Immersion

Digital Collaborative Environments

By

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Abstract

This thesis investigates the potential of Virtual Reality (VR) to solve established clashes in order to improve collaboration between industry professionals, while reducing spatial confusion. Industry professionals and academics state that it is collaboration itself that is one of the most critical factors in ensuring that a construction project is successful. In recent years people have investigated VR as a tool to provide a better environment for design due to its immersive properties and training potential. Current research is primarily focussed on the technology itself, but there are few studies conducted on the people using the technology and what they need in order to do so effectively. While it is essential to further the knowledge in the technological aspect, it is also vital to ensure that people can use it to its full potential. The aim of this study is to explore the relationship between advanced technology being developed and the way that people will be using it, alongside VR's applicability as a collaborative tool for architecture and construction projects. The focus of this study. While there are companies using VR in different stages of a project, it is unknown how productive people are when using this medium and what they require in order to use the technology effectively. Initial interviews with professionals have shown that there are problems in both peoples understanding of the technology used on projects as well as the methods of Building Information Modelling (BIM). The second part of this study involved multiple experiments in which users were put in different scenarios to solve clashes in a digital model using VR and Computer Assisted Design (CAD). This was performed in groups to investigate how they used the technology as well as how they collaborated within the digital environments. Initial experiments were run in Unity without a VR headset, and the final experiment was run using a VR headset (HTC Vive) for the full immersive experience. From these interviews and multiple experiments, the results produced insight into current user issues surrounding advanced BIM technology and the best way to implement them to make full use of the technologies capability during the design phase of a project. The results provided a framework detailing the information users need when using this technology to solve clashes collaboratively. Considering level of detail within the model alongside navigation tools, and perspectives provided a reliable method for aiding users in all aspects of collaborating in digital environments.

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1.0 Introduction

1.1 Research Question and Scope

Current research shows that the field of BIM and VR is an ever-developing area with a significant amount of advanced technologies constantly investigated and improved. Current scholarly research is primarily focussed on the technology itself, but there are few studies conducted users of the technology and what they need in order to do so effectively. While it is important to further the knowledge in the technological aspect of collaboration in BIM it is essential to ensure that people can use it to its full potential. To explore these proposed issues, this thesis is based around the following questions:

- *How can Virtual Reality be utilised for collaboration to help resolve clashes when reviewing the digital model, during the design phase?*
- *What information is needed in order to maximise collaboration between different disciplines when resolving established clashes within a digital model?*

The problem this research aims to solve is the lack of research undertaken on what users of advanced technology need to use these technologies effectively in the field of architecture and construction.

1.2 Significance of Research

For a construction project to produce the required output, collaboration and coordination from a diverse team of different disciplines are required. A collaborative process is defined as (Parvard, 2002):

“A set of tasks performed by the collaborative network members towards the achievement of a common goal”.

According to Vaaland (2004) it is collaboration itself that is one of the most critical factors in ensuring that a construction project is successful. One of the most important aspects of collaboration is communication between all parties involved. A project manager has to ensure that communication is clear between disciplines as there are usually a significant amount of parties involved. Studies have shown that ineffective communication has had adverse effects on projects resulting in a loss of time and money (Torneman, 2015; Lofgren & Eriksson, 2009). A study conducted by the Project Management Institute found that ineffective communication impacted the success of a project and that ineffective communication was the primary contributor to project failure one-third of the time (Hignett, 2017). The study also found that high performing companies had formal communication plans for twice as many projects as their lower-performing counterparts. This showed how essential communication plans are in a project involving multiple different disciplines, as well as large amounts of money and time.

A more user-centred approach is needed in order to investigate the user's relationship with the advancing technologies and to find what the users need to use the technology to its full potential. Miscommunication can occur for multiple reasons, ranging from a conflict of interest to poor communication method (Kassem & Dawood, Building Information Modelling: Protocols for Collaborative Design Processes, 2014). In order for all disciplines to work in harmony, there needs to be effective collaborative platforms and methods in place (Adamu & Akponeware, Clash Detection or Clash Avoidance? An Investigation into Coordination Problems in 3D BIM, 2017). With the introduction of digital collaborative environments, the mediums of communication have increased with people able to communicate extensively, at once and over a greater distance (Heydarian, 2015). A lack of evenly spread technical knowledge and the sheer amount of digital information, however, has caused issues surrounding the use of BIM in a project (Kassem & Dawood, Building

Information Modelling: protocols for collaborative design processes, 2014). With the introduction of VR in certain aspects of a project, matters have been further complicated, as the technology is advancing faster than the user's knowledge and ability with the technology (Kensek & Noble, 2014). One recent study tested a newly developed workflow to indicate whether BIM could soon be technologically implemented into VR for data management, processing, and visualisation (Rysanek, Miller, & Arno, 2017). It found that software for BIM-like applications could be produced by software developers and that this technology will soon be at the point of industry application throughout an entire project. Whilst this conclusion holds promise for the future of BIM technology, it did not incorporate how people reacted to this workflow, or how effectively individuals could use it. A similar publication investigated BIM translation from proprietary software into Augmented Reality (AR) applications (Zaher, Greenwood, & Marzouk, 2018). Much like the previous study, this was a technology focussed project that had promising conclusions about the technology but did not involve people in the process. As VR technology develops there needs to be an equally developing understanding of how people can or will use this technology. This technology can only be useful if people have the ability to use it effectively.

1.3 Aim and Objective

The aim of this study is to explore Virtual Reality's applicability as a collaborative tool for architecture and construction projects. This will focus on the design phase of projects, more specifically when solving established clashes in a digital model. This thesis aims to produce a framework for the information users need in order to collaborate effectively during this phase of a project. This framework will also define the information needed to maximise collaboration when different disciplines are collaborating on architecture and construction projects. This will be explored through literature and precedent review, interviews with professionals, and user-centred experimentation.

1.4 Defining Collaboration

It is essential to establish the different forms a project's information will take as it revolves around collaboration and portraying information in dynamic environments. This section establishes the key concepts of collaboration, cognition, and navigation in both real and digital environments. Following this is a brief background of architectural documentation that includes the evolution of standardised data sets in the construction industry from 2D to 3D towards 4D and beyond. VR is then defined, and its current state, as well as its current implementation within the industry, is assessed. This provides the motivation for this study and the direction to take by using this technology for a user-centred study. When defining collaboration for this project it is important to note that there are two types of collaboration to consider; in-person collaboration and virtual collaboration. Collaboration itself is defined as the action of working together with other people to create or achieve the same thing (Cambridge Dictionary, 2018). Collaboration is still defined as working together towards a common goal, regardless of whether or not it is successful. In relation to a project, the goal of achieving the same thing is the delivery of the building that meets the client's requirements; a virtual environment adds a medium to work in reaching this goal. Virtual collaboration in this project involves pairs of individuals working in the same environment to achieve the end goal. Building Information Modelling (BIM) was introduced as a process to increase productivity in projects and encourage multi-party communication, which in turn reduces mistakes made and the cost and time related to these (MBIE, Productivity Benefits of BIM, 2014). VR presents the ability for people to collaborate, as if in person even where they are not physically in the same place. If this method of communication can be validated to the point where little to no information is lost in translation between parties, then this can provide a platform to enhance further collaboration in the BIM process. This would be useful when reviewing the BIM model and planning the construction process (IndiaCADworks, 2017).

1.5 Cognitive Map

A cognitive map is how knowledge and information are represented to an individual (Axelrod, 1976). In architecture, the cognitive map is how people interpret their environment and all the information this presents. A representation of the building is created in the mind of an individual from the information an individual perceives from their environment. Because of this, it is likely that every individual's cognitive map of a built environment is different. This construct that an individual makes in their mind is used to enable people to "acquire, code, store, recall, and manipulate information" (Downs & Stea, 1974) about the environment they are in. When applying this method in the built environment, it dictates an individual's navigation and interaction with the environment depending on the way they have perceived this information (Calori, Johnson, & Sarnin, 1994).

Within this project, cognitive mapping is an integral part of determining how people interact with a virtual environment, and how they perceive the information presented. Due to the extremely personal nature of a cognitive map, it is difficult to measure or compare different people's maps; however, there are two aspects of a cognitive map that can be analysed (Reger 1990; Hackner 1991):

- *The content of the map, and the meaning behind it; and*
- *The configuration of the map, in terms of cognitive complexity.*

Several approaches have been used in the past to elicit information about an individual's cognitive map. Interviews with open-ended questions and accompanying analysis of their answers have been a tested method for obtaining the information mentioned above, as an individual's cognitive theory cannot readily be obtained by directly asking for it (Bettis & Prahalad, 1986). Another approach is the Repertory Grid Technique, which is a technique to determine these personal representations of information. There are three major components to the Repertory Grid: Elements, constructs, and links (Tan & Hunter, 2002).

- 1- *Elements are the objects of attention within the domain of investigation. They define the entities upon which the administration of the Repertory Grid is based;*
- 2- *Constructs represent the research participant's interpretations of the elements. Further understanding of these interpretations may be gained by eliciting contrasts resulting in bipolar labels; and*
- 3- *Links are ways of relating the elements and constructs. The links show how the research participants interpret each element relative to each construct. Further, the links reveal the research participant's interpretations of the similarities and differences between the elements and constructs.*

(Tan & Hunter, 2002)

The Repertory technique is a very rigorous and in-depth procedure that would yield more accurate results than an open-ended interview, however past projects have reported that participants become disinterested of this method as it takes so long, which decreases the accuracy of the outcome (Brown, 1992). The Self Q technique developed by Bougon is another lengthy way of retrieving this data from individuals, alongside other techniques such as the laddering technique. For this research, open-ended interviews and analysis will be a more appropriate method alongside close-ended questions, to ensure that both subjective and objective data can be obtained about each participant's cognitive map. This method provides a balance between keeping participants interested, thereby ensuring the information they provide will be accurate, while still retrieving enough information about people's different cognitive maps to form a data set that conclusions can be drawn from.

1.6 Digital Navigation

Navigation is typically the process of accurately ascertaining one's position in order to follow or plan a route to another place (Oxford Dictionary, 2018d). This tends to involve using external aids such as maps, landmarks, signs, or navigational devices. Navigation is primarily a cognitive exercise as it relies on the individual's perception of their environment to form a cognitive map using the information they receive. The information they receive from the environment allows the individual to forge a path to their destination. Indoor navigation faces more unique challenges as opposed to outdoor navigation as buildings are not always uniform, and multi-storey buildings will have differing floor plans. Another unique problem is the problem of 2D and 3D information, where outside navigation can be achieved through using a 2D map of the geographical surroundings, but to navigate a multi-storey building the navigator needs either multiple 2D maps or 3D information (Karimi, 2015).

A BIM model aims to provide a comprehensive representation of a building that is either built or going to be built, but through the digital medium it provides fewer sources of information to use for navigation. Physical sources of information such as air flow, temperature, sound, and general feel of a space are lost in a BIM model. Different spaces have different cognitive representations, which can be either a comparison between different buildings or different mediums of navigation (Freundschuh & Kitchin, 2000). Navigation is normally achieved in digital models through devices such as a keyboard and mouse, which is not necessarily intuitive for everyone. Digital navigation presents the challenge of navigation through a more complex medium that requires background knowledge to understand how to use the technology to navigate, whilst providing fewer sources of information to form a cognitive map. VR presents another medium to use when navigating a digital model but aims to provide more sources of information to provide an immersive experience (Willaert, Aggarwal, Isabelle, Cheshire, & Vermassen, 2012). The headset provides free movement when looking around as the camera moves with the head of the individual wearing it and can sit down or squat down which is not normally an option when using a computer monitor and keyboard and mouse. VR also provides the immersive feel that makes you feel as if you are actually in the digital space in reality, as opposed to simply looking at a computer screen (Antonio & Boas, 2013). These added cognitive stimuli aim to provide more information to form a better cognitive map than traditional 3D CAD models would allow, which could also provide a different way of perceiving this information. Comparatively, these different mediums all provide different

sources of information to perceive to form a cognitive map to use for navigation, which means basic navigation is achieved differently in all of these presented mediums. The participant's navigation will be assessed in the user-centred experimentation section of this project, and the results will examine how these differing sources of cognitive inputs affected the participant's navigation and wayfinding when using different mediums.

1.7 Architectural Documentation

Architectural Documentation has evolved with the advance of technology and available resources. The documentation used to construct buildings has evolved from verbal instructions, to official 2D plans made by draughting, and is now inclusive of 3D digital models detailing entire buildings and their systematic construction plan.

2-Dimensional Information

Every set of information or data has a general structure (Bartke, 2005). These structures are typically characterised by the variables they contain. 1-Dimensional (1D) data is typically linear and involves a list of data items with one variable such as a list of transactions, whereas 2-dimensional (2D) data is typically planar and contains two variables such as several transactions in a particular time period. There are many tools for visualising information within the construction industry, although the tools have since evolved from traditional construction drawings. The method of basing construction off 2D architectural drawings has been traced back as far as ancient Egypt (Lightbody & Monnier, 2016). As time passed 2D

Figure 1.1: 2D Autocad Practice

drawings became the standardised way of communicating design intent and the method of construction (McClendon, 2005). This eventually evolved into using 2D drawings to coordinate the different disciplines involved in construction, throughout the construction process. The level of information in these drawings increased to the point that the graphical representation provided a plan that the construction parties could follow to construct the entire building (Toledo & Cristina, 2008). How these drawings have been made has also changed from traditional drawing with stencils, pencils, and other technical drawing instruments, to 2D computer-aided design (Autodesk, 2D Drafting and Drawing, 2018). 2D Drafting software has made drafting more precise and quicker than the traditional methods and allows for easier sharing and distribution of these drawings as they are in a digital format. Today 3D models are used in the design process but are still supplemented by 2D drawings as they effectively portray information needed for both design and construction.

3-Dimensional Computer Assisted Design

With such a long-established method of graphical representation the introduction of 3D modelling was met with some difficulty. 3D visualisation software provides an extra dimension of information, with the ability to produce 2D architectural drawings from the 3D model (Autodesk, BIM and the Future of AEC, 2018). The 3D modelling concept is an object-based method, where the digital model contains both structural and object information which is used to “create, exchange, and use the significant design information” (BIPS, 2006). The major software companies in this area developed BIM platforms for collaborative design and sharing. With these platforms came more automation and background work for the software to complete, to assist in the design (Toledo & Cristina, 2008). The 3D modelling software has the ability to detect clashes in solid geometry during the design process, so that fewer mistakes are made along the way. The major clashes normally occur when different disciplines cross over, and coordination is not achieved between different parties. This method is considered to have fewer errors than 2D drawing as the error finding process is, to an extent, automated, and less training is needed to locate these errors when compared to 2D drawings as it is less abstract and symbolic than the traditional method (Toledo & Cristina, 2008). Overall 3D modelling has been proven to be more comprehensive than 2D modelling and provides better spatial awareness and perspectives (Yan & Demian, 2008).

There are several research papers that both agree and disagree with the notion that 3D modelling provides a more comprehensive way of portraying information and provides better perspectives and spatial awareness than 2D modelling. One study found that 3D methods provided greater efficiency and efficacy over 2D methods when dealing with collaboration and design coordination (Toledo & Cristina, 2008). However another study found that 3D information provided an overload of data to people, and that people still need to break it down into 2D data to understand it, which takes more time (Bartke, 2005) and contradicts the previously mentioned study. Due to the time difference between these two studies an assumption can be made that this overload of data was present in the early stages of 3D modelling implementation, but that due to its current status as a standard method of modelling people have grown accustomed to it and how to interpret the information it presents. One study on the perception of 2D and 3D spaces used eye-tracking software and found that people have different strategies for the cognition of 2D and 3D visualisation of information, but did not find what method was best (Poelka & Brychtova, 2013). However, through the use of questionnaires this study found that people prefer the 3D method of visualisation, which is further backed up by the findings of a thesis undertaken on quantifying the benefit of 3D systems over 2D (Ryan, 2007). Currently companies are using 3D modelling software for almost everything, with some even using 4D BIM methods on projects. 4D BIM is when the 3D CAD model contains schedule or time related information as the added dimension of information. There is also 5D BIM which contains cost related information, and 6D BIM which contains all aspects of “project life-cycle management information” (NBS, 2018). The conclusion to be drawn from this is that while there were initial issues with overhauling the standard method of conveying building information, it is now widely accepted as the standard method. This does not mean that 3D is more effective at

Figure 1.2: Building Information Modelling ArchiCAD

communicating information than 2D in certain areas but is something that is still being explored today. This thesis builds on these papers and will focus on how users interpret the information within the modelling software's and mediums, and what they need to understand the information portrayed in digital environments when using these advanced technologies to collaborate on a project.

Building Information Modelling

One of the drives of BIM as a method for data sharing between multiple people and parties is to enhance communication, data management, and coordination in projects, particularly large projects where multiple parties are involved from different disciplines. The benefits of using BIM in a project are split into 6 categories (MBIE, 2019):

- *Coordination;*
- *Communication;*
- *Data Management;*
- *Analysis and Simulation;*
- *Improved Productivity during Construction; and*
- *Better Information for Facilities Management.*

BIM's implementation has been limited in effectiveness between projects and its execution varies between countries and companies (Kensek & Noble, 2014). The same can also be said for certain strategies used in projects through BIM, such as the process of reviewing the digital architectural model. Whilst BIM is supposed to be a collaborative process, recent studies have found that disciplines are often not collaborating to the full extent that the technology provides, which can result in an increase in the clashes within the central model (Adamu & Akponeware, Clash Detection or Clash Avoidance? An Investigation into Coordination Problems in 3D BIM, 2017). It is for this reason that a model needs to be reviewed near the end of a project. Whilst design coordination is one of the main advantages of BIM, with such a wavering level of implementation it does not always work, this has been proven by the need for clash detection in a project (S Pace, 2016). It is in this area where clash avoidance can

improve upon a project, which is an active strategy to minimise clashes before they are made through full collaboration and transparency between disciplines. Its implementation however, is even more limited with this being seen as a future tool for BIM (Adamu & Thorpe, How universities are teaching bim: A review and case study from the UK, 2016).

1.8 Clash Detection

In Computer Science, a clash or collision is when a function maps two inputs to the same output or have the same hash value (a function to map data of arbitrary size to data of fixed size) (Hashimoto & Okamoto, 1990). Clashes are programme implementation issues as opposed to programme specific issues (Lin & Gottschalk, 1998). Clash detection software has been made to automate the process of determining clashes, which has evolved from overlaying 2D drawings to an integral part of a 3D modelling software. Collision detection is used in games, robotics, architecture, and many other computer-based processes where clashes of geometry is a hazard.

Within a 3D model, objects are usually encased in basic shapes that can be used to quickly determine if there is an overlap (Weller, 2013). This enables the computer programme to remove objects that are not immediately in a collision, at the basic level of basic shapes overlapping. This is called the broad phase collision detection. The simplest method for this phase is the brute force approach, which compares bounding volumes (Luque, Comba, & Freitas, 2005). Overall this phase of the clash collision lists the pair of possible colliding objects, where the narrow phase then determines “exact collision checks between these pairs” (Weller, 2013). In this phase, geometry is divided into subsets using the Bounding Volume Hierarchy (BVH) principle. These geometries are broken down into children of the larger geometry until it finds the exact intersections where there is a clash. These clashes are then normally highlighted in a bright colour to draw attention to them.

Clash detection is normally split up into two phases, a broad and narrow phase. The broad phase involves a computational operation that answers the question “which objects have a strong possibility of colliding?” (Petersen, 2012). The narrow phase focusses on what part of

these objects collides with each other. This narrow phase typically cannot be done on the entire model as it is very computer intensive. In BIM this broad phase takes the form of software such as Navisworks; finding the basic geometries colliding that should not be colliding. The narrow phase typically involves people solving the clashes and is not automated in projects. This narrow phase is normally only automated in games where they constantly need to update collision detection frame by frame (Petersen, 2012).

Clash detection is a major part of the BIM modelling process due to the fact that there are always multiple models and multiple versions of these models. This process gets more complex when multiple disciplines create their own models and are not always in the same software. This is why clash detection is normally undertaken after each discipline has finished their work (Association of Construction and Development, 2012). Clash detection is not a new process. It has developed alongside the development of architectural technology. Clash detection used to involve analysing the physical drawings as well as seeing the clash on the construction site. For example, a beam designed by the structural engineer is in the way of the air conditioning units placed by the Mechanical, Electrical and Plumbing (MEP) engineer. The advance in technology now allows projects to save large amounts of money by being able to solve clashes before it gets to the construction stage.

Figure 1.3: Navisworks BIM clash detection

Figure 1.4: Navisworks BIM clash detection simulation

1.9 Clash Detection in BIM

For BIM clash detection is used to detect clashes in different areas of the models, most likely in two areas that involved separate disciplines e.g. plumbing and structure. Clash detection is needed because of modelling issues, which stem from collaborative issues regarding people working on an area of a central model separately. The significance of this is that currently the estimated cost savings on a project after using clash detection through the BIM process is around 20-30% (BSI, 2017). The three most commonly used classifications of clashes are as follows (ACD, 2012) :

Hard Clash – When two objects are occupying the same space e.g. a beam running through plumbing. Hard clash detection brings not only geometry-based detection, but semantic and rule-based detection algorithms, due to embedded information in BIM modelling objects;

Soft Clash – When an object needs a certain buffer zone or clearance, and this is not being met e.g. insulation or maintenance access. Custom soft clash detection can go as far as checking components for building code compliance; and

4D/Workflow clash detection – Refers to resolving scheduling clashes for work crews, delivery of materials etc, and other project timeline related issues.

1.10 Virtual Reality

VR is a digital environment that is experienced through sensory stimuli to create a realistic and immersive experience (Willaert et al, 2012). It is a constantly developing research field that has seen a lot of recent advancements involving its capabilities and the software surrounding its use. VR is widely used in gaming as an immersive platform and is being used as a medium for teaching and learning in multiple professions including medicine, engineering, and transportation. A major benefit of VR is the ability to recreate environments or procedures with minimal cost, compared when they were produced in reality (Antonio & Boas, 2013). This allows for expensive designs to be explored in VR, as well as the simulation of procedures such as medical procedures and flight simulators.

VR's main use is to make accurate representations of models that can compare to reality, and provoke a sense of immersion that the user would not feel in a traditional 3D environment on a computer screen. The technology behind the game engines used to construct the environments currently produce realistic renderings of both environments and people within them (Unreal Engine, 2017). These engines do this by utilising in built features:

- *Physically-based Materials;*
- *Pre-calculated bounce light via Lightmass;*
- *Stationary lights using IES profiles;*
- *Post Processing;*
- *Reflections; and*
- *Scaling.*

There are other methods of creating environments and importing them into VR. 3D Scanning is a method that is used to scan a real environment with a handheld object, which then recreates this environment into a 3D model. This can currently be a slow method, but is a means for recreating a real environment without having to model it.

Whilst a majority of the focus on VR surrounds the gaming and entertainment industry, the progress made in these areas directly affects other industries (Hughes, 2014). As game technology advances, it advances the tools used in visualisation and modelling for design, as they use the same platforms (Zyda, 2005). As the gaming platforms have advanced in recent years, the potential uses for VR in architecture have changed dramatically. The applications go beyond design for simulations. Flight simulators have been a method for training pilots for years as it provides an immersive environment for learning, whilst not facing the same risk of an inexperienced pilot flying an actual plane (Air New Zealand Aviation Institute, 2018). The same can be said for high risk operations for surgeons (figure 1.5). VR is experiencing implementation in the field of medicine in order to simulate surgeries at a more advanced level. As the technology advances, its applications will increase (figure 1.6), however it is not a one solution tool. In certain fields it may not be better than current technology and this needs to be explored further so that correct industry implementation can be achieved. Implementation of VR in the field of Architecture could provide advantages that 3D CAD could not provide, however it is currently in its infancy when analysing its use with design. Visual walkthroughs, rendering environments, and iterative designs are all viable options for designing in VR, and are not widely used in the current industry as a tool for design but more of a supplemental tool for clients to see what has been designed (Antonio & Boas, 2013). Similarly its potential applications in the construction industry have yet to be explored to the point of an industry-wide acceptance, and this project aims to provide clarity on the areas where VR can benefit projects over currently used technologies and methods.

Figure 1.5: Medical Simulation in VR

Figure 1.6: VR in the Military

One aspect of the BIM process that VR has a lot of potential to improve on is reviewing the model. Reviewing the model is important for both clash detection and for planning the construction phase of a project (Seo, Lee, Kim, & Kim, 2012). This process ensures costly mistakes are fixed before the project has started being built, which in turn reduces time spent on fixing clashes on site and reduces the cost of re-design during the construction phase (Seo, Lee, Kim, & Kim, 2012).

Figure 1.7: Realistic Rendering

2.0 Literature Review

2.1 Literature Review

BIM has been created as a method for data sharing between multiple people and parties in architecture and construction projects. Its implementation, however, has been limited in effectiveness between projects and its execution varies between countries and companies (Kensek & Noble, 2014). The same can also be said for certain strategies used in projects through BIM, such as the process of reviewing the model. Whilst BIM is supposed to be a collaborative process, recent studies have found that disciplines are often not collaborating to the full extent that the technology provides, which can result in an increase in the clashes within the central model (Adamu & Akponeware, Clash Detection or Clash Avoidance? An Investigation into Coordination Problems in 3D BIM, 2017). It is for this reason that a model needs to be reviewed near the end of a project. It is in this area where clash avoidance can improve upon a project, which is an active strategy to minimise clashes before they are made through full collaboration and transparency between disciplines. Its implementation, however, is even more limited, with this considered to be a future tool for BIM (Adamu & Thorpe, How universities are teaching bim: A review and case study from the UK, 2016).

Because of the recent advancements in technology VR has the potential to be implemented into a BIM Model to convey more information and in a more intuitive and immersive way, while introducing a wide range of new applications beyond that of traditional CAD. The ability to better visualise data and immerse people within it has the opportunity to improve understanding of the information presented (Olshannikova, Ometov, Koucheryavy, & Olsson, 2015) and the added immersive aspects of VR have the potential to convey more information between parties, in some situations even more so than traditional CAD software. VR could be used as a medium to reduce clashes through 3D design coordination particularly when reviewing the BIM model.

BIM in Architecture

The BIM Handbook clearly demonstrates how to use BIMs methods throughout the duration of projects, it is used in varying degrees across New Zealand and with varying levels of effectiveness (Huber, 2014). Even with these varying levels of applied research, interest in BIM is increasing with a significant increase in papers published about this subject between 2010 and 2015 in particular (Santos, Costa, & Grilo, 2017). The highest number of published papers within these periods were related to collaborative environments and interoperability. Significant advances in technology interoperability are particularly important when different mediums are used, such as VR. This relates to a new trend in Santos's (2017) review of existing BIM literature, which was the development of BIM-based tools. As the capability of technology is expanding companies like Autodesk are producing new tools for different areas, some of the newer ones being a channel for making a BIM model VR capable. Because of the recent advancements in technology VR has the potential to be implemented into a BIM Model to convey more information and in a more intuitive and immersive way, while introducing a wide range of new applications beyond that of traditional CAD. The ability to better visualise data and immerse people within it has the opportunity to improve understanding of the information presented (Olshannikova, Ometov, Koucheryavy, & Olsson, 2015) and the added immersive aspects of VR have the potential to convey more information between parties, in some situations even more so than traditional CAD software.

VR offers an added immersive aspect to the process of BIM that has various advantages that range from being able to take a client in to a design to showcase it, or for a different collaborative medium for design entirely. VR could be used as a medium to reduce clashes through 3D design coordination and provide a more collaborative and immersive environment for BIM, particularly when reviewing the BIM model. As VR is a new and developing technology it still requires extensive validation for the claims made about its potential. It does have the potential to be a better medium for data sharing in certain areas compared to traditional CAD due to its ability to represent data differently, however a lot of this is still to be proved.

Information Exchange and Flow

A major variable of a construction project is the exchange of information. There are many differing factors surrounding the information and the exchange of information that determine how effective they are. There is a current trend throughout construction projects with designs becoming more complex and requiring more detailed drawings, thereby making effective information exchange more important than ever (Kumar, 2017).

When one individual exchanges information with another it can take place in a variety of ways and have differing degrees of effectiveness. Lengel and Daft (1989) state that the richness of information is defined as “the ability of information to change understanding within a time interval, and that the richness of the information decides whether it provides a high level of new understanding or a low level of new understanding”. Furthermore, they explain that the type of communication used to exchange the information has a direct effect on its richness. Communication media have differing levels of capacity to convey information, so it is both the richness of information exchanged and the way in which it is exchanged that affects how useful it is for the other party. Lengel and Daft (1989) compared the different types of communication media and their level of information richness on a scale that can be seen below in Figure 2.1.

Figure 2.1: Information Richness vs Media

On a large-scale construction project all the above communication media are not always available. If a company is liaising with an international company for one aspect of a project then face-to-face meetings would rarely occur, so they will communicate over the phone or through conference calls. This can mean that the information exchange is not as effective and not all of the information is received by the other party due to the method in which it is exchanged. In the digital age where most data is stored, used, and shared through computers

it is important to effectively communicate to ensure costly mistakes involving time and money, are not made.

A recent introduction of Big Data proves the dire need for efficient methods of storing, sharing, and using data sets on large-scale projects in construction and architecture. Big Data is defined as an extensive data set that fulfils three characteristics:

- *Volume (Large quantities of data ranging from tera to zillion-bytes);*
- *Variety (Different file types, formats, structures etc.);*
- *Velocity (Produced in real time that forces continuous processing).*

(Douglas, 2001).

Compared to 2D CAD systems used in the past, BIM provides a more transparent and flexible interaction with information, where data is aggregated and accessible for most, if not all involved (Hattab & Hamzeh, 2013). BIM systems on large scale projects use cloud-based data sharing techniques in order to share data across multiple disciplines which creates Big Data sets. Recently BIM coordinators have been needed in order to manage these vast quantities of data on construction projects. It is their job to ensure that information is exchanged between the right people, at the right time, and interpreted the right way so that there is no information loss between parties.

BIM Levels

BIM is mainly used at level two currently (see figure 2.2 below), involving collaborative working across disciplines with all parties using 3D CAD models, integrated but not necessarily shared. Design information is shared through a common file such as IFC (Industry Foundation Class) or COBIE (Construction Operations Building Information Exchange) (BSI, 2017). One hypothesis surrounding this area is that BIM level three would reduce the number of clashes in a project due to wider collaboration across all disciplines within a project, so that the clashes are avoided before they are made (BSI, 2017); achieving clash avoidance. With every individual having the same level of situational awareness on a project, the potential for clashes could decrease, or be resolved earlier in the project. It has become evident that technology that facilitates collaboration has become a crucial part of the BIM process, and in doing so helps integrate large teams for multidisciplinary collaboration (Adamu & Akponeware, 2017). This is where VR has the potential to improve this process. VR has the ability to convey information in a unique way with an added immersive aspect and is a vital visual tool for design. As a medium, it could provide the base for a collaborative design environment. With multiple people able to see design changes in real time, this could provide a platform for streamlining the BIM process, using clash avoidance to do so.

Figure 2.2: Levels of BIM Maturity

BIM Protocols

Numerous BIM protocols, frameworks and tools are being developed to further both implementation and understanding of BIM (Kassem & Dawood, 2014). In a project that evolves around information sharing and interpretation, and collaboration, it is important to define the current status of such frameworks, as well as what is needed in a project to maximise BIMs effectiveness in providing a collaborative design process.

BIM protocols are steps or conditions that aim to guide the implementation of BIM into a project, to reach the goal of the deliverables (Kassem, Succar, & Dawood, 2013). These protocols are constantly evolving as further methods are proven right or wrong and adapted accordingly. New BIM protocols are aiming to increase design collaboration efficiency on projects by enhancing the quality of design information shared between all parties involved (Kassem & Dawood, 2014). In New Zealand BIM protocols tend to be standardised by in house protocols that can change depending on the clients wants and needs (MBIE, 2014), but falls short in comparison to the UK's BIM protocol which is a legalised standard supplementary agreement to ensure production of information models is achieved to a high standard (The BiM, 2018). There are two major areas in this agreement that apply to the design and construction stage of a product:

- *Model Production and Delivery, and*
- *Information Requirements.*

(CIC, 2013).

These two areas are major parts of any protocol as they ensure that parties involved have obligations to produce a certain level of work, in both the model and contractual documents. Protocols also help to enable production at defined stages of a project. Collaboration is supported by protocols as it enhances the outcome of a project and is considered best practice (CIC, 2013). Whilst New Zealand does not have a standardised legal document for this, BIM protocols are still a major part of projects, and provide a structure for collaborative work to ensure the production of the project is defined at all stages.

VR in the BIM Environment

In an environment where multi-disciplinary collaboration is crucial, exchanging and managing information is essential to this process. Studies into presenting VR into the design process as a collaborative tool have found that performance time for design error detection has been halved (X Wang, 2011) as well as an increase in reliability and performance of information due to a higher degree of collaboration, and understanding of the information presented in VR (Woksepp, 2006). These are not without their drawbacks however, as other studies have found that when implementing VR into a live project that limited technical knowledge and financial considerations affected the project negatively. It also produced scepticism surrounding industry professionals taking up the new technology in the design process (S Woksepp, 2008). As more and more construction companies are currently taking up VR in various ways it is safe to say that this scepticism is now irrelevant.

In more recent year's VR has been used for a number of experiments surrounding the built environment, ranging from analysing user experience to comparative studies of a real building vs the virtual counterpart. One such study aimed to validate VR as an empirical research tool for user behaviour, by having a VR model of a real building and then observing different parties as they navigated either the VR model or the real building (S Kuliga, 2015). Findings from this research concluded that there were few differences when comparing immersive aspects, other than the ones unable to be simulated such as the warmth of the building in VR. This study concluded that VR can be a good experimental medium for when real world environments are not feasible, but that more investigation is needed in order to understand the relationships between VR and real built environments (S Kuliga, 2015). A similar study that focussed on task completion in a comparative environment found similar results, finding that the task completion rate was almost identical and that the only thing that got in the way was the navigation and controls in VR (Heydarian, 2015).

In more recent year's VR has been introduced into the BIM process. With 3D BIM showing potential for further streamlining this process the development of tools and software for this area is increasing. VR has been used to show clients designs, collaborate on conceptual design, and has been used for minor clash detection. It has been emphasised that technology that facilitates collaboration is essential in the BIM process (Adamu & Akponeware, Clash Detection or Clash Avoidance? An Investigation into Coordination Problems in 3D BIM, 2017), and VR is currently being explored as a tool for this. Due to information transferral across

mediums VR may not be beneficial to every stage in a project, however there are certain areas where it could improve the process. Current coordination frameworks for BIM emphasises the need to exchange data and manage information accurately between participants and across disciplines, to minimise clashes (Nbims, 2007). This aims to provide transparency of data across all people involved so that clash avoidance is used as opposed to clash detection being needed later on. This is something that BIM level three aims to provide with everyone working on one collaborated and coordinated building model to prevent errors in communication or lack of.

2.2 Precedent Review

As the scope of this research revolves around collaborating on different platforms and mediums, a review of current precedents in this area will be assessed through the use of academia, software reviews, and through manufacturers. Accurately assessing these different platforms through applying them is outside of the time constraints of this project, so the design of the methodology will be based upon the outcome of the review. In a field that is constantly evolving it is important to keep up to date on current technology and its capability to ensure that the findings of this project remain relevant and useful to the field. The first part of this section will involve a review of the current engines and software being used and developed for AEC projects, and the second part will discuss projects that have used VR and CAD in a project to explore its relationship with the built environment. This exploration of previous projects will provide precedents for this project's method and provide insight into the application of these technologies in real world aspects.

Gaming Engines

Game engines are software that allows developers to create games and applications (GameDesigning, 2018). CAD software such as Revit, 3DS Max, and Navisworks all utilise gaming engines to function. The gaming industry is a vastly growing market that encourages progress for the development of faster engines and more powerful gaming engines. As these engines improve, this betters other industries that use these core engines, including Architecture. The most popular and recent game engines will be reviewed on their capabilities and applications in this section.

Unreal Engine 4

Unreal Engine 4 is a product suite that includes creation tools that can be used to make virtual environments in a high level of detail. It allows photo realistic renders to be made as well as AR and VR experiences for architecture and design, product design, and manufacturing (Engine, 2018). Unreal Engine is designed for “demanding applications such as AAA games, filmmaking and photo real visualisation” (Engine, 2018). This provides a solid foundation for building a virtual environment for an architectural application. Unreal Engine also features an editor mode where you can build whilst in VR using motion controls. Unreal Engine has a CAD importer for native file types that allows for importing of BIM models. The data is imported and then some aspects are converted so that unreal engine can use it (Unreal Engine, Datasmith, 2018). The following data is converted:

- *Object Instances:*
- *Pivot Locations:*
- *Scene Hierarchy and layers:*
- *Material and Physical based Rendering Characteristics and Textures;*
- *Light Positions, Colours, Sizes and Intensities:*
- *Camera Properties:*
- *Meta Information and Custom Attributes: and*
- *Unit Conversion.*

(Unreal Engine, Datasmith, 2018).

Unreal Engine is currently one of the forerunning game engines for creating photorealistic virtual environments and when BIM models are imported into it, can be used for extremely realistic visual walkthroughs. This is normally done once the model is finished however and is not normally used for iterative design whilst in the digital environment as the controls are limited and it is a slow process.

Unity 3D

Unity3D is another cross-platform game engine and is on similar levels as Unreal Engine. It supports both 2D and 3D graphics whether this is for gaming, product design, or design and architecture. Unity can also import CAD files such as .3ds, .obj, and .fbx files (Unity3D, 2018). There is also a direct link created between proprietary files so that if the original file changes then it will change in Unity. For exporting 3D files, there are a number of advantages and disadvantages, and these are listed below:

Advantages

- *You can import parts of the model that you need, you don't have to use the whole model;*
- *These exported files are generally smaller than their proprietary equivalent;*
- *These files can be imported from software that Unity does not directly support; and*
- *You can re-import exported 3D files into 3D modelling software after exporting to ensure that all the information has been exported correctly.*

Disadvantages

- *If changes are made to the original file, the file needs to be exported again; and*
- *You need to keep track of versions between the source file and the files imported into Unity.*

(Unity3D, 2018).

Unity has been compared to Unreal Engine multiple times by different sources and they have found similar performance outputs, however unreal engine provides better graphical output which can develop more photorealistic renders (Keane, 2019). Unity is seen as generally easier to use with a better asset store, however the overall difference between these two seems small and the decision to use either will depend on the intended use.

3ds Max Interactive

3ds Max Interactive is a VR engine based on Autodesk Stingray, that uses 3ds Max to create 3D visualisations. It is more focussed on visualisation workflows as opposed to real-time rendering for games (Autodesk, 2018). This plug-in has the ability to take a 3ds max file into VR in a few simple steps. Changes cannot be made to the model once in VR, however at this stage it is mainly a tool for VR walkthroughs aimed at clients. Its computing power is similar to the previous two gaming engines; however, these gaming engines provide a narrow focus, aimed at providing visual walkthroughs of designs for 3DS Max in particular. It is incompatible with most other software unless the files are taken through 3DS Max first.

Software, Plug-Ins and Computer Applications

This section focusses on the specific applications and software that are directly compatible with currently used CAD software. As VR is a recent acquisition to the construction industry most of these applications are in their infancy and improvements can be expected in the near future.

Autodesk Revit Live

Revit Live has a combination of features that allows a simple workflow for a BIM model to be turned into an immersive virtual environment. These features include a Revit plug-in, a cloud service with automated data preparation, and the automatic transfer of BIM data (AUTODESK, 2018). The workflow consists of preparing a 3D view in Revit and then clicking the 'Go LIVE' button. The software then checks over the model and alerts the user to any missing aspects needed in order to convert it into a VR model. The model will then be uploaded to the cloud service for processing (AEC Magazine, 2017). View height can be set, and the VR model allows for automation of interaction with objects such as staircases and doors (e.g. after processing, walking up to a door and looking at it will open the door). At this stage, Autodesk live is mainly for visualisation and navigation of a model, as you are unable to make changes to the model whilst immersed in VR (AUTODESK, 2018). A major drawback with this is the time it takes to enter VR, as you cannot change the model whilst in VR, the iterative design will take time because of the need to go back and forth and upload new designs to the cloud system.

IrisVR - Prospect

Much like Revit Live, IrisVR Prospect (herein referred to as Prospect) offers a straight forward workflow for CAD or BIM models to be turned into VR models. Unlike Revit Live however, Prospect supports models from other programmes such as Rhino, Sketchup, Grasshopper, and FBX, with future work aimed at including ArchiCAD and Navisworks compatibility (IrisVR, 2018). Prospect allows for the model to be viewed as a scale model or at a 'human scale' where you can navigate the building in a 1:1 aspect. There are multiple tools that can be used whilst in VR from a tool palette, and are as follows:

- *Simple annotation tools;*
- *Daylighting tool (explore how light and shadows change depending on the time of day in the model);*
- *Layer tool (Can take away layers even down to the structural frame of the model);*
- *Measuring tool (can measure distances and clearances);*
- *360 panorama tool; and*
- *A Multi-user mode.*

When Prospect takes a BIM or CAD model into VR it automatically optimises geometry, materials and all other aspects in a short amount of time (IrisVR, 2018). This allows for a more iterative design process compared with Revit Live as this back and forth process will take little time, as well as the tools that you are able to use whilst in VR. Currently, metadata is not transferred over into VR to allow for better performance, but IrisVR are looking into ways in which metadata could be viewed by clicking on an object, and a tool like this may be released at a further date (AEC Magazine, 2017).

Enscape

Enscape is a real-time visualization and rendering tool designed specifically to work with Revit (ENSCAPE, 2018). It allows for a live link to be made between a VR model and Revit so that changes made in Revit will be displayed in the VR model moments later. This unique workflow allows for quick and iterative design changes to be made almost instantaneously (ENSCAPE, 2018). Enscape is currently a great visualisation tool for exploring iterative design and alternative design choices comparatively but does not offer many tools once inside VR. Basic navigation tools as well as lighting and shadow tools are present, but that is the extent of it. As the workflow is almost seamless between VR and Revit, this is less of an issue than with other software. This software focuses on high-level renderings and realistic level of detail visually.

Vectorworks

Vectorworks is both a 3D design software and BIM software solution that has recently had VR capabilities added. These features allow for models from Vectorworks to be exported to a web-based interface, where you can share these virtual experiences (Vectorworks, 2018). There are a few tools available when in the VR model such as the ability to toggle shadows and the ability to section and isolate parts of the model. The VR capabilities are add-ons to an already established software, so at this stage it is mainly a visual tool for showing clients around a model. Making design changes requires the model to be re-uploaded to the cloud service whenever changes are made.

Revizto

Revizto is a cloud-based collaboration software that allows for architects and designers to navigate the 3D design. It is compatible with most CAD software and is also used as a tool for visualisation of model-based issues such as clash detection (Revizto, 2018). The workflow involves exporting the BIM model into a navigable 3D file, and then uploading this file to the cloud-based workspace, where it can then be shared. This can then be viewed in either the HTC Vive or Oculus Rift (Revizto, 2018). If changes are made to the central model these will be relayed into the VR model in real time, so that changes can be tracked. This provides an accessible and updatable environment for a shared model when reviewing the model, but the size of the model affects the upload time of the model and is not recommended for large models that some projects may have.

VR Applications in Current Industries

As mentioned previously, VR has many applications in different industries with differing levels of implementation. This section aims to critically assess current industry applications of VR with the following questions:

- *What is VR being used for?*
- *How are industry professionals using it?*
- *Are they using it effectively?*
- *Is VR the right tool for this job?*
- *What were the results of using VR for this?*

Empirical Research Tool for Built Environments

This study examined the relationships between user experience when travelling through a building and its corresponding digital model in VR, in order to understand to what extent VR can represent a real environment. The researchers conducted three studies of guided walkthroughs of these two environments with varying degrees of detail in the model. The users had varying levels of control on the walkthrough. The quantitative data found that there were very few differences when rating the real environment compared to the digital one. This quantitative data was in the form of rating scales for different aspects of the environments, and are as follows:

- *Feeling of involvement in the experience;*
- *Level of control of events during navigation;*
- *Natural interaction with the virtual environment;*
- *Involvement with the task, and;*
- *Level of presence.*

(Kuliga, Thrash, & Holscher, Virtual reality as an empirical research tool — Exploring user experience in a real building and a corresponding virtual model, 2015).

The major quantitative difference found was in atmospherics, such as warmth, attractiveness and how inviting the environments were (Kuliga, Thrash, & Holscher, Virtual reality as an empirical research tool — Exploring user experience in a real building and a corresponding virtual model, 2015). Few differences were expected in the quantitative data and the outcome proved this hypothesis correct. There is one major thing that this study did not address and that is the level of immersion the individuals felt in the virtual environment. The quantitative aspects measured were surrounding the human senses (sight, sound, touch) which were addressed in multiple ways, including the main difference of environments being the digital environment lack of atmospherics. VR's advantage over CAD is its immersion which allows an individual to be in a digital environment that seems real. The level of detail was assessed in the qualitative data in the results section and is one of the major aspects of a digital environment that can affect the immersion felt by the user, however immersion was not a measured quantity in this study.

Open-ended questions allowed for a more personal response to the comparison between environments within this study (Kuliga, Thrash, & Holscher, Virtual reality as an empirical research tool — Exploring user experience in a real building and a corresponding virtual model, 2015). These questions focussed on the level of detail, atmospheric cues, feel of the model, and viewing of the digital environment. The main differences found were the difference in atmospherics, perception of size, and visual depth perceptions. Although certain simulators in VR offer temperature changes and wind effects, this is not a standard VR implementation. Some participants of this study found that colours were too bright in VR, and that smaller spaces felt too narrow (stairs, hallways, walls). This could be linked to both the level of detailing in modelling and that depth perception is different in VR to reality. The main focus of this study was on digital and real environment comparisons. The conclusion from this study was promising, showing that at a basic level VR can provide an accurate representation of a real environment, the relationship between real and virtual environments need to be explored further in order to create more accurate representations.

Real Estate

The advance of VR technology has brought some very useful tools to benefit the real estate market. The introduction of 3D scanners allows for a built environment to be physically scanned by the device which then formulates an accurate scale model of the scanned environment. These scanners make recreating a built environment into a virtual one easier than having to model it from scratch. These devices have made it possible to make 3D walkthroughs of houses for sale so that clients can view them, which is particularly useful for people looking at buying in different cities or countries.

Matterport is an American company that provides interactive VR experiences for existing houses (Matterport, 2018). They provide services for an expert to scan a home with specialised 3D cameras and upload the 3D digital experience to the cloud where potential buyers can view it, either in 3D or VR. This system can also provide clients with technical documents such as floor plans and section drawings. These models are dimensionally accurate and are perceived “exactly how the human eye would see it” (Matterport, 2018). Matterport services have yet to make it to New Zealand but it is looking to become a part of New Zealand real estate in the future (New Real Estate, 2018).

Figure 2.3: 3D Camera and Virtual Tour Platform

RoOomy is a virtual staging technology that allows people to visualise a space and decorate it in the way they choose (Athwal, 2018). RoOomy provides the service for customers to view 2D or 3D images of rooms from potential houses they intend to buy, and decorate it with furniture to see what it would look like with their personal touch on the space (RoOomy, 2018). As a sales tool this could provide a selling point for potential buyers as they have one step over the competition, with the buyer able to simulate how they would decorate their home before buying it. RoOomy have close relations with Matterport and are, again, an American based company, but has the potential to offer their services internationally.

Figure 2.4: RoOomy CGI and 3D Modelling

Whilst the previous two examples are focussed on selling houses through VR, Virtual Xperience uses VR to access properties under development so that investors can start selling the spaces before they are built. This creates an interactive real estate experience that benefits buyers and investors (Virtual Xperience, 2018). Pre-construction development is one of their main focusses, providing one of VR's main advantages of displaying a virtual environment before it has been constructed.

This section covered a few leading examples of VR in real estate it is still in its infancy. Most of these services are rare and not widely implemented, making them very specialised and expensive. It is currently more of a novelty than a sales advantage, however it has the potential to provide buyers with more information and access to house they are interested in purchasing and could save time and money for all parties involved.

High-Tech Simulators

VR has been seen as an educational tool to further learning through simulations that would otherwise be costly to make. It is also used to train employees in dangerous scenarios that wouldn't be able to be recreated without danger to the users. Pilots, Doctor, and Engineers are a few of the demographic that are benefitting from VR training simulators.

Aviation Institutes across the world use full flight simulators to train airline professionals without presenting the danger of flying a real plane whilst still learning (Air New Zealand Aviation Institute, 2018). This has been a used and tested method for decades and is one of the main way's pilots are trained. New Zealand's Aviation Institute operates eight full flight simulators alone. These simulators are not classed as VR, they are placed in a cockpit that is a real-life replica, but with a screen simulating the environment outside the cockpit window. Advances in haptic feedback have made VR based simulations more viable for areas such as variation training. Haptic feedback is the use of mechanical actuators placed on different parts of the user's body to simulate the sensation of touch, benefiting the simulation of a plane's cockpit so that the feeling of pulling switches and pushing levers can be felt (GoTouchVR, 2018). An introduction to this kind of simulator as opposed to traditional methods, would provide a cheaper, more convenient alternative to training. Traditional flight simulators are very large and expensive to make and maintain, whilst VR is able to provide the hands-on experience that gives trainees a more comprehensive learning environment. In its current state, Haptic feedback is still being refined and developed but could be the next step to add another immersive aspect to VR training.

Figure 2.5: VR Pilot Simulation

Figure 2.6: VR Pilot Training

Medicine is a field that requires future doctors to undergo extensive training over a number of years in order to be fully qualified to deal with patients independently. Simulating operations and scenarios with patients can be hugely beneficial to medical trainees to complement their studies (Virtual Medical Coaching, 2018). Medical training has seen recent advancements in simulation training with VR that simulate different types of surgeries as well as scenarios with interactive patients. According to Oxford Medical Simulation (2018), VR simulation has provided an increase in “safety, visibility, and reproducibility of actions as well as reducing costs”. The simulation of dangerous environments in a safe environment (through VR) has allowed medical trainees to learn how to deal with these situations and prepare for them in reality. Studies have found that trainees using simulation training for surgical skills have made fewer errors and carry out more accurate procedures than those who did not (Virtual Medical Coaching, 2018). It is becoming to be a routine undertaking in the training of medical students and is directly benefitting the field by providing a more comprehensive learning environment with a more complete learning experience, without the consequences of reality.

Figure 2.7: Medtech Simulation

Safety training is a key aspect to a lot of different industries, including construction and engineering. An Australian company called Sentient developed a project in VR that simulated dangerous environments for train operators that have to deal with high voltage equipment. This system used a VR headset and controls to train the user how to deal with these high danger situations, having to perform the correct movements and sequence of events in order to complete the tasks (Sentient, 2017). This high voltage switching simulation allowed for the user to identify equipment and switches in the simulation and decide on the correct procedure to complete the task whilst being able to practice the movements necessary without the danger of being electrocuted. Similar scenarios in construction and engineering would see a benefit of using VR in simulation training for high-pressure situations that might result in harm to the workers.

Figure 2.8: High Voltage Switching

Figure 2.9: High Voltage Switching Exercise

City Planning

VR services have been developed so that stakeholders can show potential buyers the project before it is built in order to sell it earlier than normally possible. The same can be said for city planning. VR can visualise huge data sets which can provide benefits for city planning, mainly due to the comparative method of scale models being hard to transport and more time consuming to make (Eon Reality, 2018). This can help in marketing and large commercial developments in the same way, able to show a client the project before completion to use as a selling point. Autodesk (2017) showcased a city planning project in Las Vegas to raise awareness for VR's potential in city planning. It proved to be a popular activity to walk through these 1:1 scale models of cities in VR to see how they would look once all projects had been completed in the area. Some European cities are even using satellite imagery to complement these kinds of projects in VR to monitor on-going projects effects on the surrounding buildings and environments (Davies, 2016). Whilst VR has benefits to city planning it is not the tool for the entire process. One study found that VR was effective when used in the evaluation stage of the planning project, but producing the digital models in VR was complicated as the architects had little information on how to produce such complex models in the VR environment (Sunesson, 2008). This may be easier with the development of the technology however it proves the valid point that VR is not the one stop solution to everything. It can be largely beneficial in aspects of a project, especially in city planning, but different aspects of a project will benefit greater from other mediums and techniques whether it be traditional 3D CAD modelling or 2D drawings.

Figure 2.10: Urban Planning Applications

3.0 Research Methodology

This section explains the methods of research used for this study and why they were chosen. These methods were chosen due to the aim of this study and proved to be the most appropriate methods to use in the timeframe allotted and with the resources available. To address the research questions the following methods were devised.

- *Literature and Software Review: Recent publications and precedents are identified and reviewed to establish the current status of the developing field and the capability of the current software.*
- *Anonymous Surveys: To establish the main problem areas when collaborating on live projects, anonymous surveys will be distributed to industry professionals.*
- *Structured Interviews: Insight into specific problems that professionals have had on past projects will be explored and evaluated through structured interviews.*
- *Analysis of Interviews and Surveys: Every interview is audio recorded and documented. Consistent problem areas are analysed and documented, forming the base of the experiments.*
- *Test Experiment: To test the method and examine what users need, a test experiment was run with a small group of participants*
- *Main Experiment: A user-centred experiment was undertaken to explore and evaluate collaboration when reviewing a digital model.*

3.1 Situating the Research

Research Questions:

How Can Virtual Reality be utilised for collaboration to help resolve clashes when reviewing the digital model, during the design phase?

What Information is needed to maximise collaboration between different disciplines when resolving established clashes within a digital model?

User-centred experimentation has demonstrated its application in obtaining information surrounding human interactions with technology, and in deducing what users need to have the best possible interactions with the technology. The output from such experiments has provided insight into what is needed to improve these interactions between people and technology in both the human and technological aspects of the process. The outcome from using this method proves it to be an appropriate method for exploring the issues presented above and will provide useable data to form conclusions about the interactions of humans with advanced technology in this scenario.

Table 3.1: Project Aims, Objectives, and Methods

Aim	Objectives	Methods
Explore Virtual Reality's applicability as a collaborative tool for architecture and construction projects	To produce a framework for the information users need in order to collaborate effectively during the design phase of a project	<p>Gather data surrounding the issues when multiple disciplines are involved in creating a BIM model in an architecture and construction project.</p> <p>Analyse current VR technology and BIM applications.</p> <p>Semi-Structured Interviews with Industry Professionals.</p> <p>User Experimentation with questionnaires to determine the users need when collaborating on a BIM model during the design phase of a project.</p> <p>Analysis of subjective and objective data alongside observational data of experiments.</p>
	Define the information needed to maximise collaboration when different disciplines are collaborating on architecture and construction projects	<p>Semi-Structured Interviews with Industry Professionals.</p> <p>Test experiment to determine hypothesis and alter methodology accordingly</p> <p>Simulate the collaborative environment of an architecture and construction project during this phase, to obtain live data on issues with collaboration of different disciplines on the same model</p> <p>Analysis of subjective and objective data alongside observational data of experiments.</p>

The Methods

1. Explore and define the issues surrounding the development of a BIM model for collaboration using advanced technology, during the design phase of a project.

Gathering data surrounding the issues of developing a BIM model for the purpose of collaboration involved a systematic literature review on the current industry implementation of BIM both within New Zealand and internationally. Analysis of current VR technology with BIM applications revealed an insight into the current level of development of the technology and software being used or developed within the industry. Semi-structured interviews were undertaken with industry professionals to develop these insights into New Zealand's position in current industry implementation and the problems faced when implementing VR in live projects with real-world consequences. These interviews took place after the initial literature and precedent review, but before the initial test experiment, so that the knowledge taken from the interviews could focus the test experiments method to achieve the desired information output. This output then influenced the design of the two main experiments of this study.

2. Evaluate using Virtual Reality to enable an advanced collaborative platform to improve collaboration when reviewing a digital model and solving clashes across different disciplines.

The literature review found a lack of user-centred studies in this field, with most being technology focussed, to define the capabilities of the technology or software being studied and was often a technology or software designed by the author of said articles. User-centred experiments have been a tried and tested method of effectively exploring human interaction with technology, as well as the interactions with each other. This chosen method was used to evaluate participants' interactions with advanced technology when being used as a collaborative platform, alongside participants interactions with each other when collaborating in this environment. Two experiments were run so that a comparative analysis could take place between CAD and VR technology and their respective advantages and disadvantages when solving established clashes collectively. Analysis of the data produced from these experiments would then influence the conclusions drawn through using advanced technology in this environment and went on to define what users need to do so effectively.

3. Develop a set of user requirements that ensure communication of information is clear between all parties involved when collaborating on solving clashes.

Developing a set of user requirements required thematic analysis of the data obtained from the user-centred experiments. Observations alongside questionnaires that provided both objective and subjective data from participants formed a data set that allowed for a comparative analysis between current CAD technologies used in the industry and VR technology. Analysis of this data informed the researcher on what users need to effectively collaborate when using advanced technology to solve clashes in a digital model.

Limitations and Constraints

Due to this research focussing a part of an emerging and constantly evolving field there were limitations surrounding this topic due to its nature. These were taken into consideration and appropriate methods of working around them were devised.

Locating material on how to solve clashes once they have been found was difficult, and there is no set official procedure. After asking multiple experts in the field they confirmed that there is no standardised method for this, and that respective companies use their own methods for solving clashes once they have been found. A legalised or standardised clash solving method is needed in the field and would benefit the industry greatly. Details surrounding the clash detection technology itself are accessible and show how it finds clashes, right down to the computer science and algorithms behind it. However, the method of solving the clashes after this process is human rather than automated, and with little guidance in this area it could be said that the current methods used could be improved upon. Finding data on information flow in projects and between software's was also difficult. This may have been due to the digital pathways constantly changing and differing from country to country and business to business. Finding a clear flow of information in a project or how it is supposed to be was challenging, as well as the methods past studies have used to get a fully functional model in VR. Even studies from two years ago used technology or software that is no longer relevant and has either been upgraded or replaced. The ever-changing nature of advanced technology in architecture affected not only the creation of the digital models itself, but also the digital pathways it will take on a project and the information flow between disciplines.

Scripting and coding in Unity has advanced rapidly alongside gaming technology, meaning certain codes, phrases, and words are no longer relevant when compared to those from one year ago. Because it is advancing so rapidly, finding material to aid coding work for this project has been. Unity updated twice during the timeline of this project, causing certain functions to no longer work, resulting in reworking or restarting. This is going to be an ongoing challenge, as Unity is evolving alongside other game engines to broaden the capabilities of VR. A prime example of this occurred during the last two months of this project. Unreal Engine released the beta for Unreal Studio, a complete suite including tools and services that make data flow, and made networking, and designing in Unreal easier and faster. Using this tool at the beginning of this project would have streamlined the process and recent amendments include features that took copious research and time to figure out without this kind of assistance. Due to the nature of this new and developing field it was predicted that the technology could advance during this research, however this advance in technology did not make the results of this project become irrelevant or outdated.

With a lack of resources and up-to-date information surrounding these advanced technologies there was also a lack of experts available within the university. One major challenge was the making of the Network Game, which is a niche field with little public information surrounding how to construct it. This Network game had to be made independently with little outside help. In future projects it would be beneficial to have a computer science expert directly involved to enhance the capabilities of the research project and allow a better digital environment to be constructed for further testing in this field.

3.2 Surveys

A survey is an “investigation of the opinions or experience of a group of people, based on a series of questions” (Oxford Dictionary, 2018c). Surveys aim to acquire quantitative data by giving a set of predetermined questions to a representative sample of people (Shaughnessy, Zechmeister, & Jeanne, 1985). The surveys are designed in such a way that the questions contain no bias, and that each individual answer with no influence from the researchers or other participants. Surveys allow for a set of standardised results that have comparable data. They provide a flexible platform for questions to be changed according to the research preferences and can be asked in a way that finds out what is being investigated whilst mitigating unrelated data. Previous studies have found surveys to be useful in obtaining users opinions, thoughts, and preferences when using VR as an experimental research tool (Kuliga, Thrash, Dalton, & Holscher, 2015; Heydarian et.al. 2015). Both surveys from these studies allowed the researchers to use the immersive aspect of VR to explore how participants complete tasks in VR. In such an immersive environment it is important to ensure that the subjective opinions of the participants can be quantified and examined, and surveys working alongside observations and measurables from experiments have proven to achieve this (Niu, Pan, & Zhao, 2016). However, there are drawbacks to using surveys. Surveys inherently depend on how the individual is feeling at the time of the survey, if they are feeling excited and motivated then they may provide more in-depth answers, but if they are grumpy and tired then they may provide shorter answers. There is a level of interpretation that may waver with certain question sets, meaning that the answer to the question may not be as intended (Fricker & Schonlau, 2002). Another issue that can arise from surveys is non-responses, which can cause bias.

The two types of surveys that will be used in this project are questionnaires and interviews. The interviews are the first step in this investigation followed by the user-centred experiments. Participants will answer the questionnaires after they have completed the experiment to obtain their objective opinion on the digital environment.

Interviews with Industry Professionals

An interview is a “session of formal questioning of a person” by another person (Oxford Dictionary, 2018b). Compared to a survey, an interview is a survey with the researcher asking the participant questions in person and can discuss the views of the participant in-depth (Kajornboon, 2005). Interviews can be structured or un-structured depending on the objective

of the research. If it is structured then it needs to be laid out, as the questionnaires are, with the questions in a logical order with no questions influencing the answer to other questions. Each participant must be asked the same questions in the same order with the same procedure followed so there is no bias (Kajornboon, 2005). The main advantage of interviews is the more in-depth answers provided compared to questionnaires, and the participant has the option to discuss the answers further to understand them. A more in-depth analysis can be gained from the participants, answers due to the human interaction. The main disadvantage is that only one interview can be performed at any given time and organising them is more time consuming than questionnaires.

These interviews were conducted by the researcher and were aimed at industry professionals with experience using BIM and digital models in collaborative environments. They were contacted either through associates at university or directly through email to gauge their interest in participating in the study. Due to the independent nature of this study it was expected that few people would be interested or have the time to participate in the interview, but that the industry perspective they provided would be valuable to this study.

Questionnaires

A questionnaire is a set of questions with a choice of answers that are designed for the “purpose of a survey or statistical study” (Dictionary, 2018). Questionnaires are designed so that they are independent of any outside bias such as the researchers influence and can be completed without the presence of any researchers. The researcher does not need to be present, so multiple people can answer the questionnaire simultaneously, and in different locations; a key benefit of obtaining data in this way. This would come in the form of either an email survey or online survey to reach people. Email and online questionnaires have proven to be both cost effective, with a fast transmission, and a quick response turnaround (Michaelidou, 2006). The downside of this is that there is no monitoring or further explanation after the participant receives the survey. This is one of the main reasons that the questionnaires need to be designed carefully so that everyone can understand the intention of the survey (Munn & Drever, 1990). The principle of anonymity will be adhered to for this research and this has been proven to affect response rates, as no information about the participant or their response is linked back to them, so they are more inclined to participate (Michaelidou, 2006). There are multiple ways to structure the questions. Yes and no questions

provide a straightforward process with ease of analysis but can provide limited information and often do not represent the participants' answer correctly. Multiple choice has a better range of answers and can still be analysed in a straightforward manner. Open-ended questions provide a longer answering process for the participants which can also produce disinterest, however they can sometimes provide the most accurate way of representing the participants answer. Analysing open-ended questions is a more difficult task than other previously mentioned methods, and usually revolves around finding recurring themes and words to compare (Munn & Drever, 1990). The layout, wording, and order of the questions need to be carefully thought out. Questions should follow a logical sequence and start out general then get more specific through the duration of the questionnaire (Rowley, 2014). The questions should not be influenced by the previous questions and vice versa to avoid bias.

The post experiment questionnaires were designed to obtain subjective feedback from participants about both the procedure and the digital environment within the experiment. Observations provided objective information about how the participants performed with one another when collaborating. Questionnaires provided the subjective information from the participants about their individual experience with the technology. The questionnaires were designed so that it would take no longer than 15 minutes to answer the open-ended questions, thereby ensuring engagement was maintained and useful information would be provided. If the questionnaires were too long the level of engagement would likely suffer, alongside the quality of information provided. If the questionnaire was too short however, there wouldn't be enough information to analyse. It was vital to reach a balance between the two. The initial test experiment revealed that the questionnaires were too long and answers to questions got progressively shorter, so the length of the survey was adjusted for the second and third experiments to negate this. Feedback about the questionnaires after these changes were made was more positive. Thereby, almost all participants answered every single question to the best of their abilities.

3.3 Observations

To find out what people do under certain circumstances observations can be one of the most straightforward ways to obtain this information. It is important to note that observations remained purely that, observing and taking data with no intervention. Both quantitative and qualitative data can be obtained from observations depending on what is being observed during the experiments. Both types of data were obtained through observations to ensure there was no bias. People tend to have a confirmation bias based on confirming a hypothesis in scientific experiments, which will make them lean towards confirming their own hypotheses as opposed to objectively observing and analysing (Shaw, 2016). These hypotheses are based off of predictions more than facts, so it is important to maintain an open and objective attitude towards the observations.

The following observations were made during the experiments:

- *The way each participant navigates the model, taken by observing their movement from within the model*
- *Time taken per clash*
- *The way they approach a clash and how they look at them (e.g. do they move around it a lot or stay in place and look)*
- *The way in which they solve the clash, their method and steps they take to ensure it doesn't make more clashes*
- *The verbal communication they use and how they explain things to each other e.g. say over there or use defining features to explain a location*

These observations provided for a complete data set that provided comparable data from both scenarios, as well as ensuring no bias from the researcher's point of view to confirm a hypothesis.

3.4 Experimental Procedure

An experiment is a “scientific procedure undertaken to make a discovery or test a hypothesis” (Oxford Dictionary, 2018a). Experiments are undertaken when a hypothesis is made regarding a gap in knowledge and is then tested to discover if the hypothesis is true or not. It is typically an exploration in a relationship between one or more dependent variables, and one or more independent variables (Graham, 2007). The method for exploring this relationship can vary depending on the nature of the experiment, but data must be obtained to understand and analyse the relationship. The two main forms of data are:

- *Quantitative data: Data that expresses a value of some sort with measurements units, whether it be a quantity, amount, or range; and*
- *Qualitative data: Data that generally cannot be represented by a number, and is generally more descriptive and subjective than quantitative data.*

Experiments provide data that can be analysed, thereby enabling a conclusion to the investigation based off the results from the experiment. Whilst this is a revered method of investigation, it requires planning and attention to detail to ensure that the data obtained from the experiment is useable, trustworthy, and relevant. According to Howard (2007) an experiment must have the following three requirements to be called a true experiment:

1. *At least two levels of an independent variable;*
2. *The samples are randomly assigned to levels of independent variables, so that each sample in the experiment is equally likely to be assigned to all levels of the independent variables; and*
3. *There is some method for controlling or eliminating confounding variables.*

If all of these conditions are met, then the experiment will allow for conclusions of causal relationships between variables to be established after analysing the results. One of the major aspects that can upset this investigation is confounding results; variables that are not the primary interest of the experiment, but affect the dependent variables being investigated. A prime example of this is experimenters bias, in which the experiment will transmit their expectations of the outcome to the participants, thereby affecting the experiment in order to reach the conclusion they are expecting (Maxwell & Delaney, 2004).

Methods for controlling these variables are vital in an experiment involving participants that have direct contact with the researcher. Research data needs to be both trustworthy and reproducible to be considered successful data. This will ensure that the research is controllable and replicable, which is important in a field that is constantly making advancements, such as construction technology (De Waard, Cousjin, & Aalbersberg, 2015). If the data can be reproduced, then it can be reused to further the investigation started by a previous researcher and can be a base for filling in future knowledge gaps.

A test experiment was run after obtaining information from interviews with professionals, to test the initial hypotheses and to obtain information on how to improve the experiment to get the unbiased data. This test experiment resulted in some minor changes, to ensure the later experiments were more refined. These results will be discussed in the following sections of this document. The later experiments were then split into two different scenarios; one involving solving clashes in Unity from a CAD perspective, and the other in Unity with VR headsets. The test experiment helped to provide clarity on what data was needed to be comparable and to see the differences between current collaborative environments and a VR environment.

3.5 Interviews

The Process

Participants were contacted through email to initially gauge their interest in participating, and from there, a time and place was organised. Five interviews took place in various public locations arranged by the interviewee and interviewer. These interviews lasted 30 minutes and followed a list of semi-structured questions, and were audio recorded. The interview began with the researcher giving a brief overview of this project. The participant was then asked to state their role within their company and their level of involvement with BIM on projects. These participants will not be mentioned by name nor the company they work for, but their roles within their various companies were:

- *Two Project Managers;*
- *A BIM Coordinator;*
- *An Architectural Visualiser; and*
- *A Design Consultant.*

The questions then explored the BIM applications they have used on past projects. This naturally led to the topic of collaboration in these projects, and finally on their experiences of VR within their company and what they have used it for, and their opinion on what they think it can be used for.

3.6 The Test Experiment

A small experiment was run on the first of September 2018, focussing on examining what a user needs to be able to collaborate with other disciplines in a digital environment. This was also used to establish the issues surrounding collaborating in digital environments and setting up the main experiment to further explore this concept. Running this experiment determined the areas that needed to be focussed on and explored in the larger experiments later. The test experiment provided a test of the process of recruitment, choice of questions, the way the experiment is run, the type of results this will produce, and the time taken to produce a working model for the purpose of the experiment. The outcome of this test determined the method of experimentation is a suitable way to investigate this issue, and ways in which to improve the method.

The Model

The model used for the test experiment was created by the researcher, in Unity Engine. Unity Engine was chosen for this experiment as it is free to use, compatible with most 3D CAD programmes, accessible on university computers, and is an environment capable of performing the experiments in.

The base geometry of the digital model was created in Revit and took the form of a small one-story building. The model was designed to be a complete model, meaning that it is an accurate representation of a real building that provides all the information required to construct the represented building (Boland, Lyytinen, & Yoo, 2007). Accurate scale geometry, materials, and structure and services were constructed using Revit. This Revit model was then exported into 3DS Max where a few changes had to be made to import it into Unity. Revit models are not directly compatible with Unity and models have to be run through a programme like 3DS Max where aspects of the model can be made compatible (Autodesk, Exporting Models from Revit to Unity, 2018). The following changes were made in 3DS Max before the model was made Unity compatible:

- All materials within the scene were converted, using a scene converter;
- UV maps created for all geometries;
- Geometry was optimized; and
- The model was exported as an .fbx. File.

The materials in the scene needed to be converted to standard materials. The Revit materials are incompatible with Unity and would not apply to the geometry should it have been directly imported to Unity from Revit. Revit uses Autodesk materials which Unity cannot recognise, so the scene converter tool in Revit converts these to materials types Unity can recognise.

Revit doesn't create UV maps for the models, so this was made in 3DS Max. The UV maps ensure that the geometry is more organised, and the textures are applied properly to create a more realistic appearance.

The geometry in the model needed to be optimized to reduce the polygon count and ensure the model runs smoothly. The geometry in the model is made up of polygons and the more polygons there are, the slower the model will run. Optimizing the geometry enhances it, and reduces the polygon count. The Pro Optimizer tool in 3DS Max was used to achieve this. Once these tasks had been achieved the model was exported as fbx. which could then be imported into Unity.

Once the model was imported into Unity it needed to be altered to create the test experiment environment. The following implementations were made so that the test experiment could be performed:

- *Constructed a Network Game with Multiplayer capabilities;*
- *Created first-person controller, motors, and avatars for each player;*
- *Created the ability to move objects when 'in-game';*
- *Colour coded all services; and*
- *Create clashes in the model.*

To simulate a clash detection scenario a Network game had to be constructed so that the participants could be in the same model at the same time and could readily communicate with each other from within this model. UNet is a system that was added to Unity in 2018 to make multiplayer network games more achievable when using Unity. UNet provides servers that users can implement into their games and use at a basic level. Some of the components necessary to make a multiplayer network game were provided through Unity, however some had to be scripted from the beginning and took a great deal of trial and error to achieve. Information on how to achieve this was limited as this technology is so new, as well as the fact that the Unity Engine had two updates during this project, meaning some aspects of this project had to be reworked. After the first experiment the Network then had to be updated to

accommodate for multiple HTC Vives within the network game. Upon completion pairs of participants could be within the same model at the same time whilst using separate computers and were able to see each other and communicate.

Creating first-person controllers, motors, avatars, and the ability to move objects whilst 'in game' required scripting these behaviours from the beginning. This project is not focussed on computer science, however a certain level of knowledge on computer science, coding, and networking was needed to create the digital environment that experiments could then be run in. C# was the scripting language used to script the behaviours in the digital environment. Unity allows for entirely new scripts and components to be made within the programme, so these were made from scratch and then implemented into the model taken from Revit.

Once the Revit model had been taken into Unity, further adjustments were made to the geometry of the model. All the exposed services within the building were colour coded to ensure participants could easily tell them apart, regardless of their experience in the field of architecture. Different materials were applied in other areas to make the model an accurate representation of a real building. Upon the completion of these tasks, parts of the model were then altered so that clashes were made within the model and were highlighted, for the purpose of solving in the experiments.

The Setup/Process

The test experiment involved ten participants. The size of the participant group was to ensure this experiment only ran for two days, which was long enough to produce results but short enough that it did not become larger than the main experiment of this project. These participants were contacted by poster advertisement around the university campus, and through emails. Emails were obtained when the potential participants emailed the researcher from the email address left on the poster, and arrangements were made from there. The recruitment email contained details about the experiments aim and the initial medical screening sheet to determine whether they were eligible to participate.

The test model had ten basic clashes inserted into it. These clashes were on multiple levels and in different areas to simulate how they could appear in a live project. The clashes were different levels of difficulty to ensure there were multiple clashes with multiple solutions that required lateral thinking. The model was a one storey building with one open room, and exposed services for ease of use for the participants. The clashes were highlighted red, and the participants were given a clash report with each clash corresponding to a number between one and ten on the report.

Experiments were run with people participating in pairs. On the day of the experiment the participants were briefed on how the experiment was going to run and were then asked to fill in a demographic sheet and to sign the consent form. There was be a brief rundown on the equipment being used and the participants were taught how to use the Unity software and navigate the digital environment. Initially they were asked a few questions to gauge their experience:

- *How much experience do you have using CAD software;*
- *How much experience do you have using Virtual Reality;*
- *Have you ever had a job involving BIM; and*
- *On average how often do you play games a week.*

For the test experiment both participants had a computer each and were seated side by side. One participant was in charge of moving the objects to solve clashes, whilst the other was there to assist in any way apart from physically altering the model. They were given a total of 20 minutes to solve the 10 clashes and the experiment was considered finished when either they had solved all the clashes, or the time ran out. They had to collaborate with each other to finish the task as effectively and quickly as possible. After the experiment, the participants were asked a series of questions and asked to fill out rating scales regarding the model and the experiment. There were both individual questions and group questions to ensure there was no bias in their answers. Observations were made on how well the participants worked together, and how effectively they completed the tasks. The time taken to perform each task was recorded.

3.7 Experiment 1

The purpose of this experiment was to determine how people solved established clashes in CAD from a first-person perspective, and if this provided a better perspective for solving clashes than current methods. Participants would be viewing the model from a first-person perspective and using video game-like controls, as with the test experiment. Participants had to decide on their own methods to solving clashes and work together to agree and then solve all of the clashes within the digital model. This would also determine problem areas with collaboration within this digital environment. This experiment aimed to identify what users would need when solving clashes using advanced technology such as VR, in a collaborative environment. The immersive aspect of VR has the potential to provide more information however it could lack vital information needed too. The focus of this experiment was on how the participants solve the clashes collaboratively with the information they had and what they needed to do so effectively.

Participants were working in groups of two, with a total of 18 individuals participating (nine groups of two). They were situated in the same room as each other but the computers they were using were opposite each other, and they were advised they were not allowed to look at each other's computer screens, but to communicate where they were and what they were trying to do to. As the screens were opposite each other they could verbally communicate in person. This was to simulate a situation where people may be working together in the same building but would not be working on the same floor or side by side. This situation was also set up to simulate how people would solve clashes whilst using the same model but not being in the same place and would be using voice communication channels such as skype. The digital model being used for this experiment was set up to be a network game so they could be in the same model simultaneously and visually see each other in the model in real-time. Both participants were navigating the model using their own respective avatars. These avatars were set up so that the participants were viewing everything from a first-person perspective. There was a brief tutorial period before the experiment began to explain all of this to the participants and for the participants to grow accustomed to the controls and navigation of the digital model.

The participants were advised that they had to solve ten clashes within the model. Feedback from the test experiment dictated that the physical movement of objects within the digital model was one of the most disruptive parts of the experiment, and was not necessary, so for

this experiment participants could not alter the model in any way and the way in which they solved the clash was to tell the researcher how they would solve a clash once they had agreed upon a solution. As with the test experiment, they would not be given any advice or structure on how to solve the clashes. The clashes were located underneath highlighted red circles, like the test experiment. Participants had a total of 20 minutes to solve clashes, and the experiment ended either when the participants had solved all the clashes, or the time limit was reached. The researcher was observing from within the digital model and was in an elevated position so that they could observe the participants navigation throughout the model and their interactions with the model and each other's avatars.

Figure 3.1: 3D View of Model in Experiment 1

Figure 3.2: 3D View of Model in Experiment 1

Figure 3.3: Interior View of Model in Experiment 1

Figure 3.4: First-Person View In-Experiment

Figure 3.5: Participant Avatar

Figure 3.6: First-Person View of Their Partner

Figure 3.7: 3D Interior View of Model in Experiment 1

Figure 3.8: Plan of Clashes in Experiment 1

3.8 Experiment 2

Experiment two was set up in a very similar way to experiment 1 except this time participants were using HTC Vive headsets. The same model and method were used:

- 18 individuals participated (nine groups of two);
- Participants worked in groups of two;
- Participants had 20 minutes to solve 10 clashes;
- Participants were physically situated in the same room;
- Participants were able to verbally communicate with each other;
- Participants solved the clashes by verbally telling the researcher their agreed solution; and
- The experiment ended either when the 20 minutes was up, or all clashes had been solved.

The clashes were changed to be different to the ones in experiment 1 but were assessed to be at a similar level of difficulty. Using VR headsets meant that navigation was slightly different. Vive handheld controls were used and the way participants could move was through teleportation. Participants pointed a laser at the ground and released the trigger on the

Figure 3.9: Plan of Clashes in Experiment 2

control to teleport to their chosen spot, so navigation took the form of many small teleports as opposed to holding down computer keyboard keys.

One limitation of this experiment was the lack of avatars. Coding the new movement and use of VR headsets was achieved however avatars portrayed across the Network game was unable to be produced within the time frame. Adding VR capabilities to an already complicated network game required further expertise in networking and scripting which was not a major focus of this study, therefore it was decided that the experiment could continue without avatars with minimal disruption to the results. This meant participants had to communicate where they were to their partners as they could not physically see them. This limitation was considered when analysing the results and making comparisons between the two experiments.

Figure 3.10: 3D View of Model in Experiment 2

Figure 3.11: Interior View of Model in Experiment 2

Figure 3.12: 3D view of Model in Experiment 2

4.0 Results

The results section is split into 3 main sections: Results from the interviews, test experiment, and main experiments. The results of the two experiments have been divided into 4 sections: The task, the observations, the subjective data, and the objective data. In each of these sections both sets of data from the respective experiments will be presented and compared. The combination of these data sets provides a means of measuring how effective VR is as a collaborative tool in the design process, and the issues surrounding clash detection and VR's application within it.

4.1 Interview Results

Questions for the interviews targeted three main areas involving collaborating on projects:

- *Issues with collaboration itself, on live AEC projects;*
- *Issues with the technology currently being used in the field; and*
- *Virtual Reality's industry applications, and problems with its current implementation.*

The 5 interviewees were of various ages and levels of experience, leading to a wide range of answers was attained. Experience ranged from two years within the industry, to almost 20 years. These differing levels of experience and age presented viewpoints that were both focussed on the present situation of the industry alongside comparisons to how the industry was in the past.

The main areas that presented problems with collaboration on projects was found to be contractual, consistent formatting of digital models, and ownership of design and input throughout the entirety of the project. Contractual obligations were found to be a big issue when design consultants hand their drawings and models over to contractors at the end of the design phase. At this point in the project the consultants have completed their contract, and most of the time have no further involvement with the project. This becomes an issue when clash detection and solving has been completed, as this will change the design of systems, structures, and the overall buildings design. Liaising with the consultants at this point of the project was proven to be difficult because they are no longer being paid, so any input or advice on their design is voluntary. This was a common theme among all interviewees and most stated that this meant that once the consultant's hand over their final designs they also hand over their ownership and will not be involved when the design may change when

planning for construction, or construction itself is happening. The BIM coordinator interviewed stated that in an ideal world there would not be two separate teams of consultants and contractors, but that a “new company” would be formed on each project where the consultants and contractors work together for the entirety of the project. This would mean that the consultants would have highlighted how systems work against plans with appropriate pictures to explain this, cost would have been attributed clearly with drawings and models, and the design team would be communicating their design throughout the entirety of the projects life cycle from design, to clash resolving and construction planning, through to construction completion. Both Project Managers (PM’s) and the BIM coordinator further stated that consistent formatting of digital modelling would streamline the design and planning for construction phase to ensure that no information is lost between disciplines. Currently there is no standard file format for this process, and the closest format to a standardised method (.ifc) cannot portray information properly, particularly when it comes to symbols. This involves a lot of coordinating and clarifying on the PM’s and BIM coordinators behalf. The reason there is currently no standardise file format is due to different disciplines using different platforms. According to one interviewee, mechanical engineers and services engineers use their own respective platforms for modelling because they have been trained in these, and there is no direct benefit to switching to a more BIM focussed software. They went on to state that they would not get paid any more in their contracts but would still be expected to take on an increased workload of learning a new software that would make their jobs more difficult and time consuming overall, in order to benefit the project but not themselves. This ties back to the contractual issues of people doing what is required in their contract but nothing beyond this which could potentially benefit the project, but not benefit themselves directly.

The technology currently used in the industry was, in the eyes of the interviewees, capable of creating a collaborative environment that would benefit projects throughout the entirety of their life cycle. However, they stated the areas that needed improving were standardised methods of achieving this as well as consistent formatting and technical knowledge of the programmes being used. A consensus was a generation gap of methodologies and training. The older generation were trained on pen and paper and primarily used this method for several years in both the design and construction phase. Clash detection in this area used to involve overlaying plans to see what overlapped and clashed. The newer generation may have

less knowledge on drafting 2D plans physically but have been trained in current technology and have picked up on it faster than the older generations. Both 2D and 3D modelling have their own uses as mentioned in the context section but merging these two generations knowledge on projects has been difficult according to the interviewees. Initially the technology was not accepted by older generations, however according to the design consultant this has changed dramatically over recent years, and the benefits of 3D modelling have been realised by the older generation. This still creates two issues, one being that the older generation have to undergo training in software in order to be able to convey their designs into a digital model, the other being that the newer generation are unable to understand the older generations designs and methods even though they are based off of experience in the field. This disparity between generations has caused time delays, communication breakdowns, and costly mistakes according to all the interviewees. The lack of standardised formatting and modelling methods was discussed previously but is among the other problems surrounding the current technology being used within the industry. In New Zealand, the BIM Acceleration Committee (BIMAC) is aiming at producing standardised methods of using BIM in projects, but this is receiving mixed feedback. One interviewee commented that they agree with what the BIMAC is trying to achieve but that they did not agree with their methods. Another interviewee stated that whilst standardised methods are needed the issues on a project would not be solved by creating a standard that people must follow, as it is more about achieving the end result together. If companies can still finish projects to a high level whilst using different methods that work for them than they should be allowed to do that. They further stated that some methods are unable to be achieved when using different software so it should not be assumed that everyone in the industry uses Autodesk products. Overall it was agreed that current technology is up to the task of creating digital environments that enhance collaboration and cohesion in projects, but that these are simply the tools to achieve this and the methods being used are either varied or inefficient and require improvement of some kind.

Industry implementation of VR is currently limited in New Zealand and is mostly used as a client liaison tool. According to the Architectural Visualiser it is a very useful tool for putting clients through digital walkthroughs of potential designs. The design consultant backed this up and further stated that it could be a very useful tool for the design phase of projects. They also said that construction companies were starting to realise its potential for saving them

money, which may be one of the main reasons it will see a large increase in use within these companies. The BIM coordinator who has more experience with the construction side and on site applications stated that it would be useful tool for the design phase as well as solving clashes as it has the potential to explain systems better, but that on site application is limited and AR will be more appropriate in this area. All interviewees agreed with the literature review findings that VR application in the industry is limited in New Zealand, but that its potential is promising, especially for the design phase. All of them have used VR at some point on a project for conceptual purposes but had not directly implanted it into their design processes on projects. It was also found that most of the interviewees knew very little about the technical side of VR and asked the interviewer about these aspects of it and its current capabilities. Overall it was agreed by all participants that VR has potential to be included in the design phase of projects and would benefit it greatly when properly applied, but that when the project reaches the construction phase that its possible applications were limited if there were any.

The results from the interviews with professionals presented significant findings as to the current situation within the industry surrounding collaboration and the technology used to achieve this on projects. The main issues surrounding ownership of design throughout a project was determined to be a contractual issue, so while it is still relevant to the study it is something that is unable to be explored further as it is outside the scope of this project. This is the same as the generational gap and will not be a focus for the following experiments. The findings regarding issues with technology when collaborating and the lack of VR implementation will be further explored within the scope of this project. Most of the interviewees claimed that VR has the “potential” to aid the areas of design and clash detection. Potential applications of VR as a collaborative tool in these phases of a project will be the primary focus of the experiments within this project.

4.2 Test Experiment Results

The Model

As mentioned above, the model was imported into Unity, where the participants used it. Pressing play in Unity allowed them to take control of first-person avatars and explore the model. In the test experiment the networking features were not enabled, so the participants were in two separate, but identical copies of the model situated on two separate computers that were side by side. They could clearly see each other's screen and were close enough to be able to point out things on each other's screens.

In the post experiment questions, the participants were asked several questions about the model itself and its level of detail. On the rating scale the model achieved an average rating of 7 out of 10 for realism and a 7.8 for ease of navigation. The general comments from the individual and group questions after the experiment told a similar story. The model was considered easy to navigate by all with a "non-confusing" layout. Objects were easily identifiable with enough level of detail to be able to differentiate between different objects and services. The scale was also considered to be 1:1 and most people stated that they felt like they were the size of a human in an accurately scaled building. Two participants said the model could have more detail but did not state that the level of detail in the model affected their performance in the experiment. The first-person view was generally seen as very helpful in solving clashes. One participant mentioned that third-person view would be unhelpful but that the ability to see objects in elevation could be a useful tool for certain situations. Observing the participants when they were solving a clash revealed that people would mostly rotate around the clash and look from multiple angles before solving it. Some clashes, such as a wrongly placed structural column required different views to see if moving it would create clashes with services on the roof as well as interior aspects of the model. The overall comments about the initial model were positive, with most people stating that the ability to see each other in the same model would be most beneficial to completing the tasks. The negative comments regarded the level of detail within the model. The level of detail was deemed to be enough to complete all tasks without any major hindrances, however it was stated that the level of detail on smaller objects was lacking.

Graph 4.1: How Realistic Was the Model?

The User Interface (UI) and Controls

In this test experiment the controls and UI were designed to be simplistic and functional. Participants controlled their first-person avatars movement with the W, S, A, and D keyboard keys and moved the mouse to change the direction they were looking at. The left mouse button was used to move objects within the game by using a click and drag function. The participants click and hold down the mouse on an object, move the object by moving the mouse, and then released the left mouse button to place the object. All the above controls were based off of basic standardised controls used in computer games for PCs.

On the rating scale, the controls received an average rating of 7.25/10 for ease of use. When discussing the controls in the individual questions there was a correlation between the intuitiveness of the controls and the participants experience playing video games. The two people that stated they play between one and three of video games a day had “no trouble” with the controls, and the results were similar for those who played video games between one and three hours a week and a month. Of the four individuals that almost never play video games, two stated the controls “needed a bit of getting used to” and that training in the technology would be required before being able to “perform these tasks efficiently”. One of these individuals with little video game experience also stated that more controls were

necessary to feel engaged with the digital environment. The participants who play video games regularly generally answered similarly when answering questions about navigation, level of detail, and performing tasks, and concluded that overall the controls were easy to use, and the UI was intuitive with few issues. This infers that gamers have an advantage in this scenario as they are more accustomed to controls and the technology compared to non-gamers.

The main issue that participants brought up about the UI and controls were regarding the function of moving objects in game. The function of selecting objects had a 10m radius and objects moved in a rotation around the avatars. Most of the participants said that the movement of objects was sometimes hard to select the object they intended on moving, and that they often accidentally moved other objects. The observations from the test experiments backed this up and most people tended to take a bit of time simply trying to select the correct object to move. Moving the wrong object caused them to take longer to complete some of the tasks as they had to spend time putting the other object back before moving the intended object. “Authority of objects’ was a suggested solution so that only the clashes themselves could be moved and all other objects would not be able to be moved. Another solution to this was to add a crosshair in the centre of the screen so that it would be easier to see what object the participants were about to move when they clicked down on the mouse. Overall comments on the UI and controls seemed to depend on the level of experience the participants had with playing computer games, with little correlation between the levels of experience with CAD modelling in comparison.

Graph 4.2: How Easy Was it to Navigate the Model?

Graph 4.3: How Easy Was the UI To Use?

Graph 4.4: How Easy Was it to Solve the Clashes?

The Clashes

The clashes in the test experiment were located underneath highlighted red circles and were written down on a clash list to simulate a clash detection scenario. The participants then had to locate these clashes, determine which one they correlated with on the clash list, and then solve them. The average rating for ease of locating the clashes was 9/10 and the ease of solving the clashes received an average rating of 6/10. From observing the participants it took little time to locate a clash, the main issue was finding the clashes after solving most of them and the participants had forgotten to tick off the clashes they had solved, or could not remember if they'd solved particular clashes due to lack in communication. This problem with keeping track of solved clashes was not related to the technology but more a user-based problem, however this was observed to have an effect on the rating scale of for the clashes as well. The main feedback received from the post experiment questions was regarding the ability to be in the same model and both be able to solve clashes would have improved the ability to solve clashes more efficiently.

Graph 4.5: How Easy Was it to Solve the Clashes?

The Collaboration

As the participants were situated side by side in the test experiment, they were given the best collaborative environment for this situation. They were able to look at each other's computer screen and communicate in person. In the rating scale the ease of collaborating with their partner was given an average of 8/10, and the ease of conveying how they wanted to solve the clash to their partner was given an average rating of 7/10. Understanding how their partner wanted to solve a clash received an average 7.25/10. One individual gave both questions a 5 out of 10, however observations did not deduce any major lack of communication with this pair so it may be down to these individuals bias in the use of numbers. The questions did any reasoning behind these scores, with almost everyone saying the communication with their partner was easy and they preferred talking in person. This feedback provided insight in to participant's opinions in a scenario where they would not be collaborating in person. Most participants stated that collaborating in a scenario such as this would have been far more difficult if they had to do it over the phone or with any other form of communication other than in person. Furthermore, some participants said that not being able to see each other's computer screens would further impact their efficiency in this task.

When asked if clash detection should be kept to smaller groups or have everyone involved at the same time, the majority stated that only a few people should be involved at any given time. Participants said ownership of objects would solve which objects belong to whom, and that smaller groups of people controlling everything would be ideal, with everyone involved being able to see and be notified about the changes. The rest of the feedback on collaboration resulted in three main issues:

- The wrong objects were being moved;
- Being in the same model would be hugely beneficial; and
- Both participants need to be able to solve the clashes was needed.

These issues with collaboration were both technology-based and user based, however the technology-based problems can be fixed for the following experiments. The user-based issues prove that sometimes miscommunication happens at any level of collaboration, so these examples were taken into consideration for the following experiments.

Graph 4.6: How Easy Was it to Collaborate with Your Partner?

Graph 4.7: How Easy Was it to Convey How You Wanted to Solve a Clash?

The Questions

Questions were used in three stages within the test experiment. The first was an objective rating scale, the second was individually answered subjective questions, and the third were open-ended group questions. Individual and group questions were used to determine whether there would be any bias from the participant's partner which was aimed to be nullified by the individual questions. Overall feedback on the questioning process revealed that the process was slightly too long and towards the end (when the group questions were being answered) the participants grew weary and unfocussed, especially as the questions were like the individual questions they had answered previously. The answers to the individual questions versus the answers to the group questions were similar in most aspects, and no clear influence of answers was detected. Because of this it was decided that group questions would not be a part of the next two experiments and would be limited to the rating scale and open-ended questions answered individually.

Summary

The test experiment highlighted several issues with the model and the experiment process itself, thereby fulfilling its purpose. Technology-based issues such as problems with the model, controls, and UI were fixed at the discretion of the researcher and improved upon as best as possible with the resources available for the following experiments. Problems with collaboration were more difficult to solve without ownership of different aspects of the model, so for the following experiments, more specific roles were assigned to participants to counter this. Group questions were eliminated from the next experiments as it was found that there was little difference in the answers other than the lack of enthusiasm to answer them due to the process being so time intensive. All changes made to the methodology were based off of this test experiment and were made to create a more refined experiment procedure.

4.3 Evaluation of the Observations

Communication

In both experiments, communication was achieved between participants verbally as they were situated close enough within the same room to be able to speak clearly to one another. The first experiment allowed for them to look at each other to communicate both physically and verbally, whilst the second experiment was limited to verbal communication only, with the researcher able to physically see them both. The way participants communicated dictated how quickly and efficiently they were able to solve all of the clashes, which became apparent when certain groups did not communicate where they were, or where they were going correctly, and used up valuable time retracing their steps and trying to figure out the others location. Even during the first experiment, when participants could see each other's location the most common phrase used was "where are you" and "where did you go". If the success of the group was judged by time and efficiency, then it can be inferred that the groups who achieved the fastest time with correct solutions were the ones who communicated effectively throughout the entirety of the project. The faster groups were observed to take a 'follow the leader' method where one of the participants decided on which clash to go to and they would either follow their avatar or go to that clash and communicate when they had arrived. These faster groups were almost always constantly talking to each other, whether it was when moving to a clash, thinking of a solution, or simply observing the clash. Groups that did not communicate effectively at the outset of the experiment were observed to spend more time trying to find each other later on, as well as becoming confused as to which clashes had been solved already. In the first experiment three groups did not mark off which clashes they had already solved meaning they then had to spend more time going back to clashes and figuring out which they had already solved. This did not occur in the second experiment, and participants were more engaged with the clashes and in understood which clashes they had already solved, even though they could not see the clash list. This information is suggestive but not conclusive, as different environments would provide different levels of engagement with the project and participants may have communicated more in VR due to it being a more exciting and newer platform, as well as it being a novelty as most participants did not have much if any experience in VR. This data does infer that the technology has the potential to get in the way of communication even where participants were situated in the same room. Being able to see each other in the model meant they could tell where each other was without

communicating it, but also provided a reason to not communicate that, whereas in VR the lack of avatars meant that they were more encouraged to verbally communicate their location to their partner.

Navigation

In experiment 1, participants could see each other in the model and were represented by avatars. These avatars took the form of spheres with a pointer so that they could see what their partner was pointing at. The researcher was in the model using a third avatar to observe the participants movement throughout the digital model, from an elevated position. In the second experiment participants were in the same model but could not see each other and navigated by using the HTC Vive control to use a laser pointer and teleport short distances. The way the participants navigated the model was observed to have an effect on their overall time taken but was not the only factor affecting this. The initial hypothesis on the participants' method of navigation was that participants would navigate to one area and complete all clashes there, before moving to the other area and complete all tasks in that area, however this was not the case. In the first experiment three out of nine groups jumped between inside and outside clashes solving a few in each area before moving on to the next area and solving them, until finally returning to the first areas and solving the remaining clashes. Only one group did this in the second experiment. When observed on which clash they went to first most groups were observed to go to the first clash they saw which was either inside or outside, and told their partner which clash they were at. In the first experiment, when the group had established a first clash they tended to follow each other to all of the clashes after that, with one participant taking the lead. This method was also used in the second experiment, however they had to communicate more as to where they were navigating so that their partner could follow them without physically being able to see them. The general method of navigation dictated by the participants in the first experiment was observed as:

- *Participants located the first clash, generally one individual chose the one closest to them and their partner followed suit;*
- *Once at the clash they would both observe the clash, consult the clash list and figure out the corresponding clash;*
- *Most often both would simply stand on the clash and look at it whilst discussing possible solutions;*
- *Participants agreed on a solution, then tick it off on the clash list; and*

- *Navigated to the closest clash to the one they just solved.*

For the second experiment it was observed as being:

- *Participants located the first clash, generally one individual chose the one closest to them and communicated where this was so their partner could follow;*
- *Once at the clash they would both observe the clash, consult researcher and figure out the corresponding clash;*
- *Participants would either physically walk around the clash, bend down and look closer, or look at it from multiple different angles;*
- *Participants agreed on a solution; and*
- *Navigated to the closest clash to the one they just solved.*

Once both participants had reached a clash, navigation became slightly different between experiments. In the first experiment, most participants moved a little around the clash but mostly stood stationary, so they would both look at the same clash from different perspectives, as they could not physically move through each other's avatars in the model. In the second experiment participants had a tendency to look at it from multiple viewpoints as well as bend down and tilt their head which they could not do when using CAD. This infers that VR provided a platform with more viewing options and a wider array of perspectives when compared with CAD, This also demonstrates how participants were able to view things from the same perspectives without getting in each other's ways with the avatars as they did in the first experiment. One challenging variable of having a physical boundary around the avatars was that three groups accidentally knocked each other off the roof at some point during the experiment, and one group did so intentionally. This was not an issue in the second experiment, as there were no avatars. There was one case where a participant could not see a clash because their partner was standing directly on the clash and covering it, leading them to try and solve different clashes, believing it to be the same. Some groups differed from the aforementioned method for multiple reasons. Two groups were unable to solve one clash and so they moved on to a different clash and came back to it at a different stage during the experiment. Some groups initially went to different clashes and tried to solve them individually before remembering that they both needed to agree on solutions together. There was no set method to solving the clashes or for navigating the digital environment, so the

methods mentioned were entirely decided upon by the participants. Their methods were similar, with several small aspects differing, however this data suggests that a logical sequence with a systematic procedure to solving clashes can result in solving clashes more quickly. This data also infers that VR provided a more efficient platform for achieving this than CAD software did.

Interaction with the Digital Environment

Participants were observed as to how they interacted with the digital environment whilst navigating and solving clashes.

At the start of the experiments it was observed that some participants immediately got lost as they were getting used to the technology. This tended to happen to participants who did not regularly play video games with the individual taking the longest adjustment period in the first experiment also being the oldest. This suggests an advantage to video game players who are used to this kind of navigation and interaction with digital environments. Overall the controls in the first experiment took longer to get used when compared to the second experiment, which could also be attributed to video game experience. Also taken into consideration was the fact that the VR controls were simpler as participants only needed to move their head and point and click, as opposed to using keys to move forward, left, right and back as well as using a mouse to look around. It was observed that people who had experience using CAD had less of an advantage than the gamers which infers that CAD users aren't used to solving clashes in models this way, utilising first-person perspective and controlling avatars.

4.4 Evaluation of the Objective Data

Objective data was obtained through the use of post experiment rating scales (1-10) that were split into four categories: the model, the clashes, the technology, and the collaboration. This data was then analysed and compared between experiments to provide insight into the objective differences between the two different technologies's when used as a collaborative platform for solving clashes.

The Collaboration

The data for the topic of collaboration was split into three categories: Ease of collaboration in this environment, ease of communicating their opinion on a solution, and ease of understanding how their partner wanted to solve the clash.

Table 4.1: Ease of Collaboration in this Environment

	1^{ST} EXPERIMENT	2^{ND} EXPERIMENT
HIGHEST RATING	10	10
LOWEST RATING	7	5
MEAN	9	8.11
MEDIAN	8.5	8.5
MODE	9	9

Table 4.2: Ease of Communicating Their Opinion on a Solution to Their Partner

	1^{ST} EXPERIMENT	2^{ND} EXPERIMENT
HIGHEST RATING	10	10
LOWEST RATING	5	6
MEAN	8.77	8.27
MEDIAN	8.5	8.5
MODE	9	9

Table 4.3: Ease of Understanding How Their Partner Wanted to Solve the Clash

	<i>1ST EXPERIMENT</i>	<i>2ND EXPERIMENT</i>
<i>HIGHEST RATING</i>	10	10
<i>LOWEST RATING</i>	5	6
<i>MEAN</i>	8.88	8.55
<i>MEDIAN</i>	9	9
<i>MODE</i>	9	9

In all three collaboration aspects the second experiment was rated as a more difficult environment to collaborate in. Other than the technology difference the main difference was the lack of avatars in the second experiment so participants could not see each other. This data infers that VR is a more difficult environment to collaborate in or that not being able to see your partner in a collaborative environment has a negative effect on solving clashes. The latter could be deemed false when directly compared to the situations where participants completed the tasks, as participants completed the tasks faster in VR compared to CAD. The area with the highest difference is the ease of collaboration which had an average difference in rating of 0.89. This infers that VR provides a more difficult platform to collaborate in, however other potential factors will be explored further in the discussion.

The Clashes

The data surrounding the clashes was split into three categories: how easy it was to solve them, how easy it was to locate them, and how the perspective helped them solve the clash.

Table 4.4: How Easy it Was to Solve the Clashes

	<i>1ST EXPERIMENT</i>	<i>2ND EXPERIMENT</i>
<i>HIGHEST RATING</i>	10	10
<i>LOWEST RATING</i>	5	6
<i>MEAN</i>	8.05	8.22
<i>MEDIAN</i>	8	8
<i>MODE</i>	8	9

Table 4.5: How Easy the Clashes Were to Locate

	<i>1ST EXPERIMENT</i>	<i>2ND EXPERIMENT</i>
<i>HIGHEST RATING</i>	10	10
<i>LOWEST RATING</i>	7	7
<i>MEAN</i>	9.16	9.33
<i>MEDIAN</i>	9.5	10
<i>MODE</i>	10	10

Table 4.6: How the Perspective Helped to Solve the Clashes

	<i>1ST EXPERIMENT</i>	<i>2ND EXPERIMENT</i>
<i>HIGHEST RATING</i>	10	10
<i>LOWEST RATING</i>	5	7
<i>MEAN</i>	8.38	8.77
<i>MEDIAN</i>	9	9
<i>MODE</i>	9	10

Comparatively, the overall results are very similar. The area that had the largest difference was how the perspective helped participants to solve the clashes, with a larger difference in both the lowest rating and the average rating. This data suggests that VR provided a better viewpoint for solving clashes, although they are both from a first-person perspective in the same model but using different technologies/environments. The area that provided the most similarity was in locating the clashes, which again was the same in both experiments. Locating the highlighted clashes was deemed easy and straight forward by almost all participants and was objectively rated the second highest next to how easy the controls were to use in VR.

The Model

Data was analysed from the feedback given on the model and split into three categories: navigation, controls, and realism.

Table 4.7: Navigation Data

	<i>1ST EXPERIMENT</i>	<i>2ND EXPERIMENT</i>
<i>HIGHEST RATING</i>	10	10
<i>LOWEST RATING</i>	6	6
<i>MEAN</i>	8.5	8.94
<i>MEDIAN</i>	8	9
<i>MODE</i>	8	10

Table 4.8: Controls Data

	<i>1ST EXPERIMENT</i>	<i>2ND EXPERIMENT</i>
<i>HIGHEST RATING</i>	10	10
<i>LOWEST RATING</i>	7	8
<i>MEAN</i>	9.16	9.5
<i>MEDIAN</i>	9.5	10
<i>MODE</i>	10	10

Table 4.9: Realism Data

	<i>1ST EXPERIMENT</i>	<i>2ND EXPERIMENT</i>
<i>HIGHEST RATING</i>	10	9
<i>LOWEST RATING</i>	5	3
<i>MEAN</i>	7.27	6.83
<i>MEDIAN</i>	7	7
<i>MODE</i>	7	7

The similarities between the navigation and control data is indicative of the controls dictating how easy it is to navigate the model. Overall the second experiment was deemed by participants to be easier to navigate and use the controls, when compared to the first experiment. This coincides with both the observations and subjective data. The level of realism presents a difference in technological interpretation as the model was the same in both experiments, with the exception of the change in clashes, yet the level of realism was rated lower in VR than in CAD. This infers that VR's more immersive aspects could create a bias perspective as it is viewed as a closer interpretation of reality than a CAD model. It is possible participants were therefore more lenient towards the level of realism in the CAD model due to lower expectations of older technologies. It is similarly possible that participants had higher expectations for the level of reality in VR, as it is a newer, more advanced technology. VR is also widely publicised in everyday life for its high level of reality, whilst CAD is an industry specific tool. The widespread publicity of VR and how it is able to be used may therefore have contributed to cognitive bias.

The Technology

The data on the technology was split into two categories: how easily participants grew accustomed to the technology and how easy the UI was to use.

Table 4.10: How Easily Participants Grew Accustomed to the Technology

	<i>1ST EXPERIMENT</i>	<i>2ND EXPERIMENT</i>
<i>HIGHEST RATING</i>	10	10
<i>LOWEST RATING</i>	5	7
<i>MEAN</i>	8.44	9.11
<i>MEDIAN</i>	9	9
<i>MODE</i>	9	10

Table 4.11: How Easy the UI Was to Use

	<i>1ST EXPERIMENT</i>	<i>2ND EXPERIMENT</i>
<i>HIGHEST RATING</i>	10	10
<i>LOWEST RATING</i>	7	7
<i>MEAN</i>	8.94	9.27
<i>MEDIAN</i>	9	9.5
<i>MODE</i>	9	10

Overall, VR was deemed easier to grow accustomed to than the CAD technology. Further data suggests this is due to controls and ease of use. Both subjective and observational data showed that the controls were easier to get used to in VR and the time taken to complete the tasks suggests that VR may be easier to use for this purpose.

4.5 Evaluation of the Subjective Data

The Model

Navigation

Using basic video game controls to navigate this virtual environment made it easier for participants to quickly become accustomed to using the technology. Even the participants who mentioned they weren't familiar with the controls said, "it got easier the more you use them". Every participant used "easy" to describe it in some way, with one stating "it was difficult at first but easy to get used to".

The navigation using point and click teleportation controls received mostly positive feedback from almost all participants. The most common answer was simply "very easy" when asked about the level of difficulty in using the technology, and several participants stated that it was easy to learn and easy to use. Where most participants focussed on the method of navigation one participant stated that the environment itself was easy to navigate and "what should have worked did, and what should not have worked, did not". One participant mentioned that "rotating your head is like real life" as part of the navigation required real movement that was mirrored in VR such as turning your head to look behind you and bending down to look at things from a lower perspective. Overall both the method of navigation and the virtual environment was deemed to be easy to navigate and intuitive, with little to nothing getting in the way of participants navigating the environment effectively.

Level of Detail

Overall feedback on the virtual environment in the first experiment concluded two main points: that the level of detail was realistic in terms of services and components, but that the rest of the model could have been more realistic and rendered to a higher level. One participant stated it “was real enough” with another stating that “it was realistic enough to be effective”. This suggests that improvements could help streamline this process but that for the purpose of this experiment the level of detail did not hinder the participants from solving all of the clashes within the model. Finer details were mentioned to be “difficult” such as taps and smoke alarms, but that the level of detail gave a good insight into the overall layout and makeup of the building.

Feedback on the level of detail and realism in the second experiment provided more negative feedback than the first experiment, even though the models were identical other than the change in clashes. The overall opinion on the level of detail was that it could have been better rendered and detailed, but that there was enough detail to understand what most components were. Location of components and overall services interactions with each other could be made out clearly and the general layout was deemed to be “simple and easy to understand”. One participant revealed that they thought the level of detail was not as good as it could be, and that was because they were aware of the fact that some detail had to be reduced so that the model could function properly using the VR technology. Multiple aspects of the model were considered by participants to be either missing or could have been improved, and were stated follows:

- *Associated meta data was not present;*
- *Labels on components to easily tell what they are (e.g. cold-water pipe label on pipes);*
- *Overall rendering quality could be improved;*
- *Lighting and shading were not realistic; and*
- *Materiality was unrealistic;*

First-Person Perspective

All participants gave positive feedback about using the first-person perspective to solve clashes in both experiments. To compare the feedback from using the same perspective in different technology the results were listed as follows, and are directly quoted from participants where the same feedback was not repeated between different participants:

CAD	VR
"Having a 360 degree view of the clash helped to understand what the clash actually is, compared to 2D view on CAD programmes".	"It helped when understanding scale, and perspective of where components are located, what effect solving clashes will have on other components, flow on effect etc".
"Navigating freely allowed me to look at all parts of a clash and see how they could be fixed".	"Helps understanding how issues can arise within technology-based procedures, and how we can solve them before they become a problem in reality".
"Easy to comprehend".	"Could look up close and view issues in areas you wouldn't always be in real life".
"Provided a natural perspective".	"Helped a lot when explaining and talking to someone else".
"It helped me see more detail from this point of view".	"Can navigate it easily at a large scale easier than on a screen in Revit".
"Helped me understand the problem quickly and form a plan to fix it efficiently".	"Being able to move my head around and look in and around things made it easier to understand".
"Made it easier to understand the clash/relationship between elements".	"It is a real perspective on issues e.g. while standing under the exit light I could see it but taking a step back I got the same perspective as my partner – that it needed to be lowered. You can get first-hand experience of detail and tech faults".
"I was able to navigate the clashes in-depth at different angles to help solve them more easily".	"The experience was more grounded in comparison to orbiting around in the model".
"Could discuss clashes with visual cues. Pointed at something and could both look around to understand the clash".	"You're immersed in the surroundings less distractions from focusing on problems".
	"Was faster to jump around and identify in 3D VR".
	"Immersion helps. Visualizing the problems within the environment. Quicker response and detection to problems are helped in a 3d model tool".

Table 4.12: Perspective Feedback from Participants

The Technology

The User Interface

Overall the interface was deemed “very easy to use” by most with some stating it took a bit of getting used to but was easy after a minute or so of use. One individual stated it was reasonably easy to use but not having spent much time on computer games meant it took a period of adjustment. A further participant stated that it was very easy “because I play a lot of games with keyboard and mouse”. The common theme was that participants who regularly played video games regularly did not struggle with the controls at all as they were used to basic navigation in games, which was similar to in this digital environment.

The VR UI was deemed simple and easy to get used to by most. One participant stated it was intuitive and after using it for a few minutes’ movement became “second nature”. Several participants stated that it was comfortable, referencing the headset. Becoming used to the VR was deemed as one obstacle when using the UI however this was not stated to be a major problem to any participants after a small adjustment period.

Ease of Use

Becoming accustomed to the technology proved easy and simple for 15 out of 18 participants. The remaining three stated it was difficult to begin with, but they did grow accustomed to it. These three participants all had little to no video game experience in general. This infers that video game experience directly affected the efficiency and effectiveness of navigating with these controls in this digital environment, and that the more experienced gamers could have achieved faster times than the less experienced non-gamers.

The major difference between the two technologies when comparing ease of use was that most participants either had no VR experience or what experience they did have as either a one-off event or a very controlled event at exhibitions, whereas everyone had used computers and either played video games or used CAD modelling software to some degree. Three participants used a metric of time to determine the ease of use, and were:

- *“It only took 30 seconds to get used to navigating”;*
- *“Felt used to it after a minute or so”; and*
- *“Took two minutes to understand tops”.*

Three participants also stated that it felt natural, whilst two participants stated it initially felt unusual and strange, but they became used to it after a short period of time. The simplicity of the controls aided to the overarching themes of comfort and familiarity.

Training in the Technology

Most participants mentioned that they would either need no training at all to use the CAD technology for a job, or that they would require an initial rundown or tutorial to understand the basics of it. Three participants stated that they would need initial training to grow more accustomed and familiar with the technology, in order to understand what can be achieved with it. One participant stated that training would “lead to better results” where another stated that “practice over time would be enough”. The general trend in the subjective feedback was that training was not needed for the basics, but a small amount of training might be needed to better understand the technology, particularly for those not used to this kind of technology.

For the VR technology most participants stated that they would not need initial training. Six participants said a brief introductory session would have helped but was not necessary as they picked it up fairly quickly. One participant mentioned that training in using the technology could be minor, but that a greater understanding of construction is what would be most vital in order to solve the clashes effectively. “Learning on the spot” or “learning as you go” was the favoured method for four of the participants with some stating it was a user-friendly technology. The biggest drawback mentioned by one participant was that they sometimes briefly forgot “that it was all virtual” alluding to VR having too much of an immersive aspect, however this did not seem to affect their performance with completing the tasks or after the experiment had finished.

Major Applications

As there were differing levels of experience in gaming, architecture, and design in both experiments the possible applications came from a wide array of backgrounds. All of the potential applications these two technologies could be applied to that were suggested by participants, are listed below, with duplicate applications not being included more than once:

CAD	VR
Remote work and shared work experiences for users in different locations	Understand the scale of clashes which cannot be portrayed on a screen
Finding flaws in the construction industry and solving them quickly and inexpensively	More accurately convey how design and construction changes will affect the final buildings, more so than drawings or a model on a screen
Identify conflicts in the design stage of a building to save time and money	easier to solve the clashes this way and it felt much faster so would make for a more productive process with faster results
Building inspection collaboration and various other CAD collaborations	Visiting the site without being on the site, as well as a tool for drafting ideas without any major implications
Generating sudoku algorithms	Games, training for surgery, visual building walkthroughs
Communication between different parties	Being able to effectively collaborate in a virtual space
	Being able to quickly visualize a space in detail and real-world scaling and feeling
	Locating different faults in buildings, being able to further this technology into something large scale like a skyscraper would be interesting to see
	Interior design, problem solving with building airports, could use a similar simulation to figure out where planes should land and take off

Table 4.13: Potential Applications Feedback from Participants

Multiple participants stated CAD and VR could be used as a tool for solving errors in models collaboratively, but this will likely be due to the experiment presenting this idea to them. However, several participants stated it could be used to solve errors in digital models with people who aren't in the same room or building as they are with the networking capabilities. Participants also stated that using this to solve clashes in architectural models before they have been built would save on time and money, with this feedback coming from people who both had experience in this field and from people who had little to no experience with architecture as a study or job.

When comparing the possible applications given for CAD versus VR, the applications for VR were more abundant and covered a wider range of areas. It can be said that this is either due to VR's immersive aspect opening the door for more applications, or that participants were more engaged with VR technology than with CAD technology. As mentioned previously several participants stated that this technology would be a good tool for solving errors in digital models alongside people who may not be in the same physical location as them. Visualisation and communication were two of the main themes that participants decided this technology could assist with in projects. Time and cost saving were the main benefits participants believed this technology could achieve when used along these lines.

Flaws with the Technology

The main flaws participants pointed out were as follows, with duplicate flaws not being mentioned more than once:

<i>CAD</i>	<i>VR</i>
“Didn’t capture the “real” feeling of a building and navigating to get a closer look at things was also lost”.	“It requires technology that people may not own and requires large amount of physical working floor space”.
“Doesn’t account for human error in the construction phase of the project which is where things could often go wrong”.	“It was very strange to use and would probably take some getting used to before being able to use it on a regular basis”.
“As a first-time user it was a bit confusing”.	“The potential side effects it can have on people”.
“Interaction with each player and humanising the avatars”.	“Quality of models, inability to change model in VR mode, have to exit and change, portability”.
“A key to show different components”.	“Generation divides, new technology some people won’t be willing to try”.
“Not being able to alter the mode ‘in-game’”.	“Some obstacles weren’t easy to notice, could do with more detail in products”.
“No flying controls for elevation”.	“You cannot see the other person and where they are. Unsure if you are getting the same perspective”.
“Lack of detail and potential for unnoticed clashes”.	“Hardware and space requirements”.
“Controls and boundaries”.	“Detail in the model”.
“The option to zoom in and zoom out”.	“You can’t see the changes happen in simulation, its more verbal than visual solutions”.
	“If designs and plans change rapidly then the tech programme will constantly have to be updated. Could take time to do so”.
	“The headset can become uncomfortable. The movement is quite unnatural”.

Table 4.14: Main Flaws Feedback from Participants

A majority of the flaws presented by the participants were either control or level of detail related. This infers that participants would need a more comprehensive set of controls and a higher level of detail to effectively solve clashes on this platform. These were both kept to a minimal yet functional level for this experiment, however this data suggests that future work can develop more in-depth digital environments to explore this further.

User-Based vs Technology-Based Issues

Out of the 18 participants four stated that, for the first experiment, the issues were technologically-based, eight were user based, one stated there were no major issues, and the remaining five stated there were both user and technologically-based issues. The reasoning given by the participants were as follows, with similar reasons not being repeated:

Technology-Based Issues	User-Based Issues	Both
Limitations in rendering and reproducing sense of physically navigating and viewing a space are still missing or lost.	Mainly because the issues identified are common in the field and users would be more acceptable for this.	Understanding clashes and how to fix and understanding how to use technology. Keeping up with development of technology.
The user can navigate simply and can spot flaws easily. The technology can be improved to allow the user to spot more.	Depends on the individuals team work and communication skills.	Users do not understand newer tech. Older users may struggle. Need the younger users to help teach them. New tech UI is often confusing for novice users.
Being able to actually make changes (move components) to the model and save it would be better.	User based as they have to determine what everything is within the model	Understanding clashes and how to fix and understanding how to use technology. Keeping up with development of technology.
It's easy for a user to navigate around it. But it seems more limiting with what you can do with the technology.	Technology is only as good as the people using it.	
	I don't really understand how it works or have much experience with it or any similar programme.	
	Not many people would be used to navigating this.	

Table 4.15: User-Based vs Technology-Based Issues Experiment 1

After the second experiment nine out of 18 participants stated that the main issues were technologically-based, five stated that they were user based, and the remaining four thought it was both user and technologically-based issues. The reasoning given by the participants were as follows, with similar reasons not being repeated:

Technology-Based Issues	User-Based Issues	Both
More detail is needed in connection to an actual BIM model that will update in real time.	It is new technology so people haven't fully explored what we could do with it yet and is something people would need time to get used to.	User based can depend on the person, more so if they haven't experienced VR yet.
Users will adapt to their environment, but the technology will only progress with time and development	People cannot use it for very long until they need to take a break.	Both as explained in previous answer for people, technology is still a new technology so will continue to develop
It is a new area of research	Either level of coding/programming capability or understanding of how to use.	User unfamiliarity with the technology is an issue that can be overcome with time and how realistically the scene is rendered relies on the tech improving.
Finding/having more detail would benefit the user. Improving model would further assist users for results.	Lack of understanding as to how all of the services work together	
The technology doesn't yet provide the visual quality traditional display set ups do. The hardware requirements for such technology are far greater than the average users	People not knowing what they're looking for	
The controls and user interface are easy to use, it is the detail in the environment that is lacking.		

Table 4.16: User-Based vs Technology-Based Issues Experiment 2

4.6 Evaluation of the Task

Speed

The time limit was present in these experiments to ensure maximum engagement from participants, if it ran too long then they could have become disinterested. This also allowed for time to be an objective data output. However, the time limit could have also had an effect on the participant's engagement in an encouraging way. The time limit was observed to produce a test condition like atmosphere where participants felt that they had to complete the tasks quicker than if there was not a time limit. The only way to test this would have been to run a comparative scenario where one was timed, and one was not to compare the times taken. This is outside the scope of this project but is important to mention as it may have affected overall result times in some way.

Experiment 1 involved solving clashes collaboratively through the use of computer keyboard controls that moved an avatar around the digital environment. The participants viewed the model from a first-person point of view. The overall time taken to complete all of the tasks was recorded alongside how long participants took on each individual task. All groups of participants solved all ten clashes within the allotted 20 minutes, with the slowest, fastest, and average times recorded as:

- *Slowest Time: 19:48;*
- *Fastest Time: 11:01; and*
- *Average Time: 14:50.*

Group two was an outlier in terms of time taken and were two and a half minutes slower than other groups which will be further explored in the observations section. The amount of time taken on each particular clash varied between clashes but there were general trends in that some clashes took longer for almost all group than other clashes. The reasoning behind this relates to the difficulty and location of clashes which will be further explored in the discussion.

Graph 4.8: Total Time Taken

Graph 4.9: Average Time Taken Per Clash

Graph 4.10: Fastest vs Slowest Time Per Clash

Graph 4.11: Average Time on Each Clash

Graph 4.12 Time Per Clash Experiment 1

In the second experiment, similar to the first experiment, all groups solved the ten clashes within the allotted 20 minutes, and the slowest, fastest, and average time were:

- *Slowest Time: 9:48;*
- *Fastest Time: 5:38; and*
- *Average Time: 7:37.*

The overall average time taken to complete all tasks was almost half as long as the first experiment. The times taken for completion were closer together in the second experiment than the first, with no major outliers. The slowest time from the first experiment will have increased the average time by an extensive margin as the second slowest group was more than two and a half minutes faster than this group. However, this data suggests that VR allowed for groups to solve clashes faster than CAD software.

The time taken on each clash remained consistent in that the more difficult clashes almost always took the longest to solve regardless of how fast the group was, overall. This was the same for the easier clashes that required simpler solutions. Occasionally, one clash took a lot longer to solve compared to the rest and it was observed that this usually involved either the groups getting lost, not communicating their positions with one another, or the groups having to stop solving clashes and figure out what they had and hadn't solved if they had not kept track of this. Because of this the data is slightly skewed for the groups that this did happen to.

Graph 4.13: Total Time Taken

Graph 4.14: Average Time Spent on Each Clash

Graph 4.15: Fastest VS Slowest Time Per Clash

Graph 4.16: Average Time Taken Per Clash

Graph 4.17: Time Per Clash Experiment 2

Order

The order the participants solved the clashes in was recorded through observations and roughly translated to a combined cognitive map of their navigation in the model. Clashes 1-6 were located outside the building on the roof, and clashes 7-10 were located inside for both experiments. When comparing the similarity in order of clashes solved between experiments it can be seen below that the order in the first experiment differed greatly between groups, especially when compared with that of than in the second experiment. There are three instances in the first experiment where different groups solved the same clashes in the same order and this is only for a span of two clashes, whereas in the second experiment there are 20 instances, including two groups that solve the clashes in the same order for the entirety of the experiment. This data infers that it was easier to plan or communicate a methodical route in VR than in CAD because even though the clashes were changed between experiments, they were placed in very similar locations. More similarities in the routes taken suggest that more logical routes were taken in VR and will be discussed in the later discussion section alongside observations of navigation.

Graph 4.18: Group VS Order They Solved Clashes in Experiment 1

Graph 4.19: Group vs Order They Solved Clashes in Experiment 2

Solutions

The solutions to the clashes within the model were verbally communicated to the researcher during the experiment and could be either approved or denied as an appropriate solution. Most clashes had multiple solutions, except for the structural clashes, which only had one solution to fit with the overall building structure. The clashes themselves were designed to have a range in the level of difficulty, from simply mounting speakers to a wall, to rearranging cable trays to move around, over, and under entire Heating, Ventilation, and Cooling (HVAC) systems. In both experiments all of the solutions to clashes were very similar across all groups. Most clashes involved moving or transforming one of two aspects of a service and most chose to go for the easier and more logical of the two. The majority of problems with solving a clash were observed to be a result of not understanding the clash in the first place. One clash in particular was interpreted differently between groups and involved a cable tray that ran lengthways through a partition wall. Almost all of the groups spent a longer time on this clash and asked multiple questions about how they could solve it. This infers that the clash was unclear on the clash list, or that a higher level of knowledge was needed about buildings to understand how to solve this clash. It was observed that people who had experience solving clashes in architectural models before these experiments understood this clash more quickly than those without experience. This demonstrates that understanding of clash detection and solving dictates the speed at which a clash could be solved if it is a more difficult clash with a less straight forward solution. A similar scenario was observed in the first experiment that involved a two-part solution to a clash as it was an HVAC system clashing with both a cable tray and sprinkler pipes in the same area. This clash required participants to get multiple viewpoints around it, in order to understand both areas it was clashing with. Average time spent on this clash was more than 30 seconds higher than the other clashes and often required multiple attempts at creating a solution that would not create more clashes. Comparatively the average time spent on the most difficult clash in the first experiment was 2:36s and 0:56s for the second experiment. This large time difference suggests a difference in level of difficulty, an easier platform for solving more advanced clashes, or that on average the participants in the second experiment had a better understanding of solving clashes. The latter can be disregarded as the participants included a mix of people of varying experiences in this field as was the case for the first experiment.

Figure 4.1: Most Difficult Clash in Experiment 1

Figure 4.2: Most Difficult Clash in Experiment 2

4.7 Knowledge Contribution

The major contribution this project makes to the field of architecture and construction is the framework for information needed to effectively collaborate in a digital environment. The advancement in technology provides the potential for more advanced platforms for collaboration in industry projects. Current studies need to move away from a technology focussed bias and focus more on user-centred approaches to ensure the potential of the technology is not being lost to users who cannot use it effectively. This study provides a framework to assist with a comprehensive collaborative environment in a digital environment that could be applied to industry projects and provide a beneficial outcome to the projects. The following conditions set out a framework for the information users require to enhance collaboration in a digital model when solving established clashes:

Level of Detail

The level of detail in the model directly affects the user's perception of the space and affects their comprehension of the model's details. A high level of detail is required in order for users to fully comprehend the information present in digital models, and to be able to interpret the model effectively.

The Technology

To use this technology for more industry related projects initial training would be needed to ensure users know the limitations of the technology. Extensive control sets combined with a first-person perspective provides the tools for users to effectively solve established clashes.

Navigation

Using video game controls provides an intuitive way to navigate around the models that are easier to pick up on than CAD controls. These control sets can be adapted to different technologies with a universal set of controls. Users would benefit from a mini map to show their location.

The Collaboration

Face-to-face exchange of information provides the best form of collaboration, especially in a digital environment. Users need to see each other and see what the other users are seeing to collaborate effectively within a digital environment. Knowing their partners location within the digital environment is crucial to effective collaboration.

5.0 Discussion and Limitations

The results of this research involved quantitative and qualitative analysis of the use of these technologies for collaborative platforms when solving clashes, which were confirmed through observational and comparative analysis. The task and its measurables on the rating scale are objective, whilst the post experiment questionnaire is subjective. Observations made during the experiments by the researcher were analysed alongside these results. All results were analysed and compared between the two experiments as the similarity in experiments was created so that comparative analysis could be made between the same performances on different platforms. The results from the objective data was considered overall to be more concise than the subjective data as the subjective data was based mainly off of opinions and outside factors. These results were not without their limitations however, and it is important to state the limitations with this project when interpreting the results.

The second major limitation was that of the researcher. A more comprehensive knowledge of coding and software would have allowed for a more advanced digital environment to be made where further investigations could be explored, however with the time frame of this project the researcher did not have enough time to learn all of the necessary skills. Further work in this area would be benefitted from collaboration with an IT specialist to assist with the computer science side of this project.

5.1 Collaboration

As a collaborative platform, VR presented the most difficult challenges but achieved the best results from both an objective and subjective point of view. The difficulties lay in collaborating in a digital environment where participants could not see their partners either in reality or as a digital representation, where-as in CAD they were represented by avatars and could also turn to talk to each other in reality for discussion. Lengel and Daft (1989) stated that richness of information is defined as “the ability of information to change understanding within a time interval” and that the highest richness of information is transferred via physical presence (face-to-face), with the next tier down being through interactive media. When this was written, interactive media meant through telephone or electronic media but can now be updated to include social or electronic media or any form of voice communication channels

using a digital medium. The richness of information was considered to be highest during the experiment involving CAD, and second highest in VR as, even though participants were in the same room, they were not face to face and could not see each other but could only hear one another. Hypothetically, one would state that as VR presented the most difficult challenges when collaborating with others, it would achieve the lesser results, yet this was not the case. Objective data revealed faster clash solving times with more efficient navigation paths compared to that of the CAD environment. Subjective data showed a higher average rating of CAD as a collaborative environment for ease of collaboration, ease of communicating possible solutions to their partner, and ease of understanding how their partner wanted to solve the clashes. This subjective data directly contradicts the fact that using CAD as a collaborative environment to solve clashes was slower than using VR by a significant amount, but produced the same results, being that all ten clashes were solved effectively. Whilst this suggests VR provided a better environment to solve clashes in, there are other aspects that need to be considered for collaborating in such an environment. When using VR in an industry project there would be multiple parties in the model at once. More people would complicate the collaboration which would cause this process to take longer and potentially be done less efficiently. Simulating face-to-face interactions in VR could provide an easier collaborative environment and is one of the main issues participants found when collaborating in VR. Most participants mentioned that the major flaw was that they either could not see their partner in VR, or they could not see what their partner was looking at. These improvements could potentially increase ease of collaboration and would, in turn, improve the efficiency of solving clashes in VR collaboratively, even with larger groups. Whilst these results may not directly conclude that VR provided a better collaborative environment, they do provide insight into what individuals require in order to collaborate more effectively in digital environments and demonstrates where research in this area could go beyond this project.

5.2 Personalities

With the main variable of a user-centred approach being the people themselves, it is important to discuss the difference in personalities and the effect they may have had on the results of these experiments. In both experiments it was observed that sometimes, one personality overshadowed the other as the more controlling of the two. This would cause the collaboration to be more one-sided than two-sided as they were basing most of the navigation and clash resolution decisions off of one person's opinion, with their partner agreeing. It is possible that differences in personalities can both positively and negatively affect the results of collaboration. Personality clashes can create hostile work environments which can decrease productivity and the overall outcome of the project. Whilst it is important to mention people's personality's potential problem to the outcome of collaborative projects, it is outside of the scope of this project and better suited for the field of personality psychology.

5.3 Perspectives

When people were introduced to 3D technology after using 2D CAD software for so long there was a level of scepticism surrounding it, as initially it was surrounded by mostly hype with little information to back it up (Gott, 2003). Multiple studies concluded that when information was presented in 3D it allowed users to have an increased understanding of the information when compared to 2D as well as a greater sense of immersion when completing tasks in 3D technology (Cockburn & McKenzie, 2002), (Tavanti & Lind, 2001) & (Ryan R. A., 2007). These results infer that the additional dimension of information portrayal has positive effects as more information can be expressed and interpreted. Both subjective and objective data confirmed this trend was true for VR's technology as well. Whilst it did not add another dimension of information it did enhance the information it provided. The increased level of immersion provided a more comprehensive environment to allow participants to solve clashes in. Several participants stated that the ability to either crouch down, move your head around, or physically walk around allowed them to get better views and perspectives of the clashes when comparing it to the CAD technology, which in turn allowed them to complete the task more efficiently and more quickly due to this more comprehensive understanding of the clashes. This information revealed that VR provided a more comprehensive information portrayal and interpretation environment than traditional CAD does, however, VR was rated as the more unrealistic environment. This emphasizes VR's enhanced level of immersion with its physical and audio aspects that allows users to have a more realistic experience, and how this can translate into industry applications. It also suggests that as it is a more advanced technology that more is expected of in several aspects including level of realism. The level of immersion VR provides allowed for participants to solve clashes quicker and more efficiently than in CAD technology and the subjective results revealed that overall the participants preferred VR as a tool for solving clashes due to its ease of use and fun aspect, alongside the fact that VR is still fresh and a new experience to most which can create a certain level of excitement. This may also have influenced the negative viewpoints in terms of the level of reality and application downsides.

5.4 Personal Preference

Previous comparative studies involving VR and built environments came to several conclusions surrounding the comparison of behaviour and of the technology. As mentioned previously basic tasks such as reading, and counting were performed to almost the same levels of efficiency and time taken in both real and virtual environments. Slight variances in time were found in time taken but were concluded to be due to controls making it easier to levitate up and down rather than people having to physically move to get better perspectives in order to count objects (Kuliga, Thrash, Dalton, & Holscher, 2015). The experiments in this project had larger variances when comparing performing tasks in two different digital environments. The fastest time to complete all clashes in the first experiment (11:01) was slower than the slowest time in the second experiment (9:48). This variation in time taken to complete clashes, which were of similar levels of difficulty, reveals an objective advantage to completing this task. There are more factors than just the difference in technology however. Navigation could be achieved quicker in VR as it was achieved by teleporting small distances at a time as opposed to a walking simulation using the W, S, A, D keys for CAD. Where participants had a route planned, they could achieve this more quickly over short distances than they could in CAD. Overall, the objective data revealed that participants preferred VR over CAD and the controls were deemed easier to use by those participants who had little to no video game experience. The main issue with the first experiments controls was that participants' efficiency in navigation did not directly relate to their experience in CAD, but in their experience of playing video games on PC. The common theme was that participants who play video games regularly did not struggle with the controls as they were used to basic navigation in games which used this same method of navigation. The issues with growing accustomed to the controls did not translate into the VR environment and navigation was overall revealed to be easier to grow accustomed to in the second experiment than in the first. It was observed that participants who had video game knowledge did not have as much of an advantage over other participants in VR than they did in the CAD scenario, as the controls were deemed to be simpler and more in line with natural physical movements (moving head, turning around physically) accounting for a part of navigation in VR. One study found that navigation was one of the main aspects that directly influenced participants feeling of immersion in a digital environment (Lorenz, et al., 2015). Natural movements simulated from Kinect sensors were found to engage participants more and to heighten their feeling of presence in the digital

environment, compared to a less realistic Wii Balance Board. This study's findings can show an insight into the large variance in times when comparing both experiments. Whilst the first experiment had simulated walking represented by an avatar which could be considered more realistic than teleporting, the technologies provided different levels of realism. Excluding the teleporting, VR's navigation was considered more realistic than the CADs navigation due to VRs level of immersion and the ability to move around physically and have this directly translate into movement in the digital environment. Sitting in a computer chair and controlling an avatar with a keyboard is inherently less realistic than standing up with a VR headset (Willaert et al, 2012). This data reveals that even though the method of movement was not the same between experiments, the method of navigation was considered more realistic in VR than in CAD, with the overall objective data stating that participants' level of immersion was higher. Participants showed a personal preference for VR which related to the ease of use alongside its novelty. However even the participants who have used VR multiple times preferred it as a tool to solve clashes in a digital environment which suggests that this may not be the case but is unclear as over half of the participants had not used VR before.

5.5 Level of Engagement

As mentioned previously, the level of immersion people feel has been found to influence people's engagement with a digital environment as well as completing tasks in these environments. A logical hypothesis to draw from this is that people's level of engagement with a task will help them to perform it faster, more effectively, and more efficiently. The same can be said for performing tasks in a digital environment. Subjective, objective and observational data revealed that most participants showed more engagement in the second experiment than in the first. Participants stated that overall, they preferred navigation, solving clashes, and the technology in VR compared to its CAD counterpart, but preferred collaborating in the CAD environment. Observational data confirmed that participants were both more engaged when solving clashes and collaborating in the VR environment as well as being more excited when participating and using the VR headsets, which is most likely due to VR's novelty and status as a new technology. This level of engagement was further observed when participants tracked which clashes they had completed. When using CAD to locate and solve clashes, participant had the list of clashes between them and physically crossed clashes off of the list to keep track of what clashes they had solved. When using VR, the participants viewed the clash list before

they put the headsets on, whereupon they could not easily view the clash list after the headset had been adjusted. Participants then went to a clash and asked the researcher if it was a certain clash or used their memory to remember which clash it was in relation to the clash list. They then had to remember which clashes they had solved which they were able to do without fail, compared to four separate groups forgetting which clashes they had already solved when using CAD and having the list next to them. This suggested a higher level of engagement in the VR experiment as all participants actively remembered the clashes they had solved without fail. This higher level of engagement could be attributed to the overall difference in performance between CAD and VR, but the reason there was more engagement when using VR as opposed to CAD has several potential reasons. The headset provides the physical advantage of having a screen in front of your eyes, so the field of view is larger than sitting in front of a regular computer screen. The increased level of immersion can create an increased sense of realism which can create a more engaging experience (Lorenz, et al., 2015), however this was found to be the opposite when comparing VR to CAD in this area. Gamification of the process of solving clashes was created by the unique environment VR creates, which can encourage players to complete tasks both more quickly and more efficiently (Chou, 2015). There is also the aspect of novelty as mentioned in the previous sections. A more exciting and newer platform can create a more engaging environment especially when people have not used it before, however just under half of the participants in the experiments had used VR before, so it is still unclear if this affected the results. Whilst it may remain unclear whether all of these aspects created a more engaging experience for solving clashes, it can be stated that VR provided a more engaging digital environment to complete these tasks than CAD software did.

5.6 Order

The objective data revealed that participants solved clashes in a more random order in the first experiment, with less similarity between groups than in the second experiment. Clashes 1-6 clashes were located outside of the building on the roof, and clashes 7-10 were located inside for both experiments. The logical hypothesis was that whether participants started inside or outside, they would finish all clashes in one area before moving on to the next, however this was not always the case. Three groups in the first experiment solved one clash in one area before moving to the next area, and then coming back to the area they started in afterwards, whereas only one group did this in the second experiment. This suggests either that clashes in the first experiment were more difficult to solve, or more difficult to locate. There were more similarities in the overall order of clashes solved in the second experiment than in the first. Different groups solved two consecutive clashes in a row only three times, compared to this occurring 20 times in the second experiment. The clashes in both experiments were different to avoid any bias from uncontrollable events such as participants from the first experiment talking to participants before the second experiment. However, the clashes were located in similar locations so that routes could be compared between experiments. More similar routes taken in VR suggest that more logical routes were taken and able to be planned by participants. The lack of moving between inside and outside areas in the second experiment strengthens the statement that more logical routes were taken in VR than in CAD. Another factor is that participants could not see each other in VR so more communication was needed which could have drawn more logical routes, whereas in CAD one participant could have wandered off without communicating, but their partner was able to follow as they could see their avatar. This “follow me” approach is something that was not directly available in VR and is one difference between them that could have affected these results. Cognitive bias could have occurred that caused participants to follow their partner’s decision rather than make their own decision on navigation, which is a hypothesis that was not established before the experiments took place (Haselton, Nettle, & Murray, 2015). As participants performed this task in groups it is possible that the cognitive map of the digital environment was based more off of one participant’s perception of the environment than the other, where the second experiment presented a more even environment for this decision-making process. Participants in VR were observed making decisions on where they would go first and would normally move to the next clash after agreeing on their route. Field of view

could have influenced participants' choices as the VR screen covers the participant's entire field of view whilst a PC screen only covers a portion of it. It is still possible that VR provided an environment for better decision making when locating and solving clashes, however it is important to note these other internal and external factors that could have affected the results.

5.7 Level of Experience

Level of experience was a limitation in two areas: Lack of experience in coding and scripting of the researcher, and lack of industry experience for the participants. In regards to the researcher a more comprehensive knowledge of coding and software would have allowed for a more advanced digital environment to be made where further investigations could be explored, however with the time frame of this project the researcher did not have enough time to learn all of the necessary skills. Further work in this area would be benefitted from collaboration with an IT specialist to assist with the computer science side of this project.

The level of experience differed between participants and where a more experienced group may have created more industry focussed results, the differing levels of experience emphasise certain problems that may have been avoided with more industry experienced individuals. Students were used instead of working professionals due to time limitations in both amount of time needed to organise this and the time of year the experiments were run. These experiments were run at time where the industry was busiest before everyone went on their summer breaks, so students were deemed to be more suitable to participate at this point in time. Because of this the demographic consisted of young students, with no one over the age of 25 participating other than 1 participant in the first experiment.

Out of all the participants involved in the two experiments, the most common measured variable that seemed to have a direct impact on how quickly and efficiently participants solved all clashes was their level of video gaming experience. Video games are inherently riddled with challenges and problem-solving scenarios with reward systems for completing them (Chou, 2015). The group that solved the clashes the fastest and most efficiently in the first experiment comprised of two people who played, on average, between one and three hours of games per week each, but one participant used CAD 1-3 hours a month whilst the second participant

stated that they almost never use CAD. The fastest three groups involved at least one participant per group that played video games between one and three hours per week. A similar outcome was revealed in the second experiment, with the fastest group having 1 participant who spent between one and three hours per week playing video games, with the other stating that they played between one and three hours a fortnight. This again, was similar to the second and third fastest groups; comprised of the highest level of experience in relation to gaming, with only one individual spending between one and three hours per week using CAD technology. The corresponding level of time spent using CAD technology within these top groups was either between one and three hours per month or almost never, with the exception being one individual who uses it on a day-to-day basis at their job. This data suggests that video game experience can directly relate to proficiency in solving problems in a game-like scenario, regardless of subject matter knowledge on the topic itself. This conclusion is limited to this scenario however as more complicated clashes in a larger BIM model would require more specific and specialised knowledge of architecture in order to solve clashes more effectively. This statement can then be revised to state that video game experience helps users verbally solve basic problems in digital architecture models regardless of their experience with CAD technology or architecture. Physically solving the clashes would almost certainly be easier for people more experienced with CAD software purely as inexperienced individuals would have to learn to use the technology before physically solving the clashes in the model.

5.8 Efficiency

Analysis of the tasks and how they were solved revealed that VR generally allowed people to solve clashes more quickly than in the CAD scenario. The questionnaires revealed that participants tended to prefer VR as a platform for completing these tasks and that the added immersive aspects such as the ability to view the space from multiple different viewpoints by tilting their heads, was helpful in completing the tasks effectively. A comparative experiment mentioned in a previous section of this project, found that when comparing time taken and efficiency of tasks completed in a real built environment and its VR counterpart, the tasks were completed to similar levels of efficiency and time (Heydarian, 2015) This study concluded that very basic tasks could be performed in VR and that this comparison proved that VR's representation of a built environment was accurate enough to perform experiments in. Based off of these conclusions it could be said that if solving clashes in VR was quicker than in CAD software, then it could be quicker to solve clashes in VR than in the real environment. The purpose of clash detection makes this statement almost irrelevant as clash detection was designed to solve clashes before the building has been built, however this reveals that VR can be used as a more efficient collaborative platform in some areas of construction and design. If VR was proved to be a more efficient platform when solving clashes during the design stage of a project, then its application in this area has the potential to save more money and time than current clash detection process already does. All three rating questions related to the clashes themselves scored higher in VR on average, than in CAD. This revealed that participants thought the clashes were easier to locate and solve, and the perspective helped them to solve the clashes faster in VR as opposed to CAD. Overall a first-person perspective in VR provided a flexible and comprehensive viewpoint for users to locate and solve clashes in the digital model and was the preferred environment over CAD. Participants solved all clashes quicker in the VR environment, indicating that VR provided a more enhanced platform to complete these tasks in, allowing participants to complete the task more efficiently and effectively.

5.9 Implications

This research has identified the different aspects that can result in a digital environment being an effective collaborative platform, or an ineffective one. Literature and precedent reviews found that research in this field tended to take a technology-centred approach with little regard to the user's needs. This research has identified the different kinds of information that individuals require to be able to effectively communicate and collaborate with others in a digital environment. Being able to see where their partner is and what they are seeing was proved to be one of the most crucial aspects to effective collaboration. Intuitive navigation controls, a first-person perspective, and a high level of detail are also required to ensure that the information within the model can be perceived by the users and used effectively to complete tasks on a project. This will help to inform future research in this area and ensure that people can use the full benefit of advanced technology in collaborative environments.

5.10 Applications

The real-world applications for this research surround industry implementation. Both the design and construction industry stand to benefit from the implementation in certain areas. The user-centred experiment proved at a basic level that VR could be of vital benefit to collaboration in solving established clashes in a digital model during the design phase. The experiments were designed with this scenario in mind, so that they could provide a comprehensive simulation of this process and inform on the technology's performance. With further research and pilot studies in real life projects, VR could be implemented into this area of a project and provide benefits to projects where other technologies have demonstrated they are incapable of doing so, to the same extent.

6.0 Conclusion and Recommendations

The primary focus of this thesis was to validate claims of VRs potential as a collaborative platform for design. These claims were based off VRs enhanced level of immersion which can provide a more interactive and engaging environment when compared to traditional CAD. This research took a user-centred approach due to the bias for current research to focus on the technology and its capabilities, rather than on the people using it and what information they need to effectively use this advanced technology. The results provided an insight into user requirements when using VR as a collaborative environment during the design phase of projects and solve established clashes in a digital model.

Collaboration is inherently surrounded with problems as people are the main variable. Collaboration on large projects is made more difficult by the environment in which people have to collaborate in and the people they have to collaborate with. Information lost in the collaboration process can cost time and money and is the reason clash detection is needed in architecture and construction projects. A lack of communication is what causes there to be clashes in digital models on these projects. VR has shown potential to enhance both locating and solving these clashes in the digital model, due to its enhanced level of immersion.

The main findings from this project revealed strong evidence that VR is able to provide a better collaborative environment for the aforementioned process. User-centred experimentation revealed that participants need to see each other and see what their partners can see in order to collaborate effectively and ensure information exchange is fluid between parties. It was also revealed that the level of detail in VR may need to be higher than in CAD due to participants both being more immersed in the environment and expecting more from a more advanced technology. This level of detail will ensure information flow between the model and the users remains clear with no room for misinterpretation. As the technology advances and digital models become more complex it is important to ensure that this complexity is able to be portrayed effectively to the users of the technology. Without users understanding the information the technology can produce, it makes itself redundant and not fit for its purpose.

The major contribution this project makes to the advancement of knowledge is the framework provided, detailing the information users need when using this technology to solve clashes

collaboratively. Users need a high level of detail so that they can fully comprehend the information present in the digital model. A first-person perspective alongside intuitive navigation controls and a mini map would benefit users and the way they move through the model, making it easy for them to know where they are and where they need to go. Training in the technology will allow for users to be effective when navigating and performing tasks in the digital environment and make them aware of the limitations of the technology. When collaborating in digital environments it was found that users benefit the most from face-to-face exchanges of information and that this provided the best form of collaboration. Users need to see each other as well as what their partners are seeing so that they can make use of the advanced technology to collaborate effectively. Knowing where their partner is proved to be crucial for effective collaboration when completing tasks.

Whilst this project revealed information on using VR as a collaborative platform, it was not without its limitations, and it is at the start of a new and developing field. The limitations of this project can inform future projects to further knowledge based on the findings of this thesis. First and foremost, it is recommended that future projects involving creating digital environments in VR to use as a platform for research, do so with the aid of an individual who has extensive coding and scripting knowledge. This is needed to create desired behaviours in the digital environment which are not included by default. An extensive amount of time was spent first learning coding for this project, and then applying it. With a specialist in this area it will make it quicker to make these digital environments and allow for projects to undergo more thorough investigations without having to focus too intensely on the computer science aspect to research of this nature.

The next step to develop the knowledge from this project would be to repeat a similar scenario but with industry professionals. The industry knowledge applied to this project would allow for an improved insight as to how this technology would perform in a professional environment, with appropriate specialists involved. Students who are used to being in a continuous learning environment stated that little to no training would be needed to use this technology for a job and are used to learning on the spot. This may not be the same for industry professionals, especially if there are variations in age and experience. The insight these professionals could provide would be invaluable to advancing knowledge in this area. This could provide more in-depth information as to how this technology would cope with

both the difference in generations learning new technologies, and how people within the industry view this tool and its potential areas of applicability.

All the experiments run within these projects focussed on collaboration within the same room. It is recommended that future research examines how effective collaboration is when people are in separate rooms and liaising over voice communication channels. This could provide comparative data for examining the effectiveness of collaboration in different scenarios, as well as a simulation as to how collaboration could work on live projects in some areas.

From a more general perspective, this project focussed exclusively on the design phase of architectural and construction projects and solving clashes when in the reviewing phase. This is not to say that this is VRs only applicable area within these projects. It was discussed that whilst VR provides enhanced immersion in digital environments, it is not applicable to every area in the lifeline of a project. This does not mean that solving established clashes is the only area where it can be applied in the architecture and construction industry. As the technology continues to develop further investigations into different relevant areas can be explored, particularly in the initial design phase once the technology allows for iterative design within the VR model. The literature and precedent review revealed that the technology had little capability in this area however future development could see this change and provide another area VR has the potential to provide an enhanced platform for.

VR has huge potential to provide an enhanced digital environment in different fields. The level of immersion provides an extra level of information interpretation and enhanced engagement. Future research can continue to explore the relationship between the users and the technology to improve the way it is used, and to the end to which it can be used. (ACD, 2012)

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Appendix

This appendix includes all consent, demographic, and medical screening forms for the interviews and experiments, and the entailing questionnaires for both of these methods.

Immersion: Digital Collaborative Environments

CONSENT TO INTERVIEW

This consent form will be held for 2 years.

Researcher: Daniel Chegwidden, School of Architecture and Design, Victoria University of Wellington.

- I have read the Information Sheet and the project has been explained to me. My questions have been answered to my satisfaction. I understand that I can ask further questions at any time.
- I agree to take part in an audio recorded interview.

I understand that:

- I may withdraw from this study at any point before 1/1/2019, and any information that I have provided will be returned to me or destroyed.
- The identifiable information I have provided will be destroyed on 2/03/2020.
- Any information I provide will be kept confidential to the researcher and the supervisor.
- I understand that the results will be used for a Masters Thesis
- My name will not be used in reports, nor will any information that would identify me.
- I would like a copy of the transcript of my interview Yes ☐ No ☐

- I would like a summary of my interview Yes ☐ No ☐
- I would like to receive a copy of the final report and have added my email address below. Yes ☐ No ☐

Signature of participant: _____

Name of participant: _____

Date: _____

Contact details: _____

Immersion: Digital Collaborative Environments

Interviewing Industry Professionals Questions

What is your role within the construction industry?

Are you directly Involved with using Building Information Modelling technology?

What form of Building Information Modelling are you using or have used in projects?

When using BIM in a project, do you yourself directly collaborate with other individuals from different disciplines?

In what form does this collaboration take? Email, in person, conferences etc.

What are the biggest issues you have had personally when collaborating or organising collaboration with other disciplines?

How do you think these problems could be resolved?

Has a lack of communication across different disciplines ever hindered a project in any major way? If so in what way?

In your personal opinion what are the major current issues with collaboration and cooperation in the BIM environment?

How do you think this can be solved? More training, better technology, different BIM platforms etc?

In what way do you think full cooperation, collaboration, and transparency of data could benefit a project?

In what way do you think this could cause problems in a project?

Do you think current technologies are up to this task?

Do you think we need a new platform or software, especially when considering BIM level 3?

Do you have any ideas/thoughts on what this could be?

Do you think Virtual Reality could help as a collaborative tool?

In what way do you think VR could help collaboration?

What specific areas do you think VR could improve collaboration, when comparing to traditional CAD (reviewing the model, planning construction etc)?

Do you have any other insights or opinions you would like to share about BIM technologies, VR, or collaboration?

Immersion: Digital Collaborative Environments

Demographic Questionnaire

Today's Date: _____

Name: _____.

Phone: _____

Email: _____.

Gender: MALE / FEMALE

Age: _____.

On average how often do you play video games?

Almost never 1-3 hours a month 1-3 hours a fortnight 1-3 hours a week
1-3 hours a day

On average how often do you use Computer Assisted Design?

Almost never 1-3 hours a month 1-3 hours a fortnight 1-3 hours a week
1-3 hours a day

Have you ever used Virtual Reality? YES / NO

On average how often do you use Virtual Reality?

Almost never 1-3 hours a month 1-3 hours a fortnight 1-3 hours a week
1-3 hours a day

On average how often do you use CAD software?

Almost never 1-3 hours a month 1-3 hours a fortnight 1-3 hours a week
1-3 hours a day

Do you have any comments you would like to add?

Immersion: Digital Collaborative Environments

Medical Screening Questionnaire

Do you have any, or have ever had any of the following medical conditions:

Epilepsy YES / NO

Seizures YES / NO

Severe Dizziness YES / NO

Eye Problems YES / NO

Blackouts triggered by light flashes or patterns YES / NO

Are you prone to motion sickness? YES / NO

Are you afraid of heights? YES / NO

Do you get migraines? YES / NO

Do you have any inner ear disorders?

YES / NO

If so, please specify:

Have you ever experienced any extreme levels of discomfort or stress when playing video games or being exposed to flashing light patterns?

YES / NO

If so, please specify:

If you have answered yes to any of the above conditions, then you may not be eligible to participate in this experiment. If you said yes to the following you are not eligible to participate:

- Epilepsy
- Seizures
- Severe Dizziness
- Eye Problems
- Blackouts triggered by light flashes or patterns

If you said yes to the following, you may still be eligible to participate if these are not extreme cases, however this will be further discussed before participation is approved:

- Are you prone to motion sickness?
- Are you afraid of heights?
- Do you get migraines?
- Do you have any inner ear disorders?

I confirm that all information I have provided in this questionnaire is true and I have not left out any information in relation to these questions, regarding any medical conditions I may have.

Signature: _____

Date: _____

Immersion: Digital Collaborative Environments

CONSENT TO EXPERIMENT

This consent form will be held for 2 years.

Researcher: Daniel Chegwidden, School of Architecture and Design, Victoria University of Wellington.

- I have read the Information Sheet and the project has been explained to me. My questions have been answered to my satisfaction. I understand that I can ask further questions at any time.
- I agree to take part in this study

I understand that:

- I may withdraw from this study at any point before 1/1/2019, and any information that I have provided will be returned to me or destroyed.
- The identifiable information I have provided will be destroyed on 2/03/2020.
- Any information I provide will be kept confidential to the researcher and the supervisor.
- I understand that the results will be used for a Masters Thesis
- My name will not be used in reports, nor will any information that would identify me.

- I would like a summary of my results from this study Yes ☐ No ☐
- I would like to receive a copy of the final report and have added my email address below. Yes ☐ No ☐

Signature of participant: _____

Name of participant: _____

Date: _____

Contact details: _____

Immersion: Digital Collaborative Environments

Post-Experiment Questions

Have you ever used that technology (VR or CAD) for design or construction work before?

Have you used that technology for any other purpose before?

How easy to use was the user interface?

How easy was it to navigate this virtual environment?

How easy was it to grow accustomed to the technology?

Do you think training in this technology would have helped you to complete these tasks more efficiently?

In your personal opinion what are the major applications for this technology?

How do you think this technology could assist the construction industry?

In your personal opinion what are the major flaws with this technology?

How intuitive was this virtual environment?

Do you think any level of detail is lost in this technology?

Were there any limitations to this technology you found?

How do you think people could use this technology more efficiently?

Do you think the current issues with this technology are more user based or tech based?

What are your reasons for this?

Immersion: Digital Collaborative Environments

Post-Experiment Ratings

Use the rating scale to answer the following questions, where 10 is the most positive and 1 is the most negative.

1 — 2 — 3 — 4 — 5 — 6 — 7 — 8 — 9 — 10

Terrible *OK* *Excellent*

How easy was it to grow accustomed to the technology?

How easy was the user interface to use?

How easy were the controls to use?

How realistic was the model?

How easy was it to navigate the model?

How easy was it to solve the clashes themselves?

How easy was it to locate the clashes?

How easy was it to solve the clashes from a first-person perspective?

How easy was it collaborating with your partner in this way?

How easy was it to convey how you wanted to solve a clash to them?

How easy was it to understand how they wanted to solve a clash?