (BIM) was established to serve this function. BIM, having been utilized over the previous two decades, enables the integration of data into the design process (Du et al., 2018).

With the incorporation of BIM in construction projects, a wave of emergent technologies has surfaced. These innovative solutions serve myriad purposes, from enabling interoperability among tools and providing access to diverse project aspects, to facilitating more intuitive collaboration among project participants. Whereas BIM embodies data accessibility for the purpose of managing the project team, the lean principles emphasis on guaranteeing the project will be delivered on time and on budget. These two concepts can be incorporated together into the project workflow to optimize the project outcomes (Eldeep et al., 2022).

Communication between the participants also plays an important role. A study found that aside the use of boundary objects, a form of communication called messy talk occurs during a collaboration effort (Dossick et al., 2015). This communication form is unplanned interactions that eventually lead to knowledge sharing between participants.

With the nature of construction projects where meetings between various disciplines are regularly planned, good communication can be an important factor to bridge the knowledge gap. As such, bridging documents may be used as visualization aid in Pull Planning. This can be in various ways, including floor plans or 3D model from the BIM process.

In addition to the use of visual aid to bridge communication, they can be used to help with learning the pull plan process in general. Studies have suggested that the shortcoming of pull plan itself can be rigorous and its learning curve can be intimidating to those who experienced it for the first time. Therefore, some aids may be needed to get the rest of the team members up to speed with the process (Tsao et al., 2014).

The concept of visual aid became the point of departure of this study. This study explored how the visualization component of geometry models could support pull planning sessions within a project. Two modalities were investigated: conventional visualization via flat screen and immersive visualization through virtual reality. Multiple experiments were performed on industry professionals and students to discern how the incorporation of visualization impacted their communication and collaborative efforts during pull planning sessions.

1.2 Research Questions

The study will be conducted to answer several questions regarding the applicability of visual intervention in pull planning sessions:

1. How can implementation of VR encourage collaboration in a pull planning session?
2. How do several visual aid types, VR or non-VR, support participant’s ability to share their knowledge in order to solve problems in developing a schedule?
3. How does different background of knowledge impact the utilizations of VR?

1.3 Research Objectives

The main objectives of this study are:

a. To investigate the viability of immersive environments using current technologies to facilitate the information exchange in pull planning sessions.

b. To evaluate features in immersive virtual reality environments that would help with pull planning sessions.

c. To analyze interactions during a pull planning with VR intervention.

1.4 Research Limitations

The research was limited to studying how the implementation of immersive visualizations in mobile VR for communication between personnel in pull planning sessions. In addition, there are limitations due to the limited resource and time constraints to the study such as:

a. Immersive Visualization in mobile VR devices.

While technically it was possible to conduct the study using tethered VR or a mobile VR device with a wireless connection to a desktop PC, it would be challenging to setup since each VR device must be supported by a PC.

b. Simplified model was used in the case studies.

The building models that were used in this study were relatively simple due to the less powerful hardware in mobile devices. To be able to provide a smooth experience to the experiment participants, the prototype must be capable of displaying the immersive environment at least 60 frames per second on average.

c. Studies were conducted in groups.

Participants responses in the studies were recorded as a team. Recording individual interaction would require additional recording hardware for each participant. Meanwhile, a typical pull planning session would involve more than ten people from various trades.

d. Limited features

The study used a subset of features since the virtual reality prototype tool used in the study had to be built mostly from ground up using Unreal Engine’s blueprint programming. The development of the features had to undergo several stages until it could be implemented on the prototype.

1.5 Benefits of the Research

This study evaluated how the implementation of immersive virtual environment could impact the communication flow between participants of a pull planning session. Using exploratory approach, this study seeks to find to what extent VR can be implemented in pull plan with minimum impact on the cost of equipment. In addition. the study compared the performance of users prior and after VR intervention.

By investigating their performances and participants’ feedback on the technology:

1. The results will contribute to determining the direction of the alternative visualization methods such as Virtual Reality as a visual aid tool in pull planning sessions.
2. It will be a contribution to the body of knowledge on the use of new technologies to help certain aspects of pull plannings.

1.6 Research Approach

This research was conducted with a mix open-ended interview and user interaction development. The open-ended interview approach was taken to identify current practices in pull planning in construction projects, so the principal investigator could use it as a departure point for the immersive VR prototype development.

In general, this research adopted a qualitative research approach where a series of interviews combined with questionnaires were distributed after study sessions. In addition, the principal investigator participated as a facilitator and an observer for each session. The dual roles of the investigator were meant to help answer any questions from the participants as well as observing the interactions that happened during the study sessions.

Chapter 2 – Literature Review

2.1 Practice and Implementation of Pull Planning in the Construction Industry

In the industry, numerous researchers have proposed collaborative efforts among team members to enhance performance. One such solution is pulling planning, which fosters a sense of collaboration and aims to optimize resources while maintaining product quality. The primary focus of pull planning is to reduce inventory and minimize waste. Pull planning enables stakeholders to precisely plan and communicate their work plan to each other. Since everyone involved is notified on the work plan stakeholders can plan to immediately use any materials that have just arrived on site without having them sit in inventory for a long time (Rios-Mercado & Rios-Solis, 2012).

Unlike conventional planning practices, pull planning involves key stakeholders in the decision-making process. Team members describe their work and release it to others, facilitating the negotiation of task sequences and relationships until a schedule network is established.

In conventional planning practices, performance issues may arise if there is a constraint that prevents the crew from proceeding with their tasks. In Lean, this is considered a form of waste since the continuity of work was broken by waiting time. The pull planning system effectively addresses this by promoting transparent communication of work descriptions by all trades involved. Consequently, the most efficient durations for tasks can be minimized (Ballard & Howell, 2003a). Pull planning enables the revelation of important information, such as the size of activities, responsible trades, and the need for smaller resource batches. The execution of pull planning is supported by various tools (Salem et al., 2005)

1. Master Schedule: It is the overall project schedule generated for the bid package. The master schedule is used for the Reverse Phase Scheduling which "pushes completions and deliveries onto the project (Gonzalez et al., 2008).
2. Reverse Phase Scheduling (RPS): It is the pull technique used to develop the schedule by working backward from the completion date: It is also considered to be at the core of the Last Planner System. It is developed by a team of last planners. Compared to the master schedule, the activities reflected in RPS are closer to the reality in the project.

3. Look Ahead Plan: This plan is used as near-future work references. It projects the planned work on the week after the weekly work plan meeting. Look ahead plan would project works several weeks ahead, varying between 3 to 12 weeks. The durations in Look Ahead Plan were calculated based on the RPS results. The look ahead plan also addresses project-related constraints, so the stakeholders can formulate solutions to eliminate as many constraints as possible earlier.
4. Weekly Work Plan: It controls the flow of the project and ensures that assignments are ready by closely managing the material procurement process, designing information to be used, and monitoring works (Issa, 2013). It promotes transparency among team members in an efficient and accurate way.
5. Percent Plan Complete: Abbreviated as PPC, it is the measurement of Last Planner System. PPC represents the percentage of completed works that was planned within a time frame, usually a week. A study found that projects with above average implementation of LPS components, on average, result in a higher PPC compared to projects with below average implementation.
6. Tool-box meetings: It is a daily meeting conducted to make employees involved in the planning process. It is also considered an improvement tool where team members briefly update the status of their assigned work.
7. 5s Process: It is a housekeeping approach that originated from Japanese language. 5s is a short of Seiri (Sort), Seiton (Set in order), Seiso (Shine), Seiketsu (Standardize), and Shitsuke (Sustain). This process separates unneeded tools from the necessary ones, arrange them, clean them up, and maintain them. The process should be integrated in the workflow, so it becomes

a habit. It can improve safety, performance, quality, and contribute to the continuous improvement.

Ghosh et al. (2017) conducted an observational study comparing pull planning practice to common planning practice, specifically Critical Path Method (CPM) planning. The study involved general contractors who adopted visual schedules as an alternative to the traditional Bar Chart typically utilized in CPM planning. Visual aids, such as sticky notes, were employed, with trades providing essential information such as activity names, durations, and logical relationships on the notes. These notes were then affixed to a whiteboard.

This visual approach allowed trades to update their progress daily by annotating their respective scope of work on the notes. Supplementary visual cues were employed by trades, such as check marks (v) to denote successful completion or an "x" to indicate incomplete work. For tasks with varying degrees of completion, trades indicated the percentage of progress within the notes. Importantly, this method enabled trades to identify potential causes of delay, such as coordination issues.

These findings highlight the significance of visual information in the planning process, even rendering traditional CPM charts unnecessary. The utilization of visual aids, including sticky notes and whiteboards, enhances communication and facilitates the identification of delays and coordination challenges. Ghosh et al.'s study underscores the value of visual planning techniques as a viable alternative to conventional CPM practices.

2.2 Building Information Modeling

2.2.1 Building Information Modeling Overview

The AEC industry has been utilizing Building Information Modeling to manage and streamline information flow during the project lifecycle. Its utilization has been shown to benefit various aspects of construction projects from mitigating potential change orders, improving safety, or visualizing the construction phases.

Building Information Modeling (BIM) is a recent advancement in the AEC industry that brings about a fundamental shift in practice, aligning with lean principles in construction. The development of BIM systems has facilitated easier access for non-technical project participants and stakeholders by enabling real-time, interactive visualization of designs.

One of the key advantages of BIM is its ability to facilitate rapid design changes as the model can be directly manipulated by the operator. Moreover, proficient BIM users can leverage automated design generation to a certain extent, including automated detailing in steel construction, which is not feasible with conventional CAD software (Sacks, Koskela, et al., 2010).

2.2.2 The 4D Aspect for BIM

The construction schedules have been created using the Critical Path Method (CPM) along with 2D drawings. It has been a widely used technique in the construction industry since the 1950s, but it has faced criticism for its lack of integration with visual representations of the planned construction (Collier & Fischer, 1996). Designers rely on 2D drawings to convey their ideas to other project participants. However, interpreting these drawings requires individuals to have received sufficient training and experience. The participant then translates the designer's concepts into a CPM schedule that outlines the construction sequence. As building designs have become increasingly complex, even experienced individuals may misinterpret the designer's intentions. This misinterpretation ultimately leads to additional time and cost expenditures.

With BIM, it has been possible to incorporate the schedule aspect into the 3D model to show the planned construction sequence according to the CPM schedule. This process is the 4^{th} dimension in BIM, hence it is named 4D BIM. The 4D model enables engineers engaged in the construction planning process to visualize how the construction sequence will be executed. Moreover, it establishes a unified medium for integration, allowing all parties involved to collaborate on the design using the same 3D model, thereby reducing misinterpretation and redundant conceptualization. The 4D model fosters a more interactive and communicative environment among process designers, making it conducive to detecting potential problems that might otherwise be overlooked when using traditional planning software (Fischer & Koo, 1998).

2.2.3 BIM Integration with Pull Plan

Similar to lean construction, BIM is believed to facilitate a more integrated design and construction process that results in lower costs and reduced project duration without compromising the quality of the project. Lean construction and BIM can be adopted independently in the construction industry, as illustrated by several cases in company practices in the past (Sacks et al., 2015).

BIM and lean have similarities in terms of the goal of their adoption: to bring collaboration into the project. BIM's implementation in the industry has developed several changes (Eastman et al., 2008) , some documented changes are as follows:

1. Increased engagement of construction knowledge and skill upstream in the design process;
2. Development of detailed design earlier than has been common with traditional systems;
3. Collocated teams.
4. Contractual arrangements to share pain and gain; and
5. Introduction of new roles, such as BIM managers or consultants.

Researchers identified principles of BIM adoption that are relevant to lean construction (Sacks, Radosavljevic, et al., 2010):

1. To reduce variability, which is achieved by getting the quality of work right the first time.
2. To reduce cycle times. Reduced cycle times can minimize variability.
3. To reduce batch sizes.
4. To increase flexibility, which is achieved through the use of multiskilled teams. This is done to anticipate changes during project execution.
5. To select an appropriate production control approach. In this study, pull systems and production leveling are considered the appropriate production control approach (Sacks, Koskela, et al., 2010).

Several studies have explored the advantages of incorporating Building Information Modeling (BIM) within a Computer Supported Collaborative Work approach. One study identified three notable areas of progress related to the implementation of BIM. (Waly & Thabet, 2003). The first area of development involves the utilization of a black-box system, in which scheduling decisions are pre-programmed into the system. This approach relies on the system to automatically generate scheduling decisions based on predefined rules and algorithms. The second area focuses on the decision-making process without direct assistance from the program. Here, users have more flexibility and autonomy in making scheduling decisions, as they are not bound by predetermined rules or algorithms. Finally, the third area represents a combination of the previous two approaches. It involves leveraging the capabilities of the system to support decision-making while still allowing users to make manual adjustments and override system-generated recommendations when necessary. These three areas of development in BIM implementation within the context of Computer Supported Collaborative Work highlight different approaches to incorporating decision-making processes and system assistance, providing flexibility and adaptability to suit various project requirements and user preferences.

The benefits of BIM and 4D model integration into construction projects have been well studied. One such study was conducted by (Tallgren et al., 2015) in which the researchers provided validation for the system proposed by Waly and Thalbet (2003). A three-stage approach was used in the research. The first stage serves as a collaborative platform for each trade. In this stage, a ***main view*** is used to visualize the building structures. Every element is color-coded based on the trade who is responsible for it. The main view will serve as a walkthrough for the zones. In the second stage, each individual begins work according to discipline. This stage utilizes the planning view which displays relevant information for the trades, displayed on an individual screen for each trade. The third stage marks the collaboration effort to build the schedule. Each trade will propose the schedule they developed for their activities. Changes in the schedule would be reflected in the main view.

Implementation of BIM in the **lean process** has been proposed by scholars in the past (Eldeep et al., 2022)**.** Past studies indicated that the addition of visual aids improves the participants' understanding of the construction work in the planning process. In addition, the use of 4D models enables the team to incorporate constraints into the model, thus furthering the effectiveness of the coordination (Toledo et al., 2014) .

2.3 Collaboration Practice in Construction Industry

Construction frequently requires the team to conduct collaborative tasks, one of them is the decision-making process. This process is inherent in the pull planning phase of construction. In the pull planning process, two mediums are involved: the lean media (charts, notes) and rich media (face-to-face communication).

In response to the growing emphasis on collaborative planning and execution within the industry, novel methodologies are necessary to accommodate this demand. Traditional project practices often involve participants sharing their knowledge through static, paper-based graphical representations. However, this approach imposes limitations on their capacity to collectively solve problems.

Relying solely on paper-based information restricts participants' ability to assess and forecast the construction work performance. The inherent nature of paper-based documents necessitates participants to rely on their imagination to interpret and understand the presented information. Consequently, the static nature of paper-based documentation hampers the dynamic evaluation and interactive exploration that are crucial for effective problem-solving in a collaborative setting (Liston et al., 2001).

The advancements in communication and information technologies have significantly expanded the possibilities for interpersonal communication (Brusilovsky et al., 2007). These technologies also introduce an additional layer of interactivity. In traditional communication, information typically flows between the communicating parties, and the interaction with technology serves as a facilitator to aid in understanding the shared information.

As technology continues to advance, visualization plays a crucial role in enhancing people's comprehension of ideas. This notion of achieving shared understanding through a specific medium is known as the media synchronicity theory. Visualization, as one form of media, can support synchronicity to varying degrees (Münzer and Holmer, 2009).

In pull planning sessions, despite the interactive nature of information sharing, participants primarily rely on sticky notes to exchange key information. This includes updates on their own work schedule, work status, and any challenges they encounter. The information gathered during pull planning sessions is then consolidated into a list of activities, which is used to formulate the weekly work plan.

One challenge in collaborative construction projects is the disparity in knowledge among team members. Without an effective means of communication, there is a risk of knowledge gaps emerging, leading to various issues during project execution.

2.4 Media Synchronicity Theory and Shared Understanding

It is important to identify the underlying theory in project participants' communication, especially during a pull planning phase. In a pull planning session, transfer of knowledge is facilitated in two media: lean and rich. Sticky notes and other project documents become the main sources of lean media, whereas the face-to-face communication between project stakeholders represents the rich media. The media used in the communication between stakeholders are deemed necessary to achieve shared understanding. In this perspective, stakeholders who achieved the same understanding of the work to be accomplished tend to believe in their collective capability. This would facilitate them in putting more effort to accomplish the goal, which in turn improve the team's performance (Aubé et al., 2015).

When a conflict occurs in a pull planning session, stakeholders would need to compromise. This conflict occurs because everyone has individual agendas despite having aligned goals. Media synchronicity focuses more on the cooperative aspects of collaboration, but a study challenged that the theory was insufficient in explaining non-cooperative actions (Windeler & Harrison, 2018) **.** The study disagreed with the idea that goals are completely congruent during communication. According to the authors, non-cooperative actions do not assume that a mutually common goal exists between participants.

In another study using the media synchronicity concept revealed that the important thing about achieving shared understanding is the integration of information into the process (Münzer & Holmer, 2009). The term |Shared Understanding" is comprised of two words. "Shared" encompasses various dimensions like similarity, consensus, consistency, and overlap (Mohammed et al., 2010). Meanwhile, the "Understanding" refers to the ability to effectively utilize knowledge to achieve cognitive and behavioral objectives. This might be caused by incoherency in communication. When groups deviate from the shared cognitive activity, the integrative communication processes are interrupted. However, the study argued that media choices do not have direct connection to this issue. The study discovered that media directly effects specific tasks or communication processes (Münzer & Holmer, 2009).

2.5 Virtual Reality as a Visualization Tool

2.5.1 Immersive and non-Immersive VR

Virtual reality is about perception. It could raise issues of psychological, philosophical, and cognitive origins. There are two different views of human-computer interaction (HCI) and VR research, “data-oriented” and “constructivist” views (Coyne, 1994). Data-oriented views assume that VR can be immersive by increasing the quantity and quality of data stream to the human sensory organs. On the contrary, “constructivist” views believe that VR immersion can be achieved with less input, as long as the user is engaged in the process of “constructing” reality.

In their book entitled The Production of Reality (Frleigh et al., 2016), the authors adopt a symbolic interactionist perspective to explore how human interaction and communication contribute to the construction and negotiation of reality. Virtual reality (VR) serves as a perfect example of this concept, as it immerses users in a 3-dimensional digital world, providing spatial understanding and interactive freedom with the environment. Given that VR's reality relies on symbol transmission within its interactive context, symbolic interaction proves to be a valuable framework for its analysis. Supporting this idea, anecdotal evidence from participants in text-based VR environments like MUDs and MOOs reinforces the constructivist approach.

2.5.2 Research of Virtual Reality for the AEC Industry

Virtual reality is a technology that immerses users in a digital 3-dimensional world, providing them with a spatial understanding and a certain level of freedom to interact with the environment. In the architecture, engineering, and construction (AEC) industry, studies have shown the benefits of virtual reality, particularly in helping individuals make more informed judgments about 3D models. These perceived advantages have motivated researchers to focus on developing workflows that incorporate virtual reality into construction projects.

A study conducted in the United Kingdom examined the potential application of virtual reality (VR) in collaborative scheduling processes. The research highlighted various uses of VR in construction projects, including site operations, office automation, design phases, and specialized areas (Bridgewater et al., 1994). In this study, the VR system is called the master Project Coordinating Program (MPCP). The development team utilized a home computer with the capacity to provide stereo images displayed through a head-mounted display. Head tracking was facilitated using a magnetic tracking system comprising three mutually orthogonal coils. To integrate the virtual reality system, it was added as another client to the existing MPCP infrastructure, and the 3D model was read into the VR world database. This integration allowed users to navigate through the CAD model of the building with the assistance of the VR system via the head-mounted display.

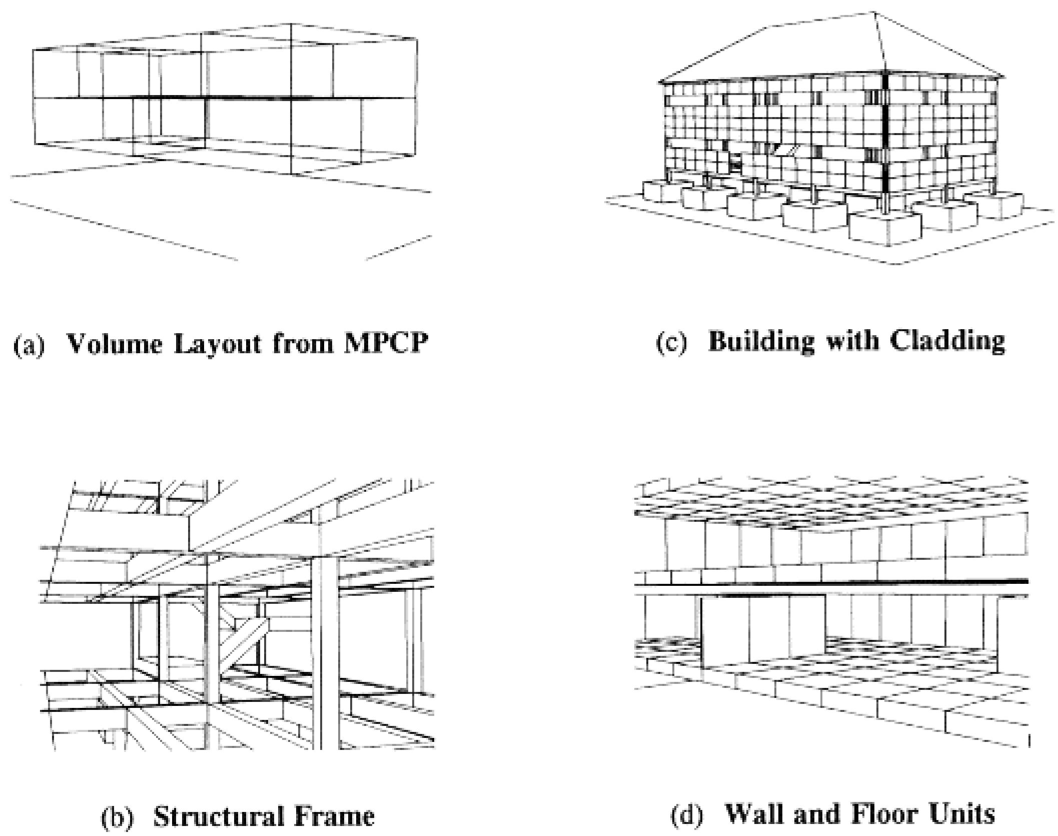

Figure 2-1 Sample Outputs from the MPCP System

Over the years, the VR hardware development has progressed to the point that it has been possible to deploy a system using components that are available for consumer market. Manufacturer has developed devices that can be relatively easy to set up. Moreover, tools are becoming more accessible to the public, that makes it easier to develop a VR tool for construction. This progress has allowed more research to be conducted on other aspects of construction, such as researching the impact of visualizing a construction sequence in an immersive environment. In the study, industry professionals and students were studied when they were wearing a VR device to investigate the construction schedule. It was found that the VR intervention could improve the users' ability to perceive errors or omissions on the interior portion of the building (Pratama & Dossick, 2018).

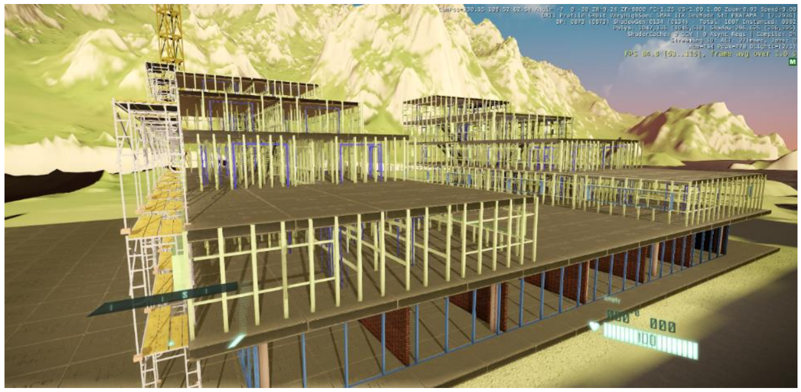

Figure 2-2 Sample output from VR-4D Prototype

There are many variations of VR devices that are available. Some VR will put the users in front of a large screen, while others allow users to use a personalized head mounted display to be immersed. For example, a CAVE system requires a large footprint, but its users do not have to wear a specific display to interact with it. It also supports multiple users in one session. Mass adoption of VR devices, however, relies more on the tethered and VR devices as they are more affordable than a CAVE system (Pratama, 2015a). The different degrees of VR devices, along with their description are listed in the table below.

Table 2-1 Virtual Reality Types

VR Type	Display Type	Features
CAVE	Large Screen	- Requires a desktop computer. - Requires a large footprint
Tethered VR	A Head Mounted Display tethered to a computer	- Requires a desktop computer - Tracking is more precise - Capable in complex visualization if the computer can run it. - Can be paired with other types of devices - Can only have one VR device per-computer - Mass deployment of devices can be cost prohibitive
Stand-Alone VR	A stand-alone Head mounted Display	- Can be easily transported to different places - The cost of ownership is relatively more affordable than the other VR types - Relatively easier to mass deploy the devices compared to tethered VR - Significantly less powerful than the other VR types

2.5.3 Virtual Reality as a Medium for Shared Understanding

An efficient construction project requires all stakeholders to gain a good grasp of the project's workflow. It is important that each team member communicates their intention as clearly as possible in order to avoid errors and omissions in the project. Therefore, a shared understanding is an important element that must be acquired by the team. Awareness of shared understanding could potentially create a simulating and encouraging effect between team members, which may lead to a better performance (Aubé et al., 2015).

The Virtual Reality technology wraps its user in a virtual environment. This environment can be tailored to the needs of its user, allowing them to interact in a meaningful way with the object in the virtual world. Unlike a conventional computer display which is operated by traditional input like mouse and keyboard, with a specifically developed interface users can intuitively manipulate objects in VR. In a construction project, the benefit of enhanced accessibility is expected to help different trades gain better understanding of the project to put them in the same perspective. Despite the supposed benefit, the true benefit of VR in an industry setting still needs more development (Wolfartsberger et al., 2018).

2.6 Utilizing Virtual Reality to Assist a Lean Construction Management Process

In lean construction management, the pull planning approach puts emphasis on the readiness of the crew and resources at the time the commitment is made. In a construction project, this requires a through planning by the crew to make sure that every issue that might delay the work is delayed. This planning involves considering various factors such as locations, schedules, material availability, anticipated production rates, and the potential for congestion in available areas. (Ghanem et al., 2022b).

Despite the considerable amount of planning that needs to be made to ensure the commitments are executed, there has been little literature that studies what kind of tools are used to help the pull planning process. Studies indicated that in a typical stakeholder meeting there are various documents that are utilized, especially the digital ones (Neff et al., 2010). Further studies are needed on which documents can be utilized for pull planning and what aspects of pull planning are affected by them.

As a tool that immerses the users in a virtual environment, Virtual Reality devices can help people to gaining better understanding of the spaces they will be working on. The need of further studies on how the Virtual Reality medium can be used in pull planning presents a gap in current research and a potential opportunity to use it as a visual aid to help construction project crews in planning their commitments and communicating them to other crew members.

2.7 Summary of Literature Review

The literature review indicated that pull planning, a lean project management approach, can significantly enhance project performance when implemented with the right tools. While sticky notes have been recognized as a common tool for pull planning, construction project teams have also been utilizing other tools to facilitate collaborative decision-making. These tools typically enable visualization of building models in either 2D or 3D formats, but it remains unclear to what extent they are or could be employed during pull planning sessions.

In addition to pull planning, lean practices often involve the integration of Building Information Modeling (BIM) processes. While BIM is more of a process than a singular tool, several supportive tools such as Visual Management and Value Stream Mapping are known to aid the pull planning process by leveraging the visual aspects of BIM, such as construction drawings and sticky notes (Aslam et al., 2020). These tools enable teams to identify potential issues and collaboratively develop solutions.

Moreover, various studies and industry practices have explored the use of Virtual Reality (VR) technology to visualize 3D models in construction projects. VR, represented through immersive displays, allows users to interact intuitively with virtual objects within the environment. This technology has proven useful in improving safety and reducing project costs through virtual mockups.

However, it is essential to note that while Virtual Reality technology provides a means to represent and interact with virtual objects, these objects must first be developed using other modeling tools. For construction projects, the primary source for building models is typically a 3D BIM model developed on Revit, supplemented by other objects developed in different modeling tools. Fortunately, tools are available to facilitate the conversion and updating of the Revit model into VR, thereby expediting the process to reflect the latest changes.

With the availability of tools to update models, it becomes feasible to employ this process for model review during the project execution phase. One particular area that stands to benefit from this approach is the pull planning sessions, where trades can now access and examine the most up-to-date version of the building model. This real-time access to the latest model allows for more informed decision-making and collaboration among the project team during pull planning sessions.

This situation presents an excellent opportunity to explore the utility of VR technology as a visual aid tool for pull planning sessions in construction projects. While existing studies have examined the use of VR for design review, only a few have delved into its application in the construction industry, particularly in the context of pull planning sessions.

Moreover, this also provides a chance to assess how the latest consumer-grade VR technology can effectively support the construction workflow. Previous versions of VR technology often required hardware that was either not very portable or unable to support a multi-user environment. However, with advancements in consumer-grade VR technology, there is potential for more accessible and collaborative use during pull planning sessions and other construction-related activities. By conducting further research in this area, we can better understand the benefits and challenges of implementing VR as a valuable tool in the construction industry.

2.8 Research Questions

The study will be conducted to answer several questions regarding the applicability of visual intervention in pull planning sessions:

1. How can implementation of VR encourage collaboration in a pull planning session?
2. How do several visual aid types, VR or non-VR, support participant’s ability to share their knowledge in order to solve problems in developing a schedule?
3. How does different background of knowledge impact the utilizations of VR?

Chapter 3 – Research Methodology

3.1 Background and Significance

Pull planning is employed by construction project teams to ensure that their crews can deliver the work based on the commitments they have made. Generally, the pull planning process consists of communications between people within the same trade, across different trades, and the moderator who facilitates the sessions. It is an intensive communication process as everyone must ensure that there are no unforeseen constraints that could potentially cause delays in the work they have already committed to completing.

Literature reviews suggest that this communication process is accompanied by tools such as digital tools (3D models in Revit/Navisworks or P6/MS Project schedule) or physical (drawings, sticky notes) that potentially aid the decision-making process. These tools utilize the visual aspect of communication, which also bridges the knowledge gap between different trades. With the many forms of visualization tools, there are several tools that are relatively new and are still being studied (Aslam et al., 2020) . Previous studies have investigated the various benefits of immersive visualization technologies in helping identify potential problems in construction projects.

Incorporating immersive visualization as an accessible tool during pull planning is anticipated to yield advantages and contribute valuable insights to the existing knowledge. As there is limited literature exploring this subject, there are few established "best practices" for utilizing this technology. Therefore, this study aims to investigate the application of immersive visualization and the benefits it can bring to pull planning sessions.

3.2 Research Approach

This research was conducted using interview and experimental approaches. There are three major phases in this research. Each phase was conducted after the previous one, forming a timeline that was quite linear. However, during the experiment phase there were several studies that occurred at the same time. These approaches were taken to ensure that the research questions were answered within the time constraints. Most of this research was focused on tool development and user research since the research tool had to be developed from the ground up. A detailed flow of the study is demonstrated in Figure 3-1

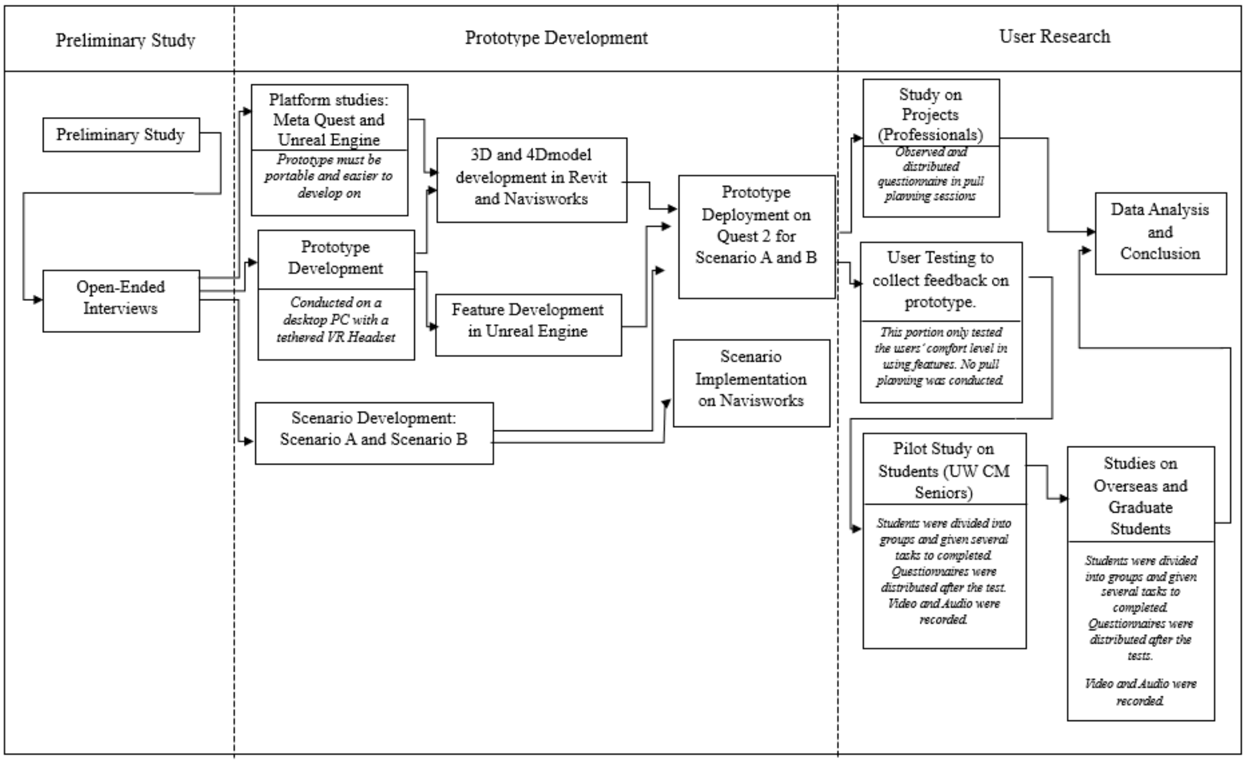

Figure 3-1 Overview of Research Workflow

3.3 Research Phases

3.3.1 Exploring Industry Implementations of Pull Planning

To get a better understanding of pull planning practices and explore the feasibility of integrating VR intervention into pull plan sessions, a series of interviews were conducted with various architecture, engineering, and construction (AEC) professionals. These professionals were selected from different general contractors in the Puget Sound region who had prior experience with pull planning implementation in their projects. While this phase could have benefited from using a questionnaire approach, open-ended interviews would provide more insight in this exploratory research. The researcher also cross-referenced this interview results during the pull planning observation with construction professionals so that the external validity of the study can be confirmed. This approach was taken since the number of responses were too small to generalize, so the study had to ensure the external validity (Cobern & Adams, 2020)

The interviews aimed to gather insights on the professionals' experiences with pull planning and to identify their perspectives on incorporating VR technology as an intervention. Additionally, the interview questions were designed to uncover the additional tools and resources utilized by the AEC professionals during pull plan sessions. This information would serve as valuable input for determining the essential features to be integrated into the prototype.

Several invitations were sent to AEC professionals and four responded with their agreement for interview. The professionals' construction experiences range from one year to more than ten years and all of them have been involved in pull planning and BIM processes. The participants were mostly project engineers, but some participants have been in different roles throughout their careers.

3.3.2 Prototype Development

Table 3-1 Devices and Software Used in the Study

Function	Platform Names
3D model Development	Revit
4D Simulation	Navisworks Manage
Software/tool used to develop the prototype	Unreal Engine 4.27
Prototype Deployment	Meta Quest 2
Audio Recording Devices	Microphone and Voice Recorder
Video Recording Devices	Mirrorless and 360 cameras
Pull Planning Board	Miro

Several virtual reality (VR) platforms have emerged to facilitate 3D model navigation and collaboration in the architecture, engineering, and construction (AEC) industry. However, these platforms often necessitate supplementary subscription fees, even for basic functionalities. These platforms are accessible for both tethered VR and standalone VR experiences but require an additional fee for accommodating extra participants.

Virtual Reality technology has advanced significantly in recent years, offering both tethered options that require connection to a desktop PC and standalone headsets that operate independently. Considering that a pull planning session involves multiple trades, the investigator opted for standalone VR headsets. These headsets do not need a connection to a desktop PC, making them a more economically viable choice for the team. Additionally, using standalone headsets significantly reduced the setup time required to prepare the VR platform, as the team only needed to bring the VR headsets. This streamlined the logistics of transporting the VR headsets from one location to another. To mitigate the need for paid platforms, a prototype was created using Unreal Engine. This decision was made due to the prototype's ability to be tailored with specific features required for the study. Furthermore, the prototype holds the potential for further development and utilization in diverse applications, as the researcher retains the original source code used for its development.

The study ultimately used Meta Quest 2 and Unreal Engine 4 as seen on table 3-1 as the primary platform for prototype development. The prototype implemented models developed in Revit and Navisworks for the participants to view and interact with.

3.3.3 User Research

A series of user tests were conducted during the experimental phases to explore the functionality of its features. The purpose of the user testing phase was to identify any bugs and gather feedback from the participants to make improvements to the prototype.

Table 3-2 Study Groups

Group Name	Participants	# Of participants
Professionals	Project Engineers, Superintendents, Labors	10-40 (8 volunteered to be interviewed and participate in the questionnaire)
User Testers	University of Washington's students	4
Pilot Studies	Senior Construction Management students	22
Overseas	Fourth year students of Construction Management lab at Andalas University	10
Graduate Students	Construction Management Master Students at University of Washington	6 (4 volunteered in interview and questionnaire)

The user population was not limited to individuals with construction experience. Instead, several students from various departments at the University of Washington and Andalas University in Indonesia were recruited to participate in the study. A total of 42 students participated across the different studies as demonstrated in Table 3-2.

During the user testing, participants were given a series of simpler tasks to assess their comfort level in accessing the features and their satisfaction with the building model's representation in Virtual Reality. After receiving feedback, the principal investigator made changes to the prototype based on the participants' suggestions.

In the user research phase, concurrent studies were conducted on an ongoing project and a mock-up scenario. The 3D models used in the study, involving professionals from various trades, were obtained with permission from the general contractor. However, for student testing, a less complicated mock-up scenario was used, which the students were expected to solve during the study.

3.4 Experimental Design

3.4.1 Tools

a. Autodesk Navisworks

Navisworks is a part of Autodesk software suite that facilitates the creation of a 4D model. This is the primary visualization tool that the participants in the control group were given access to. With this tool, the participants were able to inspect the building’s 3D model, play construction sequences, and plan what kind of commitments they could come up with during the pull plan session. This visualization tool was mainly used for the student experiments.

b. Digital Whiteboard

This experiment utilized a digital whiteboard in Miro that allowed participants to collaborate digitally. The digital whiteboard is browser based, so participants could use it from any computer and mobile devices they had access to. The digital whiteboard functions similarly to a real-life whiteboard. To participate, participants were assigned to a team on the digital whiteboard. On the digital whiteboard, participants could post a sticky note and the changes were be reflected on the shared board with everyone who were in the same team as them.

In addition to collaboration, the tool made it possible to record the screen during an experiment.

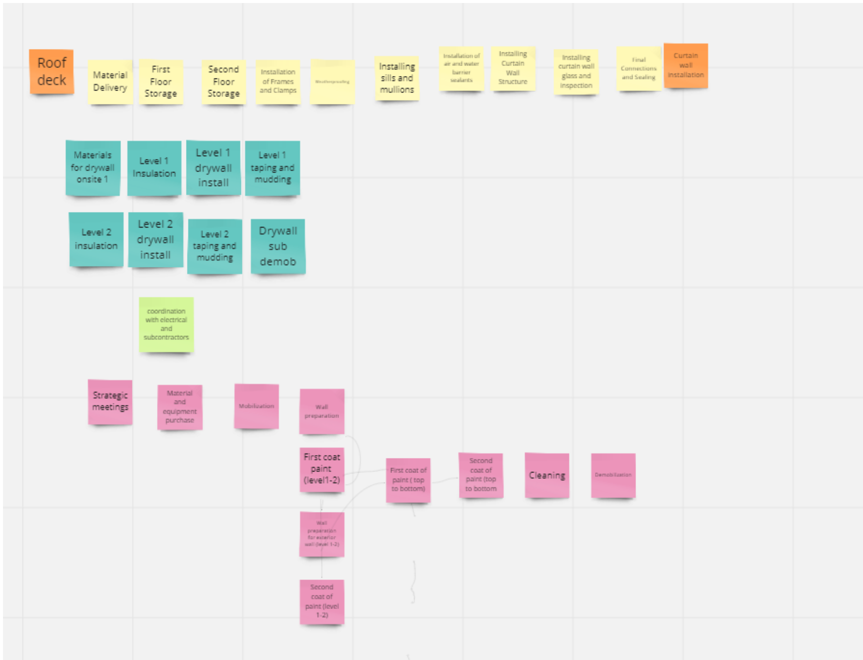

Figure 3-2 Digital Whiteboard for Pull Planning

c. VR Prototype

The meeting room was developed using Unreal Engine 4. It could support multiple participants at one session. In this meeting room, participants could inspect a 4D model and conduct a discussion.

In the room, a 3D model that was programmed to simulate the construction sequence was provided. The users were provided several functions to navigate through the model alone or with other users. Some features were developed to help with the model inspection such as section cut and markup tool. Several other functions were also planned, however due to time constraints they were not incorporated into the user research phase.

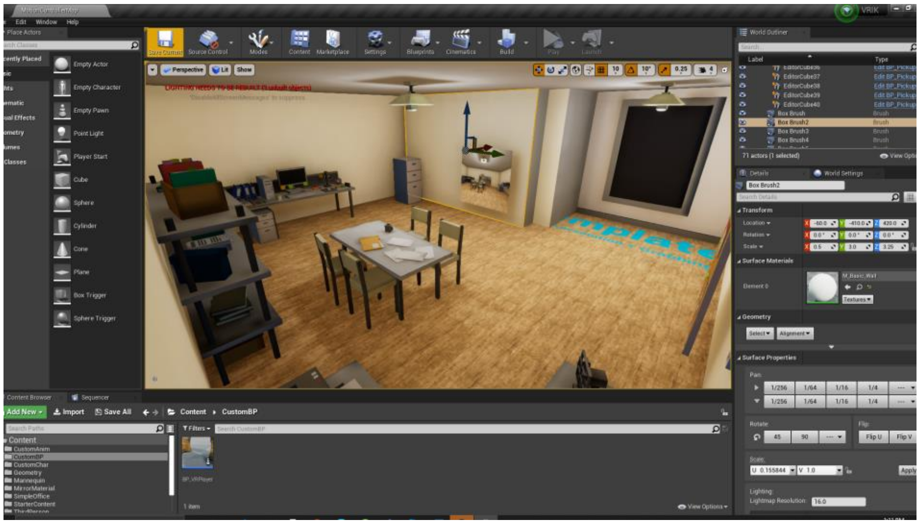

Figure 3-3 VR Prototype Designed in Unreal Engine 4

3.4.2 Study Populations

3.4.2.1 Industry Professionals

As shown in figure 3-1, a study was conducted at an ongoing construction project in Bellevue, Washington. The researcher conducted the study in several pull plan sessions and the study was conducted at the jobsite office meeting room, with several groups of trade contractors. Each meeting lasted for 2 hours as shown on Table 3-3.

Table 3-3 Pull Plan Meetings Time and Agenda at the Case Study Project

Meeting date	Meeting duration	Agenda
8/15/2022	2-hours	Tenant improvement works on amenity floor (2nd floor)
9/6/2022	1-hour	Three months lookahead for elevator shaft

Since putting the headset on and off took some time and would break the already established pull plan workflow, the participants were allowed to wear the VR headset any time they wanted to use it. In addition, a large screen with a mirrored view of one of the VR headsets was provided to the participants in the meeting room to allow those who didn't have access to the VR hardware to see the model together.

3.4.2.2 University Students

The test on university students were conducted in three phases, starting from the pilot studies that involved 22 seniors students, overseas with 10 participants, and graduate students with 6 participants. To facilitate the pull planning process for university students, several simplified scenarios were developed. Since most students had no prior experience with pull planning, the primary investigator acted as the moderator, answering questions, and providing information during the study. During the pull-planning sessions, student groups actively participated in a customized scenario focusing on a specific construction aspect involving multiple trades: drywall, curtain wall, and wall finishes/paint. There are several considerations in choosing this scenario:

1. Curtain walls are typically delivered to the site prior to them being installed.
2. The scenario is easier to follow to participants who are not familiar with MEP
3. The delivery of curtain wall material might impact other activities.

Each role within the group, consisting of three to five students, made commitments regarding their tasks using the pull method. They were then tasked with creating or updating a schedule based on these commitments.

Throughout a series of experiments, the student groups were presented with predetermined scenarios, and their performance was observed. The groups were divided into control and intervention groups, and the tests were structured into various categories, including pre-treatment and post-treatment segments.

The study incorporated virtual reality (VR) technology into the pull-planning process. The VR tool was designed to provide participants with a visual and interactive experience, allowing them to manipulate the model. Participants had control over the 4D model, which presented the project's schedule up to a specific stage.

In the control group, participants were permitted to use files or documents to assist with pull planning. The deployment of the 4D model in a traditional display utilized Navisworks, while a custom-made program in Unreal Engine 4 was used for model deployment in the virtual reality environment.

3.4.3 Video and Screen Recordings

Video and screen recordings were taken during the experiment phases with the subjects' permission. The video recordings were intended to help with identifying when interactions between the participants occurred. The video recordings were not used to identify the conversation types due to the nature of the pull plan sessions. In a typical session, discussions and conversations occurred at the same time. Therefore, it was difficult to identify individual conversations since they overlapped with others.

The video recordings were done with a 360 camera and screen recordings on both PC and tablet. The video recordings were mainly used to time the session durations and to observe what interactions occurred between participants. The screen recordings were mainly used to record the digital pull plan process. To achieve this, each team was provided with a table or a computer that had a screen recording tool installed.

In total, 408 minutes of footage and 197 minutes of conversation were recorded. The difference in the total duration of the recordings was due to the absence of audio recordings for the pilot studies.

3.4.4 Questionnaire

Questionnaires were distributed before and after the experiment sessions. The questionnaires are aimed to obtain feedback on the study as well as the users' opinions and difficulties that they encountered during the sessions.

The pre-experiment questionaire was distributed to ask the participants about their background, such as their experience in the construction industry, what roles have they been assigned to, and their knowledge about pull planning and VR.

Meanwhile, the post-experiment questionnaire was distributed to gather what aspects of the VR prototype helped them in the decision-making process, what problems they encountered with the VR prototype, and their suggestions for what aspects of the VR prototype that could be improved in the future.

3.5 Experiment Groups

3.5.1 Overview

In the usability study, a minimum number of five participants were recommended for qualitative study. The number of participants can be scaled up whenever necessary(Faulkner, 2003)Based on that notion, the research made a minimum threshold of 20 participants for the student research. In this study, 38 students participated in the pilot study, oversea, and graduate student studies. The number of participants is deemed sufficient. Meanwhile, 8 professionals volunteered to participate in the study.

3.5.2 Study Groups

3.5.2.1 Professional Group

Participants of the professional groups was a combination of various project participants in the Bellevue project. While the observation was conducted on two separate pull plan meetings over the Summer of 2022, eight professionals voluntarily participated in the study.

3.5.2.2 User Testing Group

This testing group was intended to only collect data and feedback on the features of the updated prototype. There were no specific requirements for eligibility since the participants did not need to participate in a simulated pull planning session.

3.5.2.3 Pilot Study Groups

The pilot study group was comprised of University of Washington' senior Construction Management students. Twenty-two students participated in the study over four separate sessions in November 2022. The purpose of this pilot study was to assess the collection methods as well as testing and getting feedback on the prototype.

3.5.2.4 Overseas Groups

The overseas group were recruited from Andalas University, West Sumatra. Ten students were recruited and participated in the study in December 2022. The overseas group went through both non-VR and VR assisted sessions. The team participants were randomized after each sessions.

3.5.2.5 Graduate Students Group

The graduate students group were comprised of University of Washington's Construction Management Master program students. Six students participated in the study and four volunteered to return the questionnaires. The structure of the study sessions were similar to the overseas group.

Chapter 4 – Professional Interviews on Common Practices and Visual Aids used in Pull Planning

4.1 Pull Planning Implementation in Construction Projects

Even though construction practices in general are similar, construction firms have different ways of managing the construction project depending on their culture. A construction schedule is primarily driven by the master schedule that was developed by the contractor. The contractor would then push that schedule into the various trades who are participating in a project. Meetings are conducted to ensure that all trades are on the same page. Even though certain trades could be the primary driver for the schedule, the overall scheduling workflow goes through the general contractor.

Multiple studies have indicated that productivity can be enhanced through collaborative endeavors among team members. Among various solutions to foster collaboration, pull planning stands out as a noteworthy approach. Its objective is to accomplish projects by optimizing resource utilization while maintaining product quality. This methodology places emphasis on reducing inventory and minimizing waste.

In contrast to conventional planning practices, pull planning involves engaging key stakeholders in the scheduling process. Team members actively participate by describing their respective tasks to determine their release to others. Once the tasks are clearly defined, team members collaboratively negotiate the sequence and interrelationships of these tasks, leading to the formation of a schedule network (Ballard & Howell, 2003b).

Ghosh et al (2017) study on pull planning process showed how different the pull planning practice compared to common planning practice/CPM. In the study, prime contractor used visual schedules instead of the conventional Bar Chart which is commonly used in CPM planning. Sticky notes are used as visual aid, whereas trades would put information such as activity names, durations, and logical relationships in the notes. The notes would then be placed on a whiteboard. By doing this, the trades could update their progress daily by marking up notes for their scope of work. Several additional visual aids were used by trades, such as denoting a check mark (v) for successful completion or an “x” for incompletion of work. For anything in between completion and incompletion, the trade would provide the percentage of completion in the note. Using this approach, the trades were also able to identify potential causes for delay such as lack of coordination. This indicates the importance of visual information in the planning process, even though traditional CPM charts are no longer needed (Ghosh et al., 2017b).

4.1 Investigating the Pull Planning Practices in the AEC Industry

It should be noted that the lean practice is adopted from the manufacturing industry, in which its goal is to mass produce a certain type of product. Unlike manufacturing, the result of a construction project is a building that is unique due to various factors beyond just the design of a building. Therefore, each construction project that applies the lean principle could have a different way of implementing it. To find out if there is a particular pattern of pull planning application in the AEC industry, a series of interviews were conducted with four construction professionals.

4.2 Various Visual Tools in the Pull Planning Process

Visual tools are important in helping stakeholders to understand the project's workflow.

1. Schedule visualizations

In conventional scheduling practices, project timelines are represented using Gantt Charts, created with scheduling software utilizing the Critical Path Method (CPM). This method allows planners to identify critical tasks that might potentially cause project delays. Typically, a scheduler or an experienced superintendent is responsible for developing the schedule.

In projects employing pull planning, scheduling is driven by the trades involved. During a pull planning session, sticky notes are utilized. Each trade briefly describes their activity on a sticky note, and then they collaboratively arrange these tasks on a whiteboard. This intuitive approach enables them to structure their workflow effectively and encourages direct feedback from all trades, enhancing the schedule's accuracy.

2. Drawings and 3D Models

Incorporating drawings into the scheduling process helps each trade visualize the physical space, allowing them to anticipate possible construction issues. Drawings often contain markups or descriptions of the space, objects, and components, providing valuable context to interpret the visual representation.

Furthermore, 3D models offer a three-dimensional understanding of the space, enabling the team to better grasp the layout while working on specific areas. With this information, they can devise a logistic plan that minimizes disruptions to other trades' work.

3. 4D Models

4D models go beyond presenting a static view of space at a particular moment; they also illustrate the changing space throughout the construction process. This dynamic visualization proves invaluable in anticipating clashes, trade parades, and other logistical issues. Moreover, available 4D visualization tools offer a clash detection feature that can be linked with the 4D model, allowing for time-based clash detection, further enhancing project coordination.

4.3 Interviews with Construction Professionals

To gain a better comprehension of existing pull planning practices, a set of four comprehensive interviews was conducted with general contractors who possess experience in lean projects. The outcomes of these interviews were subsequently utilized to formulate both the virtual reality (VR) prototype and the experimental scenarios for the forthcoming phase. A preliminary study was done by conducting interviews with professionals regarding issues they frequently faced during pull planning sessions. The results from these interviews served as a benchmark for the subsequent tests. During this phase, a set of interviews were distributed among industry professionals. The interviews were able to validate variables that were measured during the experiment phase.

Four professionals from different construction firms were interviewed between summer and fall of 2019. Professional (1) was a project engineer with a 1.5 year of experience, Professional (2) had more than 10 years of experience and has been involved in various responsibilities, including 6 years involvement in projects that utilized lean principles. Professional (3) had been working for more than 20 years in the industry and was a Vice President of Operations at the time of the interview. Lastly, Professional (4) was a scheduler at a local general contractor and had been involved for 14 years in several projects that utilized pull planning.

During this interview phase, it was identified that most of the subjects utilize some form of visual aid during the development of schedule. Traditional plans, whether digital or printed on paper are the most prominent form of visual aid because they are readily available.

Audio recordings were taken during some of the interviews with the permission of the interviewees. The recordings were stored anonymously and only linked to the related interviews. The recordings were used to support the notes taken during interview sessions.

The interview inquiries encompassed various aspects of pull planning, such as the frequency at which it is employed, the tools utilized throughout the process, and the key stakeholders typically involved in the sessions. Additionally, the interviews explored project performance by posing questions related to measuring progress and resolving conflicts within the designated area of interest.

4.4 Interview Structure

There were several questions asked that were meant to identify the common practices of pull planning, this included who participated in the process, conflict resolutions, performance indicator, and tools used to facilitate the process. The participants were expected to response based on their experience. If the participants believed that the questions were irrelevant or may cause them to provide sensitive information, they may choose to decline the questions.

The interviews were conducted in places that the participants were comfortable with. Most of the participants were content with meeting at their offices, although one preferred to meet at a public space.

4.5 Interview Findings

4.5.1 Challenges in Pull Planning

During an initial interview with a construction professional experienced in multiple lean construction projects, a notable challenge associated with pull planning emerged. The interviewees highlighted that the main issue stemmed from the participants' limited familiarity with the last planner system, which is utilized during planning sessions. Inexperienced participants often included irrelevant activities in the last planner system session, thereby complicating the development of an effective schedule.

The presence of activities introduced by inexperienced participants could be an issue for the team. The team required to filter through the extraneous information provided and distinguish it from the pertinent elements. This additional task of discerning and eliminating irrelevant input consumed valuable time and resources, making the schedule development process more arduous and less efficient.

4.5.2 Common Practices

4.1.1.1 Breaking Down the Sessions

All respondents had similar responses that during a pull planning session, the master schedule (CPM schedule) was not presented/shown to the participants. On its own, the master schedule is also not too helpful since the goal of a pull plan session is to brainstorm work for a specific portion of the project. While WBS provides information on the work, it does not show the sequence in a granular manner. According to Professional (4), even if the CPM had to be used, it would only be used outside of the pull plan to identify milestones or project baselines so delays can be mitigated.

A pull plan output is not a schedule, but a set of commitments. These commitments would be used as references by the project superintendent to develop their weekly work plan and lookahead plan. According to Participant (1), their team conducts pull plan sessions typically one month in advance of the upcoming work.

4.1.1.2 Attendance

Generally, the respondents had similar responses that only trades who are involved in the pull plan's scope would be participating in the session. For example, as noted by Professional (2), if the goal of the pull plan session is to plan work around finishes at a specific time, only the trade contractors whose work were affected would be participating in the session. To facilitate the session, a moderator would lead the process. The moderator is usually the superintendent or project engineer.

If one of the trades does not show up for the pull planning, they will be asked later if they can accommodate the schedule or the look ahead plan that was developed after the pull plan had been done.

4.1.1.3 Tools Used in Pull Plan

The respondents mentioned various tools were used to support the pull plan sessions. The most common tool was 2D drawings and blueprints since they are typically readily available and accessible through their project management platform. This document could be brought up on the shared screen and the session participants could resolve issues around the certain area presented in the drawings.

3D and 4D models were also mentioned by the professional respondents as tools that were used to assist the pull plan sessions. Participant (3) mentioned that usually the general contractor would be required to have a complete 3D model for the project, so it can be used for various purposes including to support the pull plan sessions in the project.

4.1.1.4 Performance Tracking

All but one respondent mentioned that Percent Plan Completed was used as their primary method to track the project. This can be done by directly asking the responsible trades for an update on their commitments they made in the previous pull plan session. The trades' responses were recorded in the contractor's system that would display the PPC value.

However, Professional (3) responded that their team did not rely on PPC as they found no value in it. According to them, what is important is whether the handoff is on-time or not. In that case, it is important for the general contractor to be clear on the trades' scope of work during the pull plan. Incomplete and delayed work will be regarded as incomplete and the trades must catch up with the lost time.

4.1.1.5 Impact on Durations and Work Sequences

All participants provided similar responses on how they expect the results of the pull planning process to have impact on the master schedule. According to them, having some leeway on the duration is acceptable so long as it is not affecting the critical paths. Professional (3) mentioned the trades were also expected to be forefront on whether they can make the commitment or not and they have to let the team know during the pull plan.

The professionals expected that problems would start mounting as the project progresses further, typically after more subcontractors got involved. Most professionals agreed that many of the problems are commonly related, but not limited to MEP activities. Safety and logistics issues are also frequently brough up in discussions.

4.6 Interview Summary

Based on the interview results, there were a few key areas that could be extracted from them:

1. The professionals seem to utilize readily available information or files/documents to help with the pull planning process. This information was mostly in the form of visualization (2D drawings or 3D models) that could either be printed or displayed on screen. In some cases, animations of the construction sequences were used as well.
2. In general, all key trades were expected to attend the pull plan, especially those whose work were directly related to the time frame of the pull plan's focus. Sometimes some trades might not make it to the meeting, usually due to their team having a schedule conflict. If that happens, they were expected to accommodate whatever the results of the pull plan are.

Problems/issues typically started to pile up once more trades had joined the project. This was attributed to the amount of work occurring on the jobsite that affects logistics such as personnel occupying certain area, materials or equipment storage area, or safety concerns such as certain work that require an area to be closed to other personnels for safety reasons.

Chapter 5 – Prototype Development

5.1 Overview of Development Timeline

The prototype development for this study started back in 2017 after the researcher picked up the original prototype that was developed in CryEngine 3. CryEngine used a node-based programming approach like Unreal Engine. CryEngine development was geared towards videogame as opposed Unreal Engine 4's more generalized use. The original prototype was a repurposed First-Person Shooter videogame template that did not have any support for Virtual Reality. The version of the CryEngine used for the previous was also no longer updated, making further development unsustainable.

Figure 5-1 CryeEngine-Based Prototype

The Unreal Engine was considered for the new prototype since its documentation and community support were widely available. Unreal Engine also had more compatibility with BIM tools such as Revit. Unreal Engine also had mobile devices development support, so the development of the prototype can be geared towards mobile VR devices. With those considerations, the researcher expected the new prototype would be able to provide features that were too difficult to implement using CryEngine.

Figure 5-2 Early Prototype Development in Unreal Engine

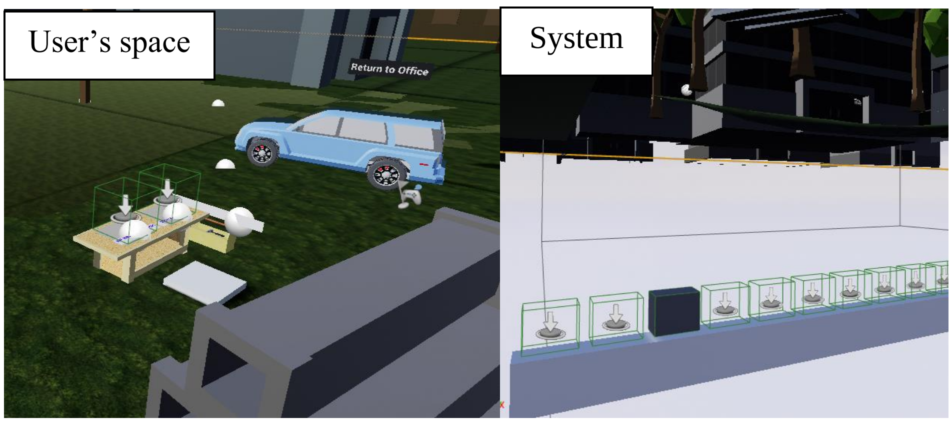

Figure 5-3 Unreal Engine-based Prototype using Old Logic

The development started from a basic tethered VR prototype that required a desktop/notebook PC developed based on the VR template that was developed in 2018. Like its CryEngine predecessor, it started as a construction sequence viewer with programming logic adapted straight of the CryEngine prototype. The CryEngine-based prototype logic utilized area triggers that would be activated if the control box overlaps with one of them. When activated, it would make several building geometries associated with the trigger to be shown on screen.

As the development progressed, more features and multi-user/online features were developed, and the development shifted to mobile VR devices. The latest construction sequence player logic was also updated to omit the need of triggers; it ran internally in the Blueprint system. There were some features that got into the development phase but were not implemented due to the incompatibility with the multi-user features. Certain features were also incompatible with the mobile VR hardware, causing visual glitches when activated. The researched canceled those features with the consideration of pursuing the development of those features would significantly impact the development time.

The prototype was continuously updated, and the development also incorporated feedback to improve the prototype's quality of life. The latest iteration of the prototype was used to test the overseas students and University of Washington graduate students in December 2022 and March 2023. It was deployed to several Meta Quest 2 devices, making the logistics of the prototype much easier and opened the possibility of running the experiment on multiple participants.

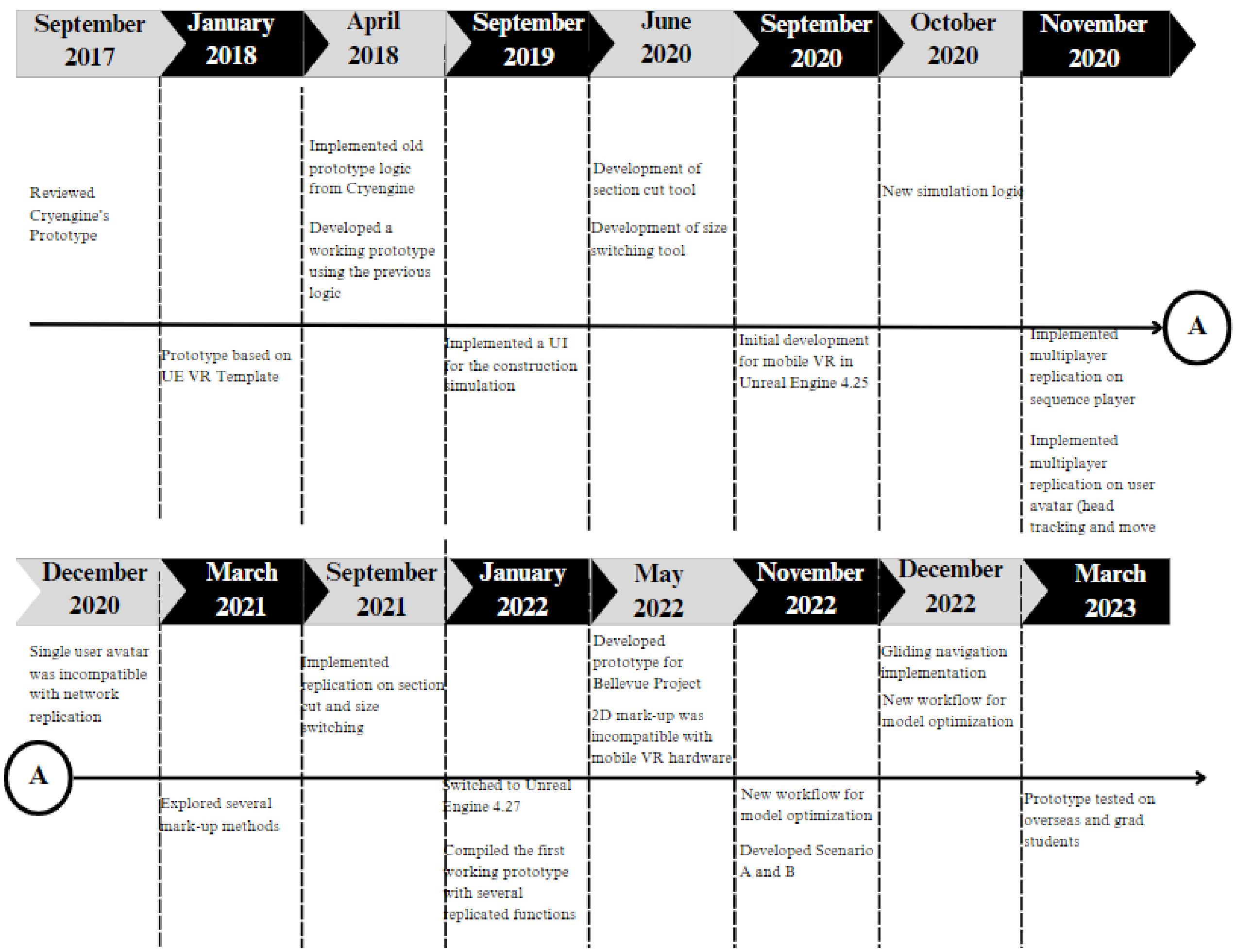

Figure 5-4 Prototype Development Timeline

5.2 VR Prototype from Prior Study

This project was developed based on prior research on VR implementation for 4D model review (Pratama, 2015b). The predecessor to this study used a prototype based on CryEngine 3 which was already obsolete by the time this study was initiated. In addition, the CryEngine-based prototype required additional drivers and hardware that were no longer supported by the current machine.

The old prototype can only ran on desktop, it couldn't run as a standalone program because it requires a system that has a CryEngine editor installed.

Figure 5-5: 3D Model Visualization in CryEngine based on prior research

Despite being obsolete the old protype served as proof of concept that it was possible to conduct a building walkthrough in VR using commercially available hardware. Users were able to review and investigate the design to identify any issues or problems that might arise during the project life cycle. Several features from the old prototype were rebuilt in the new prototype.

Figure 5-6 Tethered Virtual Reality Setup in Prior Research

5.3 Hardware and Software Considerations

Prior studies required VR hardware that was tethered to a desktop computer. This configuration limited the amount of people who could participate in a review session using VR since a multi-user setup would require both the VR and computer, which makes the setup also not financially viable for many projects. The tethered setup could not support multiple people in the same room due to the hardware limitations of some VR hardware.

With these considerations, the researchers decided that it was better to develop the new prototype on mobile Virtual Reality hardware. By the time this study was initiated, there had been several mobile VR devices released on the market at a relatively affordable price. The mobile devices could run the VR applications natively from the headset, they could also mirror the display on large screens without the need for tethered connectivity. Participants who did not have access to a VR device could still see the mirrored view and make decisions based on what they observed on screen. For this study, Meta Quest 2 was selected since it is widely available and provided hardware that was powerful enough to display 3D models extracted from Revit.

5.4 Prototype Features Development

Unreal Engine provided a visual scripting solution for programming object interactions called Blueprint. This study utilized the Blueprint system to program several functions such as player locomotion, UI interaction, and Networked Interaction. A summary of the implemented features can be found in table 5-1 as well as the features not implemented.

Table 5-1 Summary of Feature Implementation

Feature name	Function	Status	Note
Multi User	All interaction that one user made can be seen by others.	Implemented	
Interactive user interface	Allows users to control or manipulate the environment using virtual buttons	Implemented	
Head Tracking	Tracks users' head orientation in VR environment.	Implemented	Used in the testing phase
Locomotion: Teleport	Users move around by teleporting to mitigate motion sickness	Not implemented	Not used in the latest version
Locomotion: Gliding	Users move around by gliding	Implemented	Used in the testing phase
3D Mark-Up	Adds mark-up or notes to the 3D environment	Implemented	Used in the testing phase
Schedule Visualization	Visualization of the construction sequence like a 4D model	Implemented	Used in the testing phase
Switching Scale	Change building size	Implemented	Used in the testing phase
Section Cut	Make a section cut of the building	Implemented but faulty	Section box did not move occassionally
2D Mark-up	Allows users to write on 2D surface/texture. If implemented, it could have been used for a fully VR pull planning.	Not implemented	Method incompatible with mobile VR device
Player Avatar	Allows users to identify each other in the VR environment with personalized appearance	Not implemented	Incompatibility with multi-user setting
Server-based multiuser	Allows the tools to be used remotely without everyone needing to be in the same network.	Not implemented	Insufficient resource and development time

5.4.1 Player movement/locomotion in VR

Unreal Engine provided a VR script template that allowed developers to apply locomotion into their VR applications with minimum effort. The template included headset head-tracking, controller tracking, as well as several interactions such as grabbing objects, teleportation approach for locomotion, and modelled virtual hands that were linked to the VR controllers.

However, the template did not include UI interaction, multi-user interaction, usable user interface, or alternative locomotion approach. This motivated the researcher into developing a custom VR blueprint that adds the aforementioned missing features.

For the initial prototype, joystick locomotion was implemented as its locomotion approach. The use of VR joystick would move the user to the direction it was pressed. Meanwhile, turning was done by looking at the direction that the user would like to move. The blueprint also made it possible for the programmer to specify the movement speed.

Joystick movement was chosen over teleportation for several reasons:

- The locomotion was smoother so people should be relatively comfortable using it while being seated, which is what to be expected during pull planning meetings.
- VR Template’s teleportation method contained several bugs that would make people get disoriented after each teleportation.
- The custom movement blueprint was easier to program for multi-user environment.

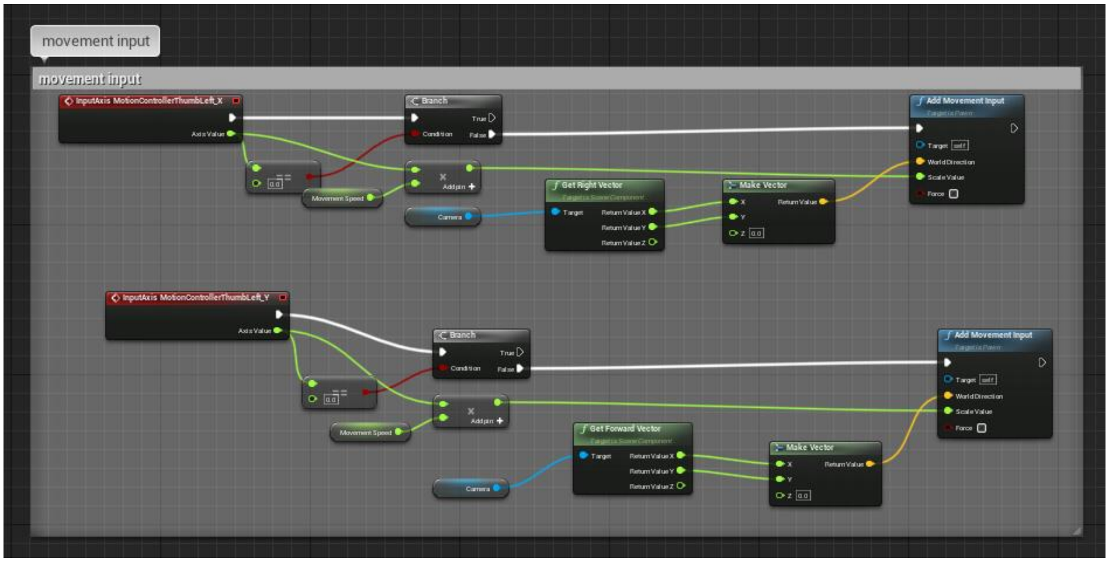

Figure 5-7 Movement control in the custom Blueprint system

5.4.2 VR controller tracking

Because of developing custom Blueprint, everything related to head tracking and VR controller had to be redeveloped. While it was possible to use the VR blueprint template for this part, the template itself was more complicated that made it difficult to apply on a multiuser environment. The study instead developed a more simplified approach that tracks the 3-dimensional position of the physical VR headset and controllers as demonstrated in Figure 5-8: VR headset tracking and Figure 5-9: Hand Tracking script

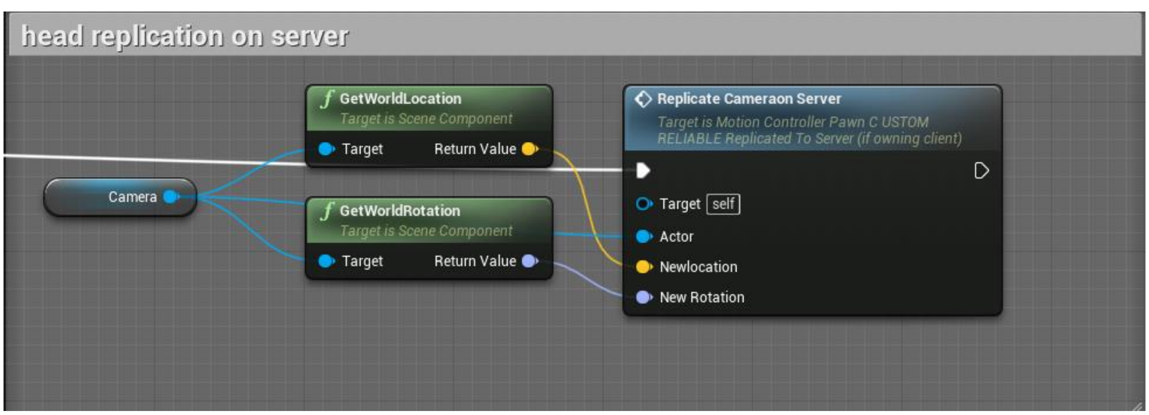

Figure 5-8: VR headset tracking

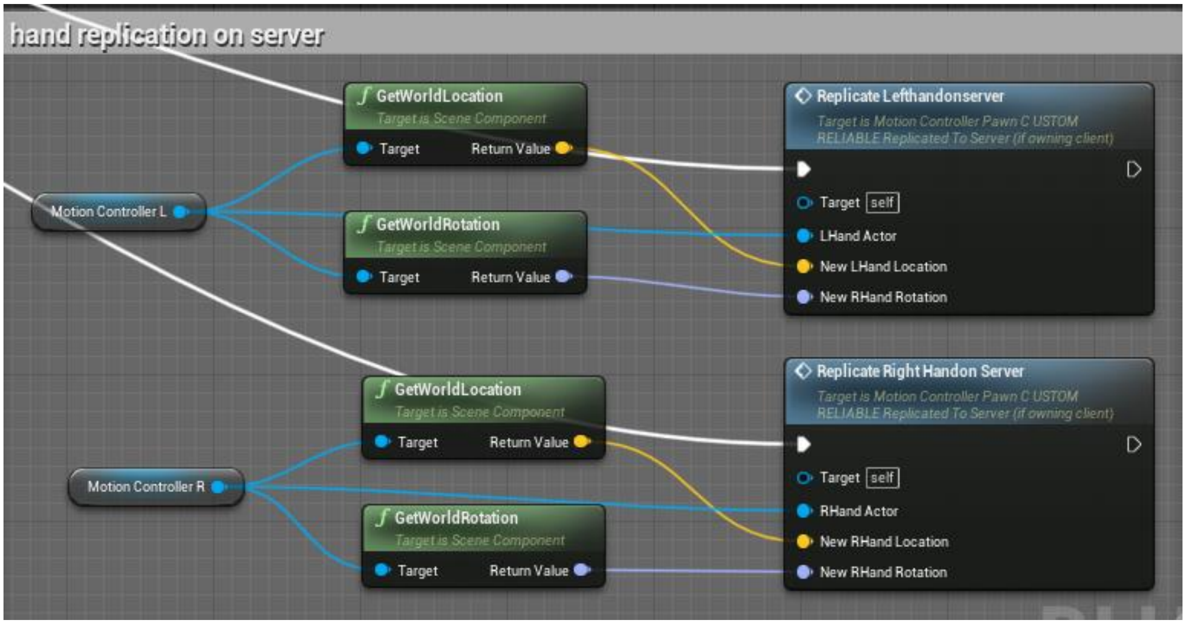

Figure 5-9: Hand Tracking script

5.5 User Interface

5.5.1 Interaction Input

As a proof of concept, the user interface that was developed for this study contained several basic functions such as changing model's scale, creating/joining a multi-user session, and playing/rewinding the schedule.

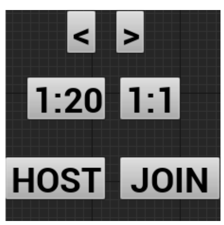

Figure 5-10: Initial Prototype for the User Interface Buttons

To interact with the user interface, the VR blueprint was programmed with appropriate script. In this prototype, interaction was done by pressing a button on the VR controller while pointing at the button on the virtual user interface. When the VR controller button was pressed, the application considered it as an interaction input. If the VR controller component happened to overlap with the button user interface, the interaction that was programmed into the button would occur.

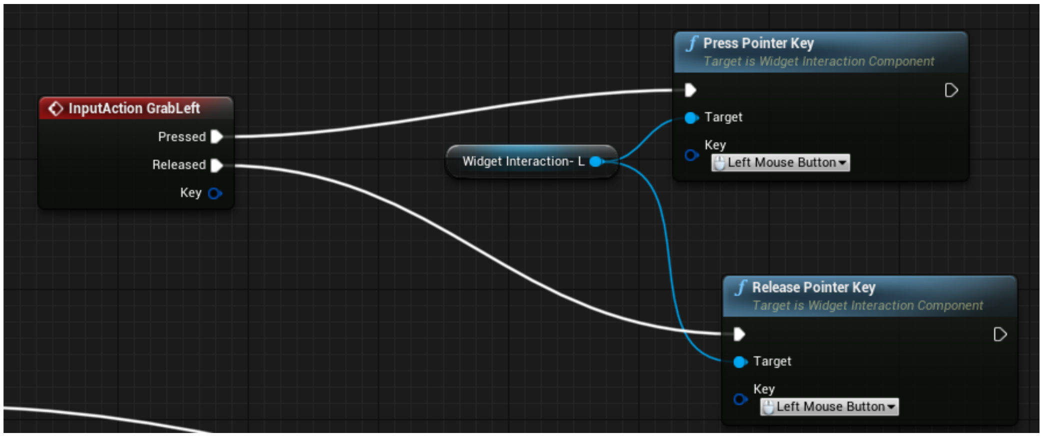

Figure 5-11: Blueprint Script for Hand Interaction with User Interface

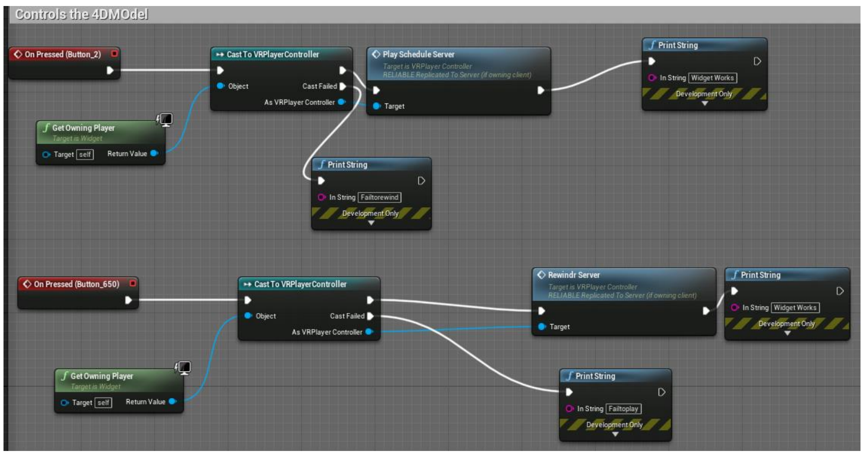

Figure 5-12 Controls for Construction Schedule Visualization

5.5.2 Multi-User System

For the multi-user system, the development decided to include a host and join buttons on the user interface. Using this system, one device would act as a host, while other systems would connect to the host as clients. During the experiment, the moderator's system was designated as the host of the session.

5.6 Conversion Process

The initial model used as the basis for development was from a Revit Example project used in CM 414: Virtual Construction course. In the source model, a schedule was developed using Microsoft project and assigned to each geometry in Autodesk Naviswork Manage.

Epic's plugin named Datasmith was used to convert 3D models into Unreal Engine - compatible models. The plugin allows for conversion of a whole project as a unified object or smaller geometries based on the model hierarchy in the source file.

In the development of the initial prototype, it was decided that the model was broken into smaller geometries based on the trades. By doing this, it allows for the development to greater flexibility during the programming process.

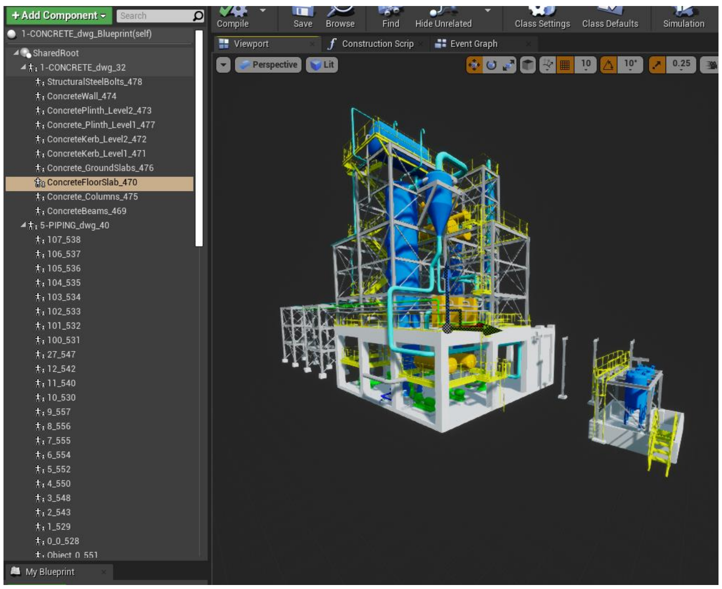

Figure 5-13 Unreal Engine 4 Model After Converted into a Blueprint

Datasmith's geometry merging feature helped in streamlining the construction sequence development, especially when working on the contractor's 3D models. On the contractor's project, the files were grouped by the trades. Each trade model contains smaller groups comprised of smaller geometries. For example, the project's fireproofing model was comprised of the geometry groups for fire sprinkler and its pipe layout. If the models were not merged, there would be too many fire sprinkler and pipe geometries to work with. The Navisworks plugin could identify the hierarchy level of the fire sprinkler geometries and merged them into one geometry.

In addition to the model being broken down by trades, certain trade models were also grouped by the floor numbers as shown in figure 5-11. This file structure helped the conversion process significantly since the standalone VR headset would not be powerful enough to visualize the whole building, including the structure, architecture, and its system elements.

On the ongoing project, several VR prototypes had to be compiled separately into different versions, each version represented which floor numbers were visualized in the VR environment. The student versions of the prototype didn't go through this process since the model was simplified enough that the VR devices were able to show the complete model in just one application.

Figure 5-14 Unreal Engine Visualization Based on BIM Geometries obtained from an Ongoing Project

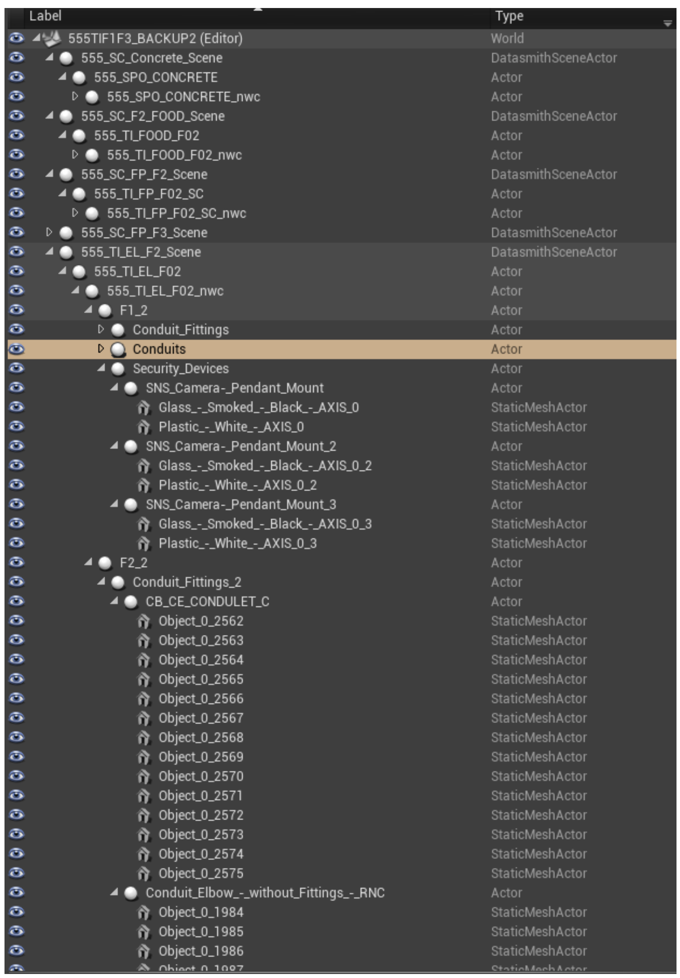

Figure 5-15 Object Hierarchy After Unreal Engine Translation

5.7 Features Development

5.7.1 Locomotion: Teleport vs Sliding Animation

Teleportation-based navigation was widely favored due to the prevailing consensus among virtual reality (VR) users and developers that it held the potential to mitigate motion sickness. The default locomotion mode offered by Unreal Engine's VR template already included this teleportation functionality as a pre-configured option. Nevertheless, individuals lacking familiarity with this specific navigation approach often experienced a state of disorientation. The abrupt shift in perspective and varying distances from the user's focal point were considerably more disorienting than a smooth, continuous transition of viewpoints. Moreover, the incorporation of viewpoint rotation in certain teleportation methods, such as the one utilized by Unreal Engine, could further amplify the sensation of disorientation.(Prithul et al., 2021)

Several solutions have been proposed to mitigate the disorientation effect. However, due to time constraints associated with further development and testing, it was decided that the research would not utilize this locomotion method. Instead, the focus would be on floating locomotion. This decision was based on multiple reasons:

1. The primary usage of the VR tool by the user would be while seated on a chair.
2. The user would need to navigate through various complex building layouts. Incorporating a teleportation method in such a setting could potentially heighten the risk of disorientation, particularly if the method is not accompanied by sufficient space for room scale movement.
3. The implementation of teleportation locomotion necessitates the placement of collision boxes within the virtual environment. Given that the study would involve several building models, generating and refining collision boxes for each model would be time-consuming. The time required to develop these collision boxes would be better utilized for other aspects of the research.

5.7.2 Multi-user Environment

The prototype incorporated a multi-user environment to foster collaboration within the virtual setting. By enabling participants to visually perceive each other, the study anticipated an expansion of their collaborative processes and the sharing of knowledge within the virtual environment.

In order to implement the multiuser environment feature, it was necessary to update every function in the blueprint with networking functionality. Unreal Engine offered several functions that facilitate the integration of network capabilities in a straightforward manner. However, functions lacking built-in networking functionality had to be programmed accordingly to support it.

The networked blueprint function had to be replicated among all users connected to the same network. This approach would not function if the users were connected to different networks or if the network configuration required authorization from the server. Such network settings are commonly encountered in commercial/business Wi-Fi setups. For the experiment, a local network connection created by a smartphone hotspot was utilized.

The typical process of replication originated from a user-initiated interaction. Within the blueprint event graph, this interaction was triggered by a custom event that sent a replication notification to all users connected to the same network. This solution was effective when the interaction occurs within a blueprint actor, such as locomotion or positional tracking.

In cases where the interaction necessitates communication across blueprints, the event must be forwarded to the player controller blueprint in Unreal Engine. The player controller assumed responsibility for event replication and subsequently transfers it to the blueprint actor with which the participant was interacting. For instance, if a participant pressed a button on the on-screen user interface, this action would generate an event that was passed to the player controller. The player controller would then identify the specific blueprint associated with the UI button, enabling functionalities such as altering geometry size, toggling the visibility of the user interface, or creating a visual markup.

5.7.3 Construction Sequence Playback

The implementation of construction sequence playback was designed to offer visual assistance to users during the pull plan process. This feature enabled participants to observe the projected appearance of the jobsite at various stages of construction. Within the user interface accessible via their VR controllers, participants had the capability to activate the playback function, facilitating both forward and backward progression through the sequence.

The overall functioning of this feature, as depicted in the chart, initiates when the user seleced the playback function within the user interface. Subsequently, the user interface blueprint 51ransmitted a command to the VR player controller to increment or decrease the construction phase number. These phase numbers corresponded to the visibility and concealment of specific building components.

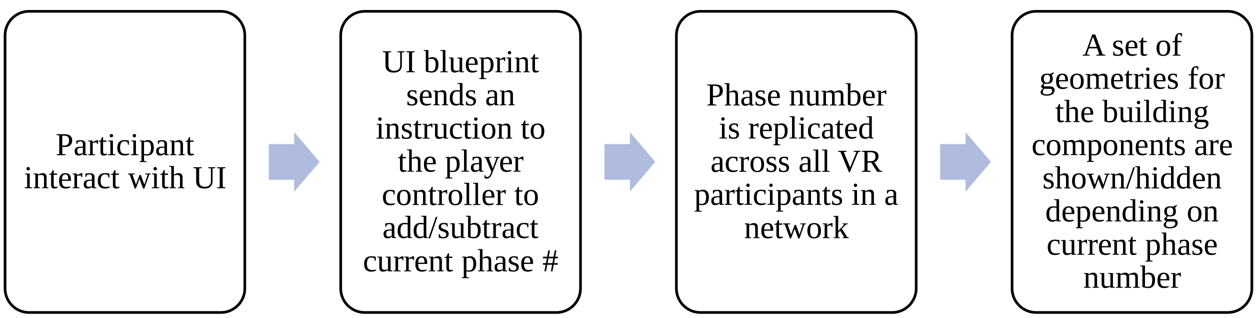

Figure 5-16 Construction Sequence Playback Logic

To enable the functionality of this system, every building component relevant to the construction activities underwent conversion into a blueprint actor. By default, these actors should have been concealed. The blueprint actors were programmed to access the phase number provided by the player controller. Upon the phase number matching a specific value, the corresponding blueprint actor would be rendered visible, indicating the completion of the associated building component as per the construction schedule. The geometries of these actors would remain hidden until the construction phase reached a predetermined number, determined by the construction schedule.

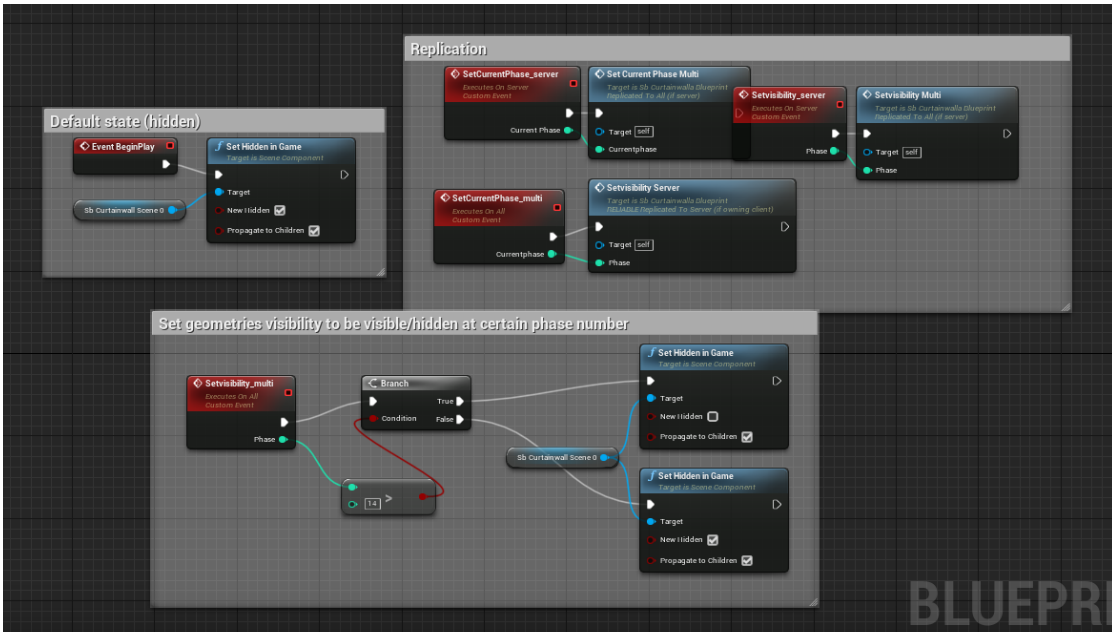

Figure 5-17 Script for Setting Visibility of Building Geometries based on the Active Phase in the Schedule

5.7.4 Section Cut

Section cut was developed to help participants in viewing the model from a distance. This was done by creating a specific section box material and creating a building material that would react to the section box material when they were overlapping. The section box material was then applied to a cube blueprint that could be controlled by the users.

5.7.5 3D Markup

Initially, the study intended to develop a 2D markup tool. However, there were some challenges during its implementation and would results in increased development time:

- The 2D markup was possible. However, this method was found to be only working when the prototype was running on desktop PCs, but not on mobile VR devices due to the less powerful hardware.

- With current solution, a specific surface material that reacts to the markup function must be developed.

The 3D markup solution was simpler, in which the users would be able to write on air by pulling the trigger key on the VR controller and started writing naturally. This solution also would not require a specialized surface, so users may use it on any space that would be visible to others.

5.8 Summary of Prototype Development

5.8.1 Challenges in Optimizing Model for Mobile Virtual Reality Devices

The project encountered a challenge in optimizing the model for mobile virtual reality devices. The typical large-scale model used in this project consisted of more than 2 million triangles for each trade model, exceeding the recommended range specified by the VR headset manufacturer. According to the documentation of the Meta Quest 2 headset, the recommended triangle budget was between 750,000 and 1,000,000 triangles (Meta, 2020a).

Although mesh decimation appeared to be a potential solution, reducing the triangle count could have potentially deformed the object to the extent that it becomes recognizable, without significantly improving performance. Alternatively, the project explored using a proxy geometry generated by Unreal Engine's built-in tool. This tool proved effective in significantly reducing the triangle count while minimally compromising the geometry appearance (Meta, 2020b).

5.8.2 Blueprint Incompatibility with multi-user mode

Several blueprint functions required further work to be replicated in a networked event. For example, the VR template that was provided by the Unreal engine needed a work-around for network replication to the point that too much work must be done to implement the networking function.

Originally, the researcher built the VR prototype for single user/non-network interaction. However, it was later observed that the solution that was developed was not compatible for multi-user interaction. Ultimately, the researcher had to rebuild the VR function using a simpler approach that made it possible for quick replication implementations.

5.8.3 Summary of Implemented tools

The following functions were built from the ground up for replications:

a. Locomotion and head/hand tracking.

b. 3D mark-up

c. Construction sequence visualization

d. Switching building scale

e. Section cut

Other features were also considered during the prototype development, but ultimately not implemented due to various challenges. Most of the canceled features were due to incompatibility with network replication and hardware limitation but should not greatly impact the utilization of VR as a visual aid tool.

An example of the canceled features was an avatar system was initially developed and had VR integration. It was ultimately canceled since with the current method, motion control combined with model animation was very taxing to simulate in a networked environment. A server based multi-user environment was also canceled since it required more development time. A list of implemented and canceled features is demonstrated in (Table 5-1).

Figure 5-18 Multi-user Avatar

5.8.4 Texture incompatibility with mobile devices

The mobile/portable devices that were used as the primary development platform for this study had some limitations in its capabilities in processing certain texture types. This resulted in missing texture or features when the program was compiled into the device. This incompatibility was not immediately visible since when the prototype was developed on desktop, there was no issue when the program was run in desktop mode. While it was possible to change/replace the texture to mitigate the texture incompatibility, some features that were texture-related had to be canceled, such as the 2D markup function.

Chapter 6 – User Tests

6.1 Overview

Scholars have been studying the impacts of virtual reality in various aspects of AEC industry. While the main goal of using the prototype was to investigate the feasibility of VR in pull planning sessions, it is important to consider the user experience aspect of the prototype.

6.1.1 Structure and Tasks

a. Industry Expert Project (Professionals)

Since the study was done on an ongoing project, the study was designed so that it did not interfere with the established workflow of the project team. Therefore, the participants were allowed to use VR or not at their convenience. The researcher acted as an observer and investigated how the professionals implemented VR.

The researcher did not formulate a specific task for the participants since the purpose of the meeting already aligned with the study. Both aims to conduct a pull plan session for a specific part of the construction project. At the end of the meeting, questionnaire sets were distributed among participants.

b. Student Project

The student study was divided into three phases: pilot studies, oversea, and graduate student. All three phases were designed for groups tasks, and they were instructed to conduct a pull planning session. To obtain as much information as possible, more than 30 students were recruited.

The researcher expected at least one VR session and non-VR session recordings were usable for analysis. So, more than five sessions were ran between Fall 2022- Winter 2023.

For the student project, the student did the planning in Miro, this decision was since it was more convenient to document the final pull plan result rather than using physical sticky notes. Every group had access to at least a computer/tablet to let them participate in the pull plan session. The students were initially provided with milestones and they had to plan their commitments for activities in between the provided milestones.

For the pilot study, students had to devise their own commitments based on their assigned roles and milestones. They were assigned to MEP subs and given the task to plan their work commitments for several weeks ahead.

After the pilot studies, the researcher changed the roles since it was too complicated to plan MEP tasks without adequate experience. On the other phases (oversea and graduate students), the roles were simplified to just curtain wall, drywall, and wall finishes. In addition to make up the lack of experience, the students were provided with several possible commitments that they can use to plan the job.

Each discipline/trade group was provided with at least one oculus quest 2 with the prototype already running on the device. Each session was divided into a training session and a simulated pull plan session. Students whoe were in the VR study were allowed to use VR at convenience.

Table 6-1 Student Study Phases Details

<table>
<tr><th>Study Phase</th><th>Study Month</th><th>Disciplines</th><th>Session</th></tr>
<tr><td>Pilot</td><td>November 2022</td><td>Drywall, Mechanical, Electrical</td><td rowspan="3">- Training (30 minutes)
- Simulated Pull Plan (1-hour)</td></tr>
<tr><td>Oversea</td><td>December 2022</td><td>Drywall, Curtain Wall, Wall Finish</td></tr>
<tr><td>Graduate Students</td><td>February 2023</td><td>Drywall, Curtain Wall, Wall Finish</td></tr>
</table>

6.2 Industry Expert Tests

6.2.1 Session 1

A study was conducted at Turner construction's project over the summer of 2022. The researcher obtained access to the project's 3D model from BIM360. In this project, pull plan was extensively used to ensure the project's timeliness and to identify constraints that could potentially delay the project.

In this experiment, the VR prototype did not have the ability to play the construction sequence due to the complexity of the model. The model was also not shown in its entirety due to the lack of processing power of Meta Quest headset. To get around this issue, the VR prototype only showed portions of the model that were part of the discussion during pull plan sessions.

During the first session, the meeting discussed commitments in the kitchen area of the amenity floor. This area is comprised of kitchen equipment and a number of MEP elements. Due to the complexity of this area, the attendance of this meetings was over 20 attendees.

6.2.2 Session 2

The second session was done three weeks after the first one. In this session, the scope that was discussed was much smaller, and it involved work in the elevator shaft area and a collaboration room. In this session, the team did not use much VR and instead uses drawings. Based on the observations, the scope of the work is very specific to works that were to be done at an elevator shaft.

6.2.3 Questionnaire Responses

Questionnaires were distributed among participants at the pull planning session for session 1. In the questionnaire, they were asked about how the features helped them in decision-making. The participants responded that navigation in VR and the overall representation of the building's model contributed to their decision-making process. Meanwhile, based on the prototype at this point, they found that it was difficult for them to tell which trades own which model.

In their comments, the professionals believe that having a feature to filter the model based on the trades would be very helpful for them. It was also quite difficult for them to identify which floor they were on. At the time of the tests, the prototype had less features. Therefore, only six aspects of the prototype were tested.

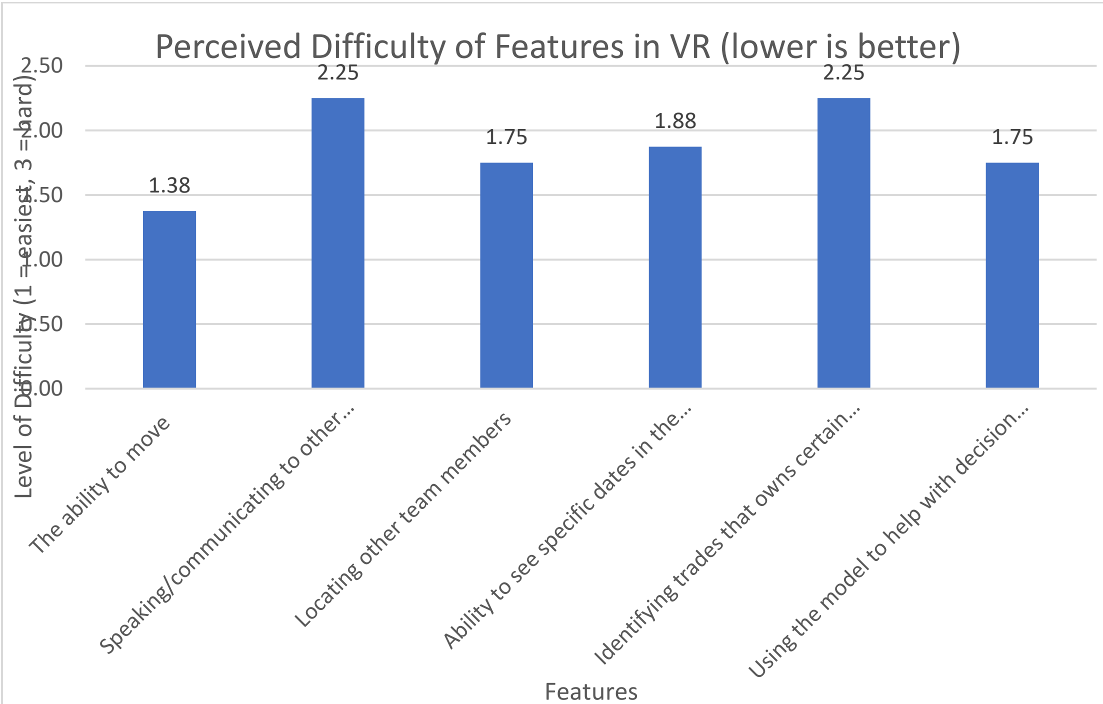

Figure 6-1 Perceived Difficulty of VR Features

6.3 Student Tests

The user tests were conducted after receiving feedback from the industry professional study and updating the prototype based on the feedback. In total, 37 students participated across different sessions. The sessions were splint into pilot studies, overseas, and graduate students.

There were several sessions of user tests conducted from November 2022 to February 2023. In the studies, the prototype was used as a visual aid rather than a primary medium for pull planning.

6.3.1 Setup

The study used a VR prototype developed in Unreal Engine 4.27 for the main tests and Autodesk Navisworks 2023 for the control group.

Questionnaires were distributed during the recruitment to identify participants' demographics such their knowledge on construction scheduling, prior experience in the industry, and knowledge of lean construction. In addition to their background, a Likert-scale questionnaire was also distributed to identify the participants' psychological condition prior to the test.

After the experiment, participants were also asked to complete a post-experiment survey to get their feedback on the tool, how they utilized the tool to help the decision-making process during a pull planning session, and how they were feeling after the experiment. The pre-experiment and post-experiment questionnaires were distributed to both the control group and the treatment groups.

During the study sessions, participants were distributed into three specialty contractor groups and were given tasks to develop commitments for a specific part of a simulated commercial project. Each trade contractor plays specific roles in the project.

For the participants across the experiment sessions to have the same information, the research developed a scenario and provided each contractor group with suggested commitments that they could come up with during the pull plan session. The group were also notified that they may develop their own commitments.

The groups were not required to use VR all the time; they were free to jump into VR as necessary. Meanwhile, in VR they were allowed to play construction sequences, add markups, or simply navigate through the model.

The VR prototype allows participants to do a walk through, play the construction sequence, or create mark-ups in the VR environment for the other participants to see. The participants were also able to view the model from their own perspective since they have access to their own VR headset.

As with the actual pull planning session, a moderator was appointed to lead the pull plan session. The moderator guided participants on how to conduct the pull plan and develop the commitment on their sticky notes. The moderator would also fill in information that was purposely not included in the scenario. For this research, the researcher was involved as the moderator.

6.3.2 Building Models

There were two models developed for the tests. The models were developed in Revit and they consist of structural, architectural, and landscape elements. The models were then brought up to Unreal Engine to be developed in VR.

6.3.2.1 Model 1

The first model was a simple two-story office building with some landscape element. In the simulation, the participants were given a task to develop the work for Curtain Wall, Drywall, and Wall finishes. The model is relatively small and simple enough to navigate.

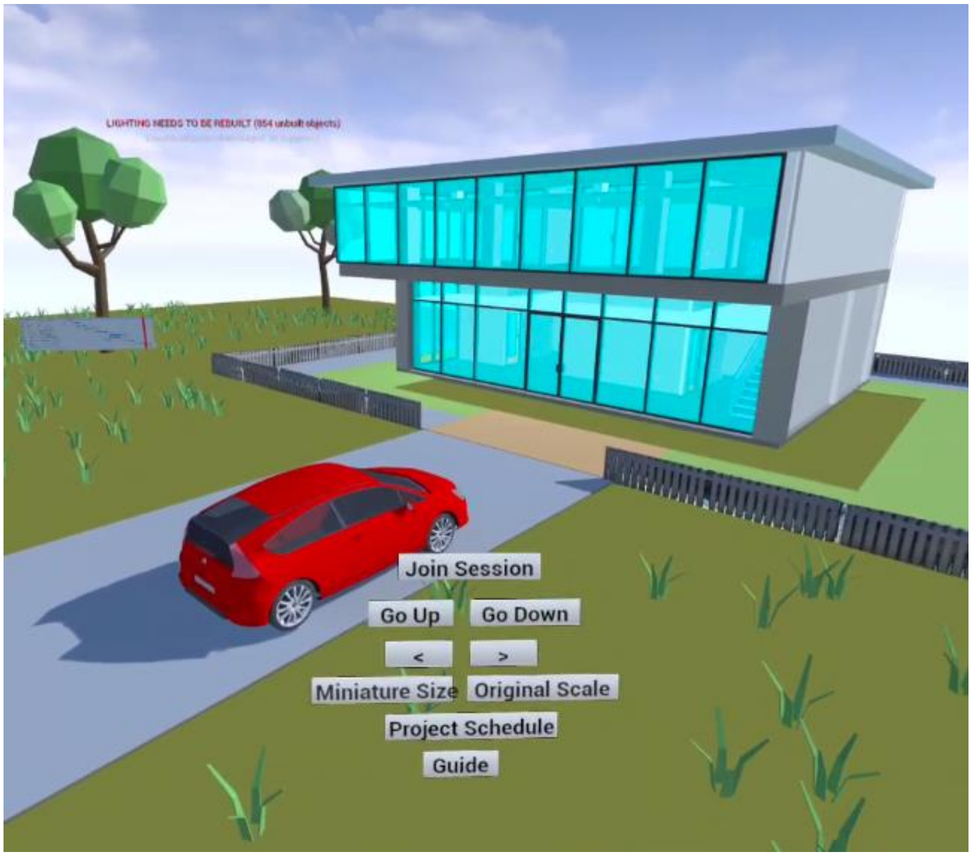

Figure 6-2 Virtual Building Model A

6.3.2.2 Model 2

Model 2 is more complicated and detailed compared to the model 1. While it has some MEP elements, but participants were given similar tasks to model 1. In this model, several optimizations had to be done in order to show it in mobile VR without much performance loss.

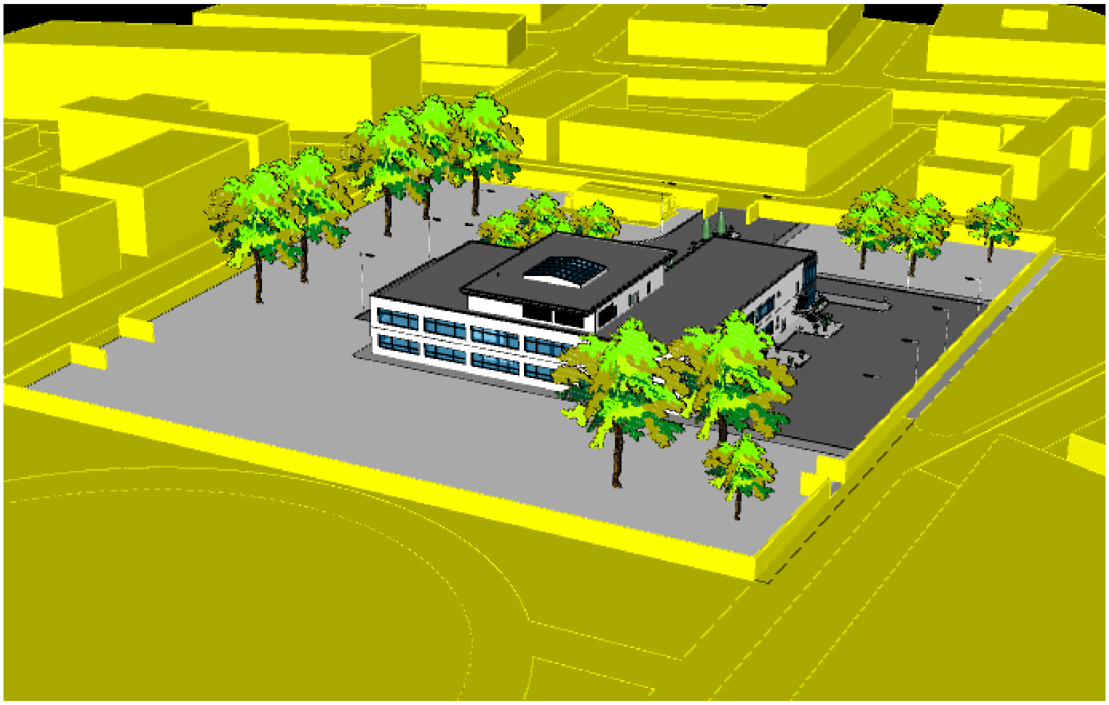

Figure 6-3 Virtual Building Model B

6.3.3 Feature Test

A series of user tests were conducted on the final version of the prototype to ensure the features were working smoothly. These tests were not aimed to measure the pull planning feature, so the participants did not have to be experienced in the industry or possess knowledge in construction. These tests were conducted to make sure people were comfortable with navigation and performance of the VR environment.

Model A and B were used in the feature test. These models were converted using the most recent conversion method using the proxy mesh, which improves the performance on model B. There are two navigation methods that were tested in this test:

a. Snap movement: This movement approach would snap users to certain angles or vertical distance every time users do a related input on the VR controller.

b. Smooth movement: This approach will rotate users' virtual avatar so long as the users were holding the input button on the VR controller.

In this test, participants were given several tasks to try out the features in the prototype. The tasks covered navigation methods and interface aspects of the prototype. No recordings were made, but participants had to fill out a series of questionnaires at the end of the tests.

6.3.3.1 Controls

To test the controls, participants had to do several tasks:

a. Going around the building

b. Climbing the interior stairs

c. Go up and down vertically using an input on the VR controller.

d. Draw a markup on specific object.

After testing both control types, most participants preferred the smoother controls over the snap one. Comments related to the controls are often related to comfort and less confusion, Participants noticed that turn speed is a little slower on the smooth control type compared to the snap control one, but they felt the smooth control is more preferable.

Table 6-2 Participants' Opinions on Controls in Feature Tests

Participant	Comments
Participant #1	"It helps to control the sudden change when we turn."
Participant #2	"I feel like it's smoother in Model 2."
Participant #3	"Not as smooth but better for the eyes"
Participant #4	"Model 1 is faster but model 2 is preferable for me"

6.3.3.2 Visualization

Participants were quite satisfied with the visualization in VR, where 50% rated the visualization 5 out of 5 while the other 50% rated the visualization 4 out of 5. Despite the rating, when asked about what can be improved, participants noted that there were area improvements, as summarized below.

Table 6-3 Participants' Opinions on the Visualization in Feature Tests

Participant	Comments
Participant #1	The environment visuals are better than scenario A
Participant #2	It has been great, yet the real visualization might be improved. For example, there is a dark area between 2nd floor and rooftop — which I'm not sure what it is.
Participant #3	The 2nd model may be too big on the renders making it dizzy.
Participant #4	Since it's quite big, it'd be nice if everything runs smoother and there is less jagged line

6.4 Student Test 1 – Pilot Studies

In the pilot study, we conducted two VR tests on twenty-two students at the University of Washington, all distributed on certain trade contractor groups. In general, the students were not familiar yet with lean construction because they would learn about it in the next academic quarter.

The participants of this test were recruited from senior year students who were enrolled in the Virtual Construction course during the Autumn 2022 quarter at the University of Washington. The participants were given a task to conduct a pull plan and develop a series of commitments based on the information they were provided with. Prior to participating in the study, none of the participants had been actively involved in a pull planning process, although some of them had known or heard of the process.

6.4.1.1 Activities during study

The aim of the pilot studies were to observe students on the activities during a simulated pull planning session. In this study, students were given the task to plan the installation of MEP component and they were only given milestone dates. This phase was also used to evaluate the data collection approach and gather feedback on the prototype.

Students had to develop the commitments mostly from their base knowledge, during the session, they could have discussions with other team members or look online for what possible commitment each trade might have.

6.4.1.2 Observation on the study

In this study phase, several observations were made on the student interactions and tools that they used. Students found that it was difficult for them to come up with commitments since they did not have much experience on MEP construction. Of the 22 participants, 10 were successful in completing the tasks.

6.4.1.3 Questionnaire Results

The questionnaires were distributed before and after the study sessions. This was done so the researcher could identify if there is any improvement before and after the study. There are some parameters that were studied:

1. The participant's feeling/physical condition (in a scale of 7, with 7 = very comfortable and 1 = extremely uncomfortable)
2. Participants' understanding of a scheduling process in general. (in a scale of 7, with 7 = fully understand, 1 = do not understand at all)
3. Participants' understanding of the pull planning process. (in a scale of 7, with 7 = fully understand, 1 = do not understand at all)

In the first study, 10 participants responded to the questionnaire. In general, half of the participants reported they felt uncomfortable after the study as demonstrated in Figure 6-4.

After the study, the students felt like they felt they understood what a pull planning process is after the study as demonstrated by Figure 6-6. However, based on their observation (Figure 6-5), their construction scheduling knowledge didn't improve that much after the study.

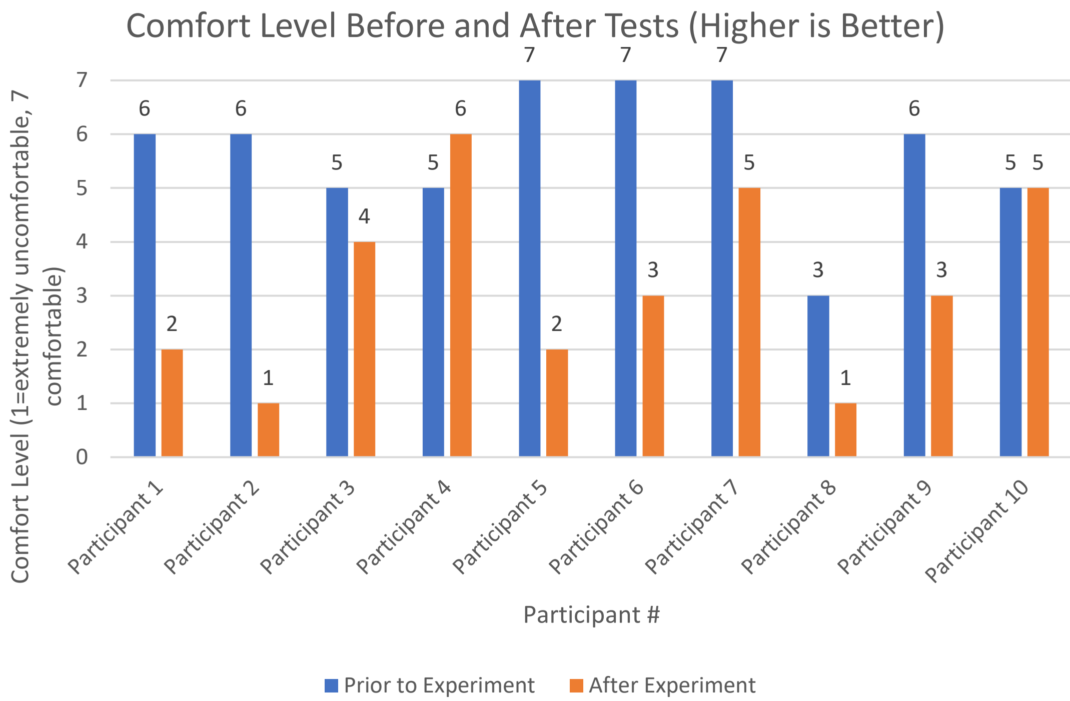

Figure 6-4 Students' Perceived Comfort Levels Prior to and After Experiment in Student Test 1

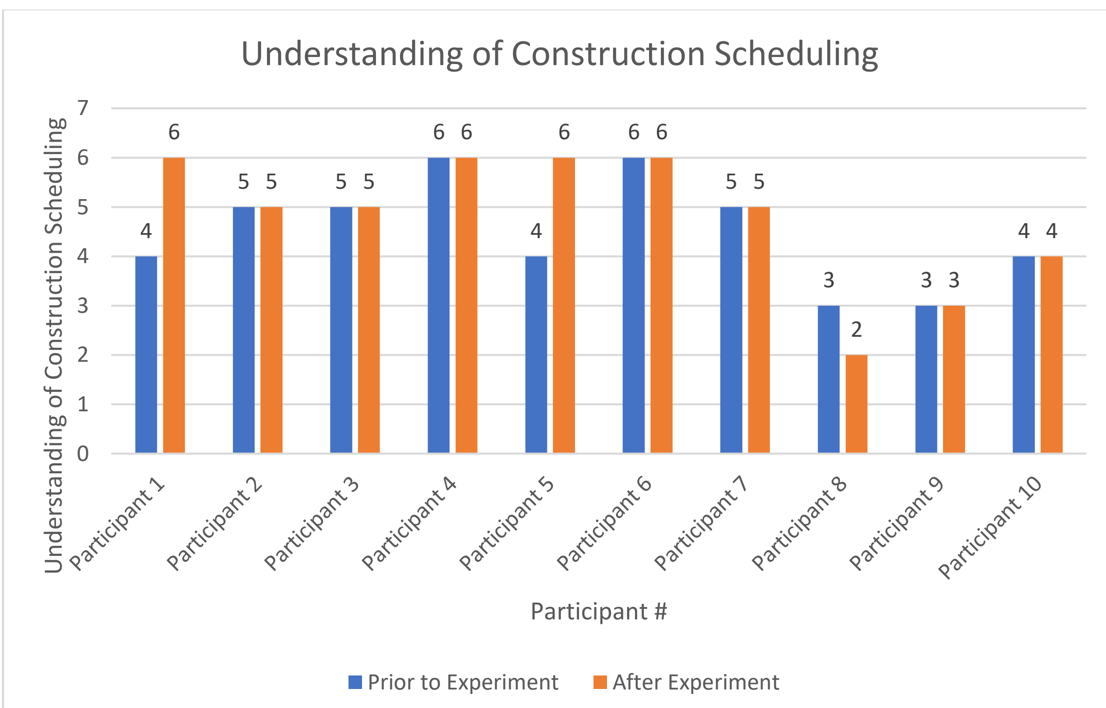

Figure 6-5 Students' Understanding of Scheduling Prior to and After Experiment in Student Test 1

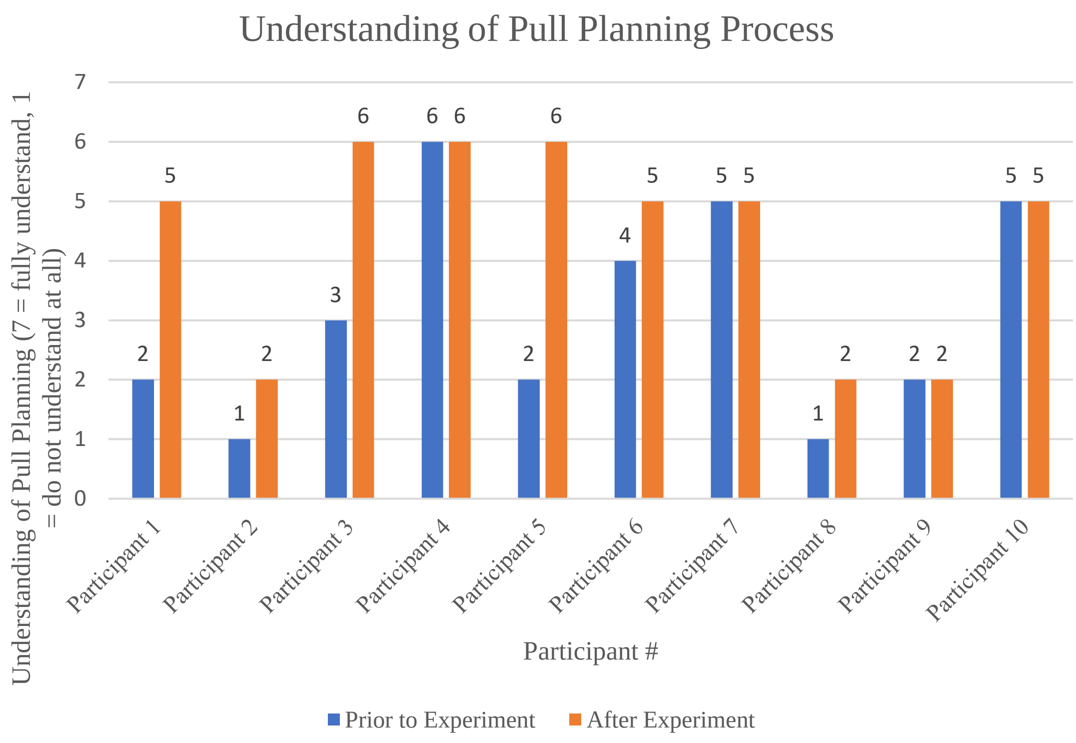

Figure 6-6 Students' Perceived Understanding of Pull Planning Process Before and After Experiment in Student Test 1

6.5 Overseas Student Tests

In the second test, the participant demographics were mostly third- and fourth-year students from Andalas University, Indonesia. Ten students were recruited to participate in the study for an hour in each session. The reason they were recruited was because the participants had completely zero exposure to both VR and lean construction. Therefore, it will be a good opportunity to learn if the use of VR could have a higher impact on the students' understandings of the pull planning process.

6.5.1.1 Study Activities

In this test, students were given instructions on the possible commitments they could make for completing the task. However, they were not limited to the suggested activities, and they are allowed to add more activities as they see fit.

Unlike in the pilot studies, students were provided with more clues instead of just milestones to compensate for their lack of experience. The activities were divided into disciplines/trades, printed on the instruction sheets.

6.5.1.2 Study Observations

In this study, participants were able to complete their tasks faster than the pilot studies' participants. On average, the groups were able to complete the pull plan in roughly 28 minutes to 30 minutes. They also conducted the discussion independently without much interference from the moderator.

6.5.1.3 Study Results

Ten students from the Faculty of Civil Engineering at Andalas University, Indonesia were recruited to conduct the study. The use of VR has less significant impact on the students' comfort level, as only three of them experienced discomfort after wearing it during the study.

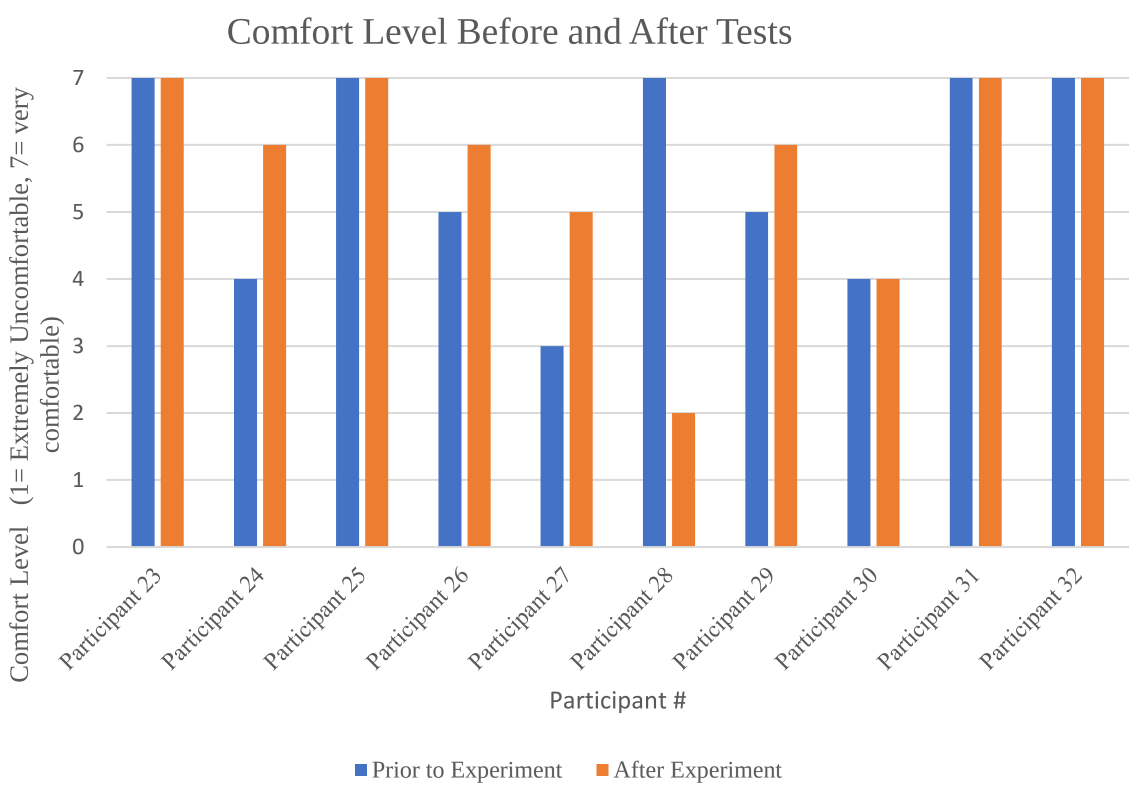

Figure 6-7 Students' Perceived Comfort Levels Prior to and After Experiment in Student Test 2

In terms of the improvement in their understanding of scheduling process, it is indicated that the participants did not feel that they have gained much better understanding of scheduling process. However, this might be attributed to their background as student assistant/grader for the construction project planning course at Andalas University.

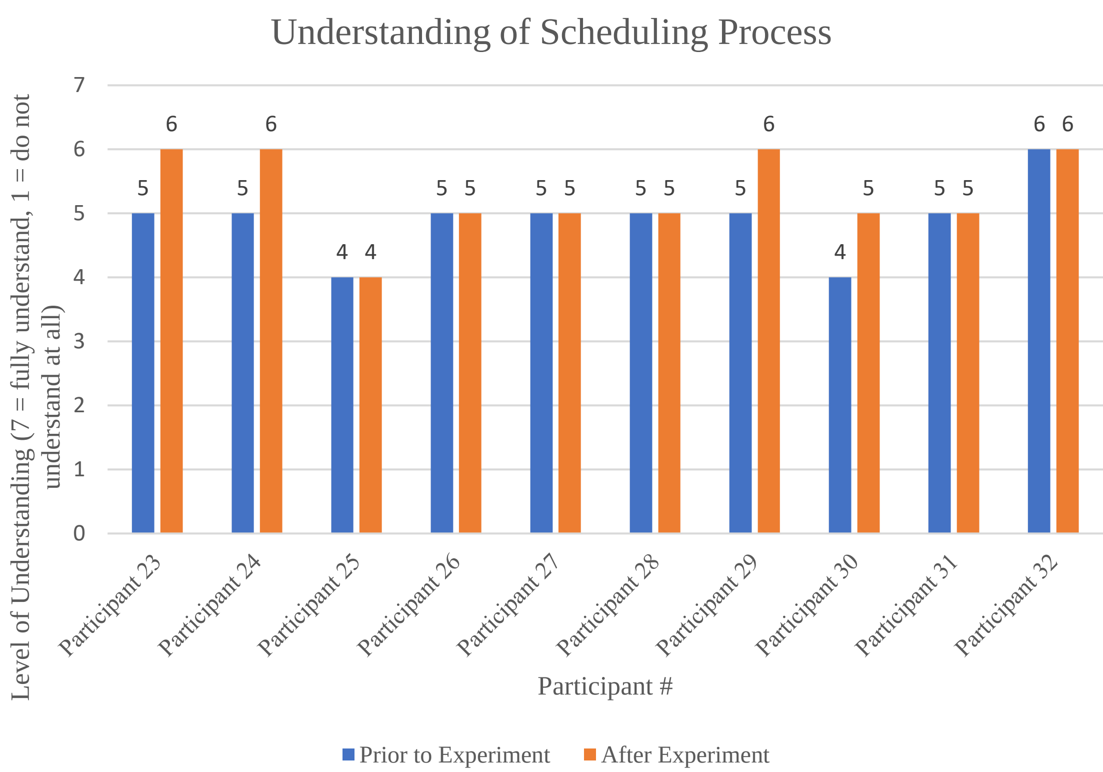

Figure 6-8 Students' Understanding of Scheduling Prior to and After Experiment in Student Test 2

The questionnaire results also indicated that the participants in this test gained better understanding of pull planning. Nine out of tent participants claimed to have better understanding of pull planning after the study, which is higher than the previous test.

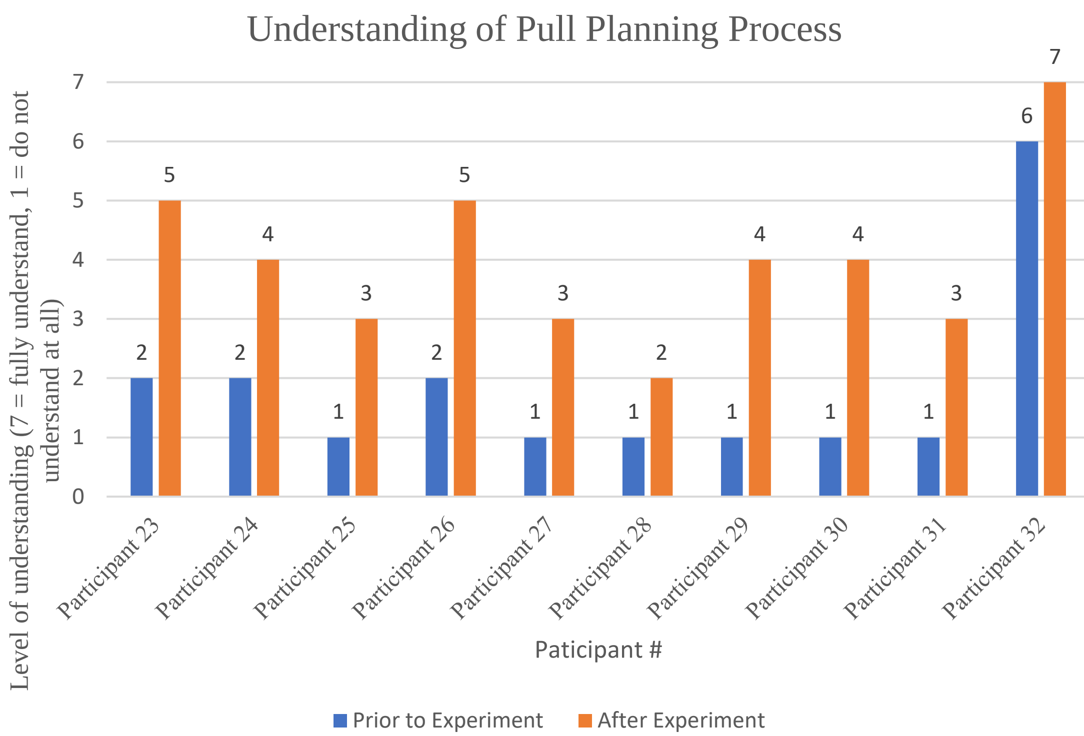

Figure 6-9Students' Perceived Understanding of Pull Planning Process Before and After Experiment in Student Test 2

6.6 Graduate Student Tests

In the third round of the test, participants were recruited from the University of Washington's Construction Management master's degree program. Six students participated but only four volunteered to participate in the questionnaire. The format of the study was largely similar to the previous one, except in this study a more optimized prototype was used. The optimization was to improve performance on the VR prototype as well as improving the control. This test was conducted after receiving feedback from the feature test.

6.6.1.1 Activities

These studies were conducted in February 2023 on two separate days. Students were given a similar problem and a set of suggested activities. Then, they had to discuss with their partners to develop commitments during the pull plan session. The

In terms of comfort level, half of the participants experienced discomfort, but the changes were not as significant as the participants in previous studies. This could indicate that the updated prototype contributed to the comfort level of the participants' experience.

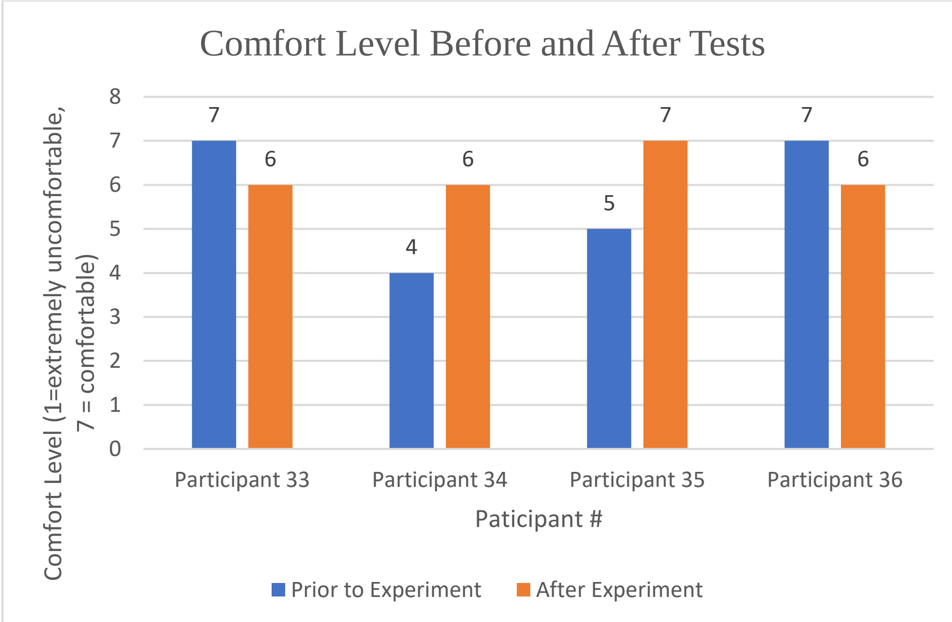

Figure 6-10 Students' Perceived Comfort Levels Prior to and After Experiment in Student Test 3

Meanwhile, the participants believed they had a better understanding of the scheduling process. This response is quite consistent across all participants, unlike the previous tests where only some participants gained better understandings of the scheduling process.

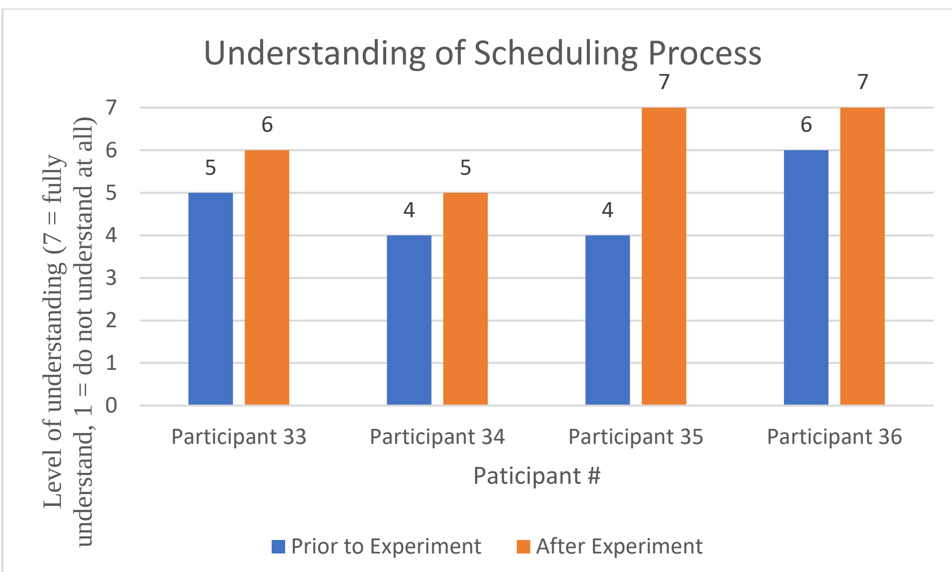

Figure 6-11 Students' Understanding of Scheduling Prior to and After Experiment in Student Test 3

The participants indicated that participating in the study improved their knowledge of pull planning. Although the improvements were not experienced by all of the participants, three out of four participants felt that they gained better understanding of the pull planning process.

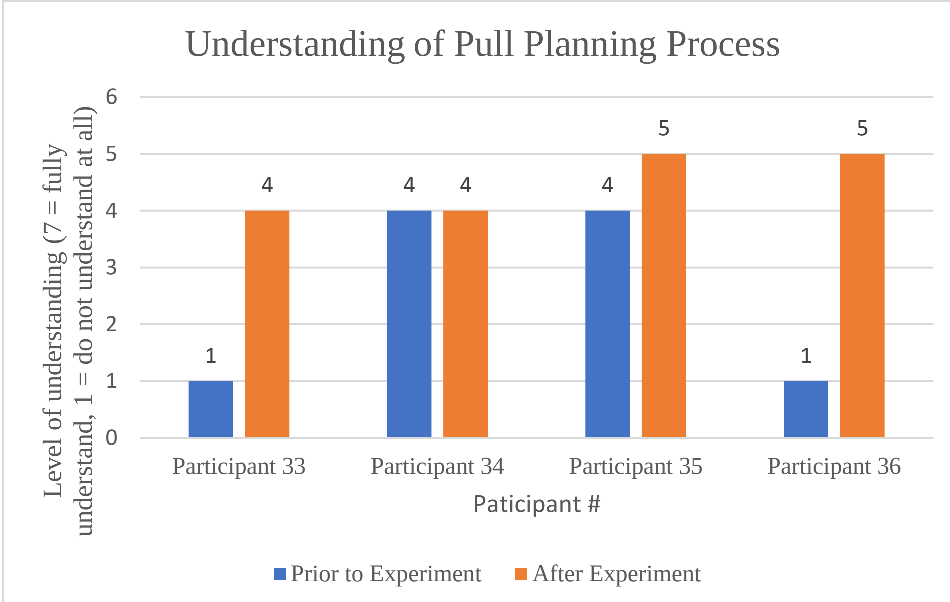

Figure 6-12 Students' Understanding of Scheduling Prior to and After Experiment in Student Test 3

6.7 Factors that contribute to participants understanding in VR based on the prototype.

Participants were also asked how each feature of the VR Prototype affected them in their decision making. In the questionnaire, participants were asked to score each feature in the VR prototype. The lower the score, the better the feature is in contributing to their experience. That means the feature is the most accessible for them while they were in VR.

The chart below shows the summarized score across 24 participants in the study. According to them, they found navigation to be the most accessible since they could explore the detailed model in VR and investigate the location where their crew will be working.

The limitations of this study were that other elements were found to be not too accessible, especially the schedule part. Some comments from the participants mentioned the difficulty of seeing the schedule since it’s too small or not visible enough for them. In addition to difficulty in seeing the schedule, the participants had difficulties in playing the construction sequence since it involved them with interacting with the interface. Some comments noted that the buttons were quite difficult to access.

Based on the principal investigator's observations during all student tests, interaction that are related to the user interface were one of the more difficult aspects of the VR prototype that participants struggled at. The user interface was presented as floating buttons that the user had to "press" with their virtual hands in order to activate. Due to the bug at the prototype, many times the prototype failed to execute the interaction that the users intended to occur. This often led to an increase in the frustration among the participants, especially on the first student test.

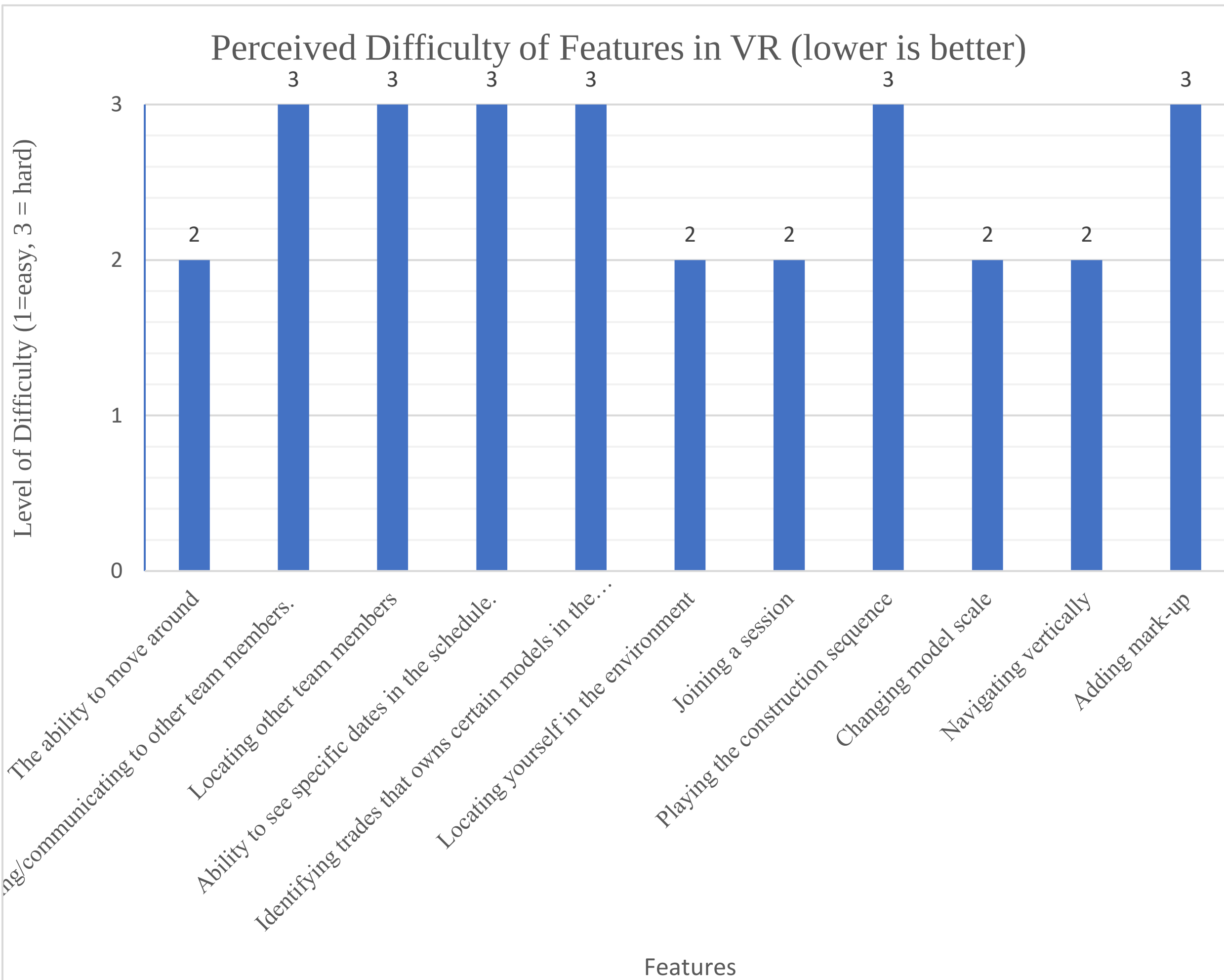

Figure 6-13 Perceived Difficulties in the VR Prototype Features

6.8 Analysis

6.8.1 General Accessibility of Features

Both the professional and student participants were given the task to fill in questionnaires about features in the prototype that they found the most accessible for decision making in pull planning. Participants across all demographics seem to agree that navigation is the most accessible feature that contributes to the pull planning process in this study. Despite both groups having the same opinion on its accessibility, the students found that being able to see the schedule was the least accessible aspect in the study that contributed to the pull planning process.

Despite the difference, it should be noted that the professionals have access to the master schedule and are already aware of their responsibilities. Meanwhile, the students who participated in the experiments did not have access to the master schedule or even know their roles.

Table 6-4 Perceived Difficulty Levels of VR Prototype Features Across Industry Participants

Feature	Difficulty
The ability to move	1.375
Locating other team members	1.75
Using the model to help with decision making	1.75
Ability to see specific dates in the schedule.	1.875
Identifying trades that owns certain models in the virtual environment	2.25
Speaking/communicating to other team members.	2.25

Table 6-5 Perceived Difficulty Levels of VR Prototype Features Across All Student Participants

Features	Difficulty
The ability to move around	1.73
Joining a session	1.57
Locating yourself in the environment	1.77
Changing model scale	1.82
Navigating vertically	1.82
Speaking/communicating to other team members.	2.05
Playing the construction sequence	2.14
Adding mark-up	2.14

Identifying trades that owns certain models in the virtual environment	2.27
Locating other team members	2.32
Ability to see specific dates in the schedule.	2.77

6.8.2 General Impact on Students

In general, the implementation of VR did not pose a significant improvement in student's knowledge since all participants in the study had scheduling knowledge from classes that they took or through internship. There were several outliers in the individual results, but in overall there weas an insignificant increase in the students' knowledge as shown on the figure 6-14. Prior to the VR intervention, students' scheduling knowledge was 4.73 on average. After the study, their average knowledge was increased to 5.65.

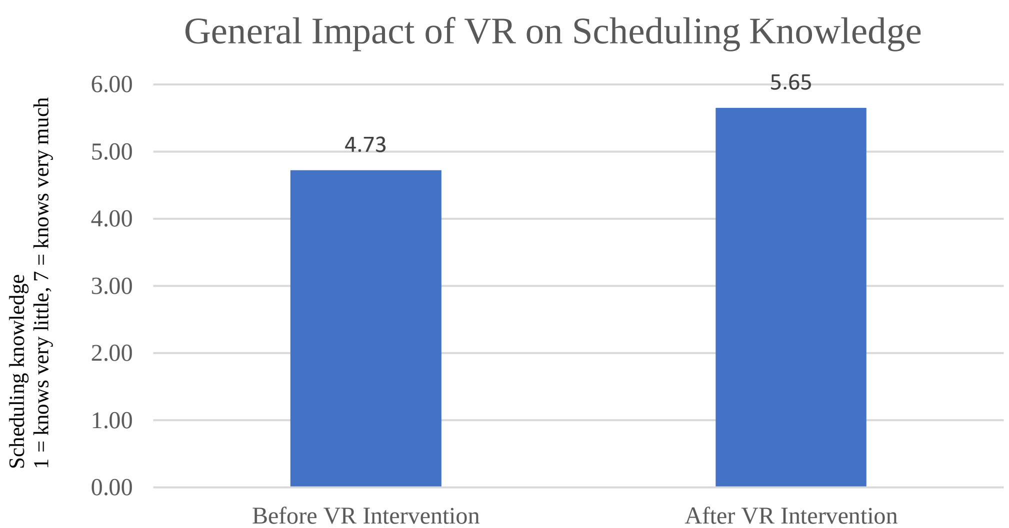

Figure 6-14 Impact of VR implementation on Students' Average Scheduling Knowledge

On the other hand, figure 6-14 indicated that VR intervention showed quite a significant increase in students' pull planning knowledge across all student participants. Based on the student demographic responses, majority did not have much prior knowledge on pull planning or lean project, which was represented by the 2.48 on their knowledge score. However, after the VR intervention, they perceived that they knew more about pull planning which was reflected in their score of 4.35.

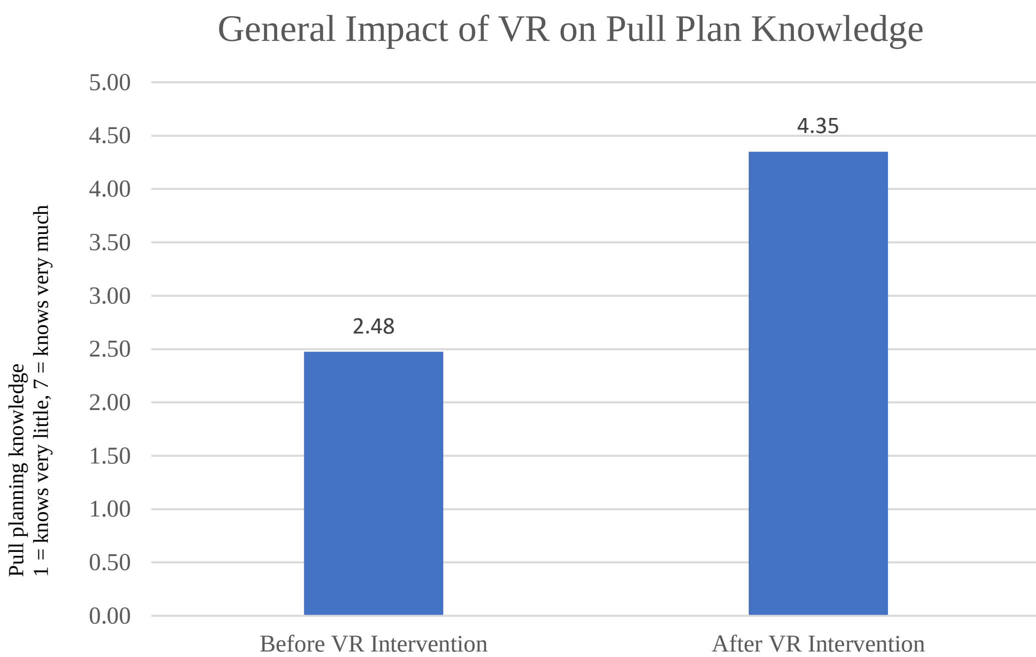

Figure 6-15 Impact of VR implementation on Students' Average Pull Planning Knowledge

6.9 Observed Interactions based on Recordings and Notes

6.9.1.1 Challenges on Recording Quality

In the studies conducted on construction projects and students, audio and visual recordings were made. However, the researcher encountered several challenges, which included the following:

a. The pull plan sessions involved a large group of people, requiring multiple recordings from different locations in the room to capture the participants' interactions effectively.

b. Due to the session's large attendance, simultaneous interactions among multiple groups occurred. Despite having multiple recording devices, conversations from other groups frequently bled into the recorded conversations of the targeted group.

c. Careful planning was necessary to position the recording devices before the meeting, ensuring they did not obstruct the participants' movements or activities.

Although some recordings were sufficiently clear for analysis purposes, it proved challenging to identify the participants who initiated specific interactions. Upon analysis of the results, researcher relied on the notes more than the recordings. In the end, the oversea study group recordings were used since they were the most intact one.

6.9.1.2 Observed Interactions

The investigator logged interactions in all studies (professionals and students) and found that the different demographics have different perspectives and utilization of virtual reality devices.

On the professional group, the participants had more interactions with each other, and they utilized VR occasionally. Most of the participants who used VR have had experience and had no trouble with getting used to the device.

Meanwhile across all student experiments, participants were observed to be spending time to get used to the tool despite participating in a 20-minute training session. Based on the principal investigator's observation, the interaction mostly occurred between team members of the same team or between the participants and the moderator.

a. Professional Groups

There were two sessions of professional groups with different topics during the pull plan. At the first meeting, the size of the group is larger than 30 participants since the meeting covered works in the whole 2nd floor. Due to the limited number of devices, not all professionals were able to participate in the study. Within a large group, those with VR had the opportunity to explore the model. However, it was more utilized when the superintendent brought up the mirrored VR view on screen. With the shared view, they were able to work as a group and coordinate the plan.

At the second meeting, the group was much smaller and had different trades participating in it. They decided not to use the VR model since it was not as detailed as they expected it to be since their work was focused on just one area that did not have much geometries when visualized in VR. The colors also made them quite uncomfortable since the model lacked shadows and details.

b. Pilot Studies Groups

In the pilot study, the tested prototype was unstable and had several freezes that interfered with the study. The numbers of participants were also varied and did not meet the ideal number for the study design. Regardless, the study was carried on according to the plan except for the first team.

From the 2nd to 4th round of pilot studies, the researcher observed that the interactions mostly occurred between the team members of the same roles. Except for the third group (UWCM-3), whereas there was a discussion between the mechanical and drywall team. In this study, each group were also observed to be navigating on the VR model and they took turns to refer to the model when coming up their commitments.

When asked about the most difficult part of the study, they responded that they were unfamiliar with mechanical and electrical work. So, they struggled and had to consult with external sources (internet) during the pull plan. Due to this response, the researcher replaced the mechanical and electrical roles for the overseas and graduate students' phases.

The researcher also investigated the issue with the prototype build and implemented fixes on the next phases of students' studies.

Table 6-6 Pilot Studies Groups

Group	Participant #	Roles	Notes
UWCM-1	9	Drywall, Mechanical, Electrical	Technical issue
UWCM-2	3		Less than 5
UWCM-3	6		Completed
UWCM-4	4		Less than 5

c. Overseas Groups

The overseas groups were divided into two groups in which they would complete the task in the given amount of time (1-hour). They were able to complete the tasks in under 30 minutes. Both with non-VR and VR intervention.

Table 6-7 Overseas Groups

Group	Participant #	Scenario	Task	Note
INA-1	5	A (Non-VR)	Curtain Wall, Drywall, Wall Finish	3rd and 4th year students
INA-B	5	B (VR)	Curtain Wall, Drywall, Wall Finish	2 participants were Master's students with more than 3 years of work experience

With recordings both from non-VR and VR groups available, we observed that the VR team were able to complete the work earlier than the non-VR team. On the non-VR team, it took them roughly 30 minutes to complete the session. Meanwhile, the VR team were able to complete it in 17 minutes and used the rest of the time for exploring it. The study was conducted in a mix of Indonesian-Minang language, so the transcript had to be translated to English.

Most of the interactions were quite similar since both teams were observed to utilize the visualization tools (either VR or Navisworks) occasionally. Although, it was observed that the VR team had more in-depth discussions on their scope of work that would affect other team members.

In the non-VR team, discussions

Table 6-8 Interactions in non-VR Team

Time stamp	Conversation	Involved Parties	Comment
10:20	"First, we order material for curtain wall and keep it out of the elements."	Curtain wall	Found defects
12:39	"..storing material.." "Let's just call it DW (Drywall)"	Drywall	Asking for confirmation
13:26	"Frame is other sub's scope"	Drywall	Assumption
13:33	"Let's add new color (sticky note)" "We don't need it, it's not our scope (framing)"	Drywall	Realization

14:21	"So, while the finishing is ongoing, we have to seal the room"	Wall Finish	Asking for confirmation
16:20	"Can we do this concurrently? The drywall will work on level 2 while we work on the first floor"	Drywall and curtain wall	Response to query
17:09	"What if we just add a marker here for the framing sub? After all, we can't really start before their work is completed"	Drywall	Observation of new problem
17:42	"So, for the painting does the room need to be sealed?"	drywall and wall finish	Resolution
19:03	"How is the sequence? What does the simulation show?"	Wall finish	Resolution
20:13	"Let's break down our activities per-level"	Wall Finish	Confirming resolution
20:44	"Let's start from the drywall, and we can break down the framing"	Drywall	Drywall
25:35	"Can we do these concurrently?" (paint)	Drywall, curtain wall, Wall finish	Cross discipline collaboration
26:52	"The interior glass partition can't get dirty, so we will begin from the second floor"	Curtain wall	Observation
31:20	"So, the curtain wall mullions are installed after storing the Curtain wall material?"	Curtain wall	Asking for confirmation
31:37	"We can't do it (installing curtain wall) since that will interfere with mobilisation"	Curtain wall	Realization
35:27	"We will put this activity (installing curtain wall) in between the mobilization"	Curtain wall	Resolution

In the VR team, there was a conversation about starting the paint work concurrently with other trades. The discussion started with one member from the wall finish subcontractor asked, "should we wait until other subs are finished?" Some of their concerns were interfering with other trades' work or having to wait until the drywall was finished. Ultimately, they found a solution to start after both curtain wall and drywall had been completed. During the discussion of the paint, they referred to the VR model twice to review the simulation.

The VR team also observed a defect on the interior part where there was no opening in the level 2 slab for stairs. One of the drywall team members asked, "Hey, the stairs are closed off on the 2nd floor". This defect was not observed by the non-VR team. It was also observed that the VR team's discussion focuses more between the members of the same discipline/trade.

Table 6-9 Interactions in VR Team

Time stamp	Conversation	Involved Parties	Comment
4:46	""Hey, the stairs are closed off on the 2nd floor. "	Curtain wall	Found defects
7:02	"Sealing, correct? Then we will do the paint"	Wall finish	Asking for confirmation
11:15	If we do curtain wall on the second floor first, we can let others work on the first floor	Wall finish	Assumption
11:53	"but the drywall is not installed yet"	Wall Finish	Realization
12:18	"If we start from the 1st level, are we not going to interfere with curtain wall work?"	Wall Finish	Asking for confirmation
12:21	"Nope, there shouldn't be any issue, but…"	Wall finish	Response to query
12:28	"The problem is if we start from the second floor, the dry wall is not installed yet."	Wall finish	Observation of new problem
12:43	"Let's just do the paint once others have completed their work."	Wall finish	Resolution

13:02	"Should we start painting on the 2nd floor? No, it should not matter since everything else is complete"	Wall finish	Resolution
13:50	"On the 2nd floor the curtain wall sub will work on the installation while drywall sub is working on the 1st floor. Then we will paint after everyone is done"	Wall finish to Drywall and Curtain Wall	Confirming resolution

d. Graduate Students Group

The graduate student phase was the last phase of the entire study. In this study, the same scenario was used like the oversea group, with students being randomly assigned to either the drywall, curtain wall, or wall finishing roles.

During the study, just like the oversea and pilot groups, students frequently assessed the model. However, for the first time in the study they made a remark that the construction sequence simulation was not as detailed as they expected. In the simulation, they mentioned that there should have been more activities being visualized such as the curtain wall material staging/delivery and installation of the framing.

Table 6-10 Graduate Student Groups

Group	Participant #	Scenario	Task	Note
UWG	6	B (VR)	Curtain Wall, Drywall, Wall Finish	All graduate students, 2 students had more than 2 years of professional experience

The graduate students group also struggled during the training session and some even accidentally disconnected from the simulation. Overall, it took longer for the graduate students group to complete the training session.

In the simulated pull plan session, however, the participants were more focused on their scope of work only and there was minimum communication or discussion across different trades. However, their internal discussions were more focused than the other groups. The curtain wall team specifically discussed where their materials should be stored and how they are going to sequence their work. Moderators were also asked more frequently for clarification on the model.

6.10 Experiment Summary

6.10.1 Experiment with Professionals at an Existing Project

Pull planning process in an actual project is a collaborative effort where each team presents their approach to the construction. In the observed project, the sessions were attended by large numbers of participants of more than twenty people from different trades. During the session, a number of participants talked at the same time, making an observation challenging.

There were several topics that arose during the session that were addressed in VR:

1. Location of a certain element on the ceiling area
2. The visualization of a mechanical component in the mechanical room

Even though not every participant had access to the VR headset, they were given access to a mirrored view through a large screen, where the superintendent instructed someone with the VR headset to go to a certain place in the virtual environment.

In the second phase, the session was conducted with a different group of trades. Compared to the first session, the scope of work discussed was much more specific. In the second session that was observed, the scope of work was activities in one of the elevator shafts.

6.10.2 Experiment with Students

The three student demographics demonstrated different ways of interaction in the pull planning sessions. Participants in the UW graduate students group demonstrated more knowledge than the others. However, it took them more time to get through the tutorial session.

In this phase, the students went through two phases of experiment. In the first phase, they had to develop the pull plan with the help of non-immersive medium live Navisworks. Meanwhile, in the second phase, the participant used VR for the visualization part.

Scenario A was used with the participants. In this session, the research team observed that two participants with more experience in the industry brought up logistic issues.

Regarding the model, participants tend to go through the model briefly but did not play the construction sequence at all. There were little interactions between group and discussions primarily occurred between participants in the same trade group.

Chapter 7 Discussion

7.1 Discussion

7.1.1 Virtual Reality and Shared Point of View

The study on the professionals indicated that having a shared point of view would be beneficial in a larger group. Below are several arguments supporting the shared point of view from the perspective of the researcher.

7.1.1.1 Time-saving

With current technology, the preparation time to get the headset ready for use takes at least 10 minutes per headset. The preparation time was attributed to powering the headset on, setting up boundaries in VR, launching the application, and setting up the multi-user session. While it is possible to cut the setup time by bypassing the boundaries setup, the headset setup time still increases as more people are involved in the meeting.

Setting up one headset to be used by an operator would save a considerable amount of time, while the rest of the meeting attendees are still able to see the model through a shared point of view. While it is arguable that it is no different from viewing the BIM model using BIM tools, the advantage of more intuitive control in VR would open possibilities of improving the flow of the meeting through the advantages of VR's more intuitive controls.

7.1.1.2 More cost-effective

The shared point of view should be more cost-effective since it only needs one headset as opposed to providing each meeting attendee with their own headset. It eliminated the additional cost of purchasing more headsets for use.

7.1.1.3 Enhances Knowledge Sharing

In a larger meeting, having a shared perspective makes the knowledge sharing more flexible. Since everyone is focused on the same perspective, the meeting would be able to focus on a specific detail and everyone else. Evidently, the observed interaction indicated such trend. During a pull plan session, there were several occasions where one of the trades were asking if there would be any work happening on the slab edge area and they asked the operator to show that area on a shared screen. Even though Revit models are designed to only display the simplified geometries that represent the actual building components, other trades were familiar with the area and responded with the requested information.

7.1.2 Virtual Reality and Individual Point of Views

Individual point of views was more prevalent in student group studies. There are some arguments that support the use of individual point of views based on the observation:

7.1.2.1 Enhances Learning Independently

The student participants typically had less experience than the professionals. Therefore, they needed to refer to the building models more frequently than the professionals. Since they had access to an individual point of view, they could study the building and sequences directly during the simulated pull planning process.

7.1.2.2 Supports Communication between Group Members

With the VR intervention, the student groups were found to discuss with their teammates, often discussing the sequence of activities or parts of the building that they thought should have been included in the simulation. However, it does not seem to contribute much to communications across different discipline groups. While they were still using the VR occasionally, the topic that the participants brought up were typically related to activities/work that they were assigned to.

7.1.3 Different impacts of VR intervention on various demographics

Based on the questionnaire, it was found that the professionals prefer time efficiency. The major drawback of the prototype that was used as the experimental tool was the time it took to setup as well as the risk of the system crashing in the middle of a session. If a project relies on such a system, the system needs to be updated to eliminate the time and stability issues.

As a visualization tool, the intuitiveness of inputs in VR made it easier for the operator to navigate through the model instead of having to learn various controls schemes of Navisworks or similar program. Unless the VR is highly customized, the professionals would prefer a conventional approach (shared POV).

For students, virtual reality did help in understanding the construction workflow and schedule. Based on the observations during the experiments, it enhanced discussions within the same team. For example, participants in the same team discussed how they would plan t he logistics of the curtain wall. Since the model was not detailed enough to display the logistics process, the participants had to discuss how they would bring the material on site and where to store it. However, during the observation there was little interaction between teams as most of the participants were occupied on their own teams.

7.1.4 Lessons Learned from implementing VR for pull planning

From the software standpoint, the implementation of VR for a pull planning session needs to address the features that would be useful to support the pull planning sessions. The research also encountered challenges when it came to recording quality.

On the study with professionals, it was near impossible to extract much information from the recording. The project that was used as the case study often implemented pull planning in a large scale with more than 20 participants. Due to the many people speaking at the same time, the recorded conversations were impossible to analyze except when the moderator was speaking.

Future studies should be able to address this issue by either conducting the observations in smaller groups or by providing more recording devices.

7.1.5 The importance of improving VR tools' quality

Feedback is key in improving a product's quality. Therefore, the VR tools should be continuously updated to support what the users actually need. User experience studies need to be conducted regularly not only to develop new features, but also to minimize faults that appear within the system.

7.2 Study Limitations

The study was designed to test the functionalities of the mobile VR prototype to support pull planning. To ensure that all student groups had the same experience, the study controlled the duration of the scenario and the responsibilities of each role. Since most students had no prior experience with pull planning, a set of pre-made commitments was provided as a reference.

The pre-set roles for student experiments was developed since it was expected that the students would not have sufficient knowledge in lean construction or pull planning processes prior to the studies. The roles were determined to be relatively easy to pick up: drywall, curtain wall, and wall finishes trades. MEP roles were considered during the pilot study. However, participant feedback indicated that the roles were too specific, and the participants had trouble developing their plans during the study.

The VR aspect of the pull plan was limited to model inspections and limited collaboration. The actual pull plan still occurred outside of the VR environment. During the pull plan, the participants were allowed to inspect the model with VR headsets, and they were given the opportunity to do so collaboratively with other participants. Similarly, in the non-VR teams, the participants were allowed to inspect the model on a non-immersive display.

The prototype that was used in this study was limited to local area network connection; a full networked connection was not possible due to the technical issues that the PI encountered during the prototype development. Therefore, this study was only conducted in a closed room within the same network. A remote collaboration was not possible at the time this study was conducted.

Another controlled aspect was the medium for pull planning. Instead of using a physical whiteboard, a digital whiteboard was provided. This allowed participants to develop their commitments on virtual sticky notes, which made it easier to record the sessions. Additionally, the chosen virtual whiteboard platform was accessible from various devices, so collaboration could be done remotely.

7.3 Future Studies

The current study acknowledges that pull planning can be chaotic, with multiple exchanges of information happening at the same time. The researcher found that the recorded conversations overlapped, making them difficult to identify. This made it challenging to break down the communication that occurred during the study. Future studies should address this issue by developing a better way to record the interactions, especially if they are using a real-world case study.

The study did not assess the impact of VR on project performance metrics such as PPC. If a future study is conducted based on this study, the observation should be extended beyond the pull planning sessions, as there are multiple outputs of pull planning, such as the weekly work plan or PPC.

The study was able to incorporate 6-DOF virtual reality and collaboration features into the prototype, but it was not able to fully utilize the collaborative aspect because it was only used for model review. Some limitations of the prototype include:

- There was no fully modeled avatar.
- The 3D markup was not perfect, and the 2D markup had a texture bug when ported to a mobile VR headset.
- The current state of the prototype did not allow for a full pull planning session.
- Models had to be brought in before compiling the prototype, so it was not possible to update or change the model components on the fly.
- Participants were not able to exchange documents in the VR environment.
- The VR prototype is a standalone application that is not interoperable with other tools.

Some of these features could be a great undertaking for a fully immersive remote collaboration pull planning platform. However, with iterative development, it is expected that future studies could produce interesting results if studied.

One of the issues with the study is the clarity of the recordings, especially the audio recordings. Future studies that investigate the VR intervention on pull planning should provide more recording devices and modify the pull plan setup. It would be better to provide a recording device for each trade group to mitigate overlapping conversation recordings. In addition, with a further developed prototype that allows multiuser connection in a separate network, the teams could be separated by trades. Each trade would participate from a different room. This would allow the analysis of the pull plan session to be done based on each trade's interaction. The current study was not able to do this because the recording file contained conversation from all participants.

7.4 Conclusion

Pull planning session is a process that is done to align goals between different trades who are involved in a construction project. During this approach, the researcher observed several themes that was brought up in addition to the one that became the main focus of the meeting. The use of VR helped with bringing the trades together to focus on the main discussion through a shared point of view.

This research also expanded our understanding of how virtual reality can be implemented in the context of AEC industry. Since visualization is the main advantage that VR is bringing to the table, it can be utilized in different parts of construction projects. Other studies highlighted the benefits of visualization during design review or preconstruction phases(Adams et al., 2014). Meanwhile, this study complemented them by highlighting the benefits of using VR during the construction phase.

7.4.1 Contribution to Industry

The prototype that was used in this study was intended to be a starting point for further development on a VR/XR/AR collaborative environment that would serve as a visual aid tool in pull planning process. It is not supposed to replace the established practices in pull planning. However, its development is expected to make VR/immersive environment as a visual aid option that industry professionals can use to help with the devision making. This solution can also be a more affordable solution

On the educational aspect, this tool can be expected to encourage students to learn pull planning process by helping them understand the sequence of major activities in the project. Through that process, the students is expected to find out that a pull plan process is more than having the construction sequence activity available to them.

Contribution to Body of Knowledge

This study is expected to be a point of departure for future research that aim to implement immersive environment on pull planning process. From the study that was conducted, it was observed that a shared VR screen is more efficient and affordable than individualized VR screen in the context of VR as a visual aid.

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APPENDIX 1 - INTERVIEW QUESTIONS FOR AEC PROFESSIONALS

Modeling Visual Aid Implementation for Lookahead Planning in Construction Industry

Interview Questions

Lucky Agung Pratama

Last Planner System Experience

- How long have you been practicing pull planning in your projects?
- How do you use a completed CPM as a reference?
- How frequently, within a project, the pull planning is used?
- What types of tools do you use to support the development of lookahead plan and weekly work plan?
- Who are usually involved in the pull planning process?
- Aside from sticky notes, do you use other documents to explain your schedule to the others?
- What are the limitations of documents that you usually use?
- If there is a conflict in the schedule, how do the parties find a solution?
- In what phase of the project typically a conflict occurs?
- If visualization would help the pull planning process, what would it be?

Project Performance Questions

- How do you resolve constraints that appeared in the project?
- What parameters do you use to measure the progress? How frequent do you measure it?
- How does the team define and forecast reliability?
- Has there been an occurrence where a stakeholder couldn't make it to the pull planning session? How does the team resolve the issue?

Clearinghouse Question

- Are there any issues that we have not yet discussed?

APPENDIX 2 SURVEY/QUESTIONNAIRE FOR PROFESSIONALS

Implementation of VR on a Pull Planning Process

Date: ______________________________

Section 1: Background

1. What is your current role in this project?

2. How long have you been in the industry?
    a. Less than a year
    b. 1-5 years
    c. 6-10 years
    d. More than 10 years
    e. Prefer not to answer

3. How long have you been working in your current company/organization?
    a. Less than a year
    b. 1-5 years
    c. 6-10 years
    d. More than 10 years
    e. Prefer not to answer

4. How long have you been involved in projects that utilize the pull planning process?
    a. Less than a year
    b. 1-5 years
    c. 6-10 years
    d. More than 10 years
    e. Prefer not to answer

5. What types of documents/tools that you typically use to help with decision making in a pull planning process? Choose all that apply

a. Printed 2D Plans/Drawings
b. Digital 2D plans/drawings.
c. Specs/Contract documents.
d. 3D models
e. A 4D model in Navisworks/Synchro/similar tools
f. Other, please specify.

Section 2: Pull Plan Experience

1. Which part of the VR platform helps you in the decision-making process?

2. Did you face any challenges trying to understand other team members' intent during the pull planning process? Please explain.

3. Did you feel other team members are having a hard time understanding your plans/commitments during the pull planning process? Please elaborate.

4. What do you wish the VR environment could do to help with the pull planning process?

Section 3: Features

After using the VR tool in the pull planning process, please rate the following features based on your experience.

	Features/Experience	**Very Easy**	**Easy**	**Moderate**	**Difficult**	**Very Difficult**
1	The ability to move around					
2	Speaking/communicating to other team members.					
3	Locating other team members					
4	Ability to see specific dates in the schedule.					
5	Identifying trades that owns certain models in the virtual environment					
6	Finding yourself in the map					

APPENDIX 3- SURVEY/QUESTIONNAIRE FOR STUDENTS

Implementation of VR on a Pull Planning Process

Date: ____________________________

Section 1: Background

1. What is/are your current major(s)?

2. How long have you been involved the AEC industry outside of UW?

3. Are you familiar with CPM scheduling?

4. Have you learned about pull planning prior to Fall 2022?

Section 2: Features

After using the VR tool in the pull planning process, please rate the following features based on your experience.

	Features/Experience	Does not apply	Very Easy	Easy	Moderate	Difficult	Very Difficult
1	The ability to move around						
2	Speaking/communicating to other team members.						
3	Locating other team members						
4	Ability to see specific dates in the schedule.						
5	Identifying trades that owns certain models in the virtual environment						
6	Locating yourself in the environment						
7	Joining a session						
8	Playing the construction sequence						
9	Changing model scale						
10	Navigating vertically						

Appendix 3 - SURVEY/QUESTIONNAIRE FOR CM STUDENTS

Implementation of VR on a Pull Planning Process

Date: ______________________________

Section 1: Pre-Test

5. What is/are your current major(s)?

6. How long have you been involved the AEC industry outside of UW?

7. Are you familiar with CPM scheduling?

8. Have you learned about pull planning prior to Fall 2022?

9. On a scale of 1 -7, how do you feel at the moment? (1 = extremely unwell, 4 = so-so, 7 = good/fine)

10. On a scale of 1 -7, what do you think of your knowledge of project scheduling? (1 = do not understand at all, 7 = Understand very well)

11. On a scale of 1 -7, what do you think of your knowledge on pull planning process? (1 = do not at all , 7 = Understand very well)

12. On a scale of 1 -7, what do you think of your understanding on pull planning? (1 is not well, 7 is good/fine)

c.

Section 2: Post-Experiment Qestionnaire

After using the VR tool in the pull planning process, please rate the following features based on your experience.

	Features/Experience	**Does not apply**	**Very Easy**	**Easy**	**Moderate**	**Difficult**	**Very Difficult**
1	The ability to move around						
2	Speaking/communicating to other team members.						
3	Locating other team members						
4	Ability to see specific dates in the schedule.						
5	Identifying trades that owns certain models in the virtual environment						
6	Locating yourself in the environment						
7	Joining a session						
8	Playing the construction sequence						
9	Changing model scale						
10	Navigating vertically						
11	Adding mark-up						

Section 3: Post-Experiment Question

1. On a scale of 1 -7, how do you feel at the moment? (1 = extremely unwell, 4 = so-so, 7 = good/fine)

2. On a scale of 1 -7, what do you think of your knowledge of project scheduling? (1 = do not understand at all, 7 = Understand very well)

3. On a scale of 1 -7, what do you think of your knowledge on pull planning process? (1 = do not at all , 7 = Understand very well)

4. On a scale of 1 -7, what do you think of your understanding on pull planning? (1 is not well, 7 is good/fine)

5. Which feature of the VR tool that you found the most difficult to access?

6. If there is anything in the VR tool that you would like to improve, what is it?

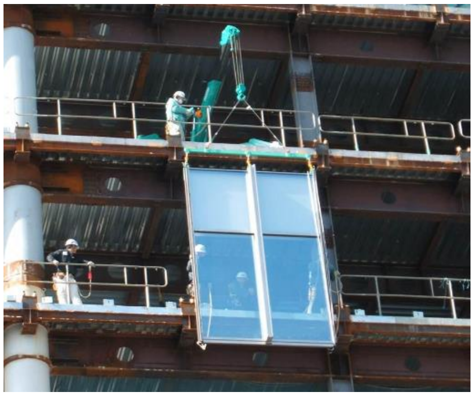
7. During the session, did you make any observation on the model? Which one was it?

8. During the session, was there any part of the process that you would have done differently? What is it?

9. Compared to the non-VR, how do you feel about navigating the project sequence in VR?

APPENDIX 4 CURTAIN WALL SUBCONTRACTOR SCENARIO

Curtain Wall



Curtain wall subcontractor

The curtain wall job starts after the roof and stair have been poured. But for the job to start right away, the materials for the curtain wall must be available on site at earlier time. The sub-contractor for the curtain wall is also responsible for installing the interior glass walls (storefronts) on the 2nd floor. Some tasks for the curtain wall contractor include:

- bringing in materials from the supplier
- storing the materials in a protected area (on the 1st and 2nd floors)
- installing the curtain wall frames/clamps
- installing weatherproofing for the exterior curtain wall (not applicable for storefronts)
- installing the curtain wall structure (sills and mullions)
- installing the curtain wall glass, and curtain wall inspection.

Note: you are welcome to come up with additional activities.

APPENDIX 5 - DRYWALL SUBCONTRACTOR SCENARIO

Drywall Subcontractor

- The drywall subcontractor is responsible for installing interior walls of the building.
- The drywall subcontractor is also responsible for installing drywall insulation before the walls are installed.
- The drywall work is done in stages starting from the first floor.
- While the subcontractor is working on the drywall, ensure that there are no materials that can interfere with the work.
- Some of the drywall subcontractor's tasks include:
    - Bringing in and storing materials
    - Installing drywall insulation after the drywall frame is installed (the drywall framing work is done by another subcontractor)
    - Installing drywall
    - Taping and mudding the drywall (to ensure a smooth finish).

APPENDIX 6- WALL FINISHES SUBCONTRACTOR SCENARIO

Wall finishing subcontractor:

- The wall finishing work can begin as soon as the first floor walls are finished.
- During the wall finishing work, the room must be sealed to prevent the smell of paint from spreading to other parts of the building. Therefore, make sure no other contractors are working in the painted area
- For drywall painting, ensure that the drywall subcontractor has completed the drywall taping
- The wall finishing on the second floor can begin after the staircase is finished being built.

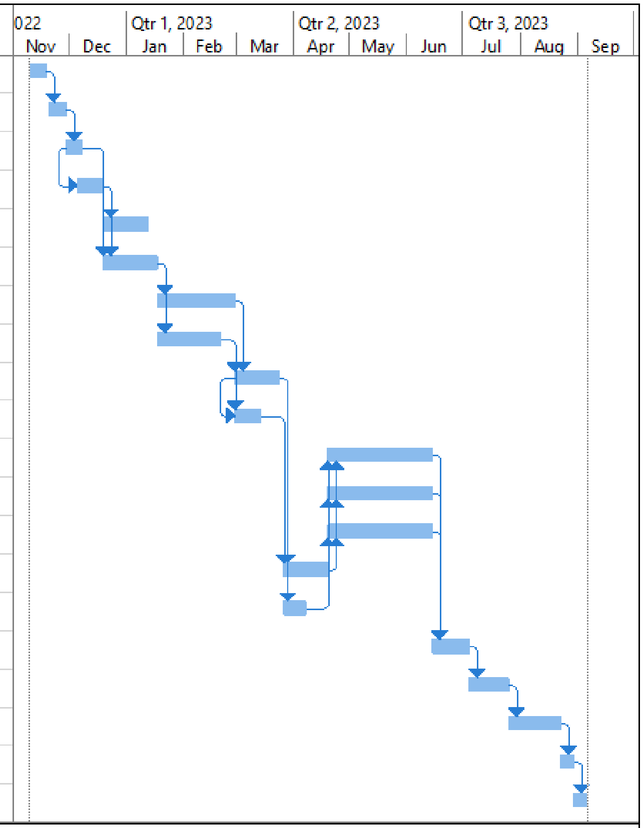
APPENDIX 7 - NAVISWORKS QUICK GUIDE

Navisworks is one of the tools that has several functions such as model coordination, quantity takeoff, and 4D simulation. In this experiment, we will use Navisworks for 4D simulation. Some of the Navisworks features that will be used in this study are:

- Selection Tree: In the selection tree, we can explore the different parts of the model that are opened in Navisworks. This model hierarchy is automatically created by Revit.
- Sets: Sets are used to group some components of the model. When one set is clicked, Navisworks will highlight the components stored in that set and we can view them in the Selection Tree. To access Sets, open the Sets drop-down menu and select manage sets.
- Timeliner: This tool can visualize the project schedule of the model opened in Navisworks. Essentially, the timeliner will transfer task data and schedule from Ms Project/Primavera/CSV files, and then connect each task with the model we choose from the selection tree or sets. The timeliner has four tabs: Tasks, Data Sources, Task Types, and Simulate. For the purposes of this experiment, use the Simulate tab on the Timeliner tool to run the project schedule simulation. The Navisworks file has been designed in such a way that the model and project schedule can be simulated. To inspect the models linked to tasks, use the Task tab on the timeliner tool (see the Attached section).

APPENDIX 8- SCENARIO A SCHEDULE

ID	Task Name	Duration	Start	Finish	Predecessors
1	Foundation	7 days	Thu 11/10/22	Fri 11/18/22	
2	Slab	7 days	Mon 11/21/22	Tue 11/29/22	1
3	L1 Columns	7 days	Wed 11/30/22	Thu 12/8/22	2
4	L2 Beams	10 days	Tue 12/6/22	Mon 12/19/22	3SS+4 days
5	L2 Slab	18 days	Tue 12/20/22	Thu 1/12/23	4
6	L2 Columns	21 days	Tue 12/20/22	Tue 1/17/23	3,4
8	Stairs	30 days	Wed 1/18/23	Tue 2/28/23	6
7	Roof deck	24 days	Wed 1/18/23	Mon 2/20/23	6
9	L1 Exterior Walls	18 days	Wed 3/1/23	Fri 3/24/23	7,8
10	L1 Interior Walls	10 days	Wed 3/1/23	Tue 3/14/23	7,9SS
18	HVAC Installation	40 days	Thu 4/20/23	Wed 6/14/23	11,12
19	Electrical	40 days	Thu 4/20/23	Wed 6/14/23	11,12
20	Plumbing	40 days	Thu 4/20/23	Wed 6/14/23	11,12
11	L2 Exterior Walls	18 days	Mon 3/27/23	Wed 4/19/23	9,10
12	L2 Interior Walls	10 days	Mon 3/27/23	Fri 4/7/23	9
14	L2 Storefront	14 days	Thu 6/15/23	Tue 7/4/23	18,19,20
15	Ceiling	15 days	Wed 7/5/23	Tue 7/25/23	14
13	Curtain Wall	20 days	Wed 7/26/23	Tue 8/22/23	15
16	Interior Doors	5 days	Wed 8/23/23	Tue 8/29/23	13
17	Exterior Doors	5 days	Wed 8/30/23	Tue 9/5/23	16



Project: Office Building Project

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

Page 1

APPENDIX 9- SCENARIO B SCHEDULE

ID	Task Name	Duration	Start	Finish
1	Site Construction	247 days	Mon 2/29/16	Tue 2/7/17
2	Foundation Excavation	5 days	Mon 2/29/16	Fri 3/4/16
3	Structural Piles	20 days	Mon 3/7/16	Fri 4/1/16
4	Backfill / Compact Foundation Excavation	5 days	Mon 4/18/16	Fri 4/22/16
5	Crushed Gravel, Ground Floor	5 days	Mon 7/11/16	Fri 7/15/16
6	Road / Parking Lot Pavement	6 days	Wed 1/18/17	Wed 1/25/17
7	Site Improvements and Landscaping	48 days	Wed 12/21/16	Fri 2/24/17
8	Pile Caps	10 days	Mon 4/4/16	Fri 4/15/16
9	Grade Beams	10 days	Mon 4/25/16	Fri 5/6/16
10	Slab on Grade	3 days	Mon 7/18/16	Wed 7/20/16
11	Slab on Deck, 1st Floor, Area 1	4 days	Thu 7/21/16	Tue 7/26/16
12	Slab on Deck, 1st Floor, Area 2	2 days	Wed 7/27/16	Thu 7/28/16
13	Slab on Deck, 1st Floor, Area 3	3 days	Fri 7/29/16	Tue 8/2/16
14	Slab on Deck, 2nd Floor / Low Roof	0 days	Wed 8/3/16	Wed 8/3/16
15	Slab on Deck, High Roof	0 days	Thu 8/4/16	Thu 8/4/16
16	Base Plates	3 days	Wed 4/27/16	Fri 4/29/16
17	Structural Framing, Area 1	8 days	Mon 5/16/16	Wed 5/25/16
18	Structural Framing, Area 2	8 days	Thu 5/26/16	Mon 6/6/16
19	Structural Framing, Area 3	10 days	Tue 6/7/16	Mon 6/20/16
20	Structural Framing, Area 4	9 days	Tue 6/21/16	Fri 7/1/16
21	Exterior Stairs	8 days	Tue 9/27/16	Thu 10/6/16
22	Interior Stairs, Ground Floor	5 days	Wed 8/3/16	Tue 8/9/16
23	Interior Stairs, First Floor	5 days	Thu 8/4/16	Wed 8/10/16
24	Exterior Metal Siding / Backup Framing (Front)	6 days	Fri 8/5/16	Fri 8/12/16
25	Exterior Metal Siding / Backup Framing (Left)	10 days	Mon 8/15/16	Fri 8/26/16
26	Exterior Metal Siding / Backup Framing (Back)	12 days	Mon 8/29/16	Tue 9/13/16
27	Exterior Metal Siding / Backup Framing (Right)	7 days	Wed 9/14/16	Thu 9/22/16
28	Exterior Metal Siding / Backup Framing (Mechanical Room)	12 days	Fri 9/23/16	Mon 10/10/1
29	Blockwork / Elevator Shaft	4 days	Mon 8/1/16	Thu 8/4/16
30	Exterior Doors, Frames, Hardware	4 days	Tue 9/27/16	Fri 9/30/16
31	Interior Doors, Frames, Hardware	6 days	Wed 12/21/16	Wed 12/28/1
32	Glass Curtain Wall	20 days	Mon 8/15/16	Fri 9/9/16
33	Punched Windows (Left)	4 days	Mon 9/12/16	Thu 9/15/16
34	Punched Windows (Right)	0 days	Mon 9/26/16	Mon 9/26/16
35	Punched Windows (Mechanical Room)	0 days	Tue 10/11/16	Tue 10/11/1
36	Partition Walls, Ground Floor	10 days	Wed 11/9/16	Tue 11/22/1
37	Partition Walls, 1st Floor	10 days	Wed 11/23/16	Tue 12/6/16
38	Partition Walls, 2nd Floor	10 days	Wed 12/7/16	Tue 12/20/1
39	Roof Parapet Cap / Trim	10 days	Wed 11/9/16	Tue 11/22/1
40	Mechanical Room Louvers	4 days	Tue 10/11/16	Fri 10/14/16
41	Glass Skylight	5 days	Thu 11/10/16	Wed 11/16/1
42	Elevator	50 days	Wed 8/17/16	Tue 10/25/1
43	Domestic Water/Sanitary Sewer	20 days	Wed 8/17/16	Tue 9/13/16
44	Toilet Room Fixtures / Trim	8 days	Wed 1/11/17	Fri 1/20/17
45	Air Handling Unit	20 days	Wed 11/23/16	Tue 12/20/1
46	Ductwork	10 days	Wed 12/21/16	Tue 1/3/17
47	Registers / Grilles / Diffusers	10 days	Wed 2/8/17	Tue 2/21/17
48	Main Switch Gear / Panelboards	25 days	Wed 11/23/16	Tue 12/27/1
49	Electrical Distribution	35 days	Wed 11/9/16	Tue 12/27/1
50	Electrical Devices	10 days	Wed 12/28/16	Tue 1/10/17