Effects of Using Virtual Reality on AEC Team Collaboration

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Abstract

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Construction projects require coordination of different disciplines, which makes knowledge management and information exchange crucial in design and construction teams. Building Information Modeling (BIM) is a powerful technology for communication and information management but has limitations in terms of the ways project stakeholders interact with design visualizations. The current method of collaboration with BIM limits the participation of all team members since the 3D model is presented on a 2D shared screen while one person has the control over the viewpoint and can create markups. Virtual Reality (VR) is a technology that provides an environment that enables each participant to have their individual point of view and markup tool while virtually collaborating with other team members in a simulated walkthrough of the project. Designers and builders need to exchange disciplinary knowledge while they vet design alternatives during different phases of the project. Project team members have in-depth knowledge in the area of their expertise, but they share a part of their knowledge understandable by other team members in explaining design ideas, disciplinary constraints, and technical analysis to collaborate, find solutions, and make decisions. This phenomenon is referred to as Shared Understanding. This dissertation studies the effects of VR's immersive environment and markup tool capabilities on building Shared Understanding among AEC project team members in asynchronous and synchronous 3D coordination processes. The research study results show that VR's immersive environment can provide a better understanding of the model to the users in comparison to BIM, and it can assist in understanding the design issues and system conflicts. Most of the participants in the asynchronous research study preferred VR over BIM to understand the technical annotations made by VR's markup tool in the 360-degree environment while BIM provides markups on a 2D screenshot of the 3D model. They also found verbal communication in VR more effective than text in the BIM platform. The synchronous research study results show that teams spent less time in VR to build Shared Understanding of the team decision. The 3D coordination meeting duration in VR was significantly lower than the meeting duration where teams used BIM. Participants found VR's markup tool capabilities and immersive environment as features missing in BIM that assisted in team collaboration and building Shared Understanding, however there were reported drawbacks in collaboration in VR. Team members could get disoriented in the 360-degree environment and the team leads were not always sure if all team members are following the markups in the environment.

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Dedication

I would like to dedicate my thesis to

my beloved parents.

Chapter 1: Introduction

1.1 – Background

Construction projects require coordination of different Architecture, Engineering, and Construction (AEC) disciplines, which makes knowledge management and information exchange crucial in design and construction teams (Carrillo and Chinowsky, 2006; Javernick-Will and Scott, 2010). Designers and builders need to exchange disciplinary knowledge while they vet design alternatives during different phases of the project. Project team members have in-depth knowledge in the areas of their expertise, but they share a part of their knowledge understandable by other team members in explaining design ideas, disciplinary constraints, and technical analysis to collaborate, find solutions, and make decisions. This phenomenon is referred to as Shared Understanding. Kleinsmann and Valkenburg (2010) described Shared Understanding with a simple example of an electrical engineer having a conflict with an ergonomist regarding the design of a circuit board. The electrical engineer tries to explain the maximum amount of space needed for the circuit board by using drawings and mathematical formulas, while the ergonomist tries to explain the maximum space requirement by providing human body movement theories. Neither understand the deep disciplinary reasons provided by the other party, but they have a Shared Understanding of the problem which is the maximum amount of space required for the circuit. Prior studies suggest that Shared Understanding is highly desirable for interdisciplinary teams as it has a positive effect on team performance (Langan-Fox et al., 2004; Mathieu et al., 2000), team member satisfaction (Langan-Fox et al., 2004), coordination of activities among team members (Hsieh, 2006), innovation (Kleismann et al., 2010), reduction of iterative loops and re-work (Kleismann et al., 2008), and team morale (Darch et al., 2009).

Shared Understanding is studied in Psychology, and researchers from other disciplines adapt psychological research methods to their discipline to conduct research studies on this topic. The term ‘Shared’ in Shared Understanding refers to “similarity, agreement, convergence, compatibility, commonality, consensus, consistency, and overlap” (Mohammed et al., 2010). The term ‘Understanding’ is the ability to exploit bodies of knowledge to accomplish cognitive and behavioral goals (Smart et al., 2009). Team members represent the understanding of their environment in the form of Mental Models (Langan-Fox et al., 2000). Mental Models are organized knowledge structures that let each team member interact with their environment and helps to predict and explain environmental behaviors or understand the relationship between different components (Rouse and Morris, 1985). Shared Mental Model and Shared Understanding are used interchangeably in the literature. To study Shared Understanding, the Mental Model of each team member need to be elicited. Mental Model elicitation methods including cognitive interview, content analysis, card sorting, observation, questionnaires, etc. (Langan-Fox et al., 2000 & Mehmet et al., 2015) capture the research-related concepts and the relationship between them in the individual Mental Model. Figure 1.1(a) shows the structure of four team members’ individual Mental Models that consist of concepts and links between them based on their relationship. The shared concepts and links among the team members’ individual Mental Model structures represent Shared Mental Model (Johnson and O’Connor, 2008). Figure 1.1(b) shows the Mental Model that is shared among all four team members, which represents the team’s Shared Understanding.

New and emerging technologies present questions regarding how technology tools can support design and construction and facilitate building Shared Understanding among team members to

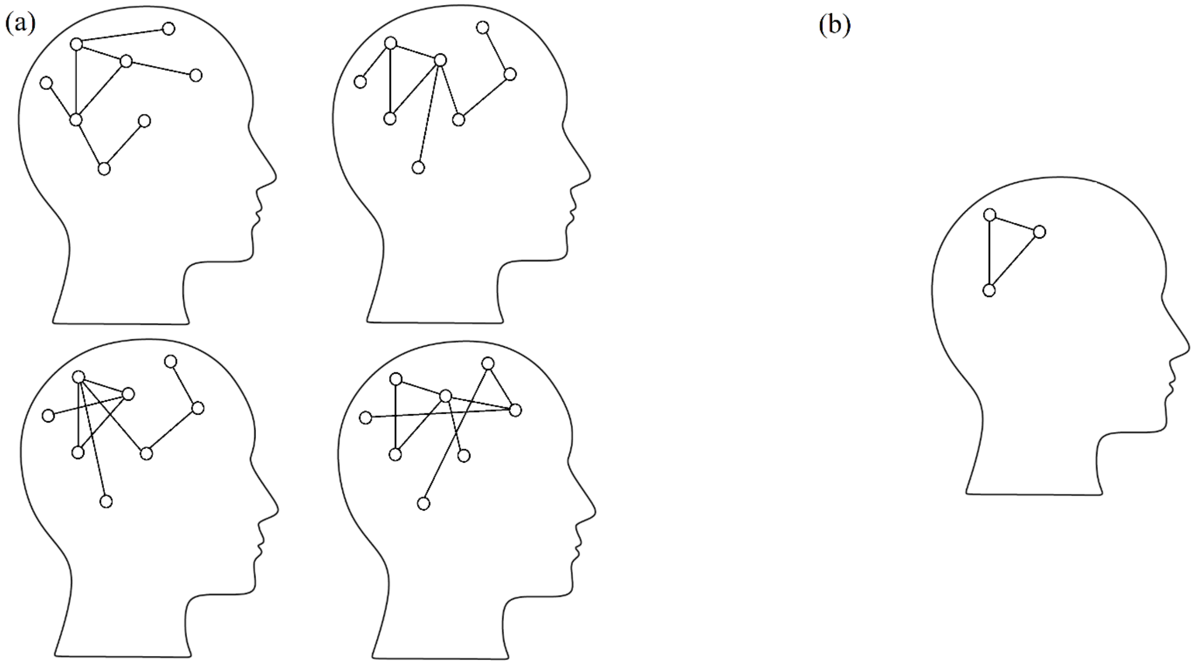

Figure 1.1 – Mental Model: (a) Individual Mental Models, (b) Shared Mental Model

make team decisions. One of the technologies practiced in the AEC industry is Building Information Modeling (BIM). BIM is a “digital representation of physical and functional characteristics of a facility." It is used by different AEC project stakeholders at different phases of the life cycle of a facility to insert, extract, update, or modify information to support and reflect the roles of that stakeholder. It is a shared knowledge resource for information about a facility that forms a reliable basis for making decisions at different phases of the project. (NIBS, 2008). While in traditional design and construction processes, two-dimensional (2D) drawings were used to communicate the technical work, BIM introduced a platform in which three dimensional (3D) objects and spaces could be created with information attached to them that allows the project team to create a simulation of construction projects using project schedule (4D BIM), perform a model-based estimation with cost information (5D BIM), do sustainability analysis (6D BIM), and manage the facility with asset data (7D BIM).

A total of twenty-five BIM uses are defined in the AEC industry with fourteen being the primary and eleven being the secondary BIM use (Messner et al., 2019). Two primary BIM uses of “3D Coordination” and “Design Review” were studied in this dissertation. The 3D coordination is a process in which 3D models of the building systems are compared to identify the conflicts between the 3D geometries to eliminate field conflicts and coordination issues before installation. This process starts from the design phase and concludes by the end of the construction phase before the owner starts operating the facility (Messner et al., 2019). The 3D coordination process is typically managed by a project team member, BIM Coordinator, who runs clash detection tests between different building systems using a BIM software like Autodesk Navisworks (https://www.autodesk.com/products/navisworks/overview) to find the conflicts and intersections of the systems as well as noting any required design changes that need to be applied to the models. Since the project team typically deal with a considerable number of clashes and design changes throughout the project, the BIM Coordinator selects the most important issues that require the involvement of multidisciplinary project team members in resolving them to be discussed in 3D coordination meetings. The rest of the issues are asynchronously coordinated through documentation with model markups that are created using BIM markup tool, like the Review tool in Autodesk Naviswroks.

The design review is a process in which project stakeholders view a 3D model to give feedback and validate the design aspects that include previewing of the space aesthetics and layout and setting criteria for ergonomics, lighting, textures, colors, etc. This process starts from the planning phase and concludes by the end of the design phase before the construction starts. It supports the communication of the design to the owner, the construction team, and end-users (Messner et al., 2019). Design review is practiced in the AEC industry by using BIM software and viewing a 3D model on a flat-screen, or by using immersive technologies like immersive Virtual Reality (VR).

VR is a computer-generated environment experienced through senses (Jerald, 2015). VR is capable of simulating the senses of vision, hearing, touch and even smell. It can also allow users to interact with the virtual environment. Unlike BIM software packages where features are already defined within the program, VR content can be created in gaming engines like Unity, which allows the creators to add customized features to the interface. Researchers in the AEC industry have studied the application of VR for design review (Dunston et al., 2007 & Castronovo et al., 2013 & Berg, 2014 & Maldonado et al., 2016 & Liu et al., 2017 & Liu et al., 2019), construction scheduling (Whisker et al., 2003 & Pratama, 2015), site planning (Al-Adhami et al., 2018), and facility management (Nopachinda & Ergan, 2016). In these research studies, different VR technologies were utilized including power wall, Cave Automatic Virtual Environment (CAVE), and Head-Mounted Display (HMD). Power wall and CAVE are projected-base VR technology where the model is projected on large screens. In power wall, large screens are set in a way that they create a curved screen. In CAVE, model is projected on the walls of the room-sized cube. The most affordable immersive VR hardware that can be used individually is HMD. The HMD headset blocks the users' view of the surrounding physical environment and immerses the user in a virtual environment. Two types of HMD hardware are currently available in the market. Hardware with three degrees of freedom (3DOF) tracks the head orientation and enables the users to look around in different directions while the virtual viewpoint is fixed, meaning, in a virtual team setting, all users are located at one point, and their head is fixed in one location in the virtual environment. Hardware with six degrees of freedom (6DOF) tracks both the head orientation and body location, which enables users to look around in virtual space and walk around to explore the world. In virtual team settings, team members can see each other as avatars. Avatars are visual representations of team members, which can be defined in different shapes like a human body or just a sphere to show the location of the team member in the virtual space.

While platforms like BIM and VR can represent designs digitally, the project team may also request the contractor to build physical mockups. Physical mockups are typically full-sized representations of the proposed construction, built for evaluation of proposed design and construction. They are usually built for complex and unique structures or costly or highly repeatable units of the building. Different types of mockups are built for a specific purpose at various phases of the project. Visual mockups are usually requested by the owner/design team to support making decisions on design options like the selection of materials. Performance mockups are built for testing the integration of assemblies and engineering performance. Prototype mockups are built for developing and testing custom assemblies. Field mockups are on-site mockups built adjunct to building prior to installation on building. The in-place mockup is built for installation quality assurance (Maing, 2012). In this dissertation, the full-sized visual physical mockup was studied that is used for the design review process.

Currently, in the AEC industry, BIM as the digital platform and mockups as the physical platform are used for multidisciplinary team collaboration. While VR simulates reality, it lacks some features to replicate the physical environment fully. Comparison of two environments of virtual with physical raises questions regarding the extent to which VR can be reliable to represent a final physical building to support design decision making, and whether Shared Understanding built among team members on design issues and their resolution will be similar in both virtual and physical environments.

BIM represents a 3D model on a shared 2D screen, and in current BIM practices, only one team member has control over the viewpoint and can apply BIM software tools. VR enables project participants to have an individual viewpoint and be immersed in the digital 3D model or look at a smaller scale and section of it from different angles. Moreover, team members can have customized tools that could support team communication. The additional features in VR in comparison to BIM suggest that VR could be a more effective tool to build Shared Understanding among multidisciplinary team members in construction projects than BIM.

1.2 – Research Question

The goal of this dissertation was to evaluate the effects of using VR on building Shared Understanding among multidisciplinary team members in construction projects. VR has mostly been used for design review and showcasing the final design to non-technical end-users in current industry practices. As a result, a practical use case for professionals with multidisciplinary backgrounds needed to be determined to base the research study. The Primary Investigator (PI) initiated this research project with a pilot study in collaboration with AEC industry partners to evaluate whether VR mockups can replace physical mockups in terms of supporting team decisions on the design options. The PI was specifically interested in comparing the Shared Understanding built among team members in two platforms of VR and physical mockups. For this purpose, an experiment on a hotel project was conducted with the employees of participating AEC industry partners to compare a VR mockup with a physical mockup of a hotel room. The decision to conduct the pilot study was made when the physical mockup was built and fully furnished. It was expected that basing the experiment on the finished mockup would result in less complex disciplinary conversations, so, team members would face fewer challenges in understanding disciplinary information provided by others. As a result, the team

Shared Understanding would be only affected by the environment. To confirm this assumption, team members completed a survey to reflect on whether they had challenges in understanding technical information shared by other disciplines or thought others could not understand them. Based on the data collected from the questionnaires and the observations, team members did not have difficulties in building Shared Understanding of the technical information provided by professionals from different disciplines. This confirmed the PI's assumption and resulted in evaluating the effects of the only one independent variable, environment, on building team Shared Understanding. The pilot study results revealed that currently VR mockups cannot fully replace the physical mockups due to the limitations in today's technology and the need for physical samples. The Shared Understandings derived from two platforms of VR and physical mockups were different in this pilot study since individual team members had different understandings of the VR mockup due to differences in dimension perception. Furthermore, lack of touch sense that allows the users to walk through walls and furniture, and unrealistic simulations, like the lack of ability to see their body in the virtual environment, prevented them from having a good understanding of the space. Although the participating AEC industry partners did not find the VR mockup a practical use case for replacing the physical mockup, they provided some recommendations for potential use cases based on their experience in the pilot study. The architects suggested using VR for design review in early design phase to evaluate conceptual ideas and layout. The participants from the Structural Engineering Firm found VR useful for structural system selection in the early design phase. They also found it a useful tool for visualizing clashes between their structural system and Mechanical, Electrical, and Piping (MEP) systems, which is performed in 3D coordination process. The General Contractor suggested using VR mockup to get feedback from the project team before building the physical mockup which could save time and money in rework. They also saw benefits of using VR for 3D coordination.

Based on the feedback from the industry partners in the pilot study, the PI focused on the application of VR for 3D coordination. A preliminary research study was conducted to understand how Shared Understanding is built among AEC team members in construction projects using current technology tools, and which VR features and customized tools could facilitate building Shared Understanding by addressing the limitations in current technology tools. For this purpose, interviews with AEC professionals, and observational studies of two medical projects were conducted.

The preliminary research study results revealed the following factors to have a significant impact on building Shared Understanding: (1) visualization, (2) voice tone, facial expression, and body language, (3) collaboration in the same space. VR's immersive environment provides better visualization of the model to the project team members in comparison to BIM where the 3D model is projected on 2D display. Project teams prefer face to face meetings where voice tone, facial expression and body language help them understand if the technical information is grasped by everyone in the project team. If teams meet virtually, they would be able to communicate by voice and partial body language can be captured by avatars in 6DOF VR. Another reason for preferring face to face meetings is that team members can work together in the same space with shared access to project resources and collaboration tools. While video conferencing can capture facial expression and partial body language with shared screens, it has limitations in terms of providing a shared collaboration space to allow team members to actively work together. As a result, the team prefers to spend the co-location time to meet face to face.

It was observed that in the shared collaboration space, team members draw sketches and markups together and use hand to point out to building system parts to discuss design options and resolutions. VR can provide a shared virtual environment for collaboration. A customized tool that would allow members to point out building system parts and create drawings and markups was specified as another potential VR feature to facilitate building Shared Understanding. This tool, which is called the VR markup tool in this dissertation, could address the limitations in ways team members interact with 3D models using BIM. While markups are created on a 2D screenshot of the 3D model using BIM's markup tool, they can be created in a 360-degree environment in VR. Since each individual has the VR markup tool, they can simultaneously create markup together on the 3D model while the BIM platform only allows one person to use BIM's markup tool.

The PI selected a mobile-based VR Application equipped with markup tool, which supports 3DOF. As a result, the avatar's body language captured in 6DOF VR was eliminated as one of the VR features that could impact team Shared Understanding. To eliminate the effects of facial expression and body language, team collaboration was studied in the remote 3D coordination process. The research question was then developed as follows.

Q: How do VR's immersive environment and markup tool capabilities affect building Shared Understanding among AEC team professionals in remote 3D coordination process?

1.3 – Research Approach

This research study was designed to evaluate the effects of VR's immersive environment and markup tool capabilities on AEC team collaboration in both asynchronous and synchronous 3D coordination. In the asynchronous collaboration study, the focus was on evaluating the VR features with regards to an individual's understanding of the model and their effect on communicating design issues and resolutions in a one-by-one offline collaboration. In the synchronous collaboration study, the VR features were evaluated at the team level to understand how they could facilitate building Shared Understanding among AEC team members to explain the design issues, discuss resolution options, and make team decisions in a 3D coordination meeting. For both the asynchronous and synchronous studies, the experimental research method was selected, and the BIM platform was considered as the control platform for comparison with VR. To design a controlled experiment, the BIM platform was set up in a way that it provided the same three degrees of freedom experience in 3DOF VR as for the BIM users.

The field of view in both the BIM and VR displays were set up the same. In the BIM platform, the experiment participants explored the model by looking at a monitor screen, while in 3DOF HMD, the same content was projected directly on their eyes, providing them an immersive experience inside the model. The markup tool capabilities for asynchronous collaboration include creating markup in VR's 360-degree environment and verbal communication during markup creation that allows the user to explain the conflicts and propose solutions simultaneously with creating markup. This was evaluated in comparison to BIM's markup tool capabilities that allow the user to use text and draw markup on the 2D screenshot of the 3D model. The markup tool capabilities for the synchronous collaboration include allowing team members to simultaneously create markups together in VR's 360-degree environment.

1.4 – Thesis Structure

This thesis consists of six chapters. Chapter 1 explains the formation of the research question, the research study approach, and the connection between the chapters to address the research questions. Chapters 2 represents the pilot study of comparing a VR mockup with a physical mockup. The preliminary study that was conducted to understand how Shared Understanding is built in current industry practices with technology tools and how VR could facilitate building Shared Understanding by addressing the gaps in current technology flaws is presented in Chapter 3. Chapter 4 represents the two experiments that study the effects of VR's immersive environment and markup tool capabilities on an individual's understanding of the design and construction issues and proposed solutions and communicating them to the team. Chapter 5 includes the final experiment that studies the effects of using an immersive VR platform enabled with markup tool capabilities on building Shared Understanding in globally distributed AEC teams. Chapter 6 provides a discussion on the research study results and their contribution by answering the research question. It then proposes future studies.

Chapter 2 describes the pilot study that was conducted in collaboration with AEC industry partners. An Architecture Firm, a Structural Engineering Firm, and a General Contracting Firm participated in this research study. The goal was to evaluate to what extent the AEC team can rely on VR mockup as a replacement of the physical mockup to make decisions on the proposed design, and whether the Shared Understanding built in both platforms are the same. The selected research method was experiment where participants were exposed to a hotel room physical mockup and its digital VR mockup. Experiment participants were volunteer employees from the participating AEC industry partners. The experiment was video recorded for observational study purposes. Questionnaires were designed to capture the individual team members' understanding of both platforms of VR and physical mockup and their reflection on platform comparison. These questionnaires are represented in Appendix A. Based on the industry partners' feedback in the pilot study, VR mockup was not approved as a replacement for physical mockup, but 3D coordination was suggested as a practical use case to base the later research studies on.

The PI conducted a preliminary study to explore how Shared Understanding is built among multidisciplinary project team members in current industry practices and which VR features could facilitate building Shared Understanding in the 3D coordination process as presented in Chapter 3. Interviews with seventeen professionals with different AEC backgrounds and observational studies of two medical projects were conducted. The interview tool is attached to this thesis in Appendix B. Among the potential VR features that could facilitate building Shared Understanding, VR's immersive environment and markup tool capabilities were selected to be studied in this research project. Based on the results from chapters 1 and 2, the PI conducted a research study to evaluate the effects of the selected VR features on building Shared Understanding among multidisciplinary team members in both asynchronous and synchronous 3D coordination processes in comparison to current BIM-based industry practices.

Chapter 4 presents the research study conducted on asynchronous 3D coordination that evaluates the effects of using VR on the individual's understanding of the design issues and proposed solutions and communicating them to other team members. In this study, an experimental research method was selected. The experiment participants were University of Washington (UW) graduate students with different AEC backgrounds, mostly enrolled in the Construction Management program. Two controlled experiments were designed where participants were exposed to a model in both BIM and VR platforms. One experiment focused on the effects of VR's immersive environment on individual's understanding of the model. This was evaluated in comparison to the control platform of BIM's representation of the 3D model on the 2D screen. In this experiment, individuals' understanding of the model as well as their ability to recall the model was evaluated. The participants' reflections of their experience in both digital platforms and their comparison were captured by questionnaires. These questionnaires are presented in

Appendix C. The data collected from the questionnaire is represented in Appendix D. The second experiment was designed to evaluate the efficiency of the VR’s markup tool capabilities for asynchronous collaboration on individual’s understanding of the design issues and proposed solutions.

Chapter 5 presents the research study on remote synchronous 3D coordination meetings. The experimental research method was selected, and an experiment was designed to study the effects of VR’s immersive environment and markup tool capabilities on team Shared Understanding. Six groups of four students participated in this study with four different roles of the architect, structural engineer, mechanical subcontractor, and piping subcontractor. Each group met online to discuss a change in structural design that was affecting three team members’ scope of work. Participants collaborated in both platforms of BIM and VR and worked on two comparable scenarios. Each individual’s understanding of the shared technical information and the proposed solution was captured by questionnaires and the meetings were video recorded for observational study purposes. The experiment description, guidelines, and questionnaires are presented in Appendix E.

Chapter 6 discusses the results achieved from the research studies explained in chapters 2 to 5 and explains how they address the research question. It also provides the next steps by proposing future studies that can be built upon the results of this thesis.

Chapter 2: Immersive Virtual Reality Mockup versus Physical Mockup: Effects of Immersive Virtual Environment on AEC Team Decision Making Process

2.1 – Abstract

This chapter presents the results from an academic-industry partnership where a team of university researchers and architecture, engineering, and construction (AEC) professionals compared a physical mockup to an immersive virtual reality (VR) environment. The goals of this research were to understand how and in what ways VR can replace the use of physical mockups. The study included an experiment where two groups of AEC professionals reviewed a physical mockup and a VR mockup of the same hotel room layout. Group members were asked to evaluate each mockup from the standpoint of hotel guests and housekeeping and suggest design changes based on their professional expertise individually. The groups were then asked to discuss the design together and make a team decision. At the end of the experiment, participants reflected on how the VR mockup did or did not meet their needs in reviewing the room design. The findings from this study show that VR cannot yet fully replace physical mockups due to the user dimension perception, lack of touch sense, unrealistic simulation in VR, and the need for physical samples. However, it also revealed that VR could be a cost-efficient tool to look at design options and layout in early design phase and get feedback from the project team and end-users before the construction of the physical mockup to save potential time and money in rework. They also suggested using VR for 3D coordination and visualization of the conflicts between different building systems.

2.2 – Introduction

There has been a renewed interest in Virtual Reality (VR) tools in recent years due to new technology developments. New viewers, platforms, and cameras are emerging on the market that push the Virtual Design and Construction (VDC) teams in architecture, engineering and construction (AEC) industry into testing these new systems. These professionals are fluent in creating Building Information Models (BIMs) for design and construction uses. The new emerging technologies present questions about how VR can support design and construction. BIMs are displayed as 3D models of designs on 2D display systems for teams of AEC professionals and their clients to study and explore. While the 2D display systems allows for first-person navigation of the model, the first person has a limited perspective where it is difficult to gauge dimensions in space. Some 2D display system software allows for adding an avatar, a human representation, to the scene to help give a sense of scale. However, this view still has limitations for understanding dimensions and space. VR introduces a new display system where the user is immersed in the world.

Virtual reality simulates the reality that human beings experience in the real world. It is a computer-aided technology that gives the user a sense of being in a virtual world. In the context of this paper, the AEC industry partners were interested in studying the immersive VR environment that surrounds a user with three-dimensional representations using head-mounted display (HMD) hardware. Two types of HMD hardware are currently available in the market. One type has three degrees of freedom (3DOF), meaning, three rotational movement of the head is supported. It allows users to look around in different directions while the virtual viewpoint is fixed. The second type has six degrees of freedom (6DOF), meaning, both the head rotational and body transitional movements are tracked. This allows the users to look around in virtual space and walk around to explore the world in the first-person perspective through their own eyes. The 6DOF technology is more difficult to get right due to body location traction, and the headset needs to be calibrated to the height of the individual for best results.

Physical mockups are typically the full-sized representation of the proposed construction, built for evaluation of proposed design and construction. Researchers in the AEC industry have studied the effects of virtual environment on decision-making processes in comparison to the physical environment in previously used VR technologies. The research studies have mostly focused on the end-user experience. In a research study, a courtroom design was evaluated by the owner, end-users and contractors both in the VR mockup and the physical mockup made up of plywood. An immersive virtual environment was presented by projecting the virtual model with three projectors on a large curved projection screen. VR enabled the users to virtually sit in different locations of the courtroom to understand the design and sightlines. Users found VR a useful technology for the design review process (Maldovan et al. 2006).

In another research study, a virtual office building mockup was compared to the completed building from the employees' standpoint. The virtual environment was projected on a concave powerwall, and to achieve the 3D effect, users worn a pair of stereo glasses called Crystal Eye. The users did not have direct control of the projected VR environment. The results show that the employees found VR a useful tool in understanding the future building comparing it to the built office building. They reported the furniture and people, static images of staff, as the most important details in VR mockup to form an opinion about the size of the room (Westerdahl et al., 2006).

CAVE is another VR technology where the virtual world is presented by projecting the virtual model on the walls of the room-sized cube. The location of users can be tracked in CAVE which enables the users to walk around in the virtual environment. A study was conducted on the comparison of the user experience in a hospital patient room both in VR mockup and the actual ward from the standpoint of nurses and patients. While CAVE was a useful technology to help the end-users understand the design and layout, users had a hard time understanding the sufficiency of the space and room size for assessing precise fittingness. Based on the observational study, the users seemed to evaluate the room on the basis of touch. As a result, the researchers suggested complementing the CAVE experience with an evaluation session where physical objects of the VR mockup are used (Wahlstrom et al., 2010).

2.3 – Research Study

The research study was developed based on an academic-industry collaboration between the research team at the University of Washington (UW), and an Architecture Firm, a Structural Engineering Firm, and a General Contractor firm to compare immersive VR mockup to physical mockup. The study was conducted on a hotel project where similar hotel rooms were designed to be built in large quantities. The project team, including the owner, the architect and the general contractor were required to finalize the room design and construction in physical mockup before they were constructed in the building. In case the project team made a design change that could affect the engineering design, then the engineer would weigh in to accommodate the change. The UW team and industry partners were interested in studying to what extent the project team could rely on the VR mockup to finalize the design of the hotel room and whether it could eliminate the need for the contractor to build the physical mockup.

The Architecture Firm owned the VR mockup of the hotel room. The General Contracting Firm owned the physical mockup that was built in a warehouse. They also owned the Augmented Reality (AR) model created based on BIM that included the structural and MEP elements embedded in the ceiling and walls of the hotel room in the physical mockup to help the project team know where non-architectural elements are located in the physical mockup if they decide to make some changes that could affect those elements. It should be noted that none of the BIM and

AR models were used by the project team in this study since the participants did not make any fundamental design changes that could affect the non-architectural elements. The Structural Engineering Firm showed interest in participating in this study to evaluate the VR mockup from their profession's standpoint and support the project team with their expertise in case they decided to make design changes that could affect the structural design. The UW research team developed the research method, procedure, and measuring tools.

2.3.1 – Participants

The research study participants were volunteer employees from the three AEC industry partners. The participants were divided into two diverse groups based on their discipline. Table 2.1 summarizes the participants in group of PV and VP. The group naming was based on the platform order the groups experienced in this study. Six Architects from the Architecture Firm, four VDC Specialists, two Project Engineers, and a Superintendent from the General Contracting Firm, and two Structural Engineers from the Structural Engineering Firm participated in this study. The superintendent was assigned to Group PV, and two Project Engineers were assigned to Group VP. They were all categorized under the Construction discipline.

Table 2.1: Research study participants in groups A and B

Group PV		**Group VP**	
Discipline	**Number of Participants**	**Discipline**	**Number of Participants**
Architect	3	Architect	3
Structural Engineer	1	Structural Engineer	1
VDC Specialist	2	VDC Specialist	2
Construction	1	Construction	2
	Total: 7 Participants		Total: 8 Participants

2.3.2 – Research Method

The UW research team selected the experimental research method to compare the immersive VR and physical mockups. The experiment variable was the environment. The participants' experience in the physical mockup was considered as the baseline, and the experience in the virtual immersive environment was compared to the baseline in this study. Questionnaires were designed to capture the effects of the environment on the individual and team decision making, and the experiment was video recorded for observational study purpose.

2.3.3 – Experiment Setup

The experiment was conducted in a warehouse owned by the General Contractor firm where the hotel room mockup was located. Since the decision for conducting this research study was made later in the construction phase, the mockups were furnished and represented the final product. Figure 1 shows the hotel room's physical mockup. The hotel room had an entrance space with bathroom on the right side, connected to the sleeping area with a size of about 11 x 20 ft. The bed was located in the middle of the sleeping area facing a wall-mounted TV with a desk on one side and a shelving cabinet including a lock system and refrigerator on the other side. An open closet was located at the sleeping area entrance next to the TV. The room window was on the wall next to the desk.

An immersive VR mockup of the same hotel room was created by the Architecture firm in the gaming software, Unity (https://unity.com). HTC Vive (https://vive.com) was the VR hardware used in this study, and it was set up in an open space next to the physical mockup. HTC Vive supports movement within a diagonal area of up to 16 ft, which means the maximum recommended navigable space for HTC Vive was about 11x11 ft. The hotel room was larger than the recommended size for HTC Vive. As a result, the VR mockup was divided into three zones based on the HTC Vive boundary recommendation. The VR mockup was set up in a way that the user would enter the environment next to the bed, and could walk around and explore the room from the sleeping area entrance up to the middle of the bed. To be able to explore beyond the current zone, the users had to be teleported to other zones, meaning the users would immediately find themselves in the middle of a different zone without experiencing walking to that location.

Figure 2.1 – The Hotel Room's Physical Mockup (on left) and VR Mockup (on right)

2.3.4 – Questionnaires

In this research study, a personal information questionnaire, and two sets of questionnaires, A and B were designed. The personal information questionnaire was focused on the participants' backgrounds and previous experiences with BIM and VR. Questionnaire A was designed to capture the participants' reflection on the environment experience and their suggestions for design change. Questionnaire B was designed to capture participants' opinions on the comparison of the two mockups. Two Questionnaires A were given to the participants to fill out at the end of their experience in each mockup, and the Questionnaire B was given at the end of the experiment.

As the research study developed, the Architecture Firm expressed specific interest in examining how the users perceive the space in the VR environment in comparison to the physical environment since they have observed some differences in dimension perception of the owner representatives exposed to their previous VR mockups to evaluate the architectural design. As an example, they shared their experience of observing some users perceiving the width of the rooms narrower than the actual size. A recent study on user dimension perception using a 3DOF VR hardware shows, on average, participants tend to see the depth 19% smaller than the actual size. In this study the width and the length are not differentiated, and the data shows a variety of dimension perceptions where participants perceived the depth both larger and smaller than actual (Loyola, 2019). Since dimension perception could be an important factor affecting the participants' understanding of the design, the UW team added a dimension perception measuring tool for 6DOF VR to both Questionnaires A and B. Participants were given the exact measurements of the room width, length, and height in Questionnaire A, and were asked to answer whether they perceive the dimension in the mockup the same, shorter or longer than the actual size. In Questionnaire B, they were asked to compare the room dimensions in VR and physical mockups.

Since there were no owner representatives participating in this study, the experiment participants were asked to evaluate the hotel room from the standpoint of a hotel guest and housekeeper to reflect on the possible owner requests on the design change. Then they were asked to reflect on what they would change from their profession's point of view in order to make a better investment considering the overall building life cycle cost. At the end of the experiment in Questionnaire B, participants reflected on the features of VR that contributed to their understanding of the design and decision making, and the features that were the drawbacks. They evaluated the immersive VR mockup by answering two questions with likert-wise multiple choices. In these questions, participants were asked to answer to what extent the VR mockup was helpful to simulate the future hotel room to understand the design and to make decisions based on their professional background. The answers ranged from Completely Helpful to Not Helpful at All on a five-level scale. Participants also reflected on which coordination task types they found VR could benefit the project team.

2.3.5 – Process

Participants were given a folder at the start of the experiment that included the research study description, the personal information questionnaire, two Questionnaires A, and one Questionnaire B. Group PV was assigned to start the experiment at the physical mockup and then move to the open space next to the mockup to experience the immersive VR mockup. On the other hand, Group VP started the experiment from the immersive VR mockup and then switched the platform to the physical mockup. In both the immersive VR and physical environment, the participants were asked to first experience the environment individually. Then they were asked to reflect on their experience and explain their individual suggestions for design changes by filling out the Questionnaire A. After the individual experience, groups were asked to discuss the room design as a team and make a team decision on the changes. After the groups made team decisions in both mockups, the participants were asked to fill out the Questionnaire B.

2.3.6 – Data Collection

The UW research team was responsible for the group facilitation and data collection during the experiment. Each participant filled out a personal information questionnaires at the start of the experiment and three questionnaires during the experiment as explained previously. To capture the individual and group interactions with the environment, and record the conversations, one camera was positioned at the corner of the hotel room next to the window in the physical mockup and another one was located at the open area next to the VR setup. The UW research team also took notes of their observations during the study.

2.4 – Results

Based on the participant reflections in the questionnaires and the team discussion for making design changes captured by the observational study, the results are summarized as follows. The personal information questionnaires showed that all the participants were familiar with BIM and had used it in their profession. Only one participant did not have any experience with VR, and the rest were previously exposed to the virtual environment. Comparing the immersive VR and BIM, all participants reported finding immersive VR environment very helpful to understand the space. Exploring the model from the standpoint of the first person in a realistic model, immersed in the environment surrounded by the building objects and being able to look at the model from different angles like exploring it while bending down were the reasons given by the participants to find the immersive VR a more useful tool over BIM to understand the model.

While VR gave the participants a better understanding of the space in comparison to the 3D models projected on 2D screens, some VR features were adversely affecting the decision-making process in comparison to the physical mockup. The results show that users had different dimension perception of the immersive virtual environment in comparison to the physical mockup, and features like lack of touch and unrealistic simulation affected their decision-making process. The research study also showed that VR does not eliminate the need for physical samples. These affecting VR features are explained as follows.

Dimension Perception. In this experiment, only one participant reported perceiving the dimensions in both immersive virtual and physical environments the same. This participant was a member of the General Contractors' VDC team, who works with the VR on a daily basis. Other participants experienced differences in perceiving dimensions. Table 2.2 summarizes the participant's report of their dimension perception by comparing the virtual sleep area dimensions to the actual size in physical mockup.

Table 2.2: Participants' Dimension Perception

	Group	$D_{Virtual} < D_{Actual}$		$D_{Virtual} = D_{Actual}$		$D_{Virtual} > D_{Actual}$	
		Participant #	Total (%)	Participant #	Total (%)	Participant #	Total (%)
Width	PV	3	53%	2	27%	2	20%
	VP	5		2		1	
Length	PV	2	40%	1	20%	3	40%
	VP	3		2		3	
Height	PV	0	0%	3	40%	4	60%
	VP	0		3		5	

More than half of the participants, 53%, reported perceiving the width of the sleeping area narrower than the physical mockup, 27% perceived it the same as the actual dimension, and only 20% perceived it wider. The results confirmed the Architectural Firm's previous experience of witnessing the majority of owner representatives perceiving narrower width of the space in comparison to the actual width size. With regards to length, only 20% reported seeing the same length in both platforms. The rest of the participants were equally grouped in two, half perceived the dimension bigger, and half perceived it smaller than the actual size. Although the VR headset was calibrated to height, tall participants felt short in this experiment. Some participants who perceived the room height dimension the same as the mockup reported perceiving the height of the countertop higher than the physical mockup. One participant who perceived all virtual sleeping area dimensions the same as the physical mockup reported seeing the virtual furniture larger than the actual ones. Several participants reported having hard time perceiving the depth. For example, some had perceived the countertop width in the bathroom smaller than the actual size. Since each participant had a different understanding of the dimensions in the immersive VR mockup, it affected the team decision as well.

Group VP, who started the experiment from the immersive virtual environment, had discussed widening the room width to provide more space for the visitors to walk around the bed with luggage and for the housekeepers to clean the area. Later in the physical mockup, the participants who perceived the virtual width smaller than the actual size realized the actual width in the physical mockup was wider than what they have perceived in the immersive VR mockup. While Group PV had a conversation about the large size of the TV and discussed installing a smaller one, they reported seeing the TV smaller than the actual size in the immersive VR mockup.

Lack of Touch Sense. In current VR practices in the AEC industry, typically, the only simulated sense is sight. The experiment participants experienced an environment that was lacking the simulation of four other senses. Potentially the senses of taste and smell did not affect the decision-making process, and evaluating the acoustic features of the room was not of interest in this study. The results of the experiment show that the touch sense has an important role in understanding the immersive virtual environment. The participants were able to walk through the virtual objects like bed and walls without hitting them. As a result, when they were exploring the room to understand if they have enough space in the room to move a luggage or bend for cleaning the space, they were not aware if some parts of their body was beyond the wall boundary or if they could hit any furniture like wall-mounted TV in the room. Based on the observational study, participants were trying to touch the objects by hand while they were immersed in the VR mockup. They reported having a hard time understanding the surfaces because of the lack of touch. Group VP found more spaces that needed to be cleaned in the physical mockup. As an example, one participant touched the bases of the bed and closet to understand the gap beneath them. Participants also wanted to open doors and try out other moving features in the physical mockup. Group VP found that the sliding door seemed flimsy and predicted it would break easily. For both groups, touch was an important element in understanding the space and design choices.

Unrealistic Simulation. Besides the lack of touch sense simulation, participants also reported some unrealistic simulation features in VR that were affecting their understanding of the environment. Participants were placed next to the bed at the beginning of the virtual experience and were limited to walk in an area of about 11x11 ft due to the HTC Vive suggested navigable area. To walk beyond the space, participants were teleported. Exploring the room in the immersive VR mockup did not have the same flow as in the physical mockup where the participant walked through the hotel room, passed the entrance area where the bathroom was located on the right, and then walked across the room towards the wall with a window. In VR, participants found the disconnection between the teleportation and the limitation for exploring the model beyond the boundaries as factors affecting their understanding of the space.

Another feature was the incapability to see their bodies. One participant suggested simulating the controllers, which would give them an idea of where their hands are. This participant suggested that would help them understand the height of objects in the rooms. Based on another input from a participant, controllers could also be used as a measurement scale to understand the dimensions, especially the depth. It was also mentioned that it is hard to imagine carrying luggage in the virtual space. This lack of self-representation was affecting their decision in evaluating if enough space is available for carrying luggage in the room and bending down or vacuuming the area during housekeeping.

Another feature reported by a few participants was the unrealistic mirror simulation. Mirrors in the virtual space were not functioning like real mirrors to reflect the light and show the background space while standing in front of them. They reported this feature as a drawback to understand the space. Participants also were not able to see themselves in the mirror, which felt weird to them.

Need for Physical Sample. Based on the feedback from the participants, VR was not able to eliminate the need for physical samples to help the participants in making a decision on design options. Group PV had decided to remove the sliding bathroom door. They moved the door back and forth to understand the functionality. The door was causing some noise. The team also discussed the door noise that could wake up the second guest in room at night. The superintendent also checked the door track and supported the decision of door removal due to the maintenance problem.

Participants had a hard time understanding the materials and the final quality of the furniture. It was impossible to figure out the quality of the material and surface textures. In the physical mockup, one participant from Group PV touched the surfaces to understand how easily the surface material could catch the dust to decide on the frequency of the dust cleaning by housekeepers. Questions like how the seams would look or how durable the furniture would be were unanswered in VR. As an example, they were not sure if the open closet shelf was well made enough to put heavy luggage on. Participants in both groups concluded that VR is useful in early phases of design when designers and owners’ representatives are making decisions, but for final product choices, the physical mockups were still invaluable to test the materials and hardware.

Table 2.3 summarizes the experiment participants' response to what extent they found VR mockup a helpful tool to (1) understand the design, and (2) make decisions based on their professional background, if they did not have the physical mockup. The results are represented based on the likert-wise scale values as described under the table.

Table 2.3: Evaluation of VR Mockup by Disciplines

Discipline	Group	Understand Design		Make Decision	
		Group Ave. (Answers)	Total Ave.	Group Ave. (Answers)	Total Ave.
Architecture	PV	2.7 (2,2,4)	3	4 (4,4,4)	4
	VP	3.3 (2,4,4)		4 (2,5,5)	
Structural Eng.	PV	2 (2)	2	1 (1)	1
	VP	2 (2)		1 (1)	
Construction	PV	3 (3)	2.3	3 (3)	2.7
	VP	2 (2,2)		2.5 (2,3)	
VDC	PV	3 (3,3)	2	2 (1,3)	1.5
	VP	1 (1,1)		1 (1,1)	

Completely Helpful = 1, Fairly Helpful = 2, Somewhat Helpful = 3, A Little Helpful = 4, Not Helpful at All = 5

Among the disciplines, architects were the most unsatisfied participants with regards to using VR mockup for both understanding the model and making decisions. Dimension perception and understanding the space are critical factors for the architects to understand the design and make architectural design decisions. On the other hand, the structural engineering group members were the most satisfied participants due to their reduced concern to understand the dimensions and space. Comparing the two groups of VDC and Construction from the General Contracting Firm shows that since the Construction group is more involved with the field they were less satisfied with using VR mockup mostly due to the lack of physical samples. The VDC group is mostly involved with virtual construction processes and VR mockups could be a more useful tool for them.

2.5 – Conclusion

Both groups in this experiment confirmed that being immersed in the virtual environment gave them a better understanding of the space in comparison to the 3D model presented on a 2D screen. However, they concluded that physical mockups cannot be replaced by virtual models due to the limitations in today's technology and the need for physical samples. The main reported drawback of using VR was the dimension perception, which was preventing the teams from making decision on design options where dimension mattered. The VR features of touch and unrealistic simulation resulted in lack of awareness of the user body in the virtual space in relation to the virtual objects that adversely affected the users' understanding of the VR mockup. In this experiment, architects reported finding VR a useful tool for early design studies to evaluate conceptual ideas and layout and a cost-efficient way of looking at design options without spending time and money on the physical mockup. VR would give them the ability to quickly evaluate different design options while having a better understanding of the space in the immersive virtual environment in comparison to the 3D model on the 2D screen. However, they would require the physical mockup for the final sign off. The structural engineering team reported finding VR a useful tool for large scale structural systems, evaluating different structural options also known as ABC studies, and visualizing clashes. Clash is referred to the conflict between different building systems like mechanical, electrical, piping (MEP), and structural. The General Contractor suggested using VR mockup to get feedback from the project team before building the physical mockup which could save time and money in rework. They would need to build the physical mockup for both the owner and designer team's approval and for evaluating construction details. The General Contractor's team also envisioned VR to be a useful tool for MEP coordination.

2.6 – Future Studies

One of the main outcomes of this research study was an understanding of which VR features could affect the AEC team decision-making process. Dimension perception was the main concern for the experiment participants, specifically for the architects. The VR hardware used in this study had limitations in terms of the navigable space which was recommended as 11' x 11'. This resulted in unrealistic simulation since the participants did not explore the VR mockup in the same way as a physical mockup. As the technology evolves, there is a need to conduct a future study with hardware that does not restrict the navigation area which could affect the dimension misperception in VR. Touch sense is another feature that can be added to VR simulation. Currently due to the high expenses of tactic gloves and jackets that could simulate the touch sense, using these technologies does not seem to be cost-efficient. Nevertheless, if space is not a concern for the project teams, the VR content could be evaluated in the future by its combination with physical environment to simulate the touch sense. For example, in this project, cardboard could be used to demonstrate the wall, bed, and desk boundaries to help the participants understand the space.

Experiment participants suggested other potential VR use cases that could be considered to evaluate in the future. All disciplines suggested using VR for visualizing and reviewing clash detection in MEP coordination. A future study could be conducted to evaluate the efficiency of using VR for MEP coordination process in comparison to the current BIM-based practices. Since the physical mockup was already built in this study and it was representing the final finishes, the architectural design was mostly discussed within the groups in this experiment. A future research project could be designed for evaluating the decision-making process of the general contractor and subcontractors during the construction phase of the physical mockup and compare it to the process in the immersive virtual environment. This would give a better understanding of how construction professionals would find the VR beneficial for construction coordination.

Chapter 3: How Could Virtual Reality Facilitate AEC Team Collaboration?

3.1 – Abstract

Building Information Modeling (BIM) is a powerful technology currently practiced in the AEC industry for collaboration. BIM has limitations in terms of the ways AEC project stakeholders interact with design visualizations. In the current method of collaboration with BIM, the participation of all team members is limited since the 3D model is presented on a 2D shared screen while one person has control over the viewpoint. Virtual Reality (VR) is a technology that provides an environment that enables participants to have their own point of view while collaborating online with other team members using collaboration built-in tools in a simulated walkthrough of the project. AEC project team members have in-depth knowledge of their expertise, but they share a part of their knowledge understandable by other team members to collaborate and make decisions. This phenomenon is referred to as Shared Understanding. This paper shares the findings of a research study on how Shared Understanding is built in AEC industry practices using current technology tools. The results of this study lead to building the theory on how VR could facilitate building Shared Understanding by addressing the gaps in current technology tools that prevent teams from collaborating efficiently.

3.2 – Introduction

Construction projects require coordination of different Architecture, Engineering, and Construction (AEC) disciplines. Designers and builders need to exchange disciplinary knowledge while they vet design alternatives during different phases of the project. Project team members have in-depth knowledge of their expertise, but they share a part of their knowledge understandable by other team members in explaining design ideas, disciplinary constraints, and technical analysis to collaborate, find solutions, and make decisions. Team members need to come to a mutual understanding of disciplinary technical works, referred to as Shared Understanding, to make a team decision. Shared Understanding is studied in Psychology and researchers from other disciplines adapt the psychological research methods to their discipline. In this research project, the most common research methods in Psychology are reviewed, and three methods are selected to study how Shared Understanding is built in AEC industry practices using current technology tools and what challenges they face in communicating their disciplinary technical work.

One of the technologies AEC teams use for multidisciplinary collaboration is Building Information Modeling (BIM). BIM is a “digital representation of physical and functional characteristics of a facility." This technology is used by AEC project stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information to support and reflect the roles of that stakeholder (NIBS, 2008). BIM supports communication, documentation, data exchange, and data management (Ku et al., 2008). BIM tools have a clear definition, shared environments, and prescribed boundaries, as team communication needs to be based on shared rules and understanding (Dossick and Neff, 2011). The design issues that are reviewed in the BIM-based collaboration are categorized as geometrical issues, which include spatial, clearance, and physical problems, and non-geometrical issues, including systematic design error, missing information, and inquiry (Mehrbod et al., 2015). The observed challenges in BIM-based design coordination due to BIM tool capabilities are (1) Inefficient transitions between artifacts which takes several minutes for transition and finding the required view, (2) Lack of easy to use basic BIM navigation that prevents the participants from navigating fast-paced in the meetings, and (3) Inadequate BIM coordination task capabilities since not all BIM tools have the same capabilities and require the team to transition between tools (Mehrbod et al., 2017). BIM tools support problem definition, but they do not support the dialogues between team members to brainstorm and create shared knowledge to resolve problems and make decisions. Researchers observed that team members draw sketches, create markups on models and plans and discuss design options to come to a resolution for the problem (Dossick and Neff, 2011). Virtual Reality (VR) is a technology that simulates the reality human beings experience in the real world. It is a computer-aided technology that gives the user an illusion of being in a virtual world. While BIM displays the 3D model on a 2D screen, VR has the capability to enable the user to be immersed inside the environment, and can provide a simulated walkthrough of the project. Research studies in the AEC industry on VR started back in times where VR was presented as projected photos and videos on large curved and cubic screens. Most of the research studies were focused on the user experience, and not on multidisciplinary team collaboration (Maldovan et al. 2006 & Westerdahl et al., 2006 & Wahlstrom et al., 2010). In an experiment, team collaboration in CyberGrid, a virtual workspace for globally distributed AEC teams which enables the team members to see each other as avatars in the model and collaboration office space, was compared to BIM-based collaboration where only one team member was able to share the desktop screen at a time using Sococo. Teams collaborating in CyberGrid had more Mutual Discovery of the model problems in comparison to teams using Sococo since the avatar was allowing each team member to control their viewpoint in CyberGrid. This is while in Sococo, all team members were forced to look at one shared viewpoint (Dossick et al., 2014). The research team did not find any prior studies on the multidisciplinary team collaboration with current VR tools, which enables the user to walk inside the model as a first-person, collaborate with other team members online, and use built-in features like annotation capabilities in the fully immersive environment. The lack of prior research studies motivated the research team to conduct this research study.

In this project, interviews with AEC professionals and observational studies of two construction projects are conducted to understand how team members with different technical backgrounds collaborate to build Shared Understanding and what challenges they face in communicating their technical work to other project team members using current technology tools. The research results reveal the main factors important for building Shared Understanding among AEC team members and the limitations of current technology tools. The research results lead to building a theory on how VR features could support building Shared Understanding by addressing the gaps in current technology tools, which could result in more efficient team collaboration.

3.3 – Shared Understanding Literature Review

The term ‘Shared’ in Shared Understanding could have different aspects such as “similarity, agreement, convergence, compatibility, commonality, consensus, consistency, and overlap” (Mohammed et al., 2010). Two different interpretations of the term ‘shared’ can be found in the literature, shared as the joint possession of some resources versus the division of a resource between multiple recipients. The first definition is related to the meaning that is interpreted in Shared Understanding, while the second refers to the distribution of tasks or knowledge among different people (Smart et al., 2009). The term ‘Understanding’ is the ability to exploit bodies of knowledge to accomplish cognitive and behavioral goals (Smart et al., 2009). Teams with higher levels of Shared Understanding have greater team expectations that influence effective team behaviors (Rouse et al., 1992). Team members represent the understanding of their environment in the form of Mental Models (Langan-Fox et al., 2000). Mental Models are organized knowledge structures that let each team member interact with their environment, and helps to predict and explain the environmental behaviors or understand the relationship between different components (Rouse and Morris, 1985). Shared Mental Model and Shared Understanding are used interchangeably in the literature. To study Shared Understanding, the Mental Model of each team member need to be elicited first. The shared concepts and links among the team members' Mental Model structures represent Shared Mental Model (Johnson and O'Connor, 2008). Mental Model elicitation methods capture the research-related concepts and the relationship between them in the individual Mental Model. The common Mental Model elicitation methods used in Psychology are as follows.

Cognitive Interviewing: This method can be conducted in three formats of (1) Open Forum, (2) Question-Answer, and (3) Inferential Flow Analysis. In the open forum format, team members are engaged in an open conversation. In the question-answer format, team members provide casual explanations about their domain of expertise. Finally, in the inferential flow analysis format, team members are asked to explain the relationship between the concepts in their expertise. The use of this method is recommended with caution since this method is heavily dependent on the researcher's interpretation of the participants' answers (Langan-Fox et al., 2000).

Content Analysis: In this method, formal written or verbal statements are analyzed to extract the critical concepts and their relationships. It is mostly used where the individuals are not available for an interview (Langan-Fox et al., 2000).

Qualitative: In this method, data is collected at the team level by observing the team interactions. Participants determine the concepts in their terminologies and the gathered data is reach and non-disrupted by the researcher (Mehmet et al., 2010).

Questionnaire: In this method, the researcher selects the concepts and creates different statements with regards to these concepts. The team members are then asked to rate the statements on a Likert-type scale, which usually ranges from "strongly agree" to "strongly disagree." Since the researcher selects the concepts, the results of this method can be influenced by the researcher (Langan-Fox et al., 2000). This method does not ask for knowledge content directly and mostly captures the individuals' perception of their work. As a result, some researchers like Mehmet et al. (2010) question the validity of this method.

Verbal Protocol Analysis: The researcher observes the participant interacting with a system while thinking aloud. The sessions are recorded, and the researcher can extract the concepts and their relationships. This method is highly valid for tasks that the researcher is not familiar with but the researcher may not have access to all the cognitive structures that underlie the participant behavior (Langan-Fox et al., 2000).

There are also two other methods that use cards to elicit Mental Models. In these methods, concepts are either selected by the participant or the researcher. Then, these concepts are written on cards. In the *Card Sorting* method, the participant is asked to sort the concepts based on their relationship and explain the reason. In the *Concept Mapping* method, the participant determines the concepts that influence others both positively and negatively (Langan-Fox et al., 2000 & Mehmet et al., 2010).

During team collaboration, team members exchange disciplinary knowledge. Team members may use Explicit communication like using text, spoken language, media like image and video or Implicit communication like body language (Eccles & Tenenbaum, 2004). With each interaction and receipt of new knowledge, individual Mental Model and, as a result, Shared Understanding changes. Shared Understanding can be studied across the team and across time during team collaboration (Johnson and O'Connor, 2008).

3.4 – Research Method

Among the Mental Model elicitation methods, three methods of Cognitive Interview, Qualitative, and Content Analysis were selected to study how Shared Understanding is built in current AEC industry practices. Verbal Protocol Analysis was also used during the interviews where the interview was conducted at the interviewee's office. The Questionnaires method was not suitable for the purpose of this project, but it would be a practical tool to be used in experiments. The research team also did not find the Card Sorting and Concept Mapping methods an appropriate and efficient way of data collection and analysis, since these methods require training of the participants and have a time-consuming process. Because AEC professionals are busy individuals, and there are various concepts related to their specific expertise, which may not be of research interest, these methods were not used.

3.5 – Data Collection

To elicit Mental Models using the Cognitive Interview method, the question-answer format was selected. The questions were designed to be open-ended to let the interviewees define the concepts and their relationships with their technical terms without the interference of the researcher. Interviewees were asked to talk about the challenges they face in understanding the technical information provided by other team members from different disciplines, and the challenges they have in preparing their technical work understandable by other team members. The interviewees were also asked to explain and show how they use technology in this interdisciplinary collaboration process and the challenges they face. In this research project, interviews with seventeen AEC professionals with different architecture, engineering, and construction management backgrounds were conducted. One Architect and two Owner Representatives, one interviewee with an architecture background and the other with a construction management background were interviewed. From engineering disciplines, interviews with two Mechanical Engineers, one interviewee with specialties in Energy Modeling and HVAC design and the other with specialties in piping design, a Structural Engineer, an Electrical Engineer, and an Acoustic Engineer were conducted. A Construction Project Manager, an MEP Coordinator, an Electrical Trade Project Manager, a Mechanical Trade Project Manager were interviewed from the Construction industry. Two interviews were also conducted with an Operations Program Manager and a Commissioning Agent.

The observational studies of two medical projects were also performed to use the Qualitative method to study Shared Understanding. One project with Progressive Design-Build delivery method was observed in the early design phase when the team members were setting goals for team collaboration. Another project with Integrated Project Delivery method and BIM-based collaboration was observed for six months during the construction phase. The project documents of the second project were reviewed, and two hundred Construction Dispute Resolution (CDR) documents were analyzed using the content analysis method.

3.6 – Results

The data collected from the interviews, observational studies, and content analysis resulted in understanding how AEC professionals collaborate with each other and build Shared Understanding by exchanging their disciplinary knowledge concepts and the reasoning for linking these concepts. The results are summarized as followed.

3.6.1 - Concepts and Their Relationships

If a construction project is considered as a puzzle, each discipline provides one piece of the puzzle. While each of these pieces is unique, they are correlated to other pieces and need to be selected wisely so that their edges match the surrounding pieces to fit. AEC professionals perform their disciplinary jobs, but the decisions they make affect other disciplines and vice versa. They need to collaborate to exchange their disciplinary requirements and provide reasoning for their requests from other team members. The Architect works closely with the owner to design the building based on the architectural standards and regulation that meets the owner goals. The Engineers design systems based on their engineering standards, codes and regulations. For example, the Structural Engineers design the structural system based on the building static and dynamic loads, the Mechanical Engineers design the HVAC system based on the occupancy and building envelope information to keep the building cool in summer and warm in winter and provide fresh air circulation for the occupants. The contractors perform cost analysis, scheduling, constructability reviews, and then fabricate and build the project.

This research study revealed that the Engineers have the most challenges among other disciplines in explaining their technical work to others since it requires other team members to have an engineering background. Engineers provide very simplified reasoning using common terms to make it understandable by other team members. For example, a Structural Engineer may state that if the team does not accept placing additional beams at the building entrance, the structural system will fail due to the high shear force induced from the high weight equipment added to the space above the building entrance at the upper floor. The team usually accepts the reasoning provided by engineers since they may have limited engineering background to question the engineering analysis. The main challenge occurs when the Engineer's decision causes a high impact on the schedule or the project cost. In this case, the Owner may hire a consultant or ask the Commissioning Agent to attend the discussion with the Engineer. Large facility owners may have their internal engineers, which makes building Shared Understanding much easier for the team by attending the meetings and collaborating with project consultants. Contractors also have challenges in explaining their disciplinary work as their knowledge is backed by experience. Sometimes it is challenging for the Contractor to convince other project team members to rely on the Contractor's experience on topics like MEP system selection by the Engineer, constructability, and scheduling. Architects seem to have fewer challenges in communicating their work to other team members in comparison to other disciplines. They mostly refer to their architectural standards and regulations.

3.6.2 - Knowledge Exchange

Team members exchange disciplinary knowledge to collaborate and build Shared Understanding. The results of the research study with regards to knowledge exchange are summarized into four categories of (1) Exchange knowledge format, (2) Exchange Knowledge Content, (3) Knowledge exchanging process, and (4) Technology tools used to exchange knowledge as followed.

Exchanged Knowledge Format

The technical knowledge exchanged between the AEC team members can be categorized into two formats: Data and Visuals. Documents like project specification, schedules, cost estimation, and Operations and Maintenance (O&M) manuals fall under the Data category. Documents like 2D plans, 3D models, sketches, photos, videos, and graphs fall under the Visuals category. The study results revealed that visualization has a significant role in building Shared Understanding. Team members try to use visualization to make their technical work understandable by other team members. As discussed before, Engineers have the most challenges in explaining their technical work. They typically do not share their engineering analysis with team members. They show the results of their technical work as 2D plans and 3D models along with notes to the contractors regarding the construction. Engineering consultants need to exchange technical information with other Engineers to perform their job. In this case, they also try to use visualization to prepare their work. For instance, Structural Engineers show the results of their shear force analysis as graphs. Geotechnical Engineers show the settlement of the soil by creating contouring maps. Mechanical Engineers create graphs of the system performance. Acoustic Engineer makes an animation of the vibration transfers in the building. Contractors use visualization to communicate their work to other team members, too. While Contractors have been using 2D plans to coordinate subcontractors, they have started using 3D models more frequently for this purpose since it creates a better understanding of the subcontractors' scope of work and BIM tools help them with understanding the system conflicts. Using 3D models helps them with constructability analysis and communicating them to the team. The Contractors also create the animation of the construction sequencing which helps with explaining the schedule and activity impacts to the team. In the analyzed CDRs, whenever 2D plans are not capable of explaining the problem, a screenshot of the 3D model is provided for better visualization and understanding of the issue, like showing the gaps between the objects. With regards to Owner’s operations and maintenance documents, written O&M manuals are being replaced by visually searchable documents and training videos.

3.6.3 - Exchanged Knowledge Content

AEC team members are dependent on the information they receive from other team members to perform their technical job. Each discipline sends the information required by other team members and receives information from other disciplines to perform their technical job.

Professionals have set standards for the project documents to ease the information exchange process and document them from a legal standpoint. They publish documents like drawings, project specifications, Request for Information (RFI) in a standard format practiced in the industry. However, team members cannot wait for each discipline to finish their part and send the information in the formal format to them. They need to know of potential design options or anticipated outcomes to base their technical work on. This requires the team members to collaborate actively and exchange information throughout different phases of the project. For instance, the Structural Engineer asks the Architect to provide the schematic design options to do the preliminary study of the structural system options. The Structural Engineer also asks the Geotechnical Engineer to provide an estimated range of soil settlement before they finish their settlement calculation to let the Structural Engineer start analyzing the structure and have a better understanding of which structural systems should be considered. If the project has an integrated project delivery method, the Contractor would be able to estimate the cost of structural options and check if they may fit into the project budget.

3.6.4 - Knowledge Exchanging Process

In the AEC team collaboration process, one team member with a specific discipline presents one or multiple design options to the team. Other disciplines then need to confirm if the design option/options would work for them. Team members start to exchange knowledge and information regarding the outcome of their technical work based on the suggested design option. If the suggested options do not work for a discipline, another option is suggested to the team. Team members continue exchanging knowledge and suggesting new design options until they find a design option that works for all disciplines and meets the project goals. Team members prefer to have everyone present during the collaboration. The absence of one team member could result in collaboration inefficiency since the present team members make assumptions about what information the absent party might need to know to perform the job, or what information they present participants need to know from the absent team member. Moreover, present participants may not realize the impact of their decision on the absent team member's scope of work. For instance, in the elevator selection process, multiple disciplines are involved, and they work with each other to finalize the elevator type that needs to be installed. The Architect specifies the number of elevators, the location of them, and their access to different building spaces. The Structural Engineer designs the foundation and the structure based on the specific elevator type. The Geotechnical Engineer provides soils report to the Structural Engineer to support designing the foundation. The Electrical Engineer provides the information for the elevator electrical needs, and the Contractor estimates the elevator and structural system cost and construction duration and checks the elevator availability in the market and constructability issues. All these disciplines work together to specify the elevator type that fits the project goals like budget and O&M cost.

3.6.5 - Technology Tools Used to Exchange Knowledge

As stated previously, team members need to exchange informal information throughout the project to perform their job and vet design options. After they come to a resolution and make a decision, they document the design option in a formal format like issuing drawings and RFIs. For informal knowledge exchange, the one-way communication methods like text messages and emails are the least preferred method since these methods do not assure the information sender that the receiver has read it and fully understood it. As a result, phone calls are more preferred especially in the one by one communication. The voice allows the information sender to guess from the voice tone if the receiver has understood the technical information. The video conferencing communication method is more preferred over teleconferencing since the facial expression and partial body language captured in the video assist in determining if all team members fully understood the shared knowledge. Face to face meetings are the most preferred method since team members can see both facial expressions and body language, and it also helps them to collaborate in the same space, draw and sketch together. While in video conferencing they share their screen with other team members with limited simultaneous collaboration options.

The results of the observational studies on the BIM-based collaboration project show that when a team member who does not have the control over the model view talks about a solution or an explanation of a problem, the team member who has the control tries to use the mouse to point out to part of the model that the speaker is discussing. In the face to face meetings, the speaker may ask to have the control of the mouse or walk to the screen to explain the problem by pointing out to the screen using the hand. The speaker may also show structure parts with hands to make the issue understandable by others. In online meetings, only one team member can share a screen, have control over the view and markup the model. Other team members are no more capable of pointing out to the model using body language or using the pointer to change the view which creates some collaboration challenges. In one of the MEP coordination meetings in the observational study, a Subcontractor was attending the meeting remotely. The subcontractor was trying to explain the location of the problem in the model by guiding the BIM Manager verbally. After spending some time explaining the problem, the subcontractor failed to bring all team members attending the meeting to the same page, and he decided to mark up the model and send it to the team after the meeting.

3.7 – Conclusion

The research study results have revealed the factors important for building Shared Understanding, and the limitations in current technology tools that prevent teams from collaborating effectively. Visualization has a significant role in building Shared Understanding. VR has a more realistic representation of the 3D models and enables the users to be fully immersed in the environment, while teams collaborating with BIM see 3D models on a 2D shared screen. Implicit communication like body language is another important factor in building Shared Understanding. VR can capture voice, and the avatars in VR could capture partial body language. Project team members need to be present during team collaboration to build Shared Understanding while team members exchange disciplinary knowledge. VR is capable of enabling the team members to meet virtually online, which could reduce the co-location expenses and enables more team members to attend the virtual meetings. This could reduce the rework due to wrong assumptions made for the absent participant’s scope of work. Since team members meet virtually in the same environment, team collaboration could happen in the same virtual space inside the digital model, while in BIM-base collaboration the collaboration environment is separated from the 2D representation of the 3D model, which causes limitations for team collaboration. In VR, each team member has a pointer tool. The pointer tools enable the users to point out objects far from the avatar arm reach. VR is capable of enabling team members to draw and mark up the models together during virtual team collaboration while in BIM-based meetings only one person has the pointer and is capable of marking up the model. Moreover, VR enables the team members to have individual viewpoints during collaboration while in BIM-based collaboration only one person has control over the viewpoint and all team members are forced to look at the shared viewpoint. By comparing VR features with current technology tool capabilities, a theory can be built that VR could facilitate building Shared Understanding and save the extra time team members have to spend to communicate their technical work to others.

3.8 – Future Studies

This research study revealed the VR features that could facilitate building Shared Understanding and result in more efficient team collaboration. For future studies, experiments need to be designed to study each VR feature and its influence on building Shared Understanding. For this purpose, the Questionnaires and Qualitative Mental Model elicitation methods are recommended. The Questionnaires method would be suitable to be used in controlled experiments where the researcher can select the concepts based on the dependent variable and capture its relationship to the independent variables. Providing open questions in the Questionnaires would let the participants explain the relationship between the variables with their own words. Using the likert-type scale is recommended with caution since the researcher could influence the results by pre-defining the concepts and it only captures the participants' perception of the concept relationships instead of direct knowledge structure. Qualitative method is highly recommended for recording the team interactions and capturing Shared Mental Model across the time as team members collaborate and exchange knowledge.

Chapter 4: Effects of Virtual Reality's Immersive Environment and Markup Tool Capabilities on Asynchronous 3D Coordination Communication Efficiency

4.1 – Abstract

Building Information Modeling (BIM) has automated the 3D coordination process using the clash detective tool and finding field conflicts by comparing 3D models of building systems. But it still requires the project team to communicate these conflicts to resolve. Team members discuss the complex conflicts in coordination meetings, but most of the issues are communicated asynchronously by sending documents electronically. In BIM-based communication processes, annotations are created by drawing markup on the screenshots of the model with comments added by text. VR provides an immersive environment and allows users to draw markup in the 360-degree environment and communicate verbally. This chapter presents the results of a research study that evaluates VR's immersive environment and markup tool capabilities on asynchronous 3D coordination communication efficiency. Two controlled experiments were designed to (1) study the effects of the VR's immersive environment on the user's understanding of the model, and (2) study the efficiency of markup tool to communicate design issues and resolutions. The experiment results revealed that exploring the model while being immersed in VR helped the users to have a better understanding of the model. Moreover, most of the users preferred the markup tool in VR over BIM to understand 3D coordination annotations.

4.2 – Introduction

Construction projects require coordination of different Architecture, Engineering, and Construction (AEC) disciplines. Traditionally, drawings are created using computer-aided drafting (CAD) software that automates the manual drafting process. The plans are then used for the paper-based coordination process by laying over the plans on top of each other, typically on a light table, to find the conflicts between different building systems. Building Information Modeling (BIM) creates scaled, parametric and object-oriented three-dimensional (3D) models for building systems (Eastman, 2011). BIM software combines different building system models into a single model, called federated model, and determines the conflicts between the systems using clash detective tool by comparing their 3D models. Consequently, BIM brought high values to the construction projects by eliminating the field interferences, increasing productivity, and reducing rework, requests for information (RFIs), change orders, and cost growth (Staub-French and Khanzode, 2007). BIM tools have clear definitions, shared environments and prescribed boundaries since team communication needs to be based on shared rules and understanding. To brainstorm and communicate the technical work, AEC team members draw, write, sketch, or talk together (Dossick and Neff, 2011). In the BIM-based 3D coordination process, one project team member runs clash detection tests and creates clash reports. The top important conflicts that require the involvement of project team members to resolve are discussed in a coordination meeting either online or face-to-face. The rest of the clashes are coordinated asynchronously by transferring documents using electronic networks. BIM tools enable the user to create annotations on a viewpoint. Viewpoint is a 3D snapshot taken of the model as it displays in the screen view. AEC professionals draw markups and add comment as a text to the viewpoint for asynchronous 3D coordination. This brings some limitations in terms of communicating the clashes and the potential resolution to the team as one viewpoint may not capture all the required digital information.

Virtual Reality (VR) is a technology that can simulate the reality human beings experience. It’s a computer-generated environment that can give the user an illusion of being in a virtual world. Unlike BIM, which presents 3D models on screens, VR provides an environment for the user to be immersed in the model. This experience is created by head-mounted display (HMD) hardware or by projection of the model on curved power wall or cubic screens in CAVE (Cruz et al., 1992). In construction projects, team members are familiar with their scope-specific model. In the 3D coordination process, they are exposed to the federated model, which contains the combination of all systems in the building and it continuously gets updated with additional details or changes to resolve the conflicts between the systems. It is crucial for team members to understand the federated model and the relevance of their scope-specific model to others to communicate the design issues, system conflicts, and suggest solutions. Previous studies show that users perceive the model space better in VR in comparison to when they explore it on the screen. These research studies were conducted on a VR system where model was projected on power wall (Liu et al., 2019; Paes et al., 2017). The team also uses sketches for communication (Dossick and Neff, 2011), which requires them to have a good understanding of the design and recalling the objects in the model. A recent research study with HMD hardware revealed that VR improves the recall accuracy compared to desktop platform. This research study was conducted based on recalling the photos of famous characters located at different parts of the memory palace (Krokos et al., 2019). VR also enables the user to draw markup in a 360-degree environment and communicate verbally by recording a message in the virtual environment. In the literature, most of the research studies are focused on the end-user experience, and very few industry professionals are involved in these studies. No previous work was found to study the efficiency of VR's markup tool capabilities, and there were no studies conducted on the effects of HMD VR's immersive environment on user's understanding of the model and recalling it.

4.3 – Research Study

This research study was developed to evaluate the asynchronous 3D coordination collaboration efficiency in digital platforms of BIM and VR. The research focus was on studying the effects of two features of VR's immersive environment and markup tool capabilities on the AEC team collaboration. The first part of this research study evaluates the effects of VR's immersive environment on the user's understanding of the federated model. The second part focuses on the efficiency of the VR markup tool capabilities for communication.

4.3.1 – Research Method

To study the asynchronous 3D coordination collaboration with VR, the experimental research method was selected. Two controlled experiments were designed, and BIM was selected as the baseline for comparison. Experiment A studied the effects of VR's immersive environment on the user's understanding of the federated model. Experiment B was designed to evaluate the efficiency of VR's markup tool for communicating building system conflicts and suggesting resolutions. In this experiment, two independent variables were studied: (1) using audio in VR versus text in BIM, and (2) creating markup in a 360-degree VR environment versus markup on 2D screenshots of 3D models.

4.3.2 – Participants

The experiment participants were twenty-four University of Washington (UW)'s graduate students with different AEC backgrounds enrolled in a graduate-level course in the Department of Construction Management. Twenty-one participants were international students. In the first week of the class, students' educational background, industrial experience, and previous experience with BIM and VR were surveyed to assist in grouping them into two diverse teams.

Students were trained to gain the skillsets required for using BIM and VR software before the experiment. The two designed experiments were given to the students as class assignments.

4.3.2 – Digital Setup

The software used for BIM and VR in this study were Autodesk Navisworks (https://www.autodesk.com/products/navisworks) and Visual Vocal (https://www.visualvocal.com/) respectively. Navisworks is a 3D design review package installed on PC computers that allow users to create federated models, navigate the models and review them using tools like commenting and redline markups. Visual Vocal (V|V) is a VR mobile Application that offers a cloud-based virtual collaboration platform that provides color-coded markup tool for virtual meeting attendants. V|V is installed on smartphones, and the immersive VR content can be viewed through glasses called Viewer attached to the smartphone. V|V supports three degrees of freedom (3DOF). Meaning, it tracks the head orientation and enables the users to look around while they are virtually fixed in one location. The user looks at a static 360-degree spherical image in V|V. Navisworks navigation tool provides six degrees of freedom to the user and allows them to both look around and change location inside the model. To design a controlled experiment, there was a need to set up the BIM platform in a way that it provides the same three degrees of freedom experience in V|V as for the BIM users. The following explains the digital setup process for both the experiments of A and B.

This research study was set up based on a federated model of the new Burke Museum building at the UW Seattle campus. The building's mechanical room was selected as the experiment space, which has a complex mechanical, electrical, and piping (MEP) system. Skanska provided this model for the research purpose in native Navisworks file format to the research team. To explore the model, two viewpoints were created in Navisworks. The Viewpoints of the model were created from the eye level of an avatar with height of 5 feet 6 inches. The users were restricted from using the Walk mode to go around the model and change location. They were only allowed to explore the model using the defined Viewpoints and only look around while fixed in the Viewpoint location.

The VR content was created using the Rendering tools in Navisworks. A static 360-degree spherical photo was captured at the location of each Viewpoint from the same eye level. Teleportation was defined to link two viewpoints to let the user toggle between them in VR to explore the model. The field of view in Navisworks was set to 90 degrees to replicate the same field of view in V|V. The digital contents created for Experiments A and B are described in their sections respectively in the following sections, 4.3.3 and 4.3.4.

4.3.3 – Experiment A

The controlled Experiment A was designed to study the effects of VR's immersive environment on the individual's understanding of the federated model compared to BIM's representation of 3D model on a 2D screen. Participants were exposed to federated models in both BIM and VR platforms. Questionnaires were designed to capture the users' understanding of the model and their feedback on comparing the experience in two platforms of BIM and VR.

4.3.3.1 – Design and Process

In Experiment A, two comparable federated models of A and B were created. Using Navisworks' Visibility tool, different parts of the structural, mechanical, electrical, and piping systems were visible to the user in models A and B. The architectural model and three large equipment were kept visible in both models as the benchmark for comparison. The focus of this experiment was on evaluating the user's understanding of two different piping routes and their relationship to other building systems. Figure 4.1 shows the expanded 360-degree spherical photos of models A and B.

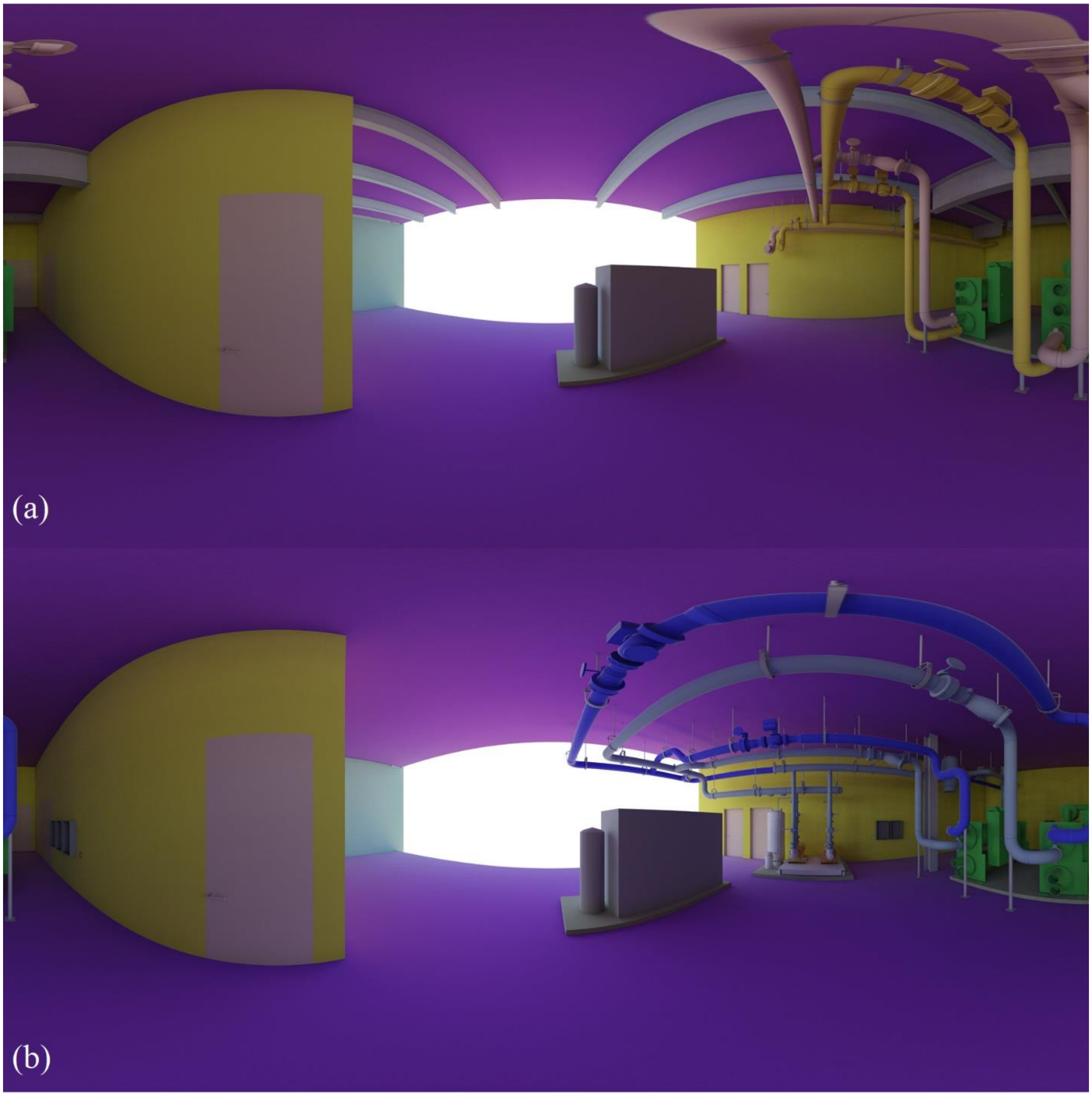

Figure 4.1 – Experiment A Federated Models: (a) Model A, (b) Model B

Questionnaires were designed to capture the user's understanding of the object's appearance, including object color, shape, and dimensions, objects' location and position, user location and orientation, and user's distance from the objects in the model. For this purpose, Questionnaires A and B were designed for models A and B respectively. In both questionnaires, participants were asked to name the colors of five different objects. They were then asked to draw two adjacent pieces of equipment in the model, the mechanical equipment in model A and the Tanker and its feeder in model B, considering the shape and their relative size to each other and to the surrounding objects. Two pieces of piping equipment, chillers in model A and pumps in model B, were given to the participants to specify the connection of the pipes to the equipment and draw the piping route in elevation. An empty mechanical room plan was also given to the participants to specify the equipment location and draw the pipeline in relevance to the equipment on the plan. At the end of the experiment, participants were asked to fill out Questionnaire C to compare their experience in two platforms based on the previously described criteria that are shown in Table 1.

Students were divided into two groups named BV and VB based on the sequence of the platforms they were exposed to the federated models. First, Group BV explored model A with BIM, and Group VB explored it in VR. Each group was given 15 minutes to memorize the model and the criteria were already explained to the participants. They were then asked to fill out the Questionnaire A. To explore model B, groups switched the platforms. They were given the same amount of time, 15 minutes, to memorize the model and then were asked to answer Questionnaire B. At the end of the experiment, Questionnaire C was given to the participants to compare their experience and understanding of the model in both platforms of BIM and VR.

4.3.3.1 – Results

The data collected from the three questionnaires were analyzed. The results of the participants' survey in Questionnaire C for the comparison of BIM and VR are presented in Table 4.1. Figure 4.2 shows the total results visually.

Table 4.1: Participants' Vote to the Preferred Platform to Understand the Federated Model (%)

Criteria	Group BV			Group VB			Total		
	BIM	VR	Same	BIM	VR	Same	BIM	VR	Same
Object Color	33%	50%	17%	17%	25%	58%	25%	38%	38%
Object Shape	8%	58%	33%	25%	25%	50%	17%	42%	42%
Object/Room Depth	17%	83%	0%	42%	50%	8%	30%	67%	4%
Object/Room Height	25%	75%	0%	25%	50%	25%	25%	63%	13%
Object Location	17%	58%	25%	17%	25%	58%	17%	42%	42%
Object Position	33%	50%	17%	25%	8%	67%	29%	29%	42%
User Location	33%	58%	8%	25%	58%	17%	29%	58%	13%
User Orientation	42%	50%	8%	33%	33%	33%	38%	42%	21%
User Distance from Object	33%	50%	17%	8%	58%	33%	21%	54%	25%
Pipeline Routing	25%	58%	17%	25%	42%	33%	25%	50%	25%

The number of votes by the participants for each platform with regards to the research study criteria is reported in percentages in which they specified the platform in which they had a better understanding of the federated model. In both groups, VR had more votes over BIM for all criteria with an exception of object position in Group VB where three participants preferred BIM and one participant preferred VR and the rest of the group, eight group members, found both platforms have the same effect to understand the object position. The platform sequencing had a significant effect on the results. In Group BV, who started the experiment from BIM and then moved to VR, more than half of the group voted for the VR as a better platform over BIM to understand the federated model. On the other hand, the number of participants in Group VB who found both platforms to have the same effect on understanding the federated model was significantly higher than Group BV. Based on the Group VB's response to the questionnaires, most of the participants reported the location of the equipment that was visible in both models and the viewpoint location in the model the same in both platforms.

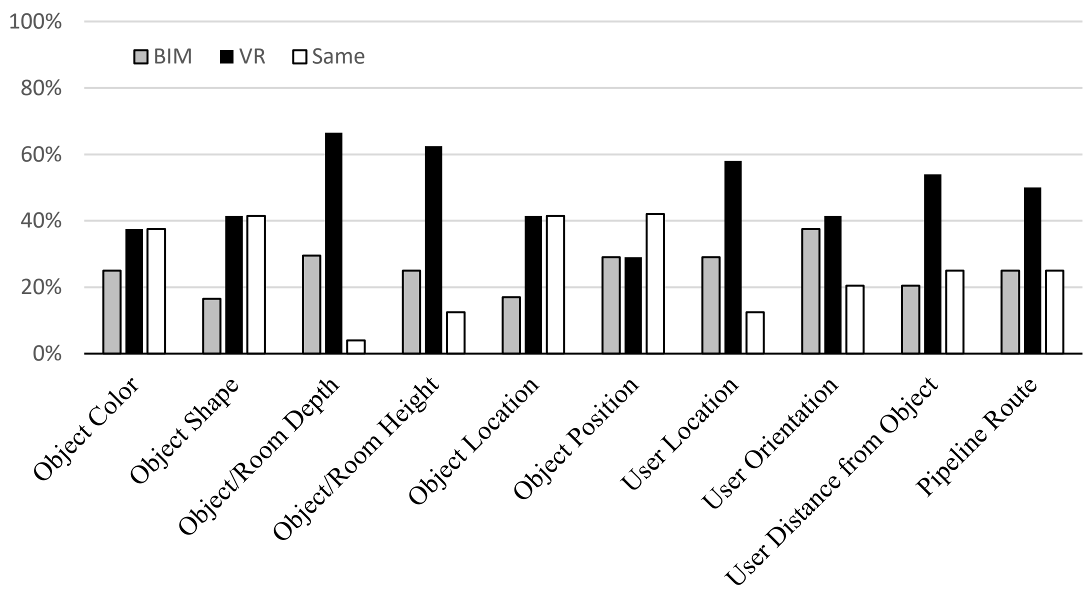

Figure 4.2 – Participants' Total Vote to the Preferred Platform to Understand the Federated Model (%)

Based on the survey results, participants reported five criteria that VR had a significant impact on understanding the model. Three of them are related to dimension, Depth, Height, and User Distance from the Object. Another criterion is the User's Location in the model, and the final one is the understanding of the piping routes, which was the focus of this research study.

Tables 4.2 summarizes the results of the Questionnaires A and B data analysis for groups BV and VB. The mean and standard deviation of the correct answers are reported in this table in percentages. Both groups could recall the colors of the objects more than other research study criteria and showed similar performance in both platforms. For the rest of the criteria, on average, groups could recall the parts of the model better when they were immersed in the VR environment than exploring them on the screen with BIM. There is one exception, the User Location criterion results in Group VB that was slightly higher in BIM. Data shows that participants had a hard time recalling the equipment they were asked to draw or describe after exploring the model with BIM while they had less challenge to recall them in VR. As a result, significant differences between the data distribution for four criteria of Shape, Width, Length, and Height are observed in two platforms.

Table 4.2: Accuracy of Federated Model Recall by Groups (%)

Criteria		Group BV				Group VB			
		BIM		VR		BIM		VR	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Appearance	Color	75%	21%	72%	16%	82%	16%	85%	12%
	Shape	44%	41%	44%	50%	29%	40%	83%	33%
Dimension	Width	38%	38%	42%	47%	29%	45%	75%	34%
	Length	38%	38%	42%	47%	33%	44%	71%	33%
	Height	17%	33%	31%	36%	15%	27%	63%	43%
Pipeline	Connection to Equipment	38%	43%	50%	43%	54%	45%	69%	44%
	Location in Elevation	35%	52%	50%	45%	38%	42%	56%	40%
	Position in Elevation	50%	39%	54%	43%	58%	47%	79%	39%
	Location in Plan	25%	45%	40%	47%	42%	43%	54%	48%
	Position in Plan	29%	40%	58%	42%	48%	40%	63%	41%
Viewpoint	User Location	27%	36%	40%	41%	56%	43%	50%	46%
	User Distance from Objects	23%	39%	44%	43%	27%	39%	33%	37%

The summary of the data for all groups is represented in Table 4.3 and it is visually represented as a bar chart in Figure 4.3. In Table 4.3, besides the mean and standard deviation, the skewness value is also calculated based on the Eq 5.1, where $\bar{x}$ is the mean, and n is the number of participants (Joanes and Gill, 1998).

$$\text{SKW} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^3}{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i-\bar{x})^2}^{\,3}} \qquad \text{Eq. 5.1}$$

A negative skewness value means the data distribution is skewed to the right, and the majority of the data is above the mean value. On the other hand, a positive skewness value indicates the data distribution is skewed to the left, and most of the data is below the mean.

Table 4.3: Accuracy of Federated Model Recall in Total (%)

Criteria		Total					
		BIM			VR		
		Mean	SD	SKW	Mean	SD	SKW
Appearance	Color	78%	19%	-0.50	78%	16%	-0.43
	Shape	36%	40%	0.55	64%	46%	-0.54
Dimension	Width	33%	41%	0.67	58%	43%	-0.32
	Length	35%	40%	0.57	56%	43%	-0.24
	Height	16%	30%	1.59	47%	42%	0.09
Pipeline	Connection to Equipment	46%	44%	0.16	60%	43%	-0.39
	Location in Elevation	36%	46%	0.40	53%	43%	-0.08
	Position in Elevation	54%	42%	-0.16	67%	40%	-0.69
	Location in Plan	33%	44%	0.73	47%	47%	0.14
	Position in Plan	39%	40%	0.48	60%	41%	-0.42
Viewpoint	User Location	42%	41%	0.25	45%	43%	0.22
	User Distance from Objects	25%	38%	1.19	39%	40%	0.32

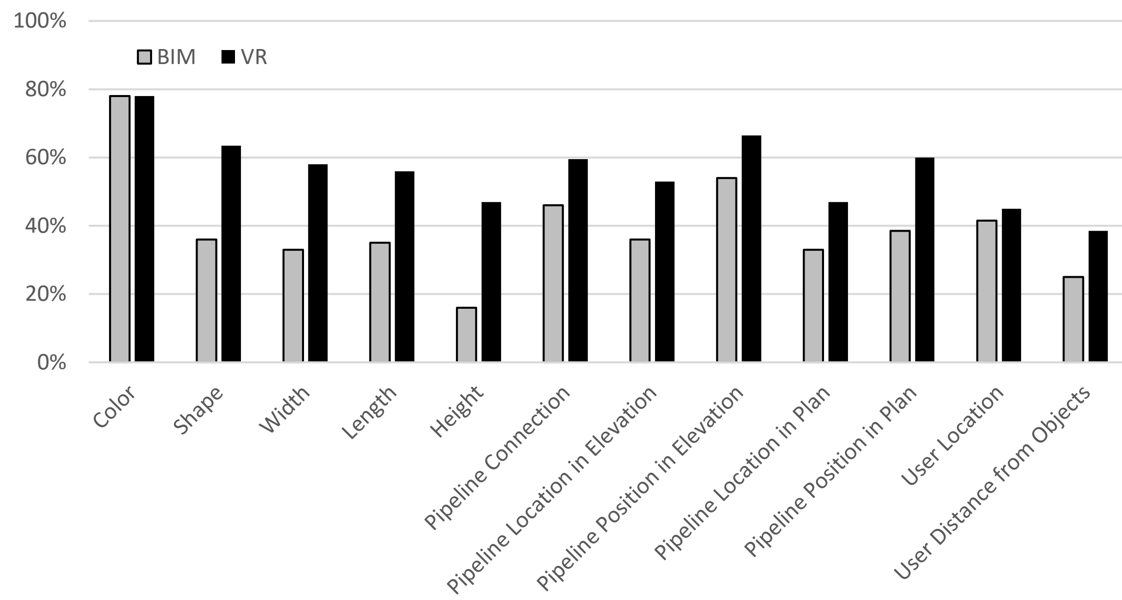

Figure 4.3 – Accuracy of Federated Model Recall in Total (%)

Excluding the color criterion where participants performed very similar in both platforms, on average, being immersed in VR's environment helped the end-users to recall the model better than BIM where they explored the model on screen. Moreover, VR's data distribution for all criteria tends to be skewed more to the right in comparison to BIM.

Overall, 79% of the students reported VR a more intuitive platform in comparison to BIM as it took them less time to understand the federated model while being immersed in the VR environment in comparison to exploring it on the screen with BIM software.

4.3.4 – Experiment B

The controlled Experiment B was designed to evaluate the efficiency of VR's markup tool in the asynchronous 3D coordination process. This experiment studied the effects of two independent variables of VR's voice and markup in 360-degree environment on the team's communication in comparison to text and markup on 2D screenshot of 3D model in BIM. The focus of this study was on both individual’s understanding of the communicated design issues and resolution, and the efficiency of the VR features to communicate design conflicts and changes to other team members.

4.3.4.1 – Design and Process

In the digital content of this experiment, all the objects in the mechanical room’s federated model were visible to the participants. The participants were asked to check an annotation regarding the clashes between the structural system and piping and the suggested resolution in both BIM and VR. A group of pipelines had clashes with two beams located at two different parts of the mechanical room. Both clashes could be seen from one location in BIM. To communicate the cause of the clashes, their relevance to each other, and the required action for resolving the clash in BIM, two markup viewpoints were created for each of the group clashes, and the explanation was given as a text in the Comments section. The VR content was created from the same location in BIM. Figure 4.2 shows the expanded static 360-degree spherical photo. A message was recorded with voice while the markup was created in a 360-degree environment describing the clashes and the possible resolution. Figure 3 shows the markups in both BIM and VR. Groups BV and VB kept the same platform sequencing in evaluating the markups. Participants were then asked to create markups in both platforms to explain another clash between a beam and a duct. They were supposed to first explain the cause of the clash and then point out the dropping bend in the ductwork in another location in the building to explain the clash can be resolved by dropping the duct further at the bend. To create markups in BIM they were allowed to use Navisworks’ Review tool and type the explanation in the Comments section. In V|V, they had to record a message with voice and create markup by touching the smartphone screen and moving the phone with head rotation. Participants were then asked to explain which platform they found more efficient to understand and communicate the cause of the clashes and the resolution.

Figure 4.4 – Experiment B Federated Model

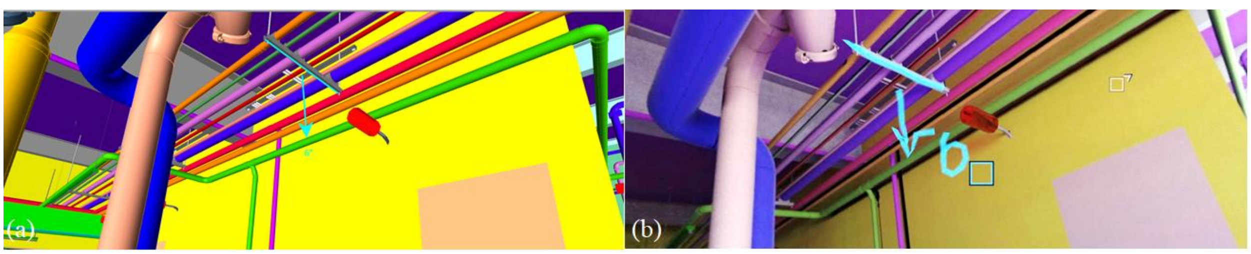

Figure 4.5 – Experiment B Markup in (a) BIM, and (b) VR

4.3.4.2 – Results

The results from the participants' feedback analysis show that 83% of the Group BV and 75% of the Group VB with a total of 79% found VR a preferred platform over BIM to understand the explanation regarding the clashes of pipeline group with two beams and the suggested resolution.

Participants reported VR's immersive environment helped them to understand the location of the clashes and their relevance to each other. Some participants in Group BV reported it took them some time to understand the connection between two viewpoints in BIM while it was much easier for them to understand it in VR. Some also reported having a better sense of the depth in VR assisted in understanding the clashes. They also found the voice an efficient way of communication over text to understand the annotation fast. The remaining 21%, five participants out of twenty-four, found BIM a preferred platform in this practice. One participant stated that he personally prefers text over voice to understand a context. Another participant indicated having hard time following the voice message and had to replay it to catch up. Three of the remaining participants reported having a better understanding of the space in BIM helped them understand the annotation. It should be noted that these participants preferred BIM over VR in Experiment A to understand the federated model.

Participants were also asked to reflect on their experience in creating an annotation in both platforms to communicate the clash resolution to the project team. The results show that 58% of the Group BV, and 50% of Group VB with total of 53% voted for VR for a preferred platform to communicate their technical work. Participants who preferred the VR platform reported they had to create two markup viewpoints in BIM to communicate the cause of the clash and the resolution while in VR they could create markup in 360-degree environment and explain both in one message. They also found the voice a fast way to communicate the technical work instead of typing the comment as text. The majority of the participants who preferred BIM over VR indicated having a hard time drawing in VR. Some had to record the message multiple times to create a clean drawing while BIM's annotation tool gives them the ability to draw neat markups. Another reported drawback was that in BIM they could easily erase a markup or change a text if they make mistakes, but in VR they have to create a new recording to correct themselves. Some found it hard to keep in mind that they need to guide the audience in the 360-degree environment so that when other team members check the message, they know where to look. There was also a note regarding people with disabilities who have difficulties in hearing that may not be able to use the voice feature.

4.4 – Conclusion

This research study was conducted to evaluate the effects of VR's immersive environment and markup tool capabilities on the efficiency of the asynchronous 3D coordination communication. Based on the results of Experiment A, VR's immersive environment gave users a better understanding of the federated model in comparison to BIM where they explored the model on the screen which helped them to understand the conflict of the systems later in Experiment B. It also showed that users could recall more parts of the federated model when they were immersed in the environment. The platform sequencing had a significant effect on the results. The majority of Group VB members who explored model A in VR drew the same room layout and viewpoint location when they answered questions regarding model B. A considerable number of participants in this group found both platforms to have the same effect on understanding the model while Group BV who experience VR later found VR a better platform. This could indicate that exposing the user to the model in VR could help the user to build a good understanding of the model that can reduce the effects of BIM environment on how they perceive the model on the screen. Overall, 79% of the users reported VR a more intuitive platform to explore the model and understand it.

Experiment B showed that the majority of the participants, 79%, preferred VR to understand the annotation. VR's immersive environment helped them to understand the location of the design conflicts and their relevance to each other. They found the voice feature an efficient way of communication over text to understand the annotation fast. While most of the participants preferred VR to understand the annotations, only about half of them preferred this platform to create an annotation and communicate technical work. The most reported reason was the challenge of creating markup with head rotation in mobile-based VR that was not giving them neat looking markup. They could also easily erase a markup or change a text in case of making mistakes using BIM tools, but they had to create a new recording to correct themselves in VR. Some found it challenging to keep in mind that they need to guide the audience in the 360-degree environment. It should be noted that the V|V interface shows the location of the markup with an arrow and guides the user if disoriented in the environment, but this could be a potential problem for other interfaces where this feature is not available.

4.5 – Future Studies

This research study was conducted using a mobile-based Application that supports three degrees of freedom. The effects of VR's immersive environment on the user's understanding of the model could be studied with hardware that supports six degrees of freedom (6DOF) that allows the user to walk inside the model. A controlled experiment needs to be designed that compares the 6DOF VR with BIM in which Naviswroks' Walk mode is allowed to be used by the user to explore the model while changing location. This experiment can also be used to study to what extent VR helps the user to memorize the federated model. Another controlled experiment could be designed to study the markup tool efficiency in 6DOF VR. For this purpose, the markup tool needs to be designed in a way that its features support team Shared Understanding.

Chapter 5: AEC Team Collaboration Efficiency in Remote 3D Coordination Meetings Using Immersive Virtual Reality

5.1 – Abstract

Architecture, Engineering, and Construction (AEC) firms seek to employ technology tools for efficient collaboration to deliver high-quality cost-efficient projects within timely manner. There is an increasing demand for global projects that prevent team members from collocate often for collaboration. As the information and communication technology progress, there is also less tendency for face-to-face meetings in local project teams. Building Information Modeling (BIM) supports different project stakeholders to communicate and exchange data. In current remote BIM-based collaboration, BIMs are shared on a shared screen while one team members have control over the view and the pointer and can create markups. Virtual Reality (VR) is a technology that enables the users to be immersed inside the model and create color-coded markups together in the virtual environment. This chapter presents the results of a research study conducted to evaluate the team collaboration efficiency in remote virtual meetings in comparison to current BIM-based practices. A controlled experiment was designed to compare the performance of six teams with different AEC roles in resolving a design conflict. The research study results show that teams in VR spent less time in comparison to BIM to find the correct design alternative and to come to a mutual understanding of the team decision. It also revealed that some team members were disoriented in the VR's 360-degree environment and could not follow the team when a markup was created.

5.2 – Introduction

Advances in information and communication technologies provide opportunities to the professionals in the Architecture, Engineering, and Construction (AEC) industry to collaborate remotely while staying at the home office. These technology tools support collaboration in globally distributed teams and save the co-location time for local teams. Construction projects require coordination of different AEC disciplines. Building Information Modeling (BIM) is used by AEC project stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information to support and reflect the roles of that stakeholder (NIBS, 2008). BIM supports communication, documentation, data exchange, and data management (Ku et al., 2008). BIM tools have clear definitions, shared environments and prescribed boundaries. To brainstorm and collaborate, AEC team members draw, write, sketch, or talk together (Dossick and Neff, 2011). In current BIM-based remote collaboration, BIM is shared synchronously on a shared screen where only one person has control over the viewpoint and the pointer and can create markups. This makes team engagement and collaboration more challenging than face-to-face meetings where team members can discuss through pointing and sketching together (Dossick and Neff, 2011). Virtual Reality (VR) is a technology that provides an immersive environment for the user to explore. The AEC industry has used different VR technologies including head-mounted display (HMD) and projected systems like CAVE, where model is projected on the sides of a large cube (Cruz, 1992). The HMD hardware is currently more affordable and available for individual use in the market, while projected VR systems like CAVE are expensive and takes large space. This makes the use of HMD more preferable for the industry. The HMD headset blocks the users' view of the surrounding physical environment and immerses the user in a virtual environment. Two types of HMD hardware are currently available in the market. Hardware with three degrees of freedom (3DOF) tracks the head orientation and enables users to look around in different directions while the virtual viewpoint is fixed. This means in virtual team setting, all users are located at one point, and their head is fixed in one location in the virtual environment. Hardware with six degrees of freedom (6DOF) tracks both the head orientation and body location which enables users to look around in virtual space and walk around to explore the world. In virtual team settings, team members can see each other as avatars. Avatars are visual representations of team members, which can be defined in different shapes like a human body or just a sphere to show the location of the team member in the virtual space. Despite BIM software packages where features are already defined within the program, VR content can be created in gaming engines like Unity, which allows the creators to add customized features to the interface like color-coded markup tools to draw in 360-degree environment.

Designers and builders have different AEC backgrounds and specialties. To vet design options, AEC professionals share a part of their knowledge that is understandable by other disciplines to exchange disciplinary information in explaining design ideas, disciplinary constraints, and technical analysis to find solutions and make decisions. Shared Understanding is the phenomenon where team members have a mutual understanding of the disciplinary requirements and constraints to discuss design options and make decisions. Our previous studies show that VR's immersive environment and markup tool capabilities could facilitate building Shared Understanding (Astaneh Asl, 2019).

Previous research studies on VR in the AEC industry were mostly conducted with a focus on design review by the end-users. The study participants explored models in a projected VR system either individually or in a face-to-face meeting (Liu et al, 2019 & Berg, 2017 & Castronovo, 2013 & Dunston, 2007 & Westerdahl, 2006 & Maldovan, 2006). In a research study on remote virtual meetings, globally distributed architecture and construction students reviewed the architectural design in an avatar-based desktop VR. The study results show that the team had more mutual discoveries in VR in comparison to BIM. In this research study, markup tool was utilized, and teams could draw markups together to convey their thoughts and highlight design problems. However, the virtual team setting was similar to BIM-based practice where they were creating markup on a screenshot of the model (Dossick et al., 2014). A prior study that was conducted with 3DOF HMD revealed that study participants had a better understanding of the model and 3D coordination annotations in VR in comparison to BIM in asynchronous 3D coordination process (Astaneh Asl, 2019). This research project aimed to continue the stream of the previous research studies by evaluating VR's immersive environment and markup tool capabilities on team Shared Understanding in synchronous 3D coordination process.

5.3 – Research Study

This research study was developed to evaluate the effects of the HMD VR's immersive environment and markup tool capabilities in facilitating building Shared Understanding among multidisciplinary team members in the remote synchronous 3D coordination process. For this purpose, team collaboration efficiency in VR was compared to the BIM platform, which is the current method of collaboration in the industry.

5.3.1 – Research Method

To study the effects of VR features on team collaboration efficiency, the experimental research method was selected and collaboration in BIM was set as the benchmark for comparison. The experiment design was based on the collaboration of four team members with different roles of structural engineer, architect, mechanical subcontractor, and piping subcontractor. Two comparable scenarios were created in which the structural design changes were affecting the scope of other disciplines in the team. Team members were asked to exchange disciplinary knowledge to find an alternative design option to accommodate the structural design changes.

The disciplinary information was provided to each team member based on the specific role in the team for the purpose of controlling the exchanged knowledge content. The observation and questionnaires were selected as the mental model elicitation method to capture Shared Understanding. To evaluate the individual's understanding of the exchanged disciplinary knowledge, questionnaires were designed and were given to the participants at the end of the meeting in each platform. Another questionnaire was given to the participants at the end of the experiment to reflect on their experience in two platforms. The meetings were video recorded for observational study purpose.

5.3.2 – Participants

The experiment participants were twenty-four University of Washington (UW)'s graduate students with different AEC backgrounds enrolled in a graduate-level course at the Department of Construction Management. Twenty-one participants were international students. In the first week of the class, students' educational background, industrial experience, and previous experience with BIM and VR were surveyed to assist in grouping them into six diverse teams of four students. Students were trained to gain the skillsets for using BIM and VR tools before the experiment.

5.3.3 – Scenarios

The designed scenarios are related to a research facility where mechanical and piping equipment in the mechanical room serve the laboratories (Labs). In the first scenario, Scenario A, the mechanical room, and the Lab are located on the same floor where the duct and pipes run horizontally. This is while in the second scenario, Scenario B, the mechanical room and the Lab are located at two different levels, and the duct and pipes run vertically. The details of both scenarios are as followed.

5.3.3.1 – Scenario A

In the first scenario, only a part of the southern zone of the research facility was presented to the participants as seen in Figure 5.1. One air handler and two boilers located in the mechanical room serve Lab B on the east side of the plan. The duct and the pipes exit the mechanical room and enter the corridor, which has ceiling soffit to embed the duct and pipes. They enter Lab B from the North corridor. The structural engineer is assigned to inform the team that the East wall of the mechanical room and the Lab office with the total length of 40 ft needs to be a shear wall based on the structural analysis. As a result, the opening area in this wall should be limited, otherwise a structural failure could happen. Currently, there are three openings; one for the door, one for the duct, and one for two pipes. The opening area should be limited to only one opening, either for one duct or two pipes, and the door needs to be relocated. To relocate the mechanical room door, the architect notes that it can be located on the West wall to use the West corridor. The door has to be located in either the corners or middle of the West wall of the mechanical room right behind one of the boilers or the air handler. The architect also informs the team that the Lab office was previously a storage room. As a result, no ceiling soffit was considered for this room. The owner does not want to pay for the ceiling soffit. If the subcontractors want to route the duct and pipes through the Lab office, a corner soffit needs to be installed which is cheaper than the ceiling soffit. Each corner soffit can embed either one duct or two pipes and should be along the East or West wall of the Lab office. The cost for the 20 ft corner soffit is $1,500 for two pipes and $2,000 for a duct. The mechanical subcontractor warns the team that due to the sensitivity of Lab A to vibration, no MEP system should be placed in the West corridor. Based on the mechanical subcontractor’s conversation with the mechanical engineer, by moving the air handler to the East wall and routing it from the East corridor, they need to spend an extra $2,000 to buy a more powerful air handler since it needs to push the air through two consequent duct bends. The piping subcontractor reminds the team that the ceiling height is low. As a result, the duct and the pipe cannot be installed at different heights. No piping or ductwork can go above the door. If the subcontractors change their routing, they need to make sure the duct route ends at the same point where the current duct and pipe are in the Lab. The ductwork and piping cost $50/ ft and $25/ft respectively. Subcontractors can only use 90 degrees bends. They should also consider maintenance areas for their equipment providing approximately 10 feet of clearance. Meaning if they line all equipment on one wall, two pieces of equipment should be located at the corners and one in the middle of the wall. The owner prefers to spend less than $2,000 on all the changes the team makes to the design.

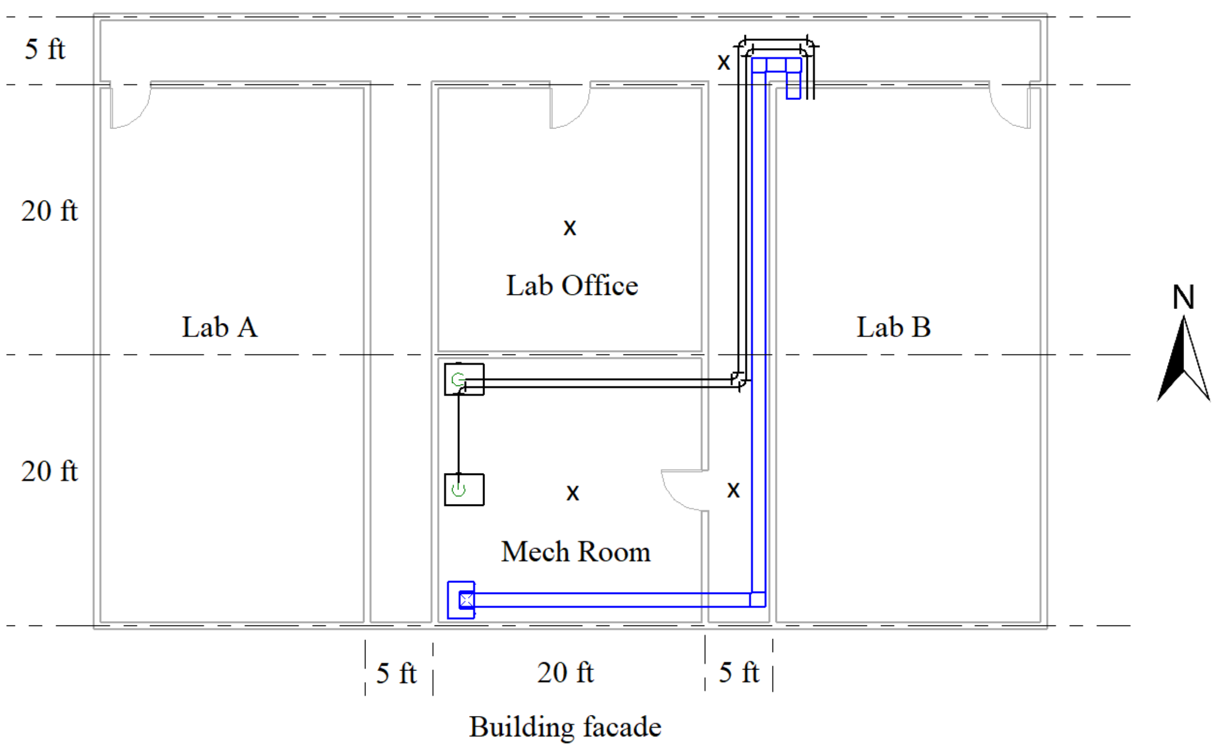

Figure 5.1 – Scenario A Plan

5.3.3.2 – Scenario B

In Scenario B, another zone of the research facility was presented to the experiment participants as seen in Figure 5.2. The mechanical room and the storage room are located on the first floor, and the Lab and the Lab office are on the second floor. The structural engineer is assigned to inform the team that the Lab on the second floor has very heavy equipment, which results in a high shear force applied to the slab underneath. During design review, the structural team has realized the two slab openings provided by the mechanical and piping subcontractor for the pipe and duct risers in the Lab floor slab would result in structural failure. By pouring a thicker concrete slab, the structural engineer can allow one opening in this slab for either one duct or two pipes. Pouring a thicker slab will result in $2,000 extra cost based on the conversation with the general contractor. The slab below the Lab office on the second floor can have a maximum of two openings, one opening for one duct and one opening for two pipes. A large opening for both the duct and two pipes will result in structural failure. The architect does not prefer the MEP routing to be seen in the Lab office, but it can be seen in the storage room. The architect prefers to have the openings in the slab on the corners of one wall so that the MEP system can be embedded in the corners of a wall-to-wall cabinet. The owner has already accepted paying for the cabinet in the Lab office, but the location of this cabinet is not specified yet. If the team decides to embed the MEP system in the cabinet, some cabinet space will be occupied that cannot be used. The team needs to consider $500 extra cost for embedding one duct or two pipes in the corner cabinets for installation and occupying the usable space. The architect prefers to have both the boilers and the air handler on one wall of the mechanical room so that the owner can use the rest of the room space for storage. Since one storage room became a Lab office as explained in Scenario A, the owner needs to use the mechanical room space for storage. Adding a duct bend to the current route results in $500 extra cost. The same constraints of ceiling height, routing over door, maintenance area, and routing angles are applied in Scenario B. The ductwork and piping cost $50/ ft and $25/ft, respectively. The owner prefers to spend less than $4,000 for all the changes team makes to the design.

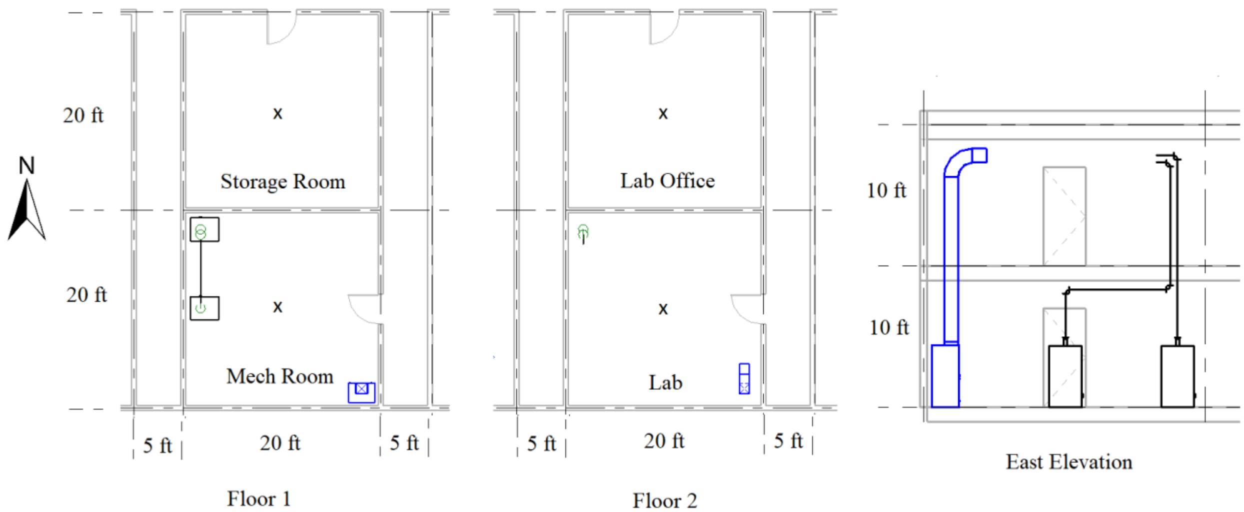

Figure 5.2 – Scenario B Plans and Elevation

5.3.4 – Questionnaires

To capture the individual's understanding of the technical information and the Shared Understanding among the team members, five questionnaires were designed. The Questionnaires AA and BA were given at the start of the scenarios A and B, respectively. Each team member was asked to draw the alternative design based on the final team decision in the questionnaires individually at the end of the meeting. This was a tool to measure if the individual was on the same page with other team members regarding the final decision and was sharing the same understanding of the selected design option. Then Questionnaires AB and BB were distributed after participants filled out Questionnaires AA and BA, respectively. These questionnaires had two parts. The first part was asking participants to answer technical questions to measure the individual’s understanding of the technical requirements and constraints of other disciplines. The second part of the questionnaire was asking participants to reflect on their experience and write about the platform features that were helpful in terms of communicating the technical information, suggesting solutions, and making the final team decision. Participants were also asked to reflect on the platform features that prevented them from working efficiently. Questionnaire C was distributed at the end of the experiment asking the participants to reflect on their experience in two platforms and compare the efficiency of their team collaboration using BIM and VR.

5.3.5 – Digital Setup

The software used for BIM and VR in this study were Autodesk Navisworks (https://www.autodesk.com/products/navisworks) and Visual Vocal (https://www.visualvocal.com/) respectively. Navisworks is a 3D design review package for PC computers that allows users to navigate models and review them using tools like commenting and redline markups. To allow the team members share the screen in their online being while using BIM, Zoom (https://zoom.us) was utilized. Zoom is a cloud-based conferencing software for online remove meetings. Visual Vocal (V|V) is a VR mobile Application (App) that offers a cloud-based virtual collaboration platform that provides color-coded markup tool for virtual meeting attendants. V|V App is installed on smartphones, and the immersive VR content can be viewed through glasses called Viewer attached to the smartphone. V|V supports three degrees of freedom, meaning, it tracks head orientation and enables users to look around while they are virtually fixed in one location since the user looks at a static 360-degree spherical image. This is while Navisworks’ navigation tool provides six degrees of freedom to the user and allows them to both look around and change location inside the model. To design a controlled experiment, there was a need to set up the BIM platform in a way that it provides the same three degrees of freedom experience in V|V to the BIM users. The digital setup for both platforms of BIM and VR are explained as follows.

Viewpoint in Navisworks is the 3D snapshot taken of the model as it displays in the screen view. Four viewpoints were created in the middle of the model spaces (e.g., mechanical room). The location of the viewpoints are shown as “x” on the plans, as seen in figures 1 and 2. The viewpoints were created from the eye level of an avatar with height of 5 feet and 6 inches. Participants were allowed to use Look Around to explore the model in the defined four viewpoints and use the Review tool to create markup. To prevent the users to change location in Navisworks by using Walk mode, a transparent wall was created around the location of the wall that was preventing the user to walk beyond the viewpoint location in the model.

The VR content was created using the Rendering tools in Navisworks. A static 360-degree spherical photo was captured at the location of each viewpoint from the same eye level. Teleportation was defined to link the viewpoints to let the user toggle between them in VR to explore the model. The field of view in Navisworks was set to 90 degrees to replicate the same field of view in V|V.

5.3.6 – Physical Setup

The experiment in the BIM platform was conducted at a computer Lab located in UW’s Seattle campus. Each participant was provided a computer with access to the internet, two monitors and a headset. Providing two monitors to the participants enabled them to have their own individual viewpoint to locally explore and mark up the model in one monitor while viewing another team member's shared screen on the second monitor. Participants in the same group were seated in a way that they cannot make eye contact with each other to simulate a globally distributed team setting and eliminate the effects of body language and facial expression variables on the results. Video conferencing was not allowed, and students used headphones to communicate verbally via audio conferencing.

For the VR platform, four spaces were reserved on campus for each team member. Participants were asked to use their smartphones and headphones. The research team provided VR Viewers to the participants to attach to their smartphones. Team members communicated verbally via audio conferencing using their phones while sharing the same digital space in VR.

5.3.7 – Process

Six participating groups were named based on the platform sequence. Group BV1, BV2, and BV3 started from the BIM platform, and groups VB1 VB2, and VB3 collaborated in the VR platform first. Groups were asked to work on Scenario A to find an alternative design to accommodate the structural design change. Participants were given time to read their role-specific technical information and explore the model individually, either in BIM or VR platforms depending on the group number, to have a full understanding of the assignment description and the model. Questionnaire AA was also distributed before the start of the meeting. Team members in BIM platform logged into Zoom and joined their already setup meeting. The meeting was recorded with Zoom's recording feature. Participants using VR, logged in to the V|V App and joined the meeting. They all called a phone number to join an audio conference using their smartphone. The audio of the meeting and the screen of the observer's smartphone were recorded. At the end of the meeting, team members filled out the Questionnaire AA. Then they were given Questionnaire AB to answer. To work on Scenario B, groups switched platforms. They met online on the second platform, and the process was repeated with Questionnaires BA and BB. At the end of the experiment, Questionnaire C was distributed to capture the participants' reflection on their experience in both platforms.

5.4 – Results

To accommodate the structural design changes in Scenario A, the team was supposed to move all the equipment to the North wall of the mechanical room, move the door to the West wall, and use the East corridor and the soffit on the West wall of the Lab office for routing. They could put the air handler on the Northeast corner and route the duct from the East corridor and route the pipes from the soffit, or put the air handler on the Northwest corner, route the duct from the Lab office and route the pipes from the East corridor. To accommodate the structural design changes in Scenario B, teams were supposed to keep the air handler, move the door to the West wall, move the boilers to the East wall and route them from the storage room and then up to the Lab office, embed them in the cabinet, and then route them into the Lab. They could also move all the equipment to the West wall, route the pipes as previously explained, and add a bend to the duct. This would cost slightly above the budget due to the extra pipe length for routing from the storage room. Table 5.1 shows the accuracy of the proposed design for all groups in both platforms. In Scenario A, two groups of BV2 and BV3 proposed the optimal design option in the BIM platform. Group BV3 moved all equipment to the North wall of the mechanical room where the air handler was located on the Northeast corner, routed the duct from the East corridor, and the pipes from the soffit on the East wall of the Lab office. To prevent the conflict of the pipes and the duct they put a gap between the North wall and the air handler unit and did not relocate the door. This alternative design was not optimal with respect to the use of mechanical room space, but since the air handler was located in a dead space between the door and the North wall that could not be used for storage, and the design satisfied all other requirements, their proposal was accepted. Among the teams in VR, Group VB1 found the optimal design alternative, and Group VB2's proposal was very close to the acceptable design option. In Scenario B, none of the groups in BIM could resolve the conflict based on the disciplinary constraints as they altered the scenario requirements. But two groups of BV1 and BV3 arrived at the correct alternative design, and Group BV2's response was very close to the acceptable design option. It should be noted that Groups BV1 and BV3 moved all the equipment to the West wall of the mechanical room and they were slightly above the budget.

In all meetings, teams started with icebreaker conversations. Then they began exchanging the technical information to come to a Shared Understanding of the structural design change and disciplinary constraints. The official start of the meeting was considered from the time the first disciplinary knowledge was exchanged to eliminate the icebreaker conversations at the beginning of the meetings. Team members had different styles in providing their disciplinary knowledge to other team members. Some members clearly defined the constrains at the beginning of the meeting. Some revealed them whenever the suggested design alternative had a conflict with their scope of work. Furthermore, a few of the members withheld information from the team. They also had different approaches to provide the reasoning why the restrictions existed. Some members clearly explained the reasoning behind each constraint, while another group of students provided the reasoning only when a curious member asked about the logic behind it. As a result, the majority of team members were not able to answer all the questions in Questionnaires AB and BB since some technical information was never shared within the team. While these questionnaires were designed for quantitative analysis purpose, they were used for qualitative analysis to determine individual's understanding of the technical information shared in the team.

Two different types of member participation in the team were observed, Active and Passive. Active members were actively participating in the team conversations, proposing a design alternative or challenging the proposed design. Passive members exchanged their disciplinary knowledge and constraints and answered other members' questions whenever they needed disciplinary information or clarification, but they did not actively participate in the team conversation to find a solution. The Questionnaires AB and BB results show that Passive members could answer the questions related to their disciplines, but their correct responses to the questions regarding other discipline's scope of work were lower in comparison to Active members.

One specific trend was observed in all teams. Team members began the meeting with exchanging information and suggesting alternative design options up to the point that an Active member came to a Shared Understanding with all team members on the disciplinary constraints and suggested the final design alternative. Then this Active member explained the desired design option and discussed it with other Active members. The Active members then asked the Passive members if they understood the final decision, or the Passive members asked the Active members to give a summary of the final design or answer some clarifying questions.

To analyze the data, three parameters were defined, as seen in Table 5.1. The meeting duration, MD, is the duration between the time when one member starts to exchange the first disciplinary information, T_{Start}, and the time at the end of the final conversation when all team members confirmed they are on the same page, or an answer to a clarifying question regarding the final design alternative was given, T_{End}. Two parameters for the duration of building Shared Understanding were defined. The time the Active member spent to build a Shared Understanding of the disciplinary constraints is called SUD_1, and the time each team spent to build the Shared

Understanding of the final design alternative is called SUD_2. The moment the Active member starts to propose the final design alternative, T_{BM}, was used as the benchmark for the calculations.

$$MD = T_{Start} - T_{End} \quad \text{(EQ – 5.1)}$$

$$SUD_1 = T_{BM} - T_{Start} \quad \text{(EQ – 5.2)}$$

$$SUD_2 = T_{End} - T_{BM} \quad \text{(EQ – 5.3)}$$

SUD_1 is not only dependent on the platform features, but it is also dependent on the way team members exchanged information. As previously discussed, individuals showed different approaches in revealing their disciplinary knowledge. SUD_1 was also dependent on the accuracy of the exchanged information and the Active member's awareness of all disciplinary requirements, while SUD_2 was more affected by the platform features and was a good measure for team performance comparison in two platforms. Figure 5.3 presents the comparison of SUD_2 values for both platforms.

Table 5.1: Team Performance in BIM and VR Platforms

Group	Accuracy of Design Alternative		MD (min:sec)		SUD_1 (min:sec)		SUD_2 (min:sec)	
	VR	BIM	VR	BIM	VR	BIM	VR	BIM
BV1	Correct	Incorrect	24:06	32:32	11:01	18:42	13:05	13:50
BV2	Incorrect*	Correct	28:36	48:53	22:42	36:30	05:54	12:23
BV3	Correct	Correct	30:45	48:39	24:56	35:09	05:49	13:20
VB1	Correct	Incorrect	32:56	23:33	20:39	07:57	12:17	15:36
VB2	Incorrect*	Incorrect	28:10	19:32	19:24	07:07	08:46	12:25
VB3	Incorrect	Incorrect	40:33	43:42	13:31	15:29	27:02	28:13

Incorrect*: Team was close to find the optimal design alternative

Duration for meetings that concluded with the optimal design alternative are highlighted

Considering Scenario A, two groups of BV2 and BV3 found the optimal design alternative using BIM within forty-nine minutes while Group VB1 solved the conflict within about thirty-three minutes. Group VB2, whose proposed solution was close to the acceptable design option, finished the meeting within twenty-eight minutes. Considering Scenario B, only two groups, BV1 and BV3, proposed the correct design alternative in VR after about twenty-four and twenty-eight minutes, respectively, which is close to what was observed in the team performance of Group VB1 in VR.

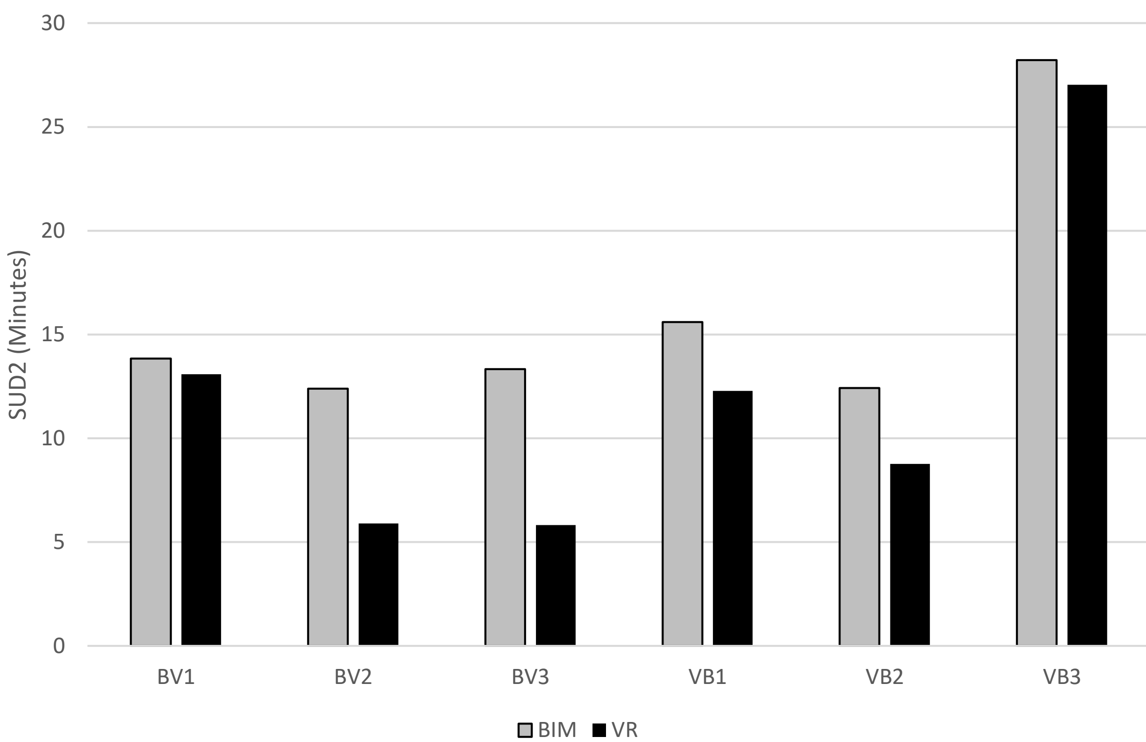

Figure 5.3 – Groups' SUD_2 values for both platforms of BIM and VR

Group BV1 had two Active members in the BIM platform, the architect and the piping subcontractor. The structural engineer was not able to communicate the structural constraints to the team in Scenario A where BIM was used, and the model was under the control of the piping subcontractor. All other team members thought one big opening in the shear wall was acceptable to allow both the pipes and the duct to go through, while the structural engineer was not aware of this misunderstanding. Questionnaire AB results show that the structural engineer had a full understanding of the structural requirements. Based on the Questionnaire AA results, the final design alternative reported by the structural engineer was meeting the structural constraints and was completely different from the team decision. Additionally, the mechanical subcontractor reported the piping and duct routes incorrectly. In Scenario B, the architect took the lead on the team and was considerably more active in comparison to Scenario A where the control of the shared screen was with the piping subcontractor. The structural engineer performed more like an Active member, could communicate the disciplinary restrictions, and created markup to join the team conversation. The team suggested the correct alternative design, and all members reported the team decision correctly except the piping subcontractor who misunderstood the routing of pipes. The piping subcontractor had a hard time understanding the model and consequently the proposed design. Team spent some extra time to help this member come to a Shared Understanding with others. As a result, the time the team spent to come to a Shared Understanding of the final design, SUD_2, was close to the time spent in BIM.

Group BV2 had two Active members, the architect, and the mechanical subcontractor. In Scenario A, the architect's screen was shared with all team members. Active members reported the final decision correctly. The structural engineer routed the duct from the West corridor which was prohibited. Neither the location of the equipment nor the piping and duct routing was reported correctly by the piping subcontractor. In Scenario B, the proposed alternative design was not satisfying the requirement for keeping all equipment on one wall of the mechanical room. The piping route, which was the challenging part of Scenario B, was designed correctly. The team was aware of the equipment location requirement but forgot to apply it when they made the final decision. Group BV2 was the only team that did not use markup in VR to communicate their disciplinary work or the final decision. Instead, they all met virtually and guided each other to look at a specific location in the model and use their imagination to understand the proposed design. While the piping subcontractor could not report the final decision correctly in the BIM platform, this team member reported the alternative design correctly in VR and reported VR's immersive environment helped in understanding the design. The structural engineer did not report the location of the air handler and routing of the duct correctly. Considering the fact that this group was close to finding the correct design in VR, both parameters of MD and SUD_1 were considerably lower in VR in comparison to BIM. With regards to SUD_2, the time they spend in VR to build the Shared Understanding of the final design alternative among team members was less than half of the time they spent in the BIM platform. Group BV3 was the only team with four Active members. They proposed correct design alternatives for both scenarios. Moreover, they all reported the team decision correctly in the questionnaires in both platforms. In Scenario A, all team members got the chance to share their screen and actively collaborated. In Scenario B, all team members used the markup tool to collaborate in VR and finally proposed the correct design alternative. Group BV3 spent 37% less time in the meeting, 29% less time to come to a Shared Understanding of the design constraints, and 56% less time to build the Shared Understanding of the final design alternative in VR in comparison to BIM.

All members of Group VB1 were Active except the structural engineer. They started from Scenario A in VR and proposed the correct design alternative. The piping subcontractor, who was an Active member, reported the routing of the duct incorrectly. The structural engineer only specified the location of the equipment correctly but did not draw the pipeline and ductwork. In

Scenario B, the architect did not share the reasoning why the equipment should be placed on one wall of the mechanical room. The team decided to move the equipment to the Lab office and assumed the wall of the mechanical room and Lab office could be considered as one wall. They misunderstood the Scenario assumptions and worked on a simplified problem. This explains why SUD_1 has a considerable low value in VR in comparison to BIM. On the other hand, it took them an extra of 26% of the time they spent in VR to bring everyone to the same page in BIM. In the BIM platform all team members could answer the team's decision correctly in the Questionnaire BB, and both the piping subcontractor and the structural engineer could follow the team conversations.

Group VB2 had two Active member: the architect, and the mechanical subcontractor. This team had the lowest meeting duration among six groups for both scenarios. The passive members clearly defined their disciplinary constraints, but the Active members shared less information to the team and mostly proposed solutions that did not have conflict with their scope of work. The architect never shared the restriction regarding the location of the equipment. As a result, the proposed design alternatives did not meet this criterion. In VR, they routed the pipes and ducts from the East corridor and the soffit in the Lab correctly, and only the equipment location did not meet the requirement for the storage space as the equipment was located on two walls. They only needed to move the air handler to the Northeast corner with no extra cost which was already discussed in the team. Group VB2's meeting took 28:10, while Group VB1 spent 32:56 to find the optimal design alternative. If Group VB2 had been aware of the equipment location constraints they might have been able to find the correct design option within a similar amount of time as Group VB1.

In Scenario B, since the team was not aware of the equipment location requirement, they made the same mistake as Group VB1 and relocated the equipment to the Lab office and worked on a simplified problem. This explains the low value for SUD_1 that is very close to Group VB1's value. Regarding SUD_2, they spent 32% more time in BIM to build a Shared Understanding of the final team decision in comparison to VR. All team members reported the team's final decision correctly in both platforms except the structural engineer, who misunderstood the pipeline routing in both scenarios.

Group VB3 had long meetings on both platforms. The meeting conversations revealed that they did not start their meetings well prepared as they did not spend the time before the experiment to read the guidelines and role-specific technical information and explore the model to be familiar with the project. They had two Active members, the architect, and the structural engineer. In Scenario A, they routed the duct from the West corridor where they were not allowed to place any MEP system due to the sensitivity of the Lab to vibration. The mechanical subcontractor had informed them of this requirement but did not warn them when they made the final decision to use this corridor for routing. In Scenario B, the team decided to move the Lab office cabinet to the Lab and worked on a different scenario. All team members reported the final decision in both platforms correctly except the structural engineer, who did not draw the routings as the team had decided.

Figure 5.3 shows two examples of the markup in both BIM and VR platforms. The results of the observational study show that team members had challenges in both VR and BIM to follow the team conversations. In BIM, some members were not aware of the building locations where the other team member was pointing or creating markup on the shared screen. Here is an example of a conversation between team members in Group VB1 while working on Scenario B.

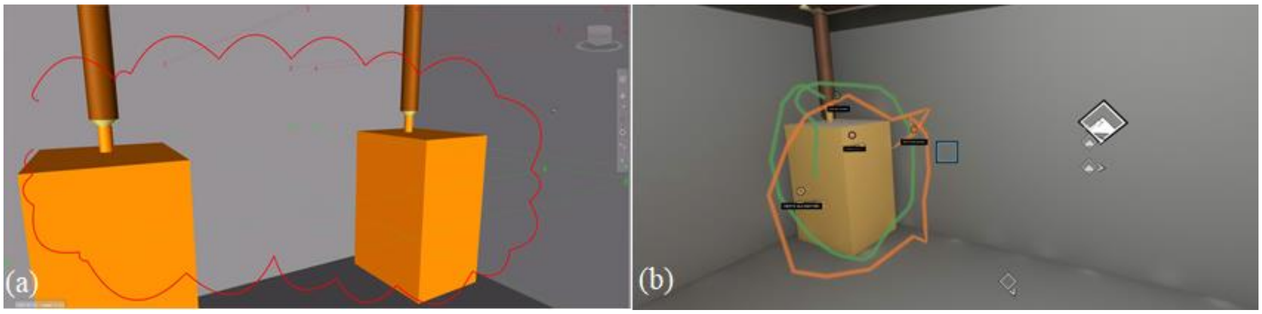

Figure 5.4 – Creating Markup During Meeting in (a) BIM, (b) VR Platforms

The Architect had control over the shared screen. The Piping subcontractor asks the Architect to go to the storage room.

Piping Subcontractor: This is the wall we are currently looking at. There will be the boilers.

Architect: Hmm.. Aa.. No!

Piping Subcontractor: Yeah!

The Architect turns right and looks at a different wall.. Then points out to the wall with mouse.

Architect: This.. This.. This wall..

Piping Subcontractor: Yeah! Mechanical Subcontractor, we want it on this wall, right?

The Architect shows the corner of the wall and says: Yeah! This one.. Here..

Mechanical Subcontractor: Which wall is that?

Architect turns to left to show the door as a reference to help the Mechanical Subcontractor understand the location then turns right and shows the location of the wall and says: This wall!

Mechanical Subcontractor: Yes.. This wall..

When team members started sharing the screen, in the beginning, they asked if everyone could see their screen. However, they did not then ask for their confirmation during the meeting. In VR, each time markup was created in the environment, most of the markup creators asked the team to confirm they could see the markup, which was reported as a drawback by the participants. To guide other team members, they were typically using the door as a reference to give direction in the 360-degree environment. Here is an example of a conversation in Group VB1 in VR while they were working on Scenario A.

The Architect starts to draw markup in VR.

Architect: OK.. What I mean is that.. If we.. Can you see me?

Mechanical Subcontractor: No!

Architect: Look towards the door

Architect continuous while drawing: If we can run the pipe through this area.. here..

Piping Subcontractor: Where?

Mechanical Subcontractor: Look up!

Architect: Yeah! Up on the..

Mechanical Subcontractor: North wall

Architect: Yeah!

Piping Subcontractor: North wall?

Architect: No! Not North wall.. East towards the door.. East side..

Piping Subcontractor: OK!

Due to these challenges in both platforms, 25% of the participants, eight members, could not follow the conversations and reported the team decision incorrectly as previously explained. Only two of these participants were Active members. They were from groups BV1 and VB1. They misunderstood their teammates with regards to the final decision in VR while they had a full understanding of the team decision in BIM platform. The Active member of Group BV1 reported feeling uncomfortable in VR and having a hard time understanding the model and communicating the technical work. Three of the Passive members from groups BV1 and BV2 had a correct understanding of the final design in VR while they reported the design alternative in BIM incorrectly. One Passive member from the Group VB1 could follow the conversations in BIM but failed to understand the team members in VR. Two remaining Passive participants had incorrect reporting in both platforms. One showed similar performance in both, and the other one could draw the boiler and pipe routes correctly in VR while the answer was completely different than what the team had decided in the BIM platform. Based on the participants' reflections, 75% preferred VR’s markup tool capabilities over BIM’s to collaborate, share thoughts, and make decisions. On the other hand, 58% preferred the BIM platform’s screen sharing for communication over VR. The Active members expressed that they were not sure whether all team members were following their markups in the VR environment and they had to ask for confirmation each time they tried to convey their thoughts. Some Passive members reported being lost in the VR environment and not being able to follow the team. Additionally, 38% of the participants reported VR’s immersive environment as a missing feature in BIM that helped them to understand the design conflict and the design alternative.

5.5 – Conclusion

This research study was conducted to evaluate the effects of VR on facilitating building Shared Understanding among multidisciplinary team members in a remote 3D coordination process. The results show that all teams spent less time in VR to build Shared Understanding of the design alternative among team members than when using BIM. In the first scenario, while two teams found the optimal alternative design within around forty-nine minutes in BIM, one team in VR found it within only about thirty-three minutes. Only one group could propose the correct design alternative for both scenarios. This group was the only group with all Active members that could also report the team decision correctly at the end of the experiment. Their meeting duration and the time they spent to build a Shared Understanding of the technical constraints and final team decision were significantly lower in VR in comparison to the BIM platform. The markup capabilities and immersive environment were two features that participants reported preferring over BIM's to collaborate. While VR could facilitate building Shared Understanding at the team level, three participants were not able to follow the conversation in VR. One participant had a hard time to understand the model in VR, and two were disoriented in the 360-degree environment and could not follow the team. On the other hand, since the viewpoint in BIM was controlled by one team member, three participants misunderstood the team and were not aligned with them, while they reported the final design alternative correctly in VR.

5.6 – Future Studies

This research study was conducted using a mobile-based Application that supports three degrees of freedom. The effects of VR's immersive environment and markup tool capabilities could also be studied with hardware that supports six degrees of freedom. A controlled experiment needs to be designed that compares the 6DOF VR with BIM in which users can walk inside the model and explore it while changing location. In 6DOF VR, partial body language could be captured by avatars. The avatar body language could resolve the team members' disorientation problem and guide team members in 360-degree environment.

Chapter 6: Conclusion

6.1 – Discussion

Project team members with different Architecture, Engineering, and Construction (AEC) backgrounds exchange technical information throughout different phases of the project. AEC professionals have developed standard formats for exchanging disciplinary information to ease the communication between project team members. These formats include drawings, 3D models, specifications, schedules, Request for Information (RFI), etc. They also informally communicate to explain design issues and system conflicts, propose resolutions, discuss design ideas and vet design options before they document the team decision formally in the standard formats. The preliminary study results revealed that teams prefer face to face meetings for collaboration. It provides a two-way communication platform, and the voice tone, facial expression and body language aid them in understanding if the exchanged technical information is understood by other team members. Moreover, they share the same space with access to project documents and collaboration tools to work together. The observational studies in this dissertation confirmed the outcomes of previous research studies (Dossick and Neff, 2011 & Mehrbod et al., 2019) that team use different formats of 2D paper drawings, 2D PDFs and 3D models during collaboration, and they draw sketches on black papers or boards, create markups on 2D drawings and 3D models, or use hand to point out parts of the building systems to discuss design options. Technology tools can support problem definition, but it's the dialogues between the team members that build shared knowledge (Dossick and Neff, 2011). This dissertation studied the technology capabilities that support the team dialogue and brainstorming to build Shared Understanding with a focus on the application of Virtual Reality (VR).

The ideal team collaboration format in the virtual environment would be a replicate of the face to face meetings in the physical environment. This format allows team members to meet virtually while they have shared access to project resources and collaboration tools and save the time spent for co-location. Additionally, it enables the users to be immersed inside the 3D model or look at the small scale of it from different angles instead of viewing the 3D model presented on a flat screen. Considering the VR technology limitations at the time this research study is conducted, a physical face to face meeting cannot be replicated in VR. For example, no product is out in the market that can track face to capture facial expression. An affordable VR hardware that tracks fingers came to the market after this research project was designed. This type of hardware can ease the process of drawing and allow the users to type and take notes for documentation if a built-in keyboard is designed in VR. In this dissertation, available and affordable VR features that could have high impacts on team Shared Understanding were exclusively studied.

Building Information Modeling (BIM) is a technology that has been practiced in the AEC industry by different project stakeholders. BIM a powerful tool for collaboration and knowledge management in multidisciplinary teams. The AEC professionals who participated in the pilot study, suggested using VR for 3D coordination, which is currently practiced in the industry using BIM. It should be noted that the 3D coordination is one of the twenty-five BIM applications in the AEC industry. In the 3D coordination process, team check for the conflicts between 3D geometries of different building systems to resolve future field conflicts. The Primary Investigator (PI) specified the VR features that could facilitate building Shared Understanding among team members in the 3D coordination process by conducting the preliminary study. Since the focus on the 3D coordination process is on the intersection of 3D geometries, VR's immersive environment was selected as a potential feature that could provide the team members a better understanding of the model and building system conflicts. As previously stated, team members use hand for pointing out or draw sketches and markups for explaining design ideas and conflicts and proposing solutions. A customized tool, that is called VR markup tool in this dissertation, for pointing out and drawing in VR environment was considered as an important tool for building Shared Understanding.

This research project aimed to study the effects of VR's immersive environment and markup tool capabilities on building Shared Understanding among AEC project members in both asynchronous and synchronous 3D coordination. The asynchronous collaboration study revealed that VR's immersive environment gives users a better understanding of the model in comparison to BIM. This includes the model appearance features as well as the relevance of the building systems with regards to each other. Having a good understanding of the model supports understanding the geometric conflicts. Seventy-nine percent of the participants reported VR a more intuitive platform to explore the model and understand it. It should be noted that they were still users who found BIM a better platform that helped them to understand the model. It is not clear if the understanding of the model in VR depends on the technology, frequency of the experience with VR, or something that is dependent on the individuals and the way they build the mental models of the environment as this experiment did not study the root causes of the differences between the individuals.

This study revealed that users could recall more parts of the model when they were immersed in VR, which can support their ability to draw sketches of the building parts. The order effect was also observed in this study. Most of the group members who started from VR built a correct mental model of the model, and it was not affected after they switched the platform. While team members in the other group were observed to change answers to the questionnaires for parts that were similar in both models after being immersed in the model in VR. In the second experiment of asynchronous research study, seventy-nine percent of the participants preferred VR's platform to understand the annotations created by VR's markup tool. Overall, VR platform showed a considerable positive affect on assisting individuals to understand the model and 3D coordination annotations.

In the synchronous collaboration study, teams had different dynamics, and team members approached differently how to share their disciplinary knowledge with others. Some explained their disciplinary constraints clearly at the beginning of the meeting, some gradually revealed information whenever a team decision contradicted their scope of work, and some members withhold information. The Active members tried the most among team members to build a Shared Understanding of the disciplinary constraints to find an optimal alternative design option for accommodating the structural design changes. The Passive members mostly checked the final decision to make sure it has no conflicts with their scope of work and had less awareness of other team members' disciplinary constraints. While it was expected that team will have a Shared Understanding of the disciplinary constraints, only one Active member came to a Shared Understanding with all team members on the disciplinary constraints and suggested the final design alternative. This Active member then discussed the proposed design option with other Active members, and they made sure the passive members understood the final decision. Regardless, all teams spent less time in VR to build Shared Understanding of the final design alternative among team members.

Only one group could propose a correct design alternative for both scenarios. This group was an example of an ideal team where all members were Active. Their meeting duration and the time they spent to build a Shared Understanding of the technical constraints and final team decision were significantly lower in the VR platform in comparison to the BIM platform. While VR could facilitate building Shared Understanding at the team level, some participants were disoriented in the 360-degree environment and could not follow the team. Active members were not sure whether all team members could follow the markups, while BIM's shared screen was assuring them everyone sees the same view. To prevent such confusion to happen, it is recommended that teams specify a point of reference to guide all team members in the environment. In the synchronous collaboration study, since each space had a door, teams used it as a point of reference to guide others to the location where they wanted to create markups.

The PI had the opportunity to study the application of VR for design review process used by AEC professionals. Previous research studies (Dunston et al., 2007 & Castronovo et al., 2013 & Berg, 2014 & Maldonado et al., 2016 & Liu et al., 2017 & Liu et al., 2019) have mostly focused on the end-user experience and none of them used 6DOF HMD. Previous studies revealed the dimension misperception in VR (Henry & Furness, 1993 & Renner et al., 2013a & Loyola, 2019), but none of these studies were conducted on 6DOF HMD. The research study compared a physical mockup with its immersive virtual mockup with regards to the Shared Understanding built among team members to make decision on design options. The study results revealed that participants built different individual mental models of the VR mockup due to the differences in their dimension perception. Additionally, the lack of touch sense and unrealistic simulations in VR resulted in the lack of awareness of the user body in the VR environment that affected the understanding of the model. Different individual mental models of the VR mockup resulted in misunderstandings when teams collaborated to discuss design options and make changes. For example, Group PV, who started the experiment from the VR mockup, had a discussion regarding widening the room since most of the team members, five out of eight, reported perceiving the virtual room width narrower than the actual size. As a result, the rest of the team members who did not perceive the width smaller than the actual size were not sure whether the discussion was based on personal preferences or their incorrect perception of the virtual dimensions. This was considered as a drawback specifically for the architects whose work depends on the design dimensions and understanding of the space. Moreover, the Construction team specifically found the lack of physical samples a drawback to make decisions related to their scope of work. For instance, questions regarding how seams of built-in furniture will look like were unanswered in the VR mockup.

Consequently, in the pilot study, architects suggested using VR for the design review in the early design phase to evaluate conceptual ideas and layout and found it a cost-efficient way of looking at design options without spending money on the physical mockup. The structural engineering group found VR a useful tool for evaluating structural design options in the early design phase and visualizing the clashes between their system and other building systems. The general contractor suggested using VR for 3D coordination and receive feedback from the project team before building the physical mockup to save time and money on rework.

While the focus of this dissertation was on the application of the technology for facilitating building Shared Understanding among AEC team members, it should be noted that based on the preliminary study results, some challenges related to building Shared Understanding cannot be addressed by relying on the standards and technology tools. The study results show that engineers have the most challenges among other disciplines in explaining their technical work to others since other team members do not have an engineering background. The team usually accepts the reasoning provided by engineers without questioning it. Nevertheless, the main challenge occurs when the engineer's decision causes a high impact on the schedule or the project cost. In this case, the owners may hire a consultant or ask their own internal engineers to weigh in to facilitate building Shared Understanding. Contractors also have challenges in explaining their disciplinary work as their knowledge is backed by experience. The architects seem to have fewer challenges in communicating their work to other team members in comparison to other disciplines as they mostly refer to their architectural standards and regulations. In the synchronous research study, a similar pattern was observed in the experiment. Participants were usually not questioning the technical information provided by other disciplines or even were not asking the reasoning behind some of the requests until it contradicted their scope of work or had an impact on the cost.

6.2 – Study Limitations

This research project focused on evaluating two VR features of the immersive environment and markup tool capabilities on team Shared Understanding in 3D coordination. For this purpose, controlled experiments needed to be designed in a way that two platforms of VR and BIM provide the same experience to the user except for the features that were of interest in the study. Moreover, the factors outside of the scope of the study that could affect Shared Understanding should have been eliminated in the experiments. The study design was based on Visual Vocal (V|V)'s capabilities. V|V is installed on smartphones that support 3DOF by tracking the head orientation. Users can explore the model at fixed locations in the model and they need to be teleported to other locations to explore other parts of the model. For this purpose, the BIM platform was set up in a way that participants were only allowed to use defined viewpoints to review the model. This setting was not simulating the industry BIM practices where users use walk mode to explore the model. This setting also forced the teams to only use the 3D model as the shared platform for collaboration. They had to check the plan and elevations on paper whenever they found the drawings more helpful to assist them in understanding the disciplinary constraints or suggested solutions.

To eliminate the effects of facial expression and body language on the results, the collaboration was studied in the remote 3D coordination process. If the experiment was designed in a way that allowed the users to meet face to face, they could see each other in the BIM platform, while this was not possible in the VR platform while collaborating virtually. To simulate the individual viewpoint in the BIM platform, a second monitor was given to the experiment participants in the to explore their model locally on one monitor while they follow the shared screen of another team member on the other monitor.

The study participants were the University of Washington's graduate students. The PI could not expect the students to have in-depth knowledge in different areas of AEC disciplines. As a result, the technical information had to be provided to the participants. Although this aided in controlling for the exchanged information, the experiment scenarios had to be designed in a way that were simple enough for the students to understand without having specific disciplinary backgrounds of the roles they were assigned to.

In the research study conducted on the application of VR for design review, a physical mockup was compared to a virtual mockup. The research study was conducted on a fully furnished mockup. Although this resulted in less complex exchanged disciplinary conversations, it allowed the PI to focus on the effects of the environment on team Shared Understanding since team members did not face challenges in understanding the technical information. A 6DOF HMD hardware, HTC vive, was selected for this study to allow the participants to walk inside the virtual mockup. HTC vive supports navigation in an area of 11' x 11'. The hotel room dimension were approximately 11’ x 30’. As a result, the mockup was divided into three zones and participants were teleported to other zones in order to explore the whole room. This resulted in an unrealistic simulation since the participants did not explore the VR mockup in the same way as a physical mockup. The virtual mockup setup was for one-player, meaning, only one user at a time was able to explore the model. As a result, team discussion did not happen inside the virtual environment and the team had to refer to the model projected on the laptop screen to discuss design options.

6.3 – Future Studies

The future can be envisioned where VR replicates the physical face to face meeting in a virtual environment that allows the team members to have shared access to project documents and collaboration tools. They would be able to use 2D drawings, 3D models, and project documents like specifications based on their specific needs, and create markups on 2D drawings and 3D models or utilize blank papers or board to draw their ideas, explain disciplinary constraints, propose solutions and vet design options. They would be able to be immersed in their model or look at its small scale or sections. This setting would not only support 3D coordination, but it could also support a variety of team collaboration in different phases of the project while saving the time spent for co-location. Since the technology is not there yet and it may not be affordable to be acquired by all project team members, this research study focused on only two VR features that could support team Shared Understanding in the 3D coordination process.

For near future studies, an experiment could be conducted on synchronous team collaboration using 3DOF HMD with AEC professionals on a real-world project. This would provide valuable feedback from the industry regarding the use of VR for multidisciplinary collaboration. Another set of experiments could be conducted to study the effects of VR’s immersive environment and markup tool capabilities on the individual's understanding of the model and annotation as well as Shared Understanding at the team level using a 6DOF HMD hardware. The 6DOF VR customized markup tool should be designed in a way that its features support the team conversation. In 3DOF VR, markups are created on a static 360-degree spherical photo. During the collaboration, all team members are fixed in one location, as a result, they see the same markup in the 360-degree environment. In 6DOF VR, understanding 3D markups could be challenging. Since team members can look at the markups, created either on a flat surface or in 3D, from different angles, they may not have a clear understanding of the annotations. On the other hand, in 6DOF VR, members can see each other as avatars. The avatar body language could resolve the member disorientation problem observed in this research study in 3DOF VR format as it can aid in guiding the members to the location where the markup is created. Regarding the application of the VR for design review, a research study could be conducted with hardware that does not restrict the navigation area, to study whether it could affect the dimension misperception in VR. Due to the high expenses of tactic gloves and jackets in current market, model could be evaluated by its combination with the physical environment to simulate the touch sense. For instance, cardboard could be used to demonstrate the wall, and the boundaries for furniture to aid the users in understanding the space. Another study could be conducted to evaluate an under-construction physical mockup that requires the involvement of different subcontractors and engineering disciplines in the study with an experiment. This could provide a case that requires rich technical conversations to be exchanged and provides the research team the opportunity to study the Shared Understanding in the subcontractor coordination process.

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Appendix A: Chapter 2 – Guideline and Questionnaires

Guideline

1. Please fill out the information sheet and return it to the research team.
2. Check your group name with the research team, or find it in the name list in your folder. Group PV will start their experience in the physical mock-up, and Group VP will start their experience in the VR.
3. First, you will have an individual experience of the future hotel room in either the physical mock-up or VR. Before the start of your experience, please read the Part A questions of Questionnaire 1 in your folder along with the assigned task description provided in this sheet. You will be asked to fill out Part A of Questionnaire 1 after your individual experience.
4. After everyone in your group finishes the individual experience, you will have a group discussion on the assigned tasks to make a group decision. Then you will be asked to fill out the Part B of Questionnaire 1.
5. At this phase of the study, groups A and B will switch the experiment environments. Steps 3 and 4 will be repeated in the new environment (VR or physical mock-up).
6. At the end of the experiment, you will be asked to fill out the Questionnaire 2.

Assigned Task Description

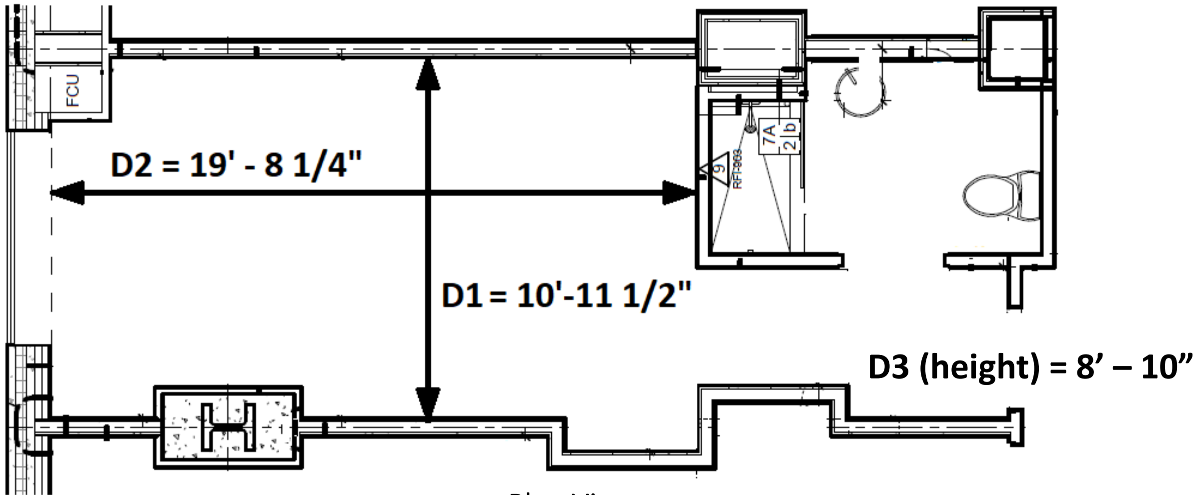
Task 1: Imagine that you are a visitor in Seattle and arriving to your hotel room as a guest after a day of traveling. Evaluate the usability of the room, how different functions of the room are located to help you start your stay as quickly as possible. Do you find the electrical outlets in good locations, is there enough room to move with luggage, is there enough storage space for your things, do you see items that provide you additional value as a guest that possibly make you book this hotel again in the future?

o From your own profession point of view, what would you change (as an architect, a structural engineer, contractor, owner/investor)? Are the change orders you want to make now a better value per dollar invested, considering the overall building life cycle cost?

Task 2: Imagine that you clean this type of room 3000+ times a year. Evaluate how the room ergonomics, surface materials and textures, furniture layout, outlet locations, etc. help you perform your job.

o From your own profession point of view, what would you change (as an architect, a structural engineer, contractor, owner/investor)? Are the change orders you want to make now a better value per dollar invested, considering the overall building life cycle cost?

Task 3: Imagine that you are the designer of the hotel room. Evaluate the spatial relations of the room. Does the space feel welcoming? Does the furniture seem appropriately placed? Do the dimensions of the space seem appropriately scaled (length, width, height)? Is there an appropriate amount of artificial light? Do the finishes seem appropriate for the hotel aesthetic? What would you change?



Plan View

Personal Information

Welcome to the team collaboration research study in the Virtual Reality (VR) and physical mock-up!

In this study, you will visit a hotel room mock-up as well as experience it in the VR, and make decisions on a series of assigned tasks. You will be divided in two groups of VP and PV. Group PV will start their experience in the physical mock-up, and Group VP will start their experience in the VR. We will ask you to fill out two questionnaires after your experience in the VR and physical mock-up. You will also be video recorded throughout the experiment. Please fill out this information sheet and let me know if you have any questions or concerns.

Name	Age	Education

Previous VR experience:

Previous BIM Experience (please explain your experience if applicable):

Questionnaire A

Name: Group: Test: VR Mock-up

Part A: Individual Experience

1. How does dimension **D1 (room width)** look in comparison to the actual measurement (10 ft- 11 ½ in)?
   Smaller The same Bigger
2. How does dimension **D2 (room length)** look in comparison to the actual measurement (19 ft - 8 ¼ in)?
   Smaller The same Bigger
3. How does dimension **D3 (room height)** look in comparison to the actual measurement (8 ft - 10 in)?
   Smaller The same Bigger
4. What is your individual choice(s)/solution(s) for **<u>Task 1</u>**? Please provide your reasoning

5. What is your individual choice(s)/solution(s) for **<u>Task 2</u>**? Please provide your reasoning

6. What is your individual choice(s)/solution(s) for **<u>Task 3</u>**? Please provide your reasoning

Part B: Group Discussion

To answer Part B questions, please write group member names/initials in the appropriate box.

7. To what extend you think **your reasoning** was understood by other team members for **Task 1**?

Completely Understood Me	Understood Me	Neither Understood Nor Misunderstood Me	Misunderstood Me	Completely Misunderstood Me

8. To what extend you think you could understand **other team members' reasoning** for **Task 1**?

Completely Understood Them	Understood Them	Neither Understood Nor Misunderstood Them	Misunderstood Them	Completely Misunderstood Them

9. To what extend you think **your reasoning** was understood by other team members for **Task 2**?

Completely Understood Me	Understood Me	Neither Understood Nor Misunderstood Me	Misunderstood Me	Completely Misunderstood Me

10. To what extend you think you could understand **other team members' reasoning** for **Task 2**?

Completely Understood Them	Understood Them	Neither Understood Nor Misunderstood Them	Misunderstood Them	Completely Misunderstood Them

11. To what extend you think **your reasoning** was understood by other team members for **Task 3**?

Completely Understood Me	Understood Me	Neither Understood Nor Misunderstood Me	Misunderstood Me	Completely Misunderstood Me
☐	☐	☐	☐	☐

12. To what extend you think you could understand **other team members' reasoning** for **Task 3**?

Completely Understood Them	Understood Them	Neither Understood Nor Misunderstood Them	Misunderstood Them	Completely Misunderstood Them
☐	☐	☐	☐	☐

Questionnaire B

Name: Group:

1. How likely will you use VR in future for making decision on coordination tasks similar to **Task 1**? And **<u>Why</u>**?

- ☐ Very Likely
- ☐ Likely
- ☐ Neutral
- ☐ Unlikely
- ☐ Very Unlikely

2. How likely will you use VR in future for making decision on coordination tasks similar to **Task 2**? And **<u>Why</u>**?

- ☐ Very Likely
- ☐ Likely
- ☐ Neutral
- ☐ Unlikely
- ☐ Very Unlikely

3. How likely will you use VR in future for making decision on coordination tasks similar to **Task 3**? And **<u>Why</u>**?

- ☐ Very Likely
- ☐ Likely
- ☐ Neutral
- ☐ Unlikely
- ☐ Very Unlikely

4. For what type of coordination tasks you find VR a useful tool to make decision upon? Please explain your reason(s).

5. **<u>To understand the future hotel room design</u>**, comparing VR to the model projected on the screen, VR was:

- ☐ Much More Helpful
- ☐ More Helpful
- ☐ Neither Helpful Nor Unhelpful
- ☐ Less Helpful
- ☐ Much Less Helpful

6. **To make decision on assigned tasks**, comparing VR to the model projected on the screen, VR was:

- ☐ Much More Helpful
- ☐ More Helpful
- ☐ Neither Helpful Nor Unhelpful
- ☐ Less Helpful
- ☐ Much Less Helpful

7. How do the dimensions look in VR in comparison to the physical mock-up?
Smaller The same Bigger

8. To what extend was the VR experience helpful to simulate the future hotel room experience, if you did not have the physical mock-up, **to understand the future hotel room design**?

- ☐ Completely Helpful
- ☐ Fairly Helpful
- ☐ Somewhat Helpful
- ☐ A Little Helpful
- ☐ Not Helpful At All

9. To what extend was the VR experience helpful to simulate the future hotel room experience, if you did not have the physical mock-up, **to make decision on the assigned tasks**?

- ☐ Completely Helpful
- ☐ Fairly Helpful
- ☐ Somewhat Helpful
- ☐ A Little Helpful
- ☐ Not Helpful At All

10. What VR features contributed to your understanding of the future hotel room design and making decision on assigned tasks? Please explain your reason(s).

11. What VR features were the drawbacks for understanding the future hotel room design and making decision on assigned tasks? Please explain your reason(s).

12. Did experiencing the future hotel room in a different environment (virtual or physical) change your understanding of the design? Please explain.

13. What had the largest impact on your decision making in today's session?

Appendix B: Chapter 3 – Interview Tool

Interviewee Code:	**Date:**

1. Please explain your role and job description.

Part 1: First we will talk about the types of information you receive from other project participants.

2. What resources you rely on to get information to do your job? (*Name of discipline, e.g information from the architect about the structure*).

3. In what format do you receive this information?

4. How do you process this information?

5. What challenges do you have in understanding information provided by professionals from other disciplines?

Part 2: Now we will talk about what information you send to others on a project.

6. Which project participants from other disciplines rely on your work?

7. What information do you share with them?

8. Do you share the same information in the same format with each party?

9. How do you prepare the results of your technical work for project participants from other disciplines to help them understand your work?

10. What challenges do you face in presenting your results to professionals from other disciplines? (*Ask for examples*)

11. Please share examples where you have had challenges in communicating your work to professionals from other disciplines.

12. What challenges do you face while collaborating with professionals from other disciplines on a shared design decision?

13. What are methods you use to resolve these challenges?

14. What visualization tools do you use to resolve these challenges?

15. How do you use these tools to collaborate?

16. If you could create the perfect tool, what would it be?

17. Is there anything that comes to mind that we haven’t yet discussed?

18. Do you have any questions for me?

Appendix C: Chapter 4 – Experiment Questionnaires

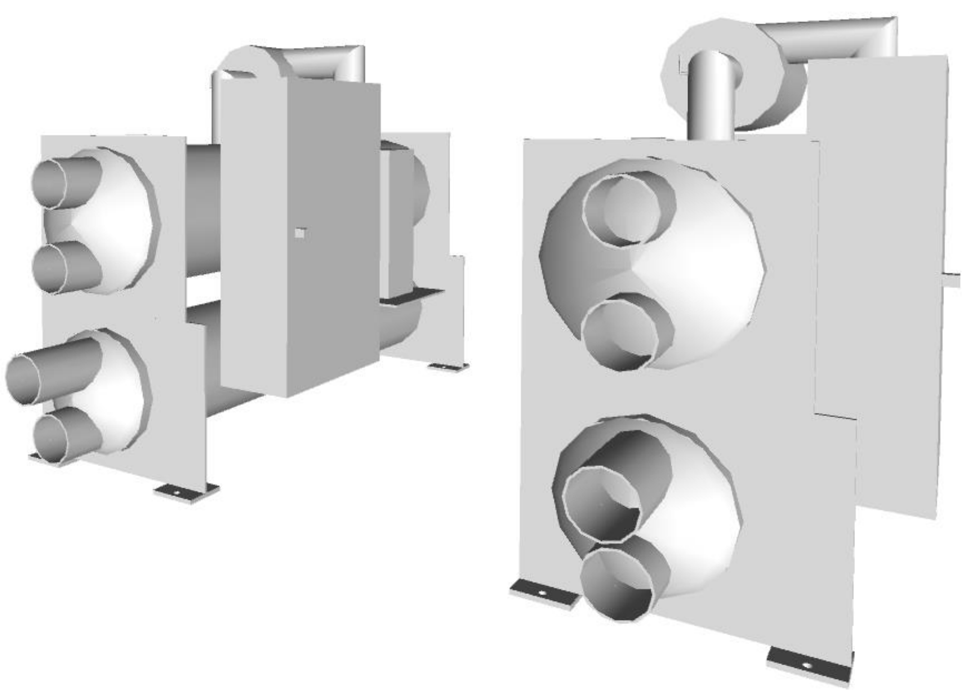
Experiment A

Name: Group: Platform:

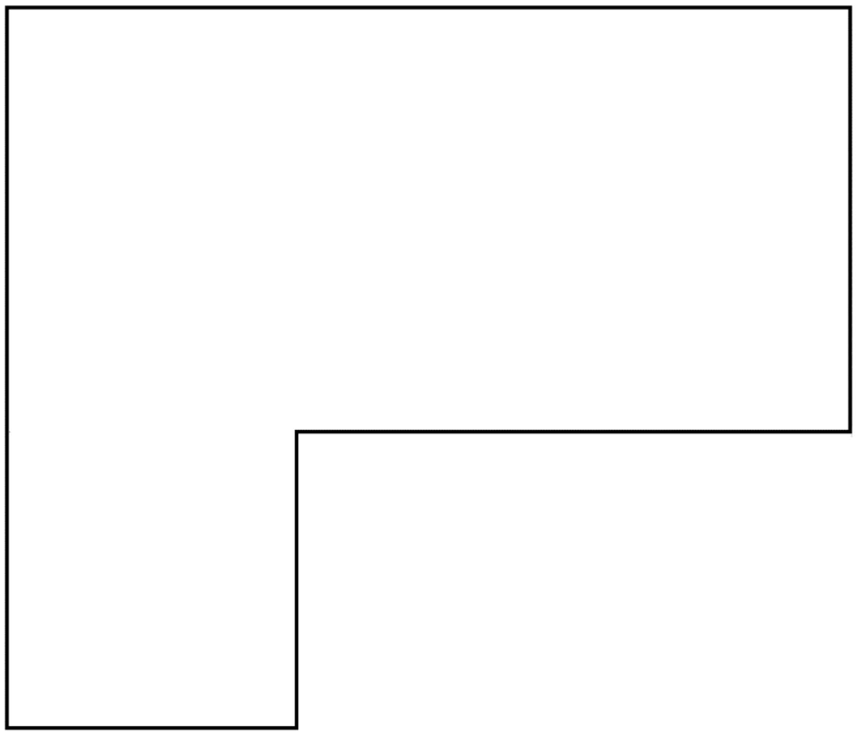
✂---

Code: Please **DO NOT** write anything in this section

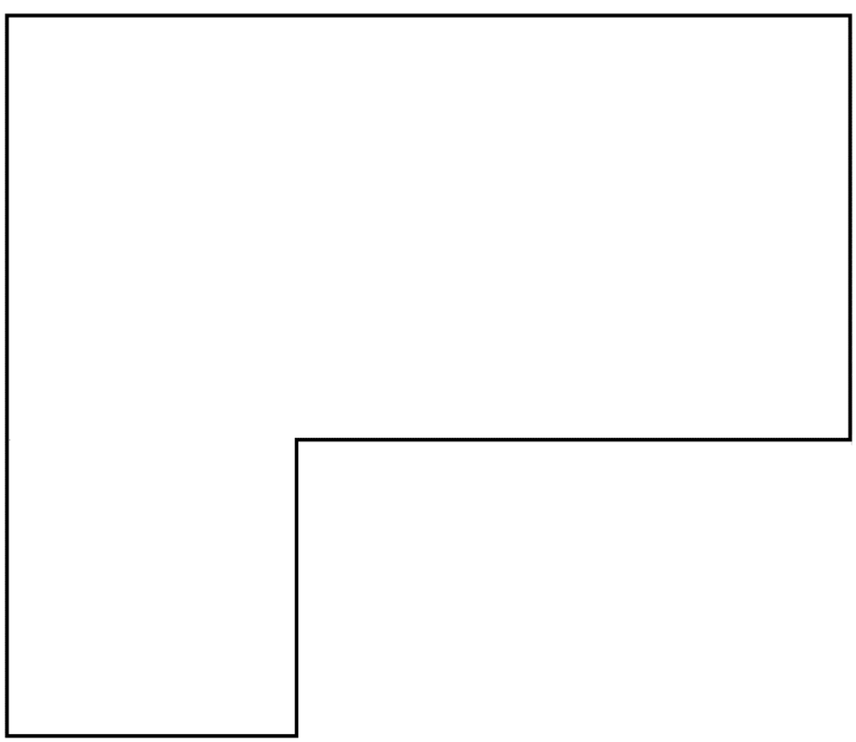
1. What was the color of the floor?
2. What were the colors of the pipelines?
3. When facing the North, you could see two equipment on your right, Chillers, as shown below. What was the color of the chillers?
4. When facing the North, you could see a piece of equipment on your left which had two parts.
   (a) What was the color of this equipment?
   (b) What were the shapes of the equipment parts? Draw the equipment.
   (c) What was the height of these parts in relevance to each other? You can show it in your drawing.
   (d) What was the height of these parts in relevance to other objects in the Mechanical Room?
5. Complete the picture below by adding the pipelines. Write the pipeline color next to each pipe.



6. In the plan below, (a) show the location of the doors, and (b) draw the beams.



7. In the plan below, show the location of the equipment, the pipeline routes, and your viewpoint locations.



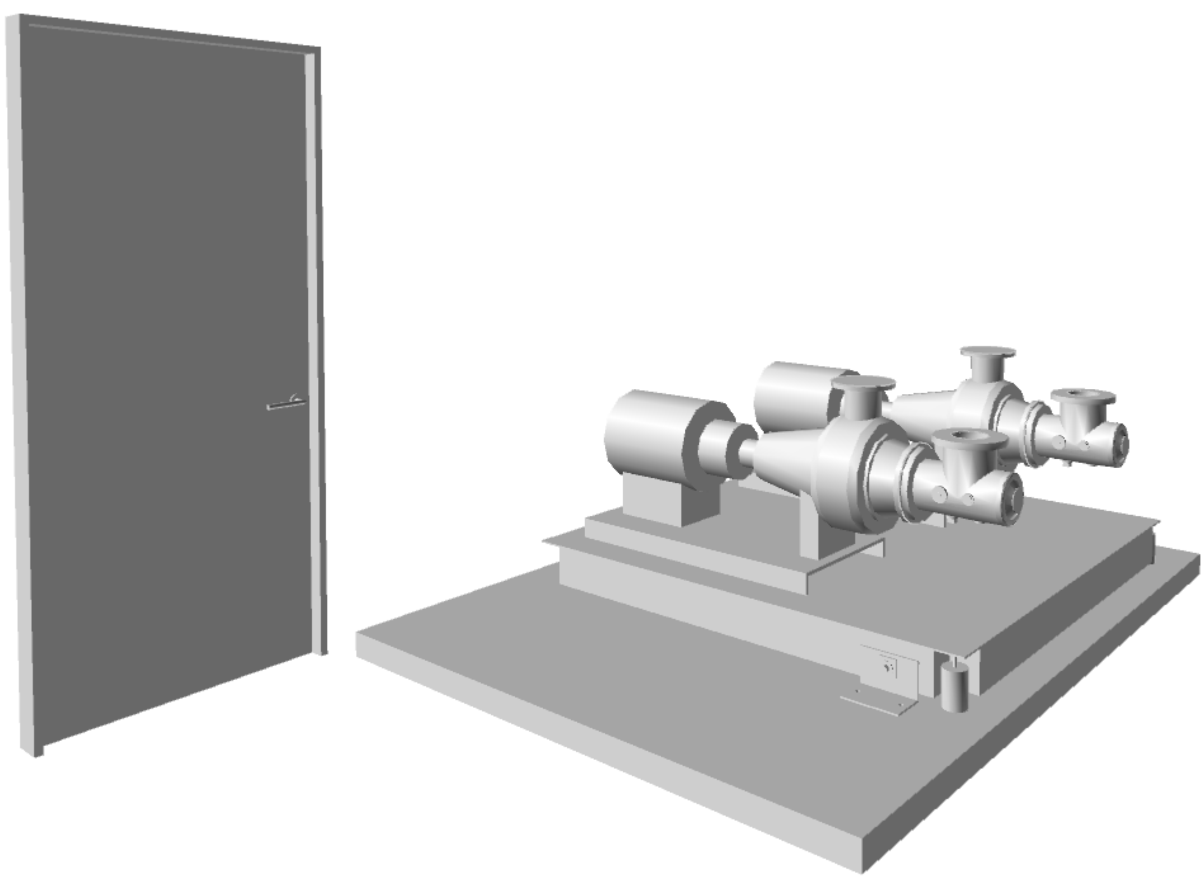
Experiment B

Name: Group: Platform:

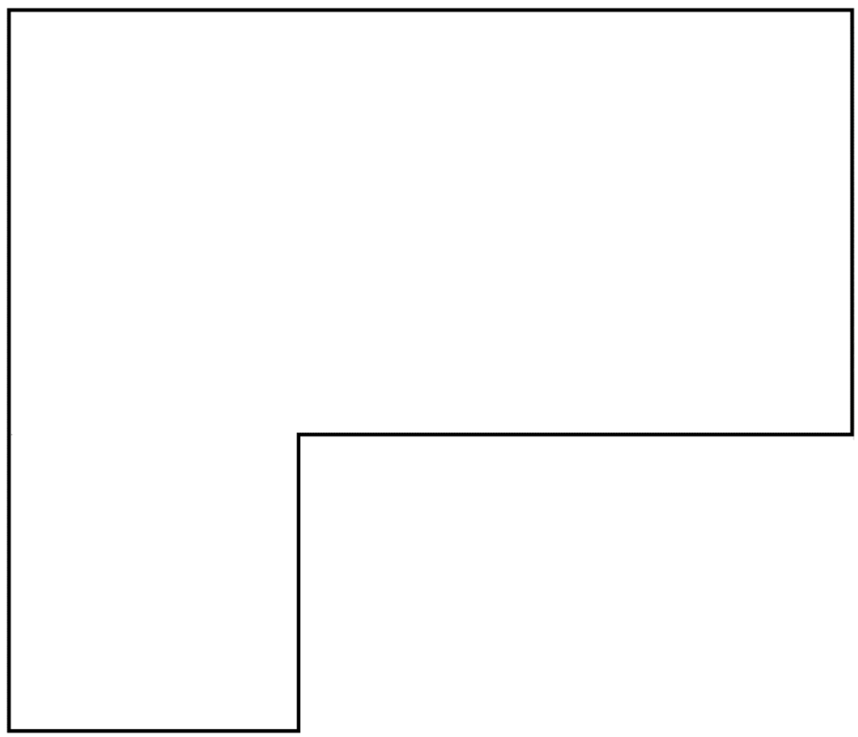
✂---

Code: Please **DO NOT** write anything in this section

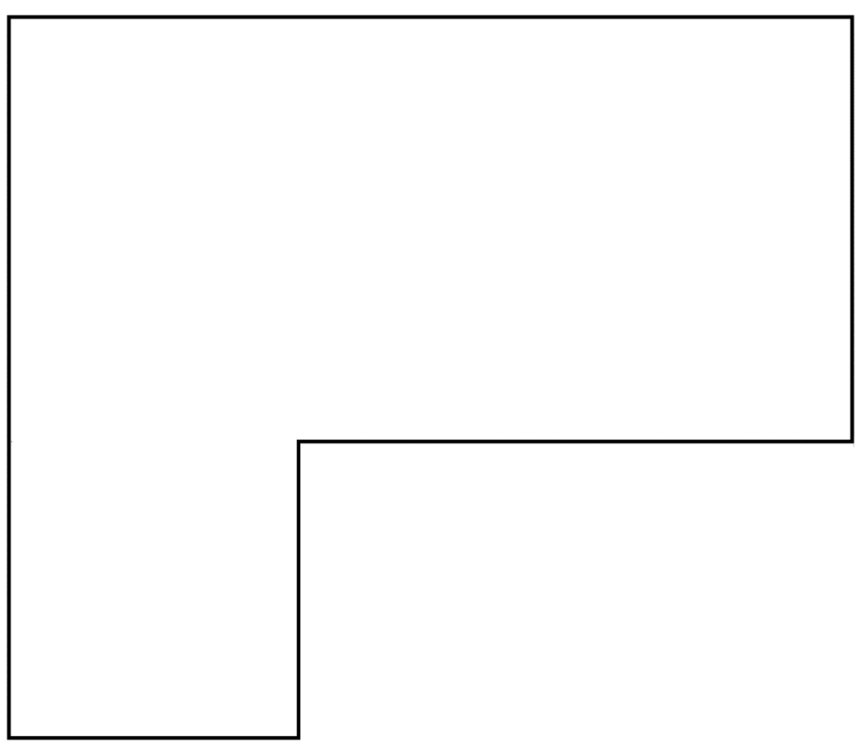
1. What were the colors of the walls?
2. What were the colors of the pipelines?
3. There were two pumps on the North wall as shown below. What were the colors of the pumps?
4. A feeder (3 Gallon) and an expansion tank (21 Gallon) were located next to the pumps. What was the color of this equipment?
5. Complete the picture below by adding the pipelines (up to the ceiling). (a) Write the pipeline color next to each pipe, (b) Draw the feeder and expansion tank, (c) Draw the pipes that connect the pump to the feeder.



6. In the plan below, (a) Show the location of the electrical boxes and write down the number of them, (b) Specify the wall(s) that has a different color, (c) Show the location of the columns.



7. In the plan below, show the location of the equipment, the pipeline routs, and your viewpoint locations.



Experiment A & B Comparison

Name: Group:

✂---

Code: Please **DO NOT** write anything in this section

1. Which platform helped you the most to understand the model with regards to:
   - (a) Color — 3D Model on 2D Screen ☐ Virtual Reality ☐ Same☐
   - (b) Object Shape — 3D Model on 2D Screen ☐ Virtual Reality ☐ Same☐
   - (c) Object/Room Depth — 3D Model on 2D Screen ☐ Virtual Reality ☐ Same☐
   - (d) Object/Room Height — 3D Model on 2D Screen ☐ Virtual Reality ☐ Same☐
   - (e) Location of the objects — 3D Model on 2D Screen ☐ Virtual Reality ☐ Same☐
   - (f) Position of the objects — 3D Model on 2D Screen ☐ Virtual Reality ☐ Same☐
   - (g) Your location in the model — 3D Model on 2D Screen ☐ Virtual Reality ☐ Same☐
   - (h) Distance from the objects — 3D Model on 2D Screen ☐ Virtual Reality ☐ Same☐
   - (i) Pipe Routes — 3D Model on 2D Screen ☐ Virtual Reality ☐ Same☐

2. Which Navisworks features did you prefer over V|V to understand the model?

3. Which V|V features did you prefer over Navisworks to understand the model?

4. In which platform did you spend less time to understand the model? Why?

5. Overall, which platform would you prefer to use in future to understand the models? Why?

Appendix D: Chapter 4 – Model Recall Data

Recalling the model based on the color criterion.

Recalling the object color correctly has 1 point.

	Model A Color					Model B Color				
Name	Floor	Pipe 1	Pipe 2	Chiller	Equipment	Wall	Pipe 1	Pipe 2	Pump	Tank
BV1	1	1	1	1	0	1	1	1	0	1
BV2	0	1	1	1	0	1	1	1	1	0
BV3	1	1	1	1	1	0	1	1	1	1
BV4	1	1	1	1	0	1	1	1	0	0
BV5	0	1	1	1	0	1	1	1	1	1
BV6	1	1	1	1	1	1	1	1	0	1
BV7	1	1	1	1	1	0	1	1	0	1
BV8	1	1	0	1	1	1	1	1	1	0
BV9	0	1	1	1	1	0	1	1	0	1
BV10	1	0	0	1	0	1	1	1	0	1
BV11	1	1	1	1	0	1	0	1	0	0
BV12	0	1	1	0	0	1	1	1	0	0
VB1	1	1	1	1	1	1	1	1	0	0
VB2	1	1	1	1	1	1	1	1	1	1
VB3	0	1	1	1	1	1	1	1	1	1
VB4	1	1	1	1	1	1	1	1	0	1
VB5	0	1	1	1	1	1	1	1	0	1
VB6	0	1	1	1	1	1	1	1	0	0
VB7	1	1	1	1	1	1	1	1	0	1
VB8	1	0	1	1	1	1	1	1	1	1
VB9	0	1	1	1	0	1	1	1	0	1
VB10	1	1	1	1	0	1	1	1	1	1
VB11	0	1	1	1	1	1	1	0	1	1
VB12	0	1	1	1	1	1	1	1	0	0

Recalling the model based on the shape criterion.

Shapes of two pieces of mechanical equipment were asked in the Model A questionnaire.

Shapes of the tank and feeder were asked in the Model B questionnaire.

Recalling the object shape correctly has 1 point. If the equipment was drawn correctly in the plan, 0.5 point was given.

	Model A Shape		Model B Shape	
Name	Shape 1	Shape 2	Shape 1	Shape 2
BV1	0.5	1	0	0
BV2	0	0	0	0
BV3	1	1	1	1
BV4	1	1	0.5	0
BV5	0	0	1	1
BV6	0.5	0	0	0
BV7	1	1	1	1
BV8	0	0	1	1
BV9	1	0	1	1
BV10	1	0	0	0
BV11	0	0	0	0
BV12	0.5	0	0	0
VB1	1	1	0	0
VB2	1	1	1	0
VB3	1	1	0	1
VB4	1	1	0	0
VB5	1	1	1	1
VB6	1	1	0	0
VB7	1	0	0	0
VB8	1	1	0	0
VB9	0	0	0	0
VB10	1	1	1	1
VB11	1	0	0	1
VB12	1	1	0	0

Recalling the model based on the dimension criterion.

Same mechanical equipment pieces in Model A and tank and feeder in Model B were considered for this analysis. Recalling the width, length, and height of each piece of equipment correctly worth 0.5 point. 0.25 point for each piece of equipment was given to the dimension in relevance to the other equipment piece, and 0.25 was given to the dimension in relevance to the surrounding objects.

	Model A Dimension			Model B Dimension		
Name	Width	Length	Height	Width	Length	Height
BV1	0	0	0	0	0	0
BV2	0.5	0.5	0	0.5	0.5	0
BV3	1	1	1	0.5	0.5	0.5
BV4	0	0	0.5	0	0	0.5
BV5	0	0	0	1	1	0.5
BV6	0.5	0.5	0	0	0	0
BV7	1	1	0.5	1	1	1
BV8	0.5	0.5	0	1	1	0.75
BV9	0.5	0.5	0	1	1	0.5
BV10	0.5	0.5	0	0	0	0
BV11	0	0	0	0	0	0
BV12	0	0	0	0	0	0
VB1	1	1	1	0	0	0
VB2	0.5	0.5	1	1	1	0
VB3	1	0.5	0.5	1	1	0.75
VB4	1	1	0.5	0	0	0
VB5	1	1	1	0.5	0.5	0.5
VB6	1	1	1	0	0	0
VB7	0.5	0.5	0	0	0	0
VB8	1	1	1	0	0	0
VB9	0	0	0	0	0	0
VB10	1	1	1	1	1	0.5
VB11	0.5	0.5	0.5	0	0.5	0
VB12	0.5	0.5	0	0	0	0

Recalling the model based on the pipeline route criterion.

Four pipes in each model were connected to piping equipment. 0.25 point was given for recalling the connection of each pipe correctly. 0.25 point was considered for recalling correctly each of the four criteria of position in elevation and plan, and location in elevation and plan for each pipe.

	Model A Pipeline					Model B Pipeline				
	Pipe	Elevation		Plan		Pipe	Elevation		Plan	
Name	Connection	Pos	Loc	Pos	Loc	Connection	Pos	Loc	Pos	Loc
BV1	0	1	0.5	1	1	0	1	0.5	1	1
BV2	0	0	0	0	0	1	0	0	1	0.5
BV3	0	0	0	1	0	0.5	0.5	0.5	0	0
BV4	0	0	0	0	0	0	0	0	0.5	0
BV5	1	1	1	0.5	0.5	1	1	1	1	1
BV6	1	1	0.75	0	0	0.5	0.5	0.5	0.5	0.25
BV7	1	1	0.75	0	0	1	1	1	1	1
BV8	0	0	0	0	0.5	1	1	1	1	0.5
BV9	0.5	1	0.75	1	1	0.5	1	1	1	0.5
BV10	0.5	1	0.5	0	0	0	0	0	0	0
BV11	0.5	0	0	0	0	0	0	0	0	0
BV12	0	0	0	0	0	0.5	0.5	0.5	0	0
VB1	1	0.5	0.25	1	1	0.5	1	0.75	0.5	0.5
VB2	0.75	1	0.5	1	0.5	1	1	1	1	1
VB3	1	1	1	0.5	0.5	1	1	0.75	0.5	0.25
VB4	1	1	0.5	1	1	0	0.5	0	1	0.5
VB5	0	1	0.25	1	0.75	1	0	0	0.5	0.5
VB6	0.5	1	0.5	0	0	0	0.5	0	0	0
VB7	0	0	0	0	0	0	0	0	0	0
VB8	1	1	1	1	1	1	1	1	1	1
VB9	1	1	1	1	1	0.5	0.5	0	0	0
VB10	1	1	1	1	0.5	1	1	1	1	1
VB11	1	1	0.75	0	0	0.5	0.5	0	0.25	0
VB12	0	0	0	0	0.25	0	0	0	0	0.25

Pos=Position & Loc=Location

Recalling the user location in the model.

Viewpoint 1 was close to chillers, and viewpoint 2 was close to the mechanical equipment and tank. The user distance from the wall and equipment were the criteria to give points for the viewpoint distance.

	Model A				Model B			
	Viewpoint 1		Viewpoint 2		Viewpoint 1		Viewpoint 2	
Name	Location	Distance	Location	Distance	Location	Distance	Location	Distance
BV1	0	0	0	0	1	1	0.5	1
BV2	0	0	0	0	0	0	1	1
BV3	0.5	1	1	1	1	1	1	1
BV4	0	0	0	0	0	0	0	0
BV5	0.5	0	0	0	0.5	1	1	1
BV6	0.5	1	1	1	0	0	0	0
BV7	0	0	0	0	1	0.5	1	1
BV8	0.5	0.5	1	0	0.5	1	0	0
BV9	0.5	0	1	1	0	0	1	1
BV10	0	0	0	0	0	0	0	0
BV11	0	0	0	0	0	0	0	0
BV12	0	0	0	0	0	0	0	0
VB1	1	0.5	1	0.5	1	0.5	1	0.5
VB2	0	0	0	0	0	0	0	0
VB3	0	0	0	0	1	0.5	0	0
VB4	0.5	1	0	0	0.5	1	0	0
VB5	1	1	1	0.5	1	0	1	0
VB6	1	0	1	0	1	0	1	0
VB7	1	0	0	0	1	0	0	0
VB8	1	1	1	1	1	1	1	1
VB9	0	0	0	0	0	0	0	0
VB10	1	1	1	0.5	1	1	1	1
VB11	0	0	0	0	0.5	0	0.5	0
VB12	0	0	0.5	1	0	0	0	0

Appendix E: Chapter 5 – Experiment Instructions and Questionnaires

Guideline VR Platform

Step 1. Read your Assignment Description sheet. If you have any questions about the technical information provided in this sheet, please ask your instructor for more explanation. **DO NOT SHARE THE INFORMATION IN THE ASSIGNMENT DESCRIPTION SHEET WITH ANY OF YOUR GROUP MATES BEFORE THE START OF YOUR MEETING.**

Step 2. Use the VV ID below to familiarize yourself with the model:

For Experiment 3A: 1V-VNN-SB

For Experiment 3B: 1V-VQP-3T

Step 3. Your instructor will be the host of your team meeting in Virtual Reality platform and will walk you through the steps below:

1) Dial this phone number for teleconferencing: (206) xxx-xxxx PIN: 555 0030#
2) Accept VV meeting invitation from your instructor
3) Go to the specified room/space for the class activity

Some notes:

a) Reminder: To create a mark-up push your finger on the phone screen and move the cellphone in your eye direction. If you take your finger off the screen, the markup will disappear.
b) If you feel dizzy while using VR viewer, you can get out of VR mode. To do this, hit the icon “<” (iOS) or “x” (Android) on the top left corner. Hit “Turn VR Off” then hit “Return to Vv.”(Hit Return to meeting if you would like to do it during the meeting). You can look around by swiping your phone screen without the need to turn around physically. In the VR Off mode, the gaze does not work. You have to hit the screen to teleport to a different scene via teleporter.

Step 4. Start the meeting. You need to collaborate in the team setting to come up with a solution for the design issue that one or two team members bring to the meeting.

Step 5. After you made a team decision, feel out the back of the Assignment Description Sheet and submit it. You should fill it out individually without asking for help from your friends.

Step 6. After you submit your Assignment Description sheet, your instructor will give you a questionnaire. Fill out the questionnaire individually without asking for help from your friends and submit it.

Step 7. If this is your second activity, you will be given another questionnaire to compare your experience in two platforms.

Guideline Shared Screen Platform

Step 1. Read your Assignment Description sheet. If you have any questions about the technical information provided in this sheet, please ask your instructor for more explanation. **DO NOT SHARE THE INFORMATION IN THE ASSIGNMENT DESCRIPTION SHEET WITH ANY OF YOUR GROUP MATES BEFORE THE START OF YOUR MEETING.**

Step 2. Your instructor will guide you to the specified computers for this assignment and will help with your setup. You will have a computer with the internet access, a laptop, and a headset. Log in to the computer with your UW Net ID. Log in to Canvas. Go to Assignment sections. Open “Reflection 8”. Download the file related to your experiment. Open the file in Navisworks and familiarize yourself with the model. During the meeting, you can check the model in laptop while looking at your teammate’s shared screen on the monitor.

Some notes:

1) DO NOT change any settings in Navisworks.
2) To explore the model, ONLY use the previously created viewpoints
3) You should ONLY Look Around. If you are in the Walk mode, don’t change the setting with collision, gravity, and crunch enabled. Do not use any other navigation capabilities.
4) You can use Review tools to mark up your model.

Step 3. Your instructor will be the host of your team meeting in Zoom. The link to your Zoom meeting is provided in “Reflection 8”. Click on the link. Launch Zoom. Join the meeting. Select “computer audio”. Make sure you can hear everyone and they can hear you through the headset. If you have technical problems, ask for help.

Step 4. Start the meeting. You need to collaborate in the team setting to come up with a solution for the design issue that one or two team members bring to the meeting.

Step 5. After you made a team decision, feel out the back of the Assignment Description Sheet and submit it to the instructor/observer. You should fill it out individually without asking for help from your friends.

Step 6. After you submit your Assignment Description sheet, your instructor/observer will give you a questionnaire. Fill out the questionnaire individually without asking for help from your friends and submit it.

Step 7. If this is your second activity you will be given another questionnaire to compare your experience in two platforms.

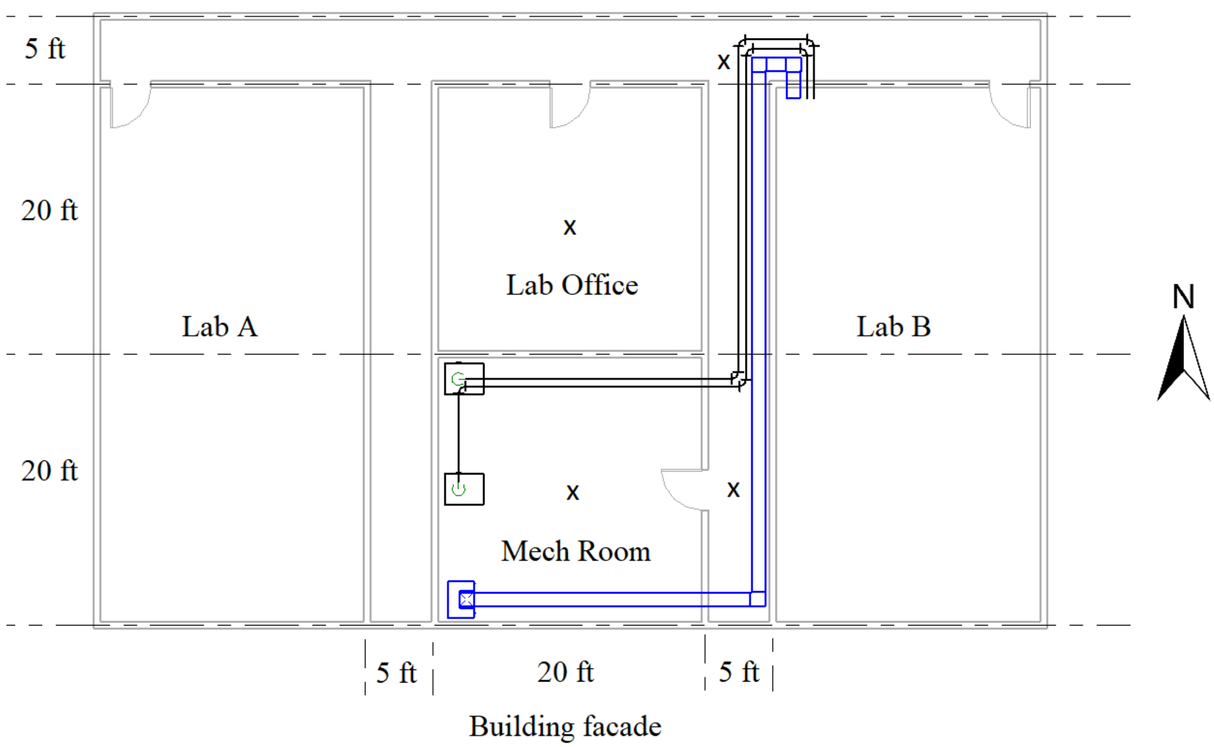
Assignment Description - Experiment A

Name: **Platform:**

Code: Please **DO NOT** write anything in this section

Role: Structural Engineer

You are the Structural Engineer of a research facility. The plan below shows a part of the building. Based on your structural analysis, the wall on the East side of the mechanical room and the Lab office with a length of 40 ft. should now be a shear wall. This means the opening area in this wall should be limited. You can allow only one opening in the wall. Either a duct or 2 pipes can penetrate this wall. As a result, the door needs to be relocated, and the duct and/or piping routes should be changed.



Note: The location of the viewpoints in the model are shown as “x” on the plan.

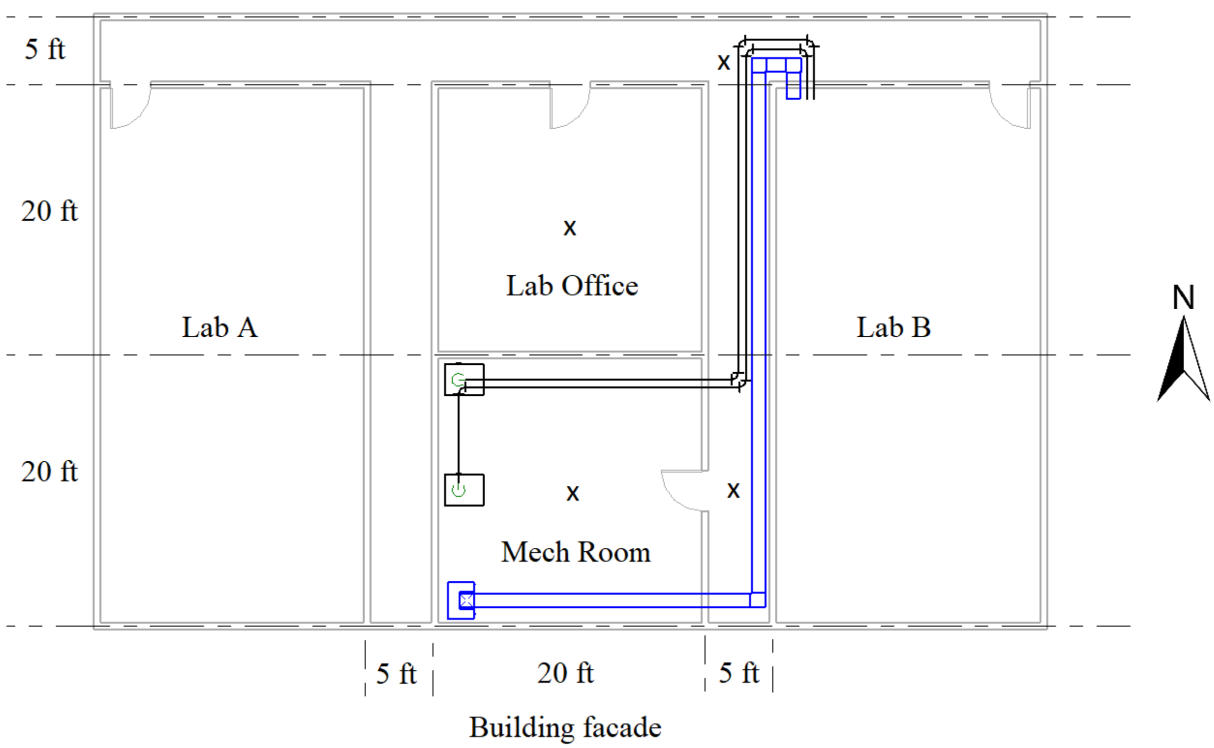
Assignment Description - Experiment A

Name: **Platform:**

Code:	Please **DO NOT** write anything in this section

Role: Architect

You are the Architect of a research facility. The plan below shows a part of the building.
The room on the North side of the mechanical room is going to be the Lab office which was previously a storage room. You prefer to have both the boilers and the air handler on one wall so that the owner can use the rest of the room space for storage.
You don't like the MEP system to be seen in the Lab office and corridors (and of course the building façade). The corridors have ceiling soffit; meaning the MEP system can be embedded in the celling. The Lab office does not have a ceiling soffit since it was previously supposed to be a storage room. The owner does not prefer to spend extra on the ceiling soffit for this room. You are okay with corner soffits along with the West and East walls of the Lab office. Each corner soffit can fit either 1 duct or 2 pipes. The cost for the corner soffit for 1 duct in the Lab office (length of 20 ft) is $2,000, and it costs $1,500 for 2 pipes. If you want to relocate the door, you can locate it on the West wall to use the West corridor. The door should be located in either the corners or middle of the West wall right behind one of the boilers or the air handler. No piping or ductwork can go above the door. The owner prefers to spend less than $2,000 to all the changes you make to the design.



Note: The location of the viewpoints in the model are shown as "x" on the plan.

Assignment Description - Experiment A

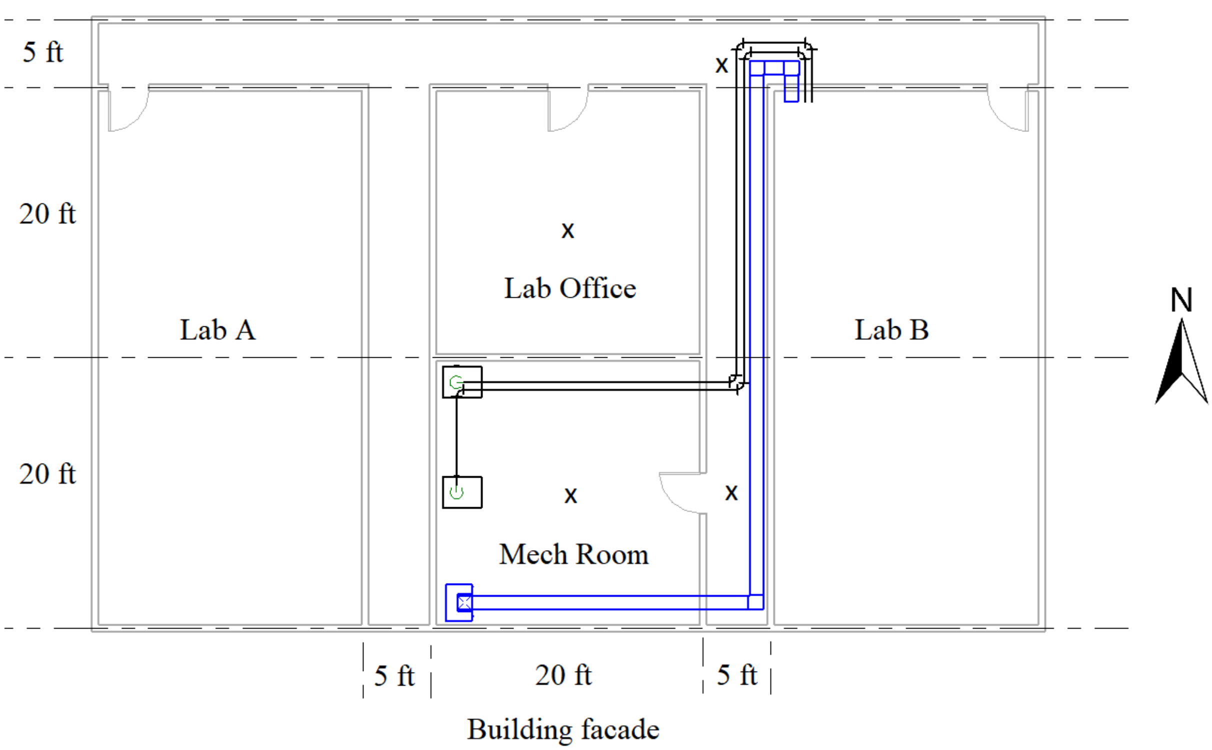
Name: **Platform:**

Code: Please **DO NOT** write anything in this section

Role: Mechanical Subcontractor

You are the Project Manager of a mechanical subcontractor working on a research facility. The plan below shows a part of the building.

The current ductwork fee is calculated in the cost. The ductwork costs $50/ft. You need approximately half of the room length (10 ft) distance from any obstacles to provide space for maintenance. That's why you have placed your air handler in the corner, and the boilers are located in the middle and the corner of the wall. Based on your conversation with the Mechanical Engineer, by moving the air handler to the East wall and routing it from the East corridor, you need to spend extra $2,000 to buy a more powerful air handler since it needs to push the air through two consequent duct bends. Due to the sensitivity of Lab A to vibration, no MEP system should be placed in the West corridor. If you change your routing, you need to make sure the duct enters the Lab B at the same spot shown on the current plan. You can bend your duct only for 90 degrees; meaning you can't route your duct diagonally.



Note: The location of the viewpoints in the model are shown as "x" on the plan.

Assignment Description - Experiment A

Name: **Platform:**

✂---

Code:	Please **DO NOT** write anything in this section

Role: Piping Subcontractor

You are the Project Manager of a piping subcontractor working on a research facility. The plan below shows a part of the building.

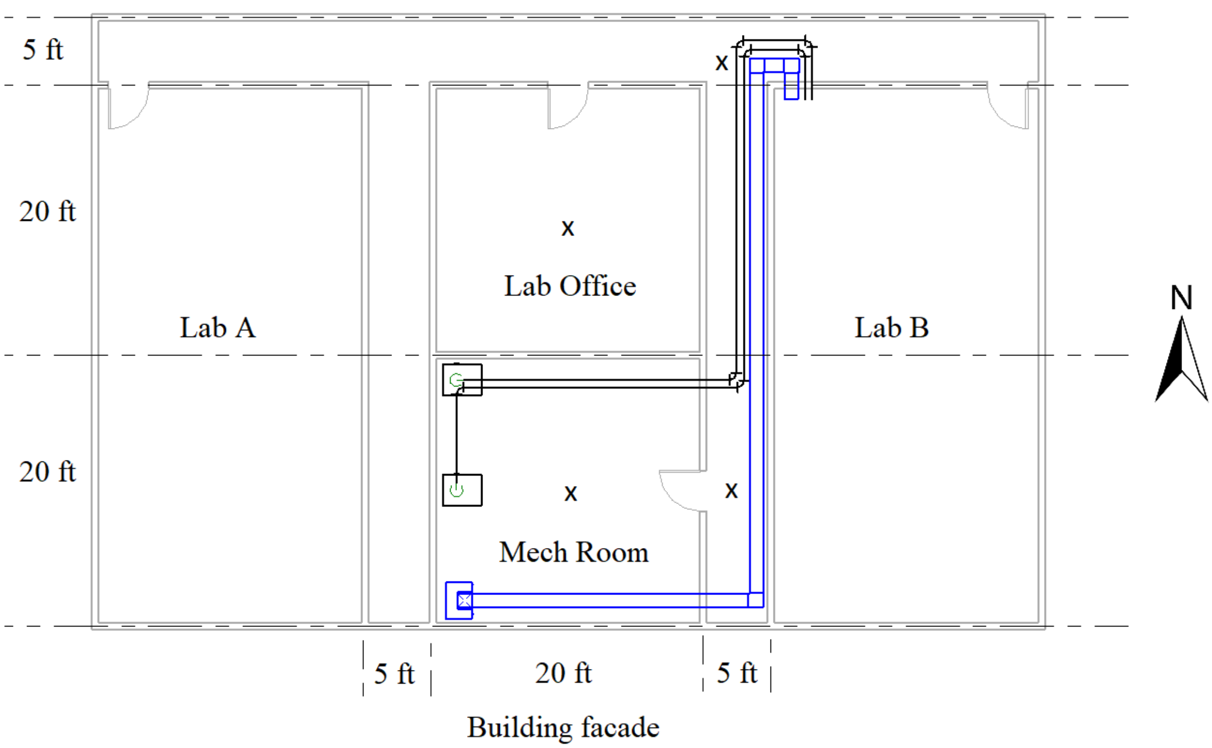
The current piping fee is calculated in the cost. The piping costs $25/ft for each pipe.

The ceiling height is low. As a result, the duct and the pipe can't be installed at different heights.

You need approximately half of the room length (10 ft) distance from any obstacles to provide space for maintenance. That's why one boiler is located in the middle of the West wall, and the other one is in the corner. The air handler is located at the corner to meet this clearance distance.

If you change your routing, you need to make sure the pipes enter the Lab B at the same spot shown on the current plan.

You can bend your pipe only for 90 degrees; meaning you can't route your pipe diagonally.



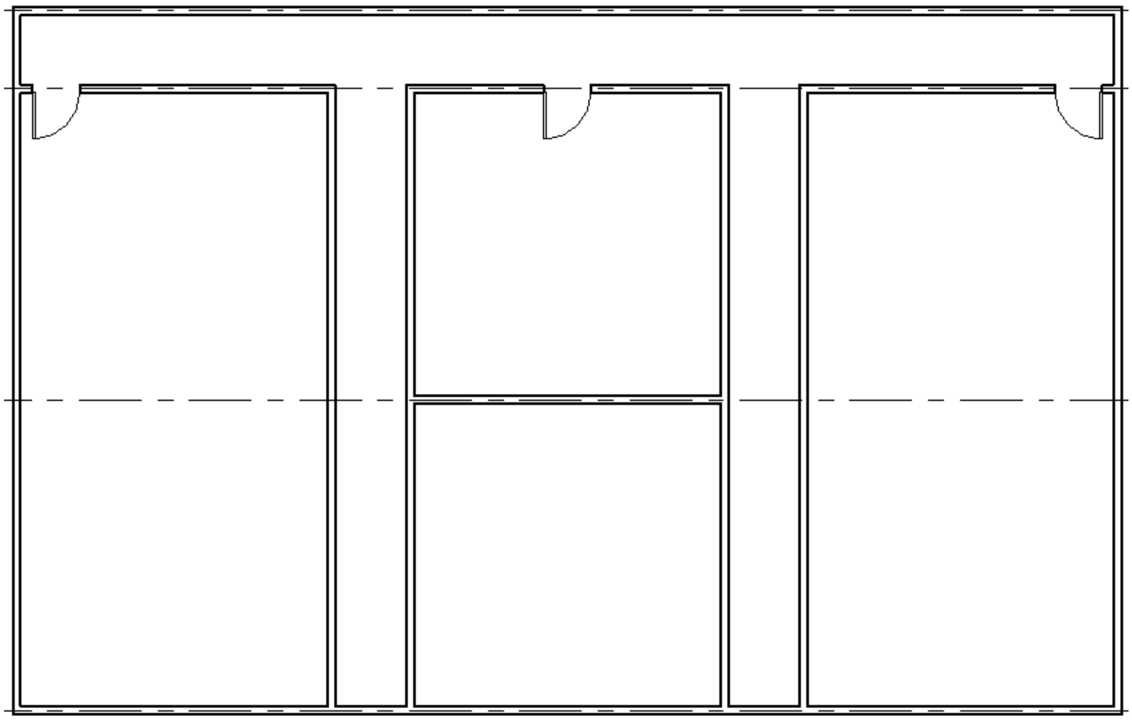
Note: The location of the viewpoints in the model are shown as "x" on the plan.

Questionnaire AA

Name: **Platform:**

✂---

1. In the plan below, show the new location of the boilers, the air handler, and the door. Draw the new ductwork and piping routes based on your team decision.



2. How much is the extra cost based on the changes you made to the design? Write down the details of your cost estimation.

3. To solve the problem, approximately what percentages of your time did you spent on:
   a) Exploring the model individually to solve the problem: _______ %
   b) Drawing/writing on the paper to solve the problem: _______ %
   c) Collaborating with your teammates to solve the problem: _______ %
   d) Other: ____: _______ %

   Total (a+b+c+d) 100%

Questionnaire AB

Name: **Platform:**

✂---

Code:	Please **DO NOT** write anything in this section

Section 1: Technical Information

1. Where was the shear wall located?
   a) Only the East wall of the mechanical room
   b) The East wall of the mechanical room and East wall of the Lab office
   c) Only the West wall of the mechanical room
   d) The West wall of the mechanical room and the West wall of the Lab office

2. What was the maximum opening area allowed in the shear wall?
   a) One opening for 1 duct or 2 pipes
   b) Two openings; one opening for 1 duct and one opening for 2 pipes
   c) One large opening for 1 duct and 2 pipes
   d) None of the above

3. Which building area had ceiling soffit to embed the MEP system?
   a) Lab Office b) Lab c) Corridors d) All areas

4. How much would it cost to move the air handler to the East wall and route it through the East corridor?
   a) $500 b) $1,000 c) $1,500 d) $2,000

5. How much was the cost of the corner soffit with the length of 20 ft to fit 1 duct?
   a) $1,000 b) $1,500 c) $2,000 d) $2,500

Section 2: Platform Experience

1. Which platform features help you communicate your technical work to your teammates? Please explain.

2. Which platform features caused challenges to communicate your technical work to your teammates? Please explain.

Questionnaire AB

Name: **Platform:**

✂---

3. Did you have any challenges in understanding any of your teammates' technical work and requirements? Please explain.

4. Did any of your teammates have challenges in understanding your technical work and requirements? Did you have to explain more? Please explain.

5. What do you wish you could do during the team collaboration to solve the problem faster?

Assignment Description - Experiment B

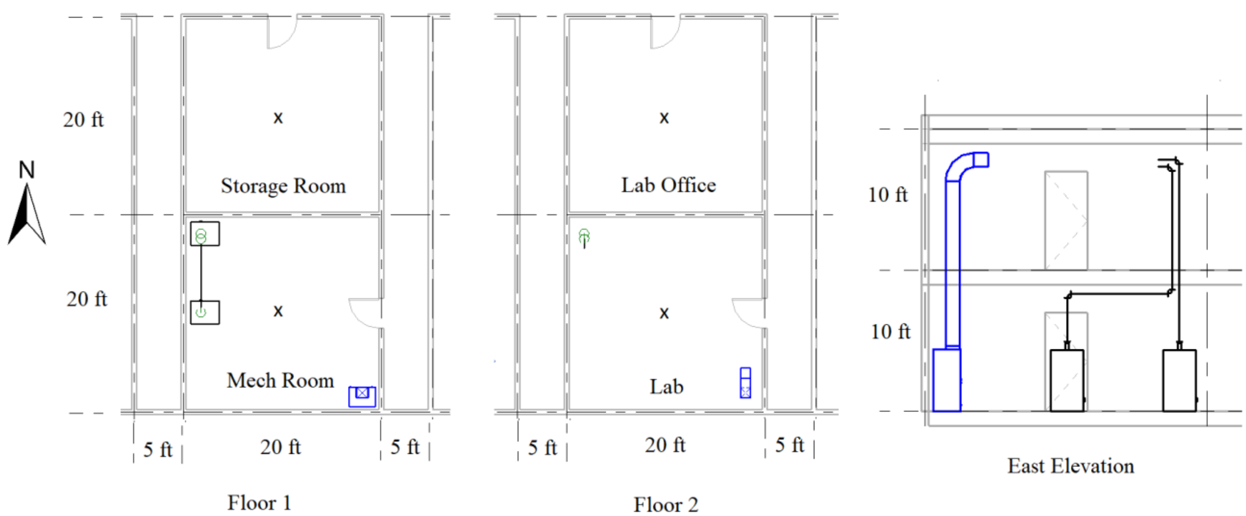
Name: **Platform:**

✂---

Code:	Please **DO NOT** write anything in this section

Role: Structural Engineer

The Lab on the second floor has very heavy equipment which results in a high shear force applied to the slab underneath. During design review, you realized the two slab openings (risers for the duct and pipes) in the Lab floor slab (ceiling of the mechanical room on the first floor) would result in structural failure. By pouring a thicker concrete slab, you can allow one opening in this slab for either 1 duct or 2 pipes. Pouring thicker slab will result in $2,000 extra cost. The slab below the Lab office on the second floor (the ceiling of the storage room on the first floor) can have a maximum of two openings. One opening for 1 duct and one opening for 2 pipes. A large opening for both the duct and 2 pipes will result in structural failure.



Note: The location of the viewpoints in the model are shown as “x” on the plan.

Assignment Description - Experiment B

Name: **Platform:**

✂---

Code: Please **DO NOT** write anything in this section

Role: Architect

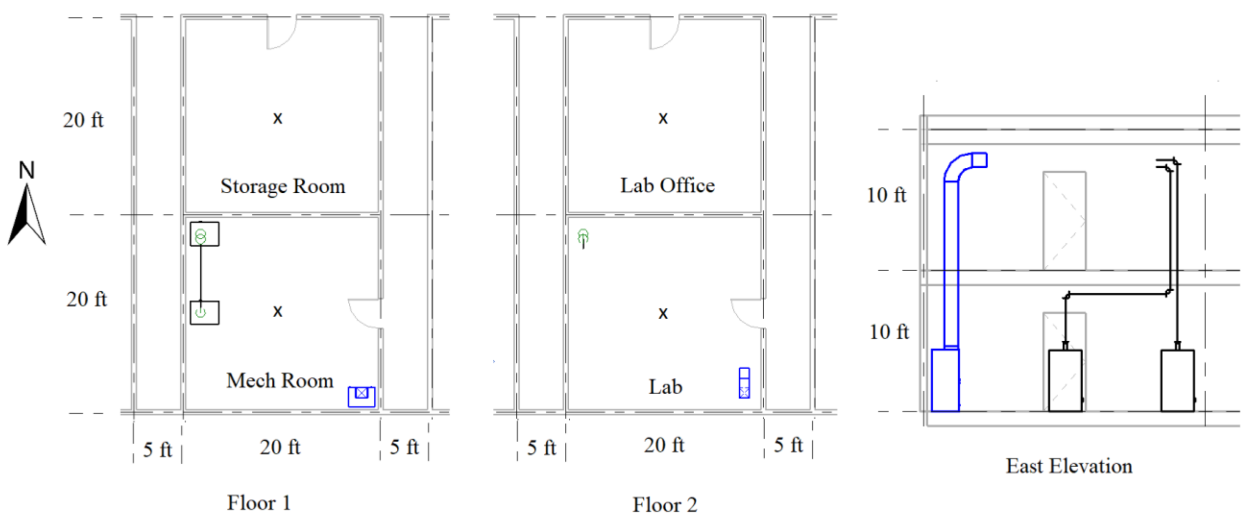
You don't like the MEP system to be seen in the Lab office. It's OK if the MEP system is seen in the storage room. You prefer to have the opening in the slab (risers for the pipes and duct) on the corners of one wall so that you can embed the MEP system in the corners of a wall-to-wall cabinet. The owner has already accepted paying for the cabinet in the Lab office, but the location of this cabinet is not specified yet. You can discuss the cabinet location based on the MEP routing. Since some cabinet space will be occupied by the MEP system and can't be used, you need to consider $500 extra cost for embedding 1 duct or 2 pipes in the corner cabinets.

You prefer to have both the boilers and the air handler on one wall of the mechanical room so that the owner can use the rest of the room space for storage. As you remember, one storage room became a Lab office, so you need to use other spaces for storage. Ask the subcontractors to relocate their boilers and the air handler.

If you want to relocate the door, you can locate it on the West wall to use the West corridor. The door should be located on either the corners or middle of the West wall.

No piping or ductwork can go above the door frame.

The owner prefers to spend less than $4,000 to all the changes you make to the design.



Note: The location of the viewpoints in the model are shown as "x" on the plan.

Assignment Description - Experiment B

Name: **Platform:**

✂---

Code:	Please **DO NOT** write anything in this section

Role: Mechanical Subcontractor

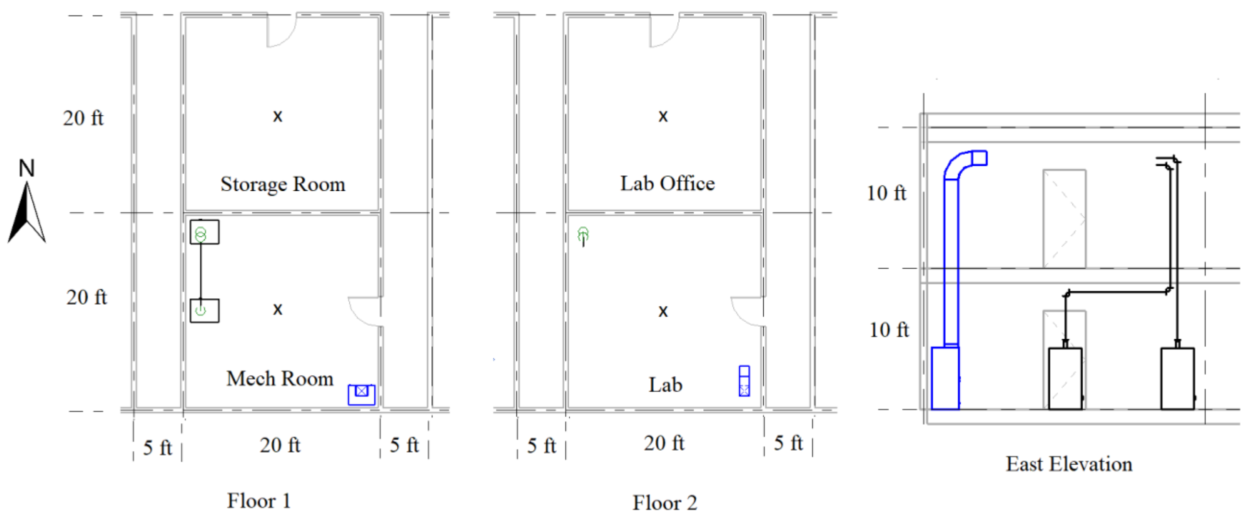
The current ductwork fee is calculated in the cost. The ductwork costs $50/ft.

You need approximately half of the room length (10 ft) distance from any obstacles to provide space for maintenance.

You can bend your duct only for 90 degrees; meaning you can't route your duct diagonally. For every bend that you add to the duct route, consider an additional cost of $500.

If you change your routing, you need to make sure the duct rout ends at the same point where the current ductwork is in the Lab.

Corridors can't be used for rising the MEP system.



Note: The location of the viewpoints in the model are shown as "x" on the plan.

Assignment Description - Experiment B

Name: **Platform:**

Code: Please **DO NOT** write anything in this section

Role: Piping Subcontractor

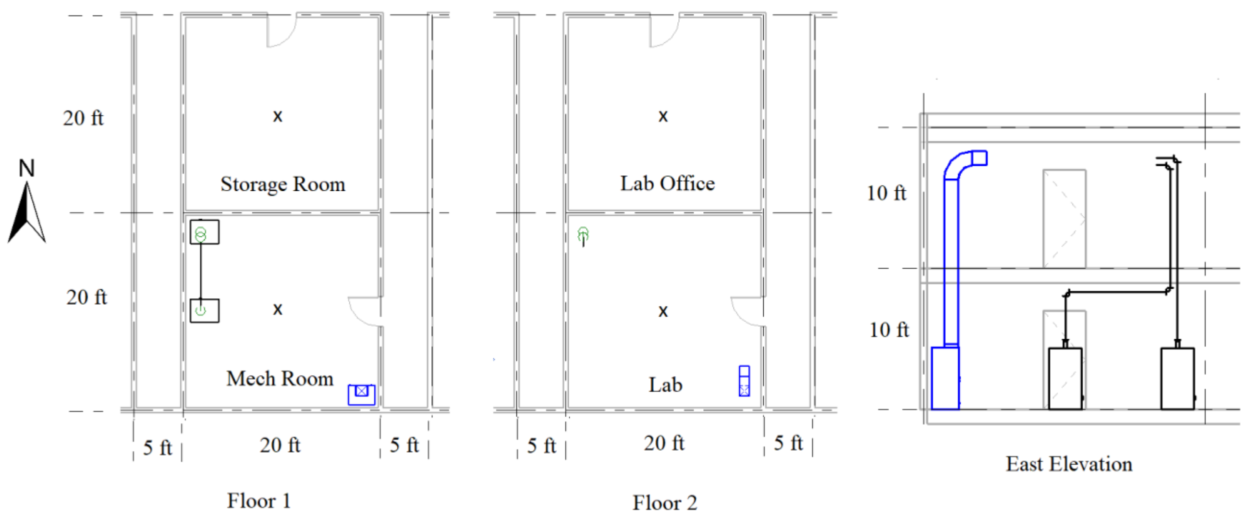
The current piping fee is calculated in the cost. The piping costs $25/ft for each pipe.

The ceiling height is low. As a result, the duct and the pipe can't be installed at different heights.

You need approximately half of the room length (10 ft) distance from any obstacles to provide space for maintenance.

If you change your routing, you need to make sure the duct rout ends at the same point where the current ductwork is in the Lab.

You can bend your pipe only for 90 degrees; meaning you can't route your pipe diagonally.



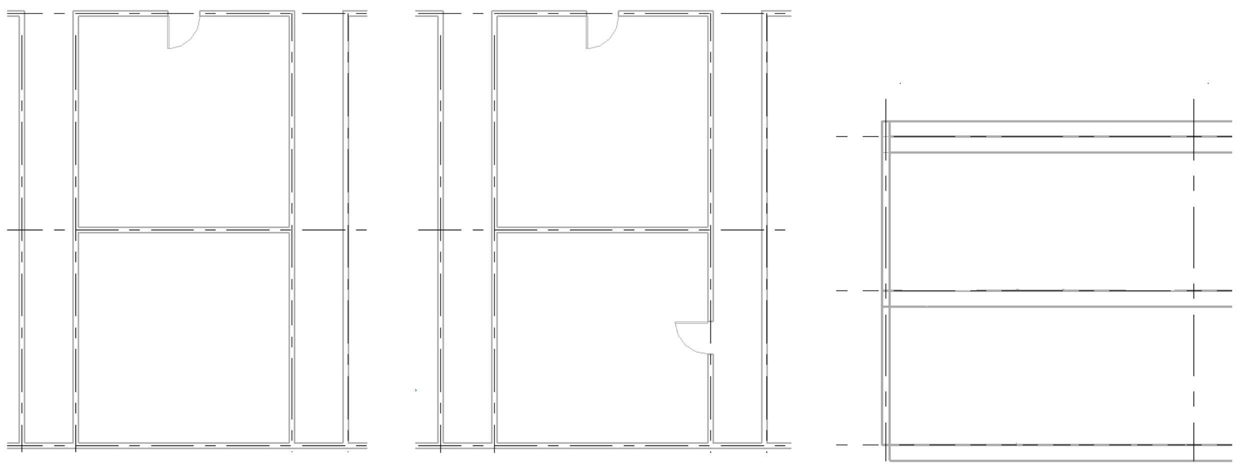
Note: The location of the viewpoints in the model are shown as "x" on the plan.

Questionnaire BA

Name: **Platform:**

✂--

4. In the plan below, show the new location of the boilers, the air handler, and the door. Draw the new ductwork and piping routes based on your team decision.



Floor 1 Floor 2 East Elevation

5. How much is the extra cost based on the changes you made to the design? Write down the details of your cost estimation.

6. To solve the problem, approximately what percentages of your time did you spend on:
   e) Exploring the model individually to solve the problem: ______ %
   f) Drawing/writing on the paper to solve the problem: ______ %
   g) Collaborating with your teammates to solve the problem: ______ %
   h) Other: ____: ______ %
   Total (a+b+c+d) 100%

Questionnaire BB

Name: **Platform:**

✂---

Code:	Please **DO NOT** write anything in this section

Section 1: Technical Information

6. What was the allowed opening for the Lab floor slab?
   e) One opening for 1 duct or 2 pipes
   f) One large opening for 1 duct and 2 pipes
   g) Two openings; one for 1 duct and one for 2 pipes
   h) Opening was not allowed unless a thicker slab was poured

7. What could cause structural failure?
   e) One opening for either 1 duct or 2 pipes in current Lab floor slab
   f) One large opening for 1 duct and 2 pipes in Lab office floor slab
   g) Two openings; One large opening for 1 duct and 2 pipes in Lab office floor slab and one opening for either 1 duct or 2 pipes in current Lab floor slab
   h) All of the above

8. Where did the architect prefer to embed the MEP risers?
   b) Corridor ceiling b) Lab office ceiling c) Lab office cabinet d) All

9. Which one costs more?
   b) Adding 4 bends to ductwork b) Pouring thicker slab for the lab floor c) a and b costs equally

10. How much was the extra cost to embed one duct in the corner cabinet? (Don't include the ductwork cost)
    b) $500 b) $1,000 c) $1,500 d) $2,000

Section 2: Platform Experience

6. Which platform features helped you communicate your technical work to your teammates? Please explain.

7. Which platform features caused challenges to communicate your technical work to your teammates? Please explain.

Questionnaire BB

Name: **Platform:**

✂---

8. Did you have any challenges in understanding any of your teammates' technical work and requirements? Please explain.

9. Did any of your teammates had challenges in understanding your technical work and requirements? Did you have to explain more? Please explain.

10. What do you wish you could do during the team collaboration to solve the problem faster?

Questionnaire C – Two Platform Comparison

Name:

✂---

Code: Please **DO NOT** write anything in this section

Compare two platforms of **Virtual Reality** and **Shared Screen** for team collaboration by answering the questions below:

1) Which platform did you prefer more to communicate your technical work to your teammates? Please explain.

2) Which platform did you prefer more to collaborate in a team? Please explain.

3) In which platform were you more actively collaborating in the team setting? Please explain.

4) Which Virtual Reality features did you prefer more over Shared Screen to collaborate in the team? Please explain.

5) Which Shared Screen features did you prefer more over Virtual Reality to collaborate in the team? Please explain.