Immersive Virtual Reality Prototype for Evaluating 4D CAD Model

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Abstract

4D CAD model is a media used to communicate a construction project schedule to a wider amount of people in a project team. This model takes advantage of 3D geometry visualization to describe each construction activity. This 4D model can be potentially improved by adding within it an element interactivity. Several parameters must be defined to determine whether element of interactivity or immersion is needed. In particular, his study aims to identify the benefits of virtual reality implementation in 4D modeling which can be used to identify errors in the construction project sequence. Based on a preliminary study conducted prior to the experiment, two common mistakes were identified in the process of planning a construction sequence aspect. The two common mistakes are omission and illogical sequence. The research developed several scenario by incorporating them into a 4D CAD model. Participants were tasked with identifying the mistakes using both a Virtual Reality prototype and a commercial 4D modeling application. It was concluded that with a proper technique, the use of virtual reality for 4D model could be more efficient that a normal 4D model. Specifically, observation of structural elements and MEP related activities are more efficient in VR than non-VR methods

Chapter I Introduction

1.1 Overview

Under the umbrella of Building Information Modelling, 4D-CAD offers many benefits especially when it comes to communicating the construction process to other project participants and clients. It is also perceived to be able to reduce reworks in complex projects because 4D-CAD is capable of providing the construction schedule with visual cues of the building components and equipment associated with the schedule.

The advance in virtual reality technology in recent years has provided many industries with its benefits. In the construction industry, for instance, the use of virtual reality system can be related to the architectural visualization and Building Information Modeling. The cost itself can be no longer a barrier in adopting a virtual reality system since the industry has been developing more affordable system to create virtual reality visualization.

There have been numerous studies that showed the benefits of virtual reality for the construction industry. However, the studies mostly use either non-immersive virtual reality set ups or expensive equipment which costs may outweigh the benefits of using virtual reality itself. This study utilized currently available peripherals and assess their potentials to be implemented in 4D CAD viewing.

1.2 Research Questions

The research questions for this thesis were centered on the effectiveness of virtual reality implementation for assessing a 4D-CAD model.

1. Is Virtual Reality a potential method for identifying errors in the visualization of construction schedule?
2. How does virtual reality affect people's perception in viewing a 4D model?
3. What actions and decisions do people usually make when viewing a 4D CAD model in virtual reality?
4. What is the most viable virtual reality system set up for viewing a 4D model?

1.3 Objectives

The main objectives of this research are:

1. To identify the potential use of virtual reality in 4D-CAD representation.
2. To develop a virtual reality system prototype for viewing a 4D model.

1.4 Limitations of the Research

The research was limited to study the reactions of participants upon the use of the virtual reality prototype. The reactions, represented through feedback obtained from questionnaire, were used to furnish the development of virtual reality system prototype. The prototype development was limited to:

1. Strictly visualizing a 4D CAD Model within virtual reality environment. Due to the limitation of the research, the prototype is not developed to provide a one-step solution for converting a 3D model into a 4D-CAD model. However, a detailed steps on integrating a 3D model with schedule as well as other important elements is described on chapter 4 of the thesis.
2. The prototype was developed based on a videogame engine since most immersive virtual reality peripherals is more compatible with it.
3. The study was limited on the evaluation of the virtual reality system assembled from consumer-grade peripherals. Therefore, the study did not conduct any evaluation on facility grade virtual reality system such as CAVE.
4. Providing several navigation options such as motion sensing control and conventional controller or mouse and keyboard.

1.5 Benefits of the Research

The research presented in this thesis assessed the viability of using virtual reality medium to represent a 4D CAD model. Since the study focused on commercial virtual reality peripherals, the study could provide what potential usage these equipment have in term of visualization the 4D CAD model. VR start-ups who would like to expand their business into architectural or construction visualization through virtual reality could use the content of this thesis as reference for developing their VR setups at an affordable cost.

Furthermore, interactions with the VR prototype could be used as an alternative method for solving constructability issues.

1.6 Approach

This thesis is intended to explore to potential benefits of virtual reality in 4D-CAD modeling. Therefore, this study addressed several problems identified in previous study then develop a solution for those problem. By mixing quantitative and qualitative results, the study is expected to be able to pinpoint the answer to the problems. The thesis involved the use of interview, questionnaires, and experiment as its main instruments.

Chapter II Literature Review

2.1 Overview of 4D Modeling

Traditionally, a construction schedule is developed using Critical Path Method (CPM) and 2D drawings. CPM has been adopted in the construction industry since the 1950s. It has been mainly criticized for its separation from the visualization of the planned construction (Collier 1996).

Designers use 2D drawings to describe their ideas to other project participants. To interpret the drawings, an individual is required to have received adequate training and experience. The ideas of the designer are then translated by the participant into a CPM schedule which will describe the construction sequence. As building geometry becoming more complex, it is common even for an experienced individual to misinterpret the designer's intention. In the end, the misinterpretation will cost additional time and money.

For a novice with limited construction experience, conceptualizing the construction process and detect problems by only viewing the CPM schedule can be a challenge. Such schedules force users to visualize and interpret the activity sequence in their minds. Components in 2D drawings must be associated with the sequence of activities mentally. The processes are a sequence of events not physical objects, therefore, it is more difficult to validate and evaluate them (Retik, 1993).

4D model is the solution to the visualization problem in construction scheduling. A 4D model is essentially a schedule which has its activities linked with a 3D model (Koo and Fischer 2000). The idea of linking a 3D model and schedule was materialized when Bechtel Corporation and Hitachi Ltd developed the Construction 4D-Planner in 1986 (Smith 2001).

To overcome the difficulties of traditional scheduling techniques, advanced visualization techniques such as 3D visualization, 4D models, and virtual reality models can be utilized. A 3D visualization system for construction operation simulation allows the system to be analyzed at the operation level of detail to plan the construction process. Interactions of various resources, such as materials, labor, equipment, and temporary structures can be viewed when the building is virtually constructed (Kamat et al. 2001).

The 4D model allows the engineers involved in the planning of the construction process (i.e., process designers) to visualize the construction sequence as it would actually be built. It also creates a single medium for integration - all of the parties involved can now collaborate in the design using the same 3D model without misinterpretation or repetitive conceptualization. The 4D model provides an environment for easier interaction and communication amongst the process designers and therefore is conducive to the detection of potential problems that may otherwise be overlooked when using traditional planning software. (Koo & Fisher, 1998)

Both the CPM schedule and the 4D model reflect the conceptual planning information sequenced in the minds of process designers. However, the 4D model allows further evaluation and analysis of this sequence through the integration of the temporal and spatial aspects of planning formation, which allows users to develop a more realistic and feasible construction schedule. (Koo & Fisher, 1998)

2.2 Applicability of 4D Modeling

The most popular example of how 4D modeling was successfully applied to construction project was the Walt Disney Concert Hall construction project in 2001. The complexity of the concert hall's architecture made the project teams utilize the use of 4D model to communicate the construction process to other participants of the project. The development of the 4D model required completed 3D model of the building and schedule information to be available beforehand.

In 3D, the complex structure was divided into building elements. Each building element was then further divided into models available for building element to facilitate the creation 4D model. After the 3D model had been completed, the construction schedule was developed using a scheduling software. The schedule divided the 3D project geometry into smaller parts relevant to each activity. Activities are identified by building element, floor, area, and subarea, then by phase, system, component, and action.

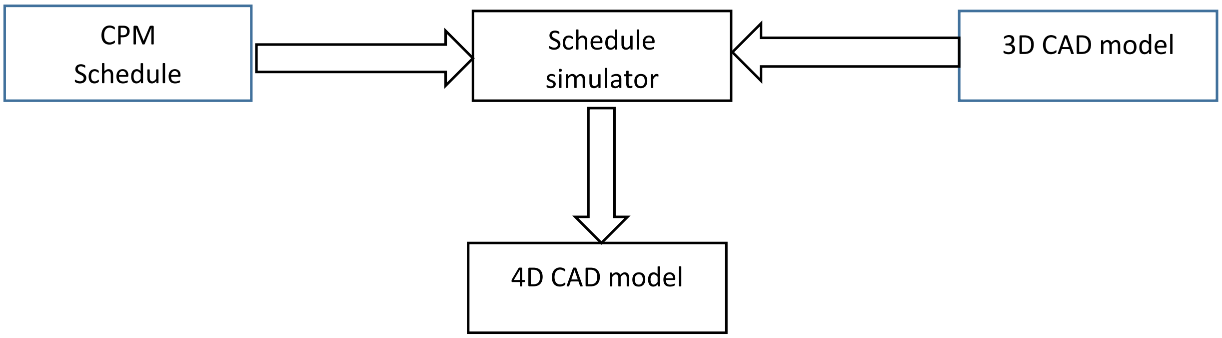

Figure 2.2-1 Process of 4D Cad model development

In the Walt Disney Concert Hall project, linking the schedule with 3D geometries was made possible by converting the geometries into a VRML-compatible geometry. Every geometries were then named to allow 4D modelers to match the geometry names to activity names quickly (Haymaker & Fischer, 2001).

The process of developing 4D model was long and required the team to meticulously name each geometry and link the geometries with the schedule. The amount of effort and time invested in the development of a 4D model means additional up-front costs will be incurred (Koo & Fisher, 1998). However, as technology progresses, the process has been streamlined by a dedicated software that automatically divides and name each geometry. This software not only allows the visualization of schedule, but also provide and automated function to identify clashes in the model.

The usability of 4D modeling can be broken down based on project's phases:

1. In project planning phase, 4D CAD is very likely to be useful in communicating plans to clients. The clients will be able to provide suggestions or acceptance (Mahalingam, et al. 2010)
2. During Construction Phase, 4D-CAD can be useful for identifying clashes, schedule conflicts, as well as a visual tool for project team in planning reviewing the project's progress.
3. One of the most popular case where 4D model was successfully applied was the in Walt Disney Concert Hall Project. Based on that case, John Haymaker and Martin Fischer (2001) described the applicability of 4D Modeling:

1. Schedule creation: The HC used the 4D models to assist in planning the laydown areas for the enclosure contractor as well as visualizing the project access points and several complex building element installations.
2. Schedule analysis: The GC's project management team was able to discover several conflicts in the schedule which were not discovered in the CPM-based Gantt chart.
3. Communication: The GC used the 4D models in training sessions with 40 people. The availability of 4D model helped the contractors, subcontractors, owners, designers, and the GC reviewed the models and discussed the strategy and constraints for erecting the project.
4. Team building: After a 4D review session ended, the project teams can discuss issues and solutions to problems or questions identified during the meeting.

4D models can be used as a tool to escape from the limitations of the 2D drawing and paper document paradigm deeply embedded in the AEC industry, by integrating the design and construction information in a single medium. The designer and builder can and must both work with the same models when viewing the 4D model, which eliminates the use of separate drawings. Because the geometric and planning information is conveyed through a single medium, both entities can benefit from viewing the other's perspective. As 4D models accurately depict the geometric configuration of the building, designers can point out the structurally significant aspects. On the other hand, as 4D models also convey the project sequence, builders can point out how they will be affected by the design. Builders can also convey schedule information without having to rely on CPM schedules, which may require extensive explanations and still not convince the designers.

2.3 4D Model as a Facilitator in Construction Schedule Review Phase

Prior to the adoption by the project team, a construction schedule is usually reviews for correctness and goodness. Songer et al (2001) investigated the impact of visualization to the construction schedule review process. The study complements previous research on the similar topic about how visualization can impact the development of project schedule. The experiment produced that 4D model provides help in identifying invalid relationships, safety problems, and overcrowding problem.

The study involved 25 participants from the construction industry. In the study, a schedule with intentionally included mistakes was developed. The mistakes included missing activities, out of sequence work, invalid relationships, and potential overcrowding or safety problem. The experiment was divided into three parts: 1) schedule review and analysis using 2-D paper-based representation, 2) making corrections in the schedule and programming the animation; and 3) schedule review and analysis using computer animation. The first part required the 25 participants to review and analyze the faulty schedule using only a set of 2-D drawings and a printout of the schedule. The participants were requested to review the design drawings and the schedule. (Songer, Diekmann, & Karet, 2001)

Once the corrections had been made, the schedule reflected each participant's interpretation of a 'correct' and 'good' schedule. These schedules were linked to the 3-D CAD model to produce an animation of the proposed construction process. Each animation begins on the start date of the project and sequentially shows each component of the structure on its respective installation date. It can be played forward or backward at various speeds and stopped at any time.

In addition to investigating effectiveness of schedule review for correctness and goodness, the researchers collected qualitative information on safety and overcrowding. For example, the research team created a schedule that had four distinct safety problems, each involving multiple crews working in tight areas with large structural members being installed overhead. Not all the participants noticed these problems, nor did they all propose as reviewed separately with respect to each schedule to determine the effectiveness of using the computer animation.

The final part of the schedule review experiment involved schedule review and analysis using computer animation. Each participant was asked to run the animation, review and analyze the schedule and complete another questionnaire. The results from this phase were compared with those from the first phase to determine if the computer animation helped the participants to identify problems in the schedule. It was determined that visual aids such as animation helped people in identifying errors in the schedule. (Songer, Diekmann, & Karet, 2001)

2.4 Benefits and Issues of 4D Modeling

Construction planners mostly used traditional CPM scheduling. The challenge in using traditional CPM scheduling is that it requires people to use imagination to visualize the construction sequence. For those who are not trained or not experienced in scheduling, the communication of the schedule to other project participants becomes a barrier and will cause misunderstanding if the schedule is not described clearly. By integrating the schedule with 3D model elements, the communication becomes easier and the viability of the schedule can be assessed thoroughly by more project participants. Ultimately, the 4D model can be used as a collaborative analysis tool for the determination of constructability review (Koo 1998).

In general, Koo et al. (2000) identified the effectiveness of 4D model as a communication tool between project team members. Those benefits are:

1. Ability to verify the completeness of the schedule
2. Ability to identify inconsistencies in the level of detail among the schedule activities.
3. Discovering illogical construction schedules
4. Anticipating site and logistics problem
5. Identifying clashes between building elements.

Therefore, Wang (2003) identified three main functions of 4D modeling to solve the problem:

1. Visualization Tool
2. Analysis Tool
3. Integration Medium

The process of linking 3D models with schedule elements still has some issues (Haymaker & Fischer, 2001) :

1. Inconsistencies: The 3D models are often incompatible with the schedule. In the Walt Disney Concert Hal Project, for example, the architect defined the building geometry by building elements, but the GC places concrete and steel not by element, but rather according to steel structure. Therefore, the geometry had to be broken down into smaller elements and recombined to accommodate the GC's construction procedures.

2. Other data: Additional models such as site logistics and heavy equipment are not part of designer’s drawings, however these elements play a large role in the construction site. Models that are not part of the architect’s drawings have to be added by the 4D development team.
3. Representation of activities with no geometry: Certain construction detail such as ductwork is usually not modeled in 3D. There are several ways to visualize the activity related to those details. The team can make the 3D model that represents the ductwork or attach the activity to another building element that is connected to the activity (floor slab or ceiling framing).

In some cases, 4D-CAD modeling may not be efficient enough and might cause additional time and effort to develop. In commercial projects, for instance, usage of 4D modeling may not be appropriate for delay analysis because of the possibility of disagreements over the model’s assumptions. In medium-sized projects, integrating cash flow and resource management with a 4D-CAD model may not be effective because visual cues do not bring benefits for the team in evaluating project’s cash flow.

2.5 Virtual Reality Overview

The term virtual reality has been associated with a computer application where people can interact with spatial data in real-time. It has been argued that virtual reality can be used by anyone in the construction industry. The technology will eventually lead to form an interface to all construction applications. Currently its use is specific and not all companies are using it over different operations.

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

An example of this approach can be found in, *The Production of Reality,* by Kollock and O'Brien (1994). The authors take a symbolic interactionist approach to explain how reality is constructed and negotiated through human interaction and communication. Because the reality created by VR is based on the transmission of symbols in an interactive environment, symbolic interaction may provide a useful schema for its analysis. Anecdotal evidence based on the experiences of those who have participated in text-based VR environments (e.g., MUDs and MOOs) would lend support to the constructivist approach. On the other hand, testimonies provided by those who have had the opportunity to don full-immersion VR gear would suggest that these technologies clearly augment the mind's ability to enter virtual "realities."

In the construction industry, there are two groups that use virtual reality:

1. Within the project team and supply chain. The models are created by consultant engineers, contractors, sub-contractors, and suppliers. The model may be complex and require high computing power.
2. Outside the project team, virtual reality system are used primarily with the end-user, clients, funding institutions, and planners. The models used may be simpler but provides high interactivity for the users. The primary focus of virtual reality development for people outside of the project team is to give a fluid and vivid representation of the completed state of the project.

As a medium, a virtual reality has three defining characteristics: interactive, spatial, and real-time. Though virtual reality is historically associated with high-end computing, a wide range of hardware and software is being used in virtual reality systems. Virtual reality systems have become more affordable and widely compatible with desktop personal computers and on mobile computing devices. Peripheral input and output devices can be used to make interaction with virtual environments more intuitive (Isdale, 1998).

There are several basic principal that can be incorporated to produce a virtual reality system: position tracking, visual, audio, and haptic feedback (Whyte, 2002).

- Position tracking and control as the simplest control of hardware is a conventional mouse, trackball, or joystick.
- Visual is experienced through sight. The representation of virtual environments can be stereoscopic, with a different picture viewed through each eye, or monoscopic, with both eyes seeing the same picture. Immersive virtual displays utilize the head-mounted display, while non-immersive displays utilize desktop monitor and bench.

- Experienced through hearing, aural inputs and outputs are often neglected in the industrial use of virtual reality. In certain applications, audio quality may become more important than visual quality (Brooks, 1999).
- Haptic feedback is produced by touch and force. Haptic feedback creates sensation of touching an object in the virtual world. The representation of haptic feedback in VR is typically done through vibration. To produce this sensation, at least a small motor is implanted in the controller. Every touch and force experienced by the user will cause the motor inside the controller to spin, producing a feedback for the user. (Brooks, 1999).

The term virtual reality was first coined in 1980s. Interactive 3D became possible on the personal computer. AutoDesk, inc. demonstrated their PC-based VR CAD system, Cyberspace at SIGGRAPH in 1989. Later in 1990s, several commercial peripherals associated with virtual reality were released. A virtual reality company named Fakespace introduced CAVE, an immersive virtual reality systems that projects the virtual environment onto three large displays.

Virtual Reality Modelling Language (VRML) was developed to provide virtual worlds networked via the internet (Bell et al,1995). Prior to the 2000s, the VRML became the main standard for studies associated with virtual reality. However, the VRMl technology was slowly abandoned as Microsoft a proprietary standards for its OS, Direct3D.

There are various ways virtual reality can be implemented to visualize construction schedule. However, the construction of a 4D-CAD model is labor intensive, and the use of virtual reality requires high skills and high investment (Whyte, 2002). The most popular example for non-immersive 4D-CAD application on the construction of Paradise Pier Project by a collaboration between Disney Imagineering Research and Development and Stanford University (Bonsang and Fischer, 2000). The 4D-CAD package enabled CAD data to be linked with scheduling information and viewed in a real-time environment. The 4D modeling allows for the visualization of construction plans; identify construction consequences and space conflicts; identify safety issues; and improve communication of the project team members (Koo and Fischer, 2000). Despite facing certain barriers in its adoption, the construction industry is more than welcome to adopt the technology when required (Elswick, 2011).

2.6 Virtual Reality Workflow

It should be noted that virtual Reality is merely one of many media in which 3D models can be visualized. Ideally, 3D data files should be independent of their use (Kiesche 1997).

2.6.1 Downstream Process

Downstream process is also called one way translation process. In architectural renderings, a CAD model is given a post-processing treatment in order to make the model look realistic. The result is a pre-rendered image which resembles the final product. A typical pre-rendered CAD model will be resource intensive when translated directly into VR model because it contains a large amount of polygons. The post-processing treatment of VR model is done in real-time which adds more burden to the hardware. Therefore, a well-rendered model must be optimized before translating it into a VR model. The optimization can be achieved through reducing the amount polygons or using pre-baked assets such as rendering a shadow into the texture. It is typically conducted in a non-industrial standard method and the process is irreversible. (Whyte, Bouchlaghem, Thorpe, & McCaffer, 1999)

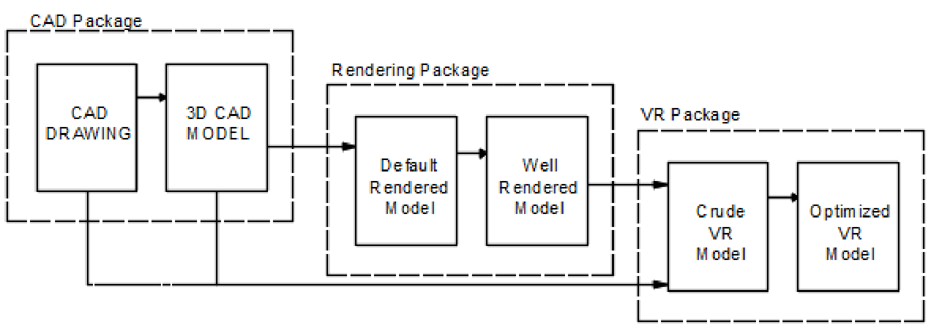

Figure 2.6-1 The Downstream Translation Process from CAD to VR

2.6.2 Straightforward Translation Approach

Complete CAD models can be used to generate VR models by straightforward translation of the whole model, sometimes in conjunction with algorithms for optimization. A translation approach has been used in research projects where there are few repeated elements, geometric data predominates and there are few activities associated with it, or the design process is completed and the design is fixed and unchanging**.** Translation and optimization can be used for the generation of highly rendered or optimized models for presentation to clients.

CAD models of entire cities that were created as student group projects have since been translated into VR urban models at Bath and at Strathclyde, although extensive reorganization and optimization has been necessary to obtain suitable frame rates in such large VR models.

2.6.3 Database Approach

A database approach to VR model creation utilizes a central database to control component characteristics and both CAD and VR are used as graphical interfaces to that database. The building model is created in the central database and viewed through the different applications, one of which is the VR package. A full implementation of such a system would allow updating of the model in both CAD and VR. Thus a two-way data exchange would be effected as opposed to unidirectional or downstream data transfer.

Whilst a database is used for internal organization and for search and retrieval of information within the urban model of Los Angeles, the link between CAD and VR is not dynamic, and there is no central building model that can be viewed in both CAD and VR. Virtual Los Angeles has instead been created by the translation of models created in the MultiGen modeler and using GIS data.

The Open Systems for Construction (OSCON) research project at Salford University used case studies from real-life construction projects to demonstrate its usefulness. This project, which builds on the earlier ICON project, has core modules that include process management, planning, CAD, estimating and VR. Thus, VR operates as the user interface for interrogation of an integrated project database. Whilst the OSCON project could not currently be used for real-time viewing and presentation of large complex building or urban models, it demonstrates the potential of such an approach to VR utilization.

There is a form of trade-off in visualizing a 3D data in virtual reality. The emphasis of virtual reality is the representation of the visible parts of the model. Unlike CAD models used for construction, typical VR model focused more on providing vivid and fluid seamless of the model. Therefore, when a CAD model is to be represented in virtual reality, several trade-offs has to be made. The process of streamlining the model is called model optimization. (Whyte, 2010)

Whyte (2010) suggested that optimization techniques include:

- Using texture maps. Texture maps are images that are mapped onto surfaces of objects to show the detail of their surfaces. This technique allows the level of detail to be reduced and increases performance.
- Using primitive solids. Primitive objects such as cubes, spheres, or cylinders can be used in the virtual reality environment. These method is appropriate for distance objects outside of user's navigation area.
- Using distance-dependent levels of detail (LODs). Similar to primitive solids, LODs are used for distance objects. LOD will replace the complex model with primitives when the user's position is relatively far from the object. The LOD geometry details will increase as the user gets closer to the object.
- Using billboards. To provide simple representations of complex objects such as trees, texture maps are used. Billboards are typically two-dimensional/planar objects that always face the viewpoint
- Selectively loading objects within the model depending on the viewpoint.

2.7 Immersive Virtual Reality

Immersive systems completely surround the user. The systems typically have a specialized method to block user's connection with the outside world. Common hardware associated with this method is a head-mounted display or large wall-mounted displays. These systems require high-end computing power to provide a high realism environment. (Whyte, 2010)

Bridgewater (1994), described that immersive virtual reality systems are where a user dons a headset and gloves in order to take an active part in the virtual domain maintained by the computer. In this way, the user can simulate the behavior of a tower crane operator or participate in a training session. The other approach is called non-immersive VR and is where a user is outside the virtual world maintained by the computer. In general, the user looks at a flat screen and comprehends the virtual world from outside. This approach is also called Projection VR.

Typically, an immersive VR system comprises a sophisticated computer system to maintain the synthetic world for the user, a headset with displays which are matched to the eyesight of the operator, a means of interacting with the synthetic world such as a hand-held wand, glove or speech recognition system, a pair of headphones for supplying auditory information and a method for tracking the body of the user so that the position and orientation of the sensory channels of the operator may be determined. By swathing the eyes and ears of the operator, much extraneous information from the local environment is blocked out which reinforces the experience of immersion for the operator.

2.8 Non Immersive Virtual Reality

Non-immersive systems typically use more generic hardware. The same software techniques are used but the system does not totally immerse the viewer. Sometimes described as window on a world systems, they allow the user to see virtual reality through a screen or display that does not take up their total field of view (Whyte, 2010).

2.9 Use of Virtual Reality in Construction Industry

The creation of a VR-based visual interface between a computer and a user for a construction context would not only facilitate the validation and evaluation of the generated construction plan but would also support further decision making such as resource allocation and progress monitoring (Blackwater, 1994).

Several researches that aims to investigate the applications of virtual reality in the construction industry had been undertaken by researchers within the last two decades whereas the primary focus of those studies were to bring the visualization of construction phases in construction projects.

An earlier study conducted at the United Kingdom in 1994 by C. Bridgewater et al. explored the possibility of using a virtual reality for collaborative scheduling process. The research suggested the following uses of VR on construction projects: site operations, office automation, design phases, and special areas. A more comprehensive list of VR uses in the industry is listed on table 2.9-1.

Table 2.9-1 Potential Applications of VR in Construction

Area	Potential Applications
Site Operations	Rehearsing erection sequences Planning lifting operations Progress and monitoring Communications Inspection and maintenance Safety training and skills
Office Automations	Tele conferences Project review and evaluation Project documentation Marketing
Design Phases	Preliminary and detailed design Lighting and ventilation simulations Data exchange File/safety/access assessment Scheduling and progress reviews
Special Areas	Nuclear industry Subsea inspections and work

	Near space operations Micro inspection and testing

The study involved two complementary computer systems integrated by local area network (LAN). A computer-aided building design system was modified to allow its results to be visualized using an immersive VR system developed by researchers at Reading University, UK. The Master Project Coordinating Program (MPCP) was developed to design highly-serviced buildings usually found on business parks. The typical buildings are usually have simple building layouts and consists of two to three floors. The architecture of MPCP is demonstrated in figure below.

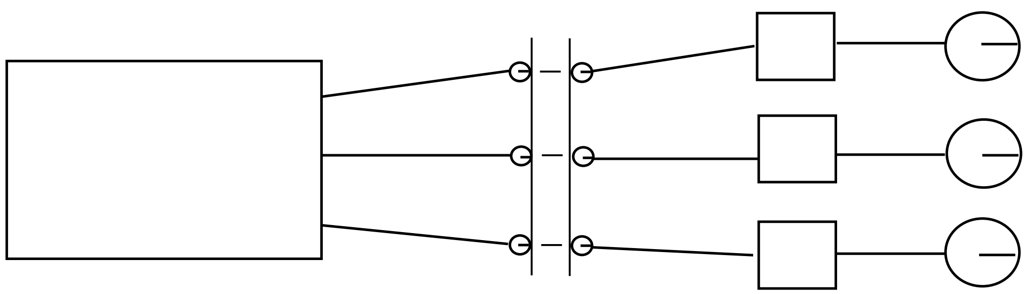

Figure 2.9-1 Architecture of MPCP

The VR system used in the study was based on a home computer with the capability of delivering stereo images to the head mounted display. Head tracking was made possible by using a magnetic tracking system incorporating three mutually-orthogonal coils. The virtual reality system was attached to the existing MPCP infrastructure by adding it as another client and reading the 3D model into the VR world database. By integrating the head mounted display with the MPCP infrastructure, it was possible for users to navigate through the CAD model of the building through the help of the VR system.

A research on the usage of 4D-CAD was performed by Pennsylvania State University. The research used Immersive Virtual Environment, an immersive virtual reality system developed by the university using CAVE^{TM} technology. The study investigated on the feasibility of using an immersive, 3D virtual environment to view and generate 4D models in improving the construction project planning process. The research subjects, consisted of construction professionals, were able to reduce their planned schedule by 28%, develop a more detailed understanding of schedule dependencies, identify more constructability issues, and improve their overall schedule confidence. The tool used for this study was proven as an effective schedule review and generation tool. (Baratta et al. 2002)

The benefits of VR system for 4D-CAD modeling is not limited to construction industry. A research that involved engineering students from Pennsylvania State University studied the educational benefit of non-immersive VR implementation on 4D-CAD modeling. Using three-display screen and a Virtual Construction Simulator tool developed by the university, students were tasked to develop a CPM schedule. The investigation showed that students who used 4D-CAD to plan a construction demonstrated a slightly better understanding and produced a better CPM schedule than the average students who did not use 4D-CAD (Wang, 2007). Wang (2007) suggested that the implementation of 4D modeling in education is still limited despite the increasing number of successful its implementation in construction industry.

Another example of the use of 3D visualization and VR technology was a study conducted by Songer and Dickman (2001). Their research indicated the following advantages of VR and 3D CAD for creating a construction schedule (Yerrapathruni 2003). For all schedules developed using only 2D standard practices:

1. Schedules developed using 3D or CAD based walkthrough environment had fewer missing activities.
2. The schedules developed using2D has more missing relationship than schedules developed using 3D CAD based walk-thru environment.
3. The use of 3D to develop schedules led to less logic errors.
4. Additionally, the participants using the walk-thru model created a flawless logic network.

The literature review has shown that VR is helpful, but development and widespread use is still lagging. According to Gopinath (2004), a well detailed model in VR can solve many ambiguities about project design and specifications. The technology is being developed to streamline this into everyday work, but is time consuming and expensive at this juncture.

2.10 Summary of Literature Review

The concept of using Virtual Reality for 4D modeling has been extensively researched in the academic area. Although 4D modeling may looks like an enhancement of the Building Information Modeling by integrating 3D model elements with schedule activities, it brings benefits to both construction industry and education. For construction planners, 4D modeling has the potential to enhance construction sequencing by identifying temporal and spatial conflicts. For students, the visualization of 4D modeling can help them in understanding the basics of construction methodology as evidenced by previous research.

One of the drawbacks of those researches required expensive technology in visualizing immersive Virtual Reality to 4D-CAD modeling in addition to the already expensive computer needed to run the 4D-CAD application. The hardware requirements become one of the barriers that still limit the wide adoption of immersive 4D modeling (Elswick, 2012). However, more alternatives are available today as companies have been able to produce a Virtual Reality headsets at a more affordable price than industry-grade virtual reality devices with similar functionality. The research will develop a prototype that will utilize the usage of immersive virtual reality system for 4D modeling. To measure the efficiency of the prototype, user's visual perception and navigation capabilities will be used as the parameters. Consequently, it is important to conduct several tests on multiple degree of proficiencies.

The goals of the research presented in this thesis were to investigate the feasibility of the device and the tool for construction engineering education, identify the limitation of the tool, and suggests what future improvements can be implemented to the tool.

Chapter III Research Methodology

3.1 Specific Aims

This study aims to identify the benefits of virtual reality implementation in 4D modeling to identify errors in construction sequence. The ultimate goal to the research is to develop a prototype tool for evaluating a 4D model in virtual reality using a videogame engine.

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3.2 Background and Significance

Despite a number of research conducted in the area of immersive virtual reality (VR) for construction engineering or 4D modeling as a constructability review tool, there is the lack of studies conducted to explain the benefits of immersive virtual reality implementation for schedule visualization. A research about the benefits of 4D modeling in construction engineering education conducted by Pennsylvania State University proved that 4D modeling could improve the identification of errors in construction schedule. However, the research did not identify what type of errors can be identified by 4D modeling. Moreover, the tool used in the part of research that measures benefits of 4D modeling did not incorporate the immersive VR technology for error identification (Wang, 2003). Another research conducted in the same university proposed an idea that the technology could enhance the understanding of construction scheduling for educational purpose, but addressed that the technology required a large amount of money to be implemented. (Messner et al, 2003)

This study will investigate the phenomenon that occurs in immersive virtual reality, especially focusing on the interactive element and the balance between interpretation of 2D symbols information and building geometries. The ultimate goal of the research is to promote the implementation of Virtual Reality for construction industry.

3.3 Preliminary Studies

Pettee (2003) presented an idea about constructability review in which it is a form of structured review of construction bid documents. Constructability review is typically performed by construction professionals to make clear of certain work requirements. Due to the nature of the process, it is best to perform constructability when the design is 90 to 100 percent complete.

Project scheduling is one part of the constructability review and there is an abundant amount of software to help people understand the schedule through visualization. The methodology to visualize the construction schedule is called 4D modeling. Essentially, 4D model is an integration between a 3D model and a construction schedule. 4D modeling offers the ability to identify construction consequences and space conflicts (Koo and Fischer, 2000). Despite facing certain barriers in its adoption, the construction industry is more than welcome to adopt the technology when required (Elswick, 2011). More research should be done on what benefits a 4D model has whether 4D modeling could help users in identifying errors in construction sequence and what kind of errors can be easily identified using 4D modeling.

An emerging trend within the construction industry is the usage virtual reality. The term virtual reality has been associated with a computer application where people can interact with spatial data in real-time. As a medium, a virtual reality has three defining characteristics: interactive, spatial, and real-time. Though virtual reality is historically associated with high-end computing, a wide range of hardware and software is being used in virtual reality systems. Virtual reality systems have become more affordable and widely compatible with desktop personal computers and on mobile computing devices. Peripheral input and output devices can be used to make interaction with virtual environments more intuitive. (Whyte, 2002)

Given the benefits of virtual reality, a number of researches were conducted to study the benefits of exploiting virtual reality for construction scheduling. One of the earlier studies about virtual reality for construction was able to draw a connection between the applications of the technology to certain parts of the construction industry (Bridgewater, 1994). The more recent research even addressed the potential of using immersive virtual reality for construction scheduling. (Messner et al, 2003)

The research presented in this thesis did not provide an expansive data for virtual reality hardware nor will it conduct an in-depth study about the technical side virtual reality. Rather, the research will explore the effects of combining the immersive technology to support a specific part of the constructability review.

3.4 Research Phases

The research presented in this thesis was divided into three major phases as shown in figure 3.4-1 and the majority of the research will be focused on the development of the immersive virtual reality system prototype. Since the focus of this research is to develop the prototype, the results from each tests was used as reference to update the prototype. Upon the research, the prototype had received three major updates.

The first phase is the initial prototype development to be used in the pilot tests. Most of the development time during this phase is spent on interviews, hardware and software identifications, and finally developing the earliest build of the prototype.

The second phase was primarily intended to test the earliest build of the prototype. There were several pilot tests in this phase. During this stage of development, the 4D logic was very simple and limited. Navigation options were not the main focus until feedbacks from the 1st batch of pilot tests had been received.

The third phase can be broken down into two parts. This phase studied the effect of VR on construction industry employees. In the first industry test, two general contractors participated. Participants were asked to fill in a preliminary survey prior to taking the tests. The tests involved each participant to identify issues in the construction sequence using conventional method in Autodesk Navisworks and different virtual reality setups. Each participant was given different 4D model scenario with at least one specific error in the construction sequence. At the end of the test, participants were given a set of questionnaires to determine difficulties they faced in the immersive virtual reality. The data from this phase is used to update the prototype. The second industry test used the latest version of the prototype with better navigation and added functions. Generally, this phase was similar to the second phase. One general contractor with four team members participated in the third phase. The difference, other than the prototype build used for the test, was the test setup. In this third phase, participants evaluated the 4D model in group. This setup allows for multiple roles within the group generally divided into three categories. The observers whose tasks are to discuss and identify the errors, the leader who coordinated the evaluation with observers and provide directions to the immersive VR user, and the VR user whose tasks is to navigate through the immersive VR model and control the construction sequence under other team member's requests.

Due to the limitation of available hardware, only one participant could use the virtual reality setup at a time. Other participants in the group were given the freedom to provide commands on the participant wearing the immersive virtual reality. After the final phase, all error identification data from the second and the third phases were compared to identity how the improvement of the prototype builds contributes to the test results. Figure 3.4-1 illustrates the different test phases.

Several data were obtained from this experiment:

1. Time needed to complete the interaction with the tool.
2. Actions taken by the participants in order to complete the tasks.
3. Interactions between participants in the group test.
4. Participants' perceptions on the virtual reality setup's level of comfort.

Each test was designed to run no more than twenty minutes, sans the setup time and rest between sessions. Once the experiment has been completed, a short survey will be distributed after the test. The survey will identify:

1. Difficulties faced by participants from each group when interacting with the tool.
2. Post effects after using the tool.
3. Participants' opinion about the tool.
4. Suggestions for improvement.

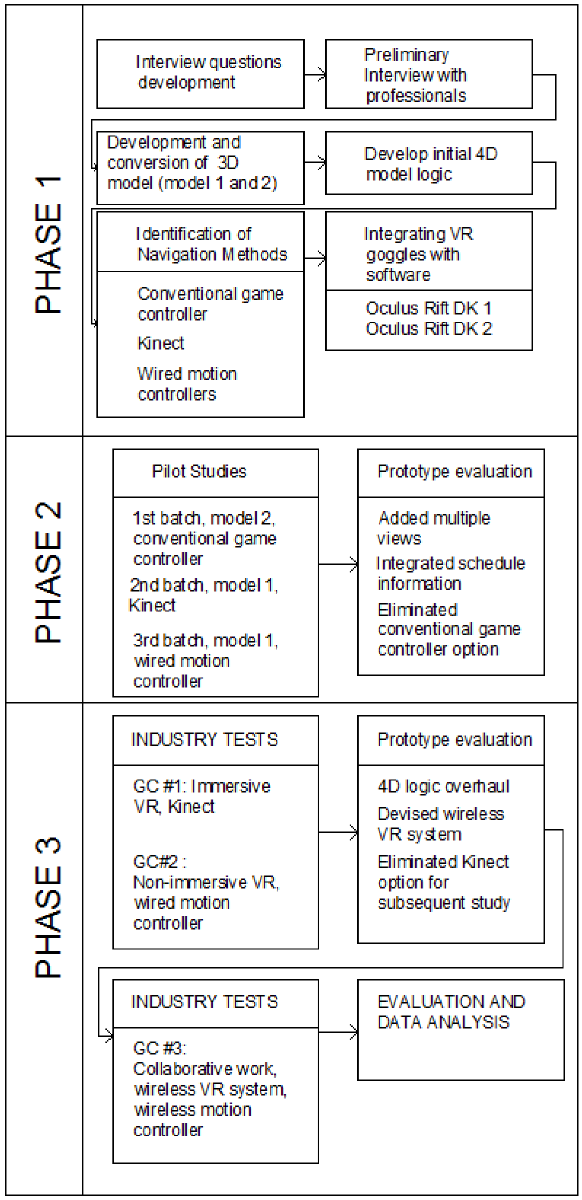

Figure 3.4-1 Research Phases

3.5 Study Population

For the test on the VR tool prototype, several subjects were notified about the research and asked if they are interested to voluntarily take part in the research. The following criteria were used for the selection of the test subjects:

1. The test subjects must be working in a construction industry or possess academic knowledge about the industry.

2. The test subjects must be familiar with construction scheduling and able to interpret the schedule.

3. The test subjects must be capable to operate conventional 4D modeling software.

The participants were divided into several groups, based on Dreyfus' model of skill acquisition (Dreyfus, 1988, pg 21-30):

1. Novices act on the basis of context-independent elements and rules.
2. Advanced beginners also use situational elements, which they have learned to identify and interpret on the basis of their own experience from similar situations
3. Competent performers are characterized by the involved choice of goals and plans as a basis for their actions. Goals and plans are used to structure and store masses of both context-dependent and context-independent info
4. Proficient performer's identity problems, goals, and plans intuitively from their own experientially based perspective. Intuitive choice is checked by analytical evaluation prior to action
5. Finally, expert's behavior is intuitive, holistic, and synchronic, understood in the way that a given situation releases a picture of problem, plan, decision, and action in one insgtant with no division into phases. This is the level of true human expertise. Experts are characterized by a flowing, effortless performance, unhindered by analytical deliberations.

3.6 Risks and Side Effects

The study expected "no more than minor" physical nor psychological risks associated with it. During the tests, several participants who were not familiar with virtual reality experienced minor motion sickness after using the prototype. No immediate medical attentions were needed during the occurrence of the event.

3.7 Setting of the Research

The research took place within an enclosed environment and participants only interacted with the prototype or with each other. The participant selection criteria will ensure that no participant may place other participant's safety in danger over disclosure of his/her identity.

3.8 Resources

The experiments were conducted in enclosed spaces with electricity enough to support the prototype. In some tests, a room with good wireless internet connection were also needed for specific equipment. A powerful computer with virtual reality headset software driver was mandatory during the tests. Additionally, the computer was also installed with several software drivers for navigation peripherals such as Microsoft Kinect and other game controllers.

On the software sides, the tests used a computer installed with Navisworks to run a conventional 4D model and a video game engine to run the virtual reality prototype. A screen capture software was used to record each test sessions.

3.9 Data and Safety Monitoring Plan

For the purpose of research, personal information such as name, age, and contact number were collected once prior to the experiment. The data were collected through a preliminary survey form distributed to subject candidates.

Sensitive information were be stored in lead researcher's storage drive and will be backed up to an online storage and a portable hard drive. To protect the confidentiality, the data will be password protected by the lead researcher. Since data leakage may cause a misuse by an irresponsible parties, the researcher would inform participants about the risk participants will be informed about the risk and participants would be allowed not to take the test.

Chapter IV Preliminary System Development

4.1 Overview

This chapter describes the development of the construction sequence viewer. More features, as well as alternate control methods were added to the prototype based on participants' suggestions and reactions from each tests. The premise of this prototype is to enable users to view different construction phases from their own perspective, thus providing a more intuitive controls and more direct interaction with the model.

This chapter is comprised of three segments. The first segment will describe survey development in order to determine the approach of the study, including determining how industry professionals use 4D modeling and the level of detail of the 4D model. The next segment describes the process of selecting the appropriate hardware for VR and the final segment of this chapter analyzes the software used and describes the early VR software development. Final prototype development which covers additional features and VR hardware will be covered in the next chapter.

This prototype does not provide a simple one click solution to convert a 4D model into an immersive virtual reality model. The development of this tool requires elaborate effort to convert an Autodesk Revit model into a format that is recognized by the game engine. Furthermore, the integration of schedule components into the game engine involves a separate process with the game engine's visual programming system. The final breakdown of the tool's components is demonstrated in figure 4.1

The tool used for the research itself does not allow real time modification of construction sequence such as changing the duration or adding more activities, although there is a possibility to implement the construction sequence modifier for future study using the development pipeline described in this chapter.

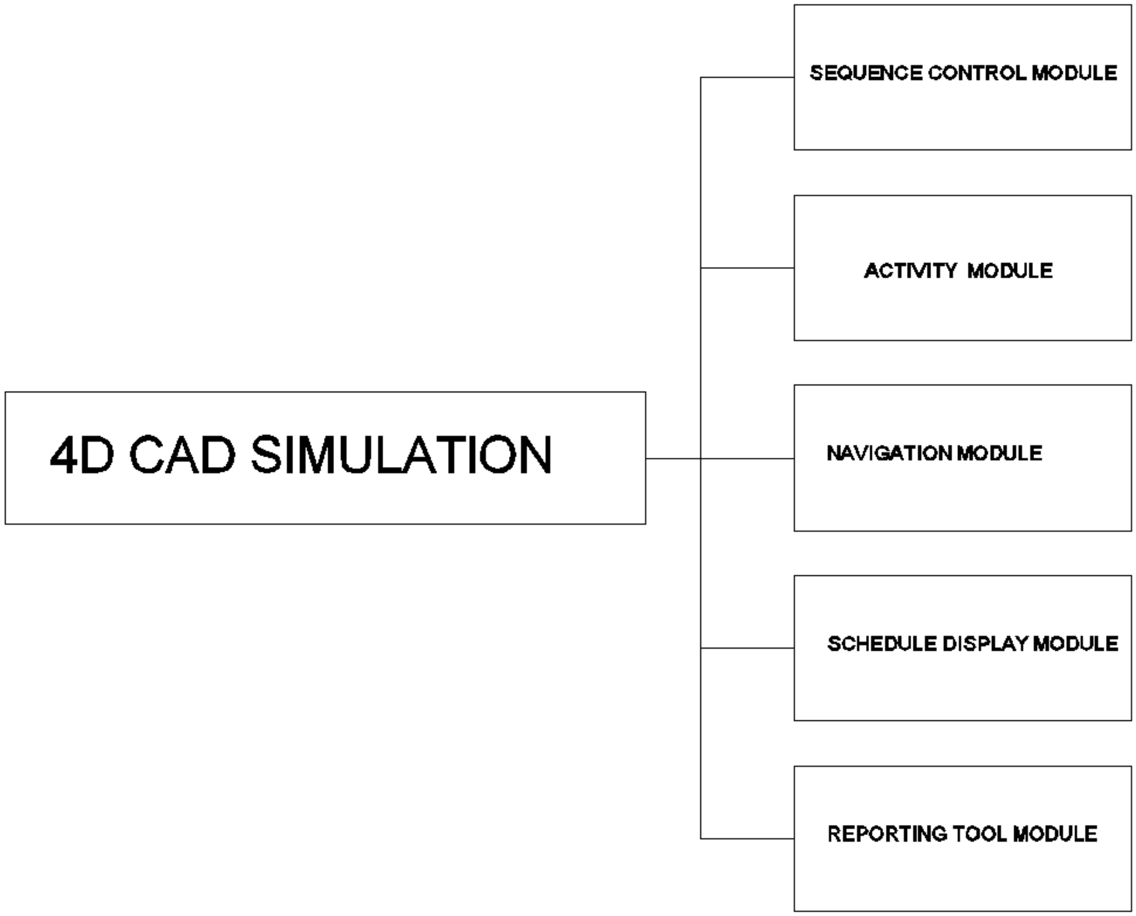

Figure 4.1-1 4D-CAD Simulation Elements

4.2 Interview with Professionals

Interviews were conducted with two professionals from different construction companies. Both interviewees have had more than two years' worth of experience in 4D modeling.

The first interview was conducted on August 21st, 2014. The interviewee was an employee of a general contractor in Seattle who has 7 years of experience in Building Information Modeling. When asked about the management of 4D model, the interviewee mentioned that project team develops 4D model as part of pre-construction process. Aside from using the model as a marketing tool, the team mainly uses 4D model to assess the construction process and identify if there is an overlap of activity on the job site. The level of detail of the model varies depending on the needs of project team. A follow up meeting was conducted during AEC Hackathon at Seattle in September 2014. The interviewee showed an example of the 4D model used in his current project. The model mainly covers building enclosure such as wall and several structural elements, but did not show a more detailed system within the building. The interviewee mentioned that to save time and computing power, activities related to building system such as installation of HVAC or plumbing are represented as a change of the color of associated wall's or slab's geometry models. Despite using different shades of color to represent activities related to building systems, the company does not have regulations on using specific color codes to represent those activities.

The second interview was conducted on December 3rd, 2014 with another employee from a different general contractor who has three years of experience in the Building Information Modeling. The respondent gave similar response, most of the 4D models were developed depending the project's needs. Upon asked on what benefit a virtual reality would bring into the 4D model, the respondent mentioned that it is a useful tool to communicate the construction process to people who work on the field. By using the virtual reality, several people would be able to view the model different angle and he believed that process would improve the identification of errors such as clashes.

4.3 Exploring Immersive VR-Capable Hardware

4.3.1 Hardware Specification

There were several issues considered when determining the most appropriate hardware to run the virtual reality program:

1. Portability

Several immersive virtual reality setup such as CAVE requires a permanent installation which limits access to the tool. Despite requiring a powerful computer, it is also inconvenient to bring a desktop personal computer to different test locations during the study. Furthermore, a desktop PC also requires a stand-alone display which made the transportation of the tool more inconvenient.

2. Setup Time and Reliability

The virtual reality system for this study must be able to be transported anywhere without having to do a lot of preparation that takes a lot of time. Reliability is also an important factor as the peripheral must not fail during the tests.

3. Graphical Processing Power

The implementation of virtual reality requires a powerful hardware (Bridgewater, 1994). For the purpose of this research, it was decided that the research uses a notebook computer that is relatively easy to transport and quite durable. The computer's hardware specification is listed in the table below. At the time of this research is conducted, the following specification is deemed to be adequate to run the virtual reality prototype.

Table 4.3-1 Computer Specification for VR Prototype

CPU	Memory	Graphical Processing Unit
Intel Core i7 4k series, 2.7 GHz Quad-Core CPU	12 Gigabyte DDR3 SDRAM	NVIDIA GeForce 880m, 2500 MHz memory clock with 8GB GDDR5

4.3.2 Virtual Reality Goggles

Oculus rift is a head mounted display aimed for full immersion of virtual reality. This peripheral gives its wearer a 360 degree view of the virtual world. For the purpose of this study, two versions of Oculus Rift were used and studied. The decision of using different versions of Oculus Rift was based on each version's advantages over the other.

Figure 4.3-1 Oculus Rift Development Kit 1 (http://upload.wikimedia.org/wikipedia/commons/a/ae/Oculus_Rift_-_Developer_Version_-_Front.jpg)

Oculus Rift DK1 uses two lenses in a head mounted display enclosure that provides a 1280x800 pixels display. The display is divided into two sides for left and right eyes. Each eye could see 640 x 800 pixels. The head tracking is accomplished through 1000 Hz absolute 9 Degree of Freedom orientation sensor. The device's head tracking components can be broken down to a gyroscope, accelerometer, and magnetometer.

Figure 4.3-2 Oculus Rift DK 2 (https://dbvc4uanumi2d.cloudfront.net/cdn/4.3.12/wp-content/themes/oculus/img/order/dk2-product.jpg)

Oculus Rift DK 2, from herein referred to as DK2, features an updated display that provides its wearer a 1920 x 1080 pixels display. In addition to higher resolution, DK2 provides a more precise head tracking that could reduce the side effects of Importance of Low Latency Head Tracking.

Despite offering higher resolution and more precise head tracking, Oculus Rift 2 possess several weaknesses over its predecessor:

1. The display it uses is unable to duplicate PC's display.

2. The device has more wires than its predecessor, this is attributable to an additional depth camera to enhance the positional tracking.

4.3.3 Motion Control and Gesture Control Device

Motion Controller

Motion controllers are essentially normal videogame controllers with an addition of peripheral to track the controller's movement. The motion functionality enables its users to manipulate objects or give command using gesture or motion. The study identified two eligible candidates for the prototype's motion control device.

The first device is Razer Sixense motion controller which uses magnetic field in the form of a tracking ball shown in figure below to track controller's position. This system is developed for PC. Its software is compatible and can substitute mouse and keyboard input. Therefore, remapping the navigation control is not difficult. The drawback of this system is that it is still wired and needs to be connected to a USB port. The two sticks are not independent since they are still wired to the tracking ball.

Figure 4.3-3 Wired Motion Controller (Razer Sixense)

The second motion controller is Nintendo's Wii Remote (Wiimote). It consists of a controller that resembles a TV remote and a joystick. To acquire movement data, the device use built-in accelerometer installed on the remote part and a separate IR transmitter and receiver. This device does not natively support PC interface and requires hardware and software modifications. To allow the device to interface with Windows-based PC, a specific USB Bluetooth dongle compatible with Toshiba Bluetooth driver is required. After the device has been recognized by the Windows system, key mapping can be done using a third party freeware such as Touchmote.

Figure 4.3-4 Wireless Motion Controller (Nintendo Wiimote)

Table 4.3-2 Difference between Motion Controller Hardware

	RAZER HYDRA	NINTENDO WIIMOTE
1	Software driver natively supports controls in personal computer environment	Does not have official support for personal computer usage
2	The controllers need to be connected using USB port.	The controllers are wirelessly connected using Bluetooth connection.
3	Mapping keyboard function may require several OS reboots due to buggy drivers	Can be mapped to every keyboard and mouse function using appropriate software
4.	USB connection is relatively stable	The device connection can be easily interrupted if there is another wireless device in its vicinity. Needs a third party Bluetooth driver

Kinect as Gesture Control Device

The Kinect infrared projector illuminates a grid of infrared dots over every object within its view. The infrared dots, as the name suggests, are not visible through human eyes. Each Kinect is calibrated to recognize exactly where each projected infrared dot appears when projected against a flat surface within a measurable distance, this measurable distance is the Kinect's coverage area. If there is an object between the Kinect and the calibrated distance, the infrared dots will be pushed out of position by one direction. Since the Kinect is calibrated to recognize the original position of the dots, each of dot's displacement can be used to determine the object's distance from Kinect. The infrared camera will translate these dots displacements into depth data.

There certain limitations that are inherent in how the infrared system works. Kinect will only translate as far as any object that is within its coverage area. That means if there is a surface directly behind the object, the infrared will not be able to translate the object into a depth image.

Aside from the infrared camera, Kinect is also equipped with a color camera. The camera has a digital sensor that is similar to many web cameras with a relatively low resolution (640 by 480 pixels). Together with the infrared camera, Kinect can line up the color image with the depth information and produce a colored depth image.

In addition to cameras, Kinect has four other microphones. These microphones are not only able to capture sounds, but also recognize the direction where the sounds came from. Inside Kinect's plastic base are motor and a set of gears. By turning the motor, Kinect can tilt the cameras and the microphones up and down within thirty degrees. The addition of this motor is intended to enable Kinect to operate within a greater variety of rooms. Depending on the size of the room and the position of the furniture, users may stand closer or further away from Kinect.

The Kinect for Windows v2 sensor is a physical device with depth sensing technology, a built-in color camera, an infrared (IR) emitter, and a microphone array, enabling it to sense the location and movements of people as well as their voices. The latest sensor is capable of providing three times more fidelity that provides significant improvements in visualizing objects more clearly.

Figure 4.3-5 Microsoft Kinect V2

The version 2 of Kinect has overall better precision, responsiveness, and intuitive capabilities than the previous iteration. Kinect v2's camera is enhanced with full 1080p as opposed to v1's 480p camera, video that can be displayed in the same resolution as the viewing screen. The sensor can track as many as six people and 25 body joints per person. More importantly, these joints are more stable and anatomically correct with a broader range of tracking.

The prototype utilized Kinect to interpret user's gesture into keyboard strokes. The translation process was achieved using a third-party software driver called Control:Mapper. It is a Unity-based application that allows Kinect to recognize specific body gestures and promptly translate the gestures into different predetermined keyboard strokes as shown on figure 4.3-7.

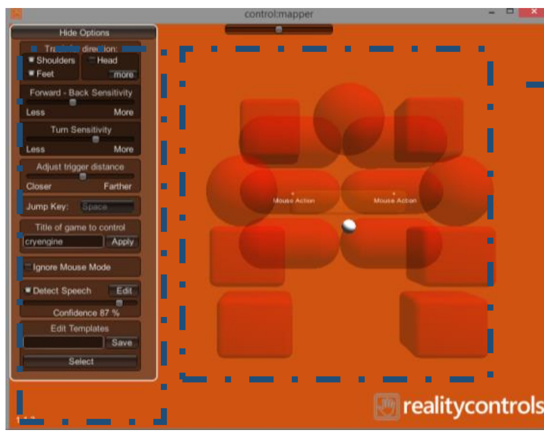

Figure 4.3-6 Control:Mapper Interface (c) reality controls

Another alternative is to use FAAST, a freeware developed by a faculty from the University of Southern California. This software is capable of recognizing a wider variety of gestures and compatible with Kinect V2. The earlier attempt of the VR development utilized Control:Mapper because it provides more precise gesture recognition than FAAST. A comparison between the software drivers are described in table 4.3-3. In general, both drivers provide similar functions. Except Control: Mapper is a paid software while FAAST is free. In terms of functions, FAAST offers more flexibility with gestures and compatibility with Kinect 2. On the other hand, Control : Mapper is more stable but less flexible than FAAST.

Table 4.3-3 Comparison between FAAST and Control:Mapper

Category	FAAST	Control:Mapper
Cost	Free	Paid application
User Interface	Text-based	Graphics by Unity Engine
Installation	Requires no installation	Must be installed on a system, requires online serial number check every time the software is booted.
Mapping Functionality	Ability to map a wide range of movements to any keyboard input.	Gestures are specified by the software, however the gestures can still be mapped to any keyboard input.
Stability	Never crashes.-	Frequently crashes, especially when there is another software is running on top of it. Possibility of memory issue but not addressed by the developer.
Sensitivity	Too sensitive, not suitable for complex controls.	Good, the software will always recognize the gestures as long as the user is within Kinect's coverage area.

4.4 Software Development

On the software side, it is important for program to be accessible by users with minimum experience in programming.

The prototype development made use of a video game engine which allows user to program the game by utilizing its visual programming system called flowgraph. The flowgraph system in the engine allows for a high level programming without requiring the user to understand a specific programming language. In flowgraph, each such node is a logical element (Flow Component) where each component has an arbitrary number of typed inputs and outputs, all inputs (except Events and any) contain default port values that can be modified with the engine and as such input ports also serve as component properties. User can still expand the engine's flowgraph system by creating their own nodes. For the purpose of accessibility, the research presented in this thesis experimented with different possibilities of visualizing the construction schedule as presented in a 4D modeling program such as Navisworks.

As a node, when a component receive a value or an event on a given input this input is said to be activated, and the Activate method of a component is called only once per step with potentially several activated input ports. This method then can check which ports where actually activated, retrieve the value of the input port and take any specific action.

A component can also arbitrarily activate any of its outputs, if this output is connected to the input port of another component, output event, or value it will immediately propagate the link and will activate the input port of another component. The output of any flow component can be connected to the input of another flow component with a directed edge. Outputs and Inputs are typed, they can be: booleans, floats, ints, strings, any type, or event type. When Output of one type connected to input of different type the reasonable type conversion on output value is applied when it propagates.

<u>Entities</u>

The main component of the prototype is the entities. Entities are class objects in which the player can interact in a specific way. It can be placed in the scene using the Objects tab of the RollupBar. There's a set of Entity components one per each entity class type, that exposes entity functionality (its events) Such components can be added in editor from selected entities and they internally hold an EntityId of the entity they linked with.

There are three types of entity used in this prototype:

1. Switch entity

Can be used to control various functions such as highlighting building elements by swapping textures of a selected geometry when activated, hiding certain geometries to facilitate the viewing of building interior, or controlling the construction sequence.

2. Proximity Trigger

   This entity is incorporated at a later stage of development. In the prototype, this entity is a part of the construction sequence system. The proximity trigger enables the switch to be turned on when a geometry entity enters its area of influence. Each switch stores information of building geometries associated with an activity.

3. Area Trigger

   For the purpose of this study, the area trigger is used as a dummy entity where the visual programming element is stored.

Geometry Entities (Geom Entities)

A Geom Entity is a very simple entity that takes its physical parameters from its assigned geometry. They are interactive entities with physical values, so they behave like real life objects. In appearance, the Geom Entities are similar to Basic Entities, but simpler, more efficient, and has fewer configurable parameters. Geom Entities can be incorporated with Cryengine 3's flowgraph system.

4.5 3D Model Development

4.5.1 Development of 3D Model

As the first step in developing the 4D model, two CAD models were developed in this study. The models are listed as follows:

1. Model 1

The model was developed as part of Innovative Project Management (CM 515) at graduate program of Construction Management of the University of Washington. The model consists of a three story reinforced concrete structure intended for office space. This model had been further developed with an addition of plumbing system used in later stages of the 4D model study.

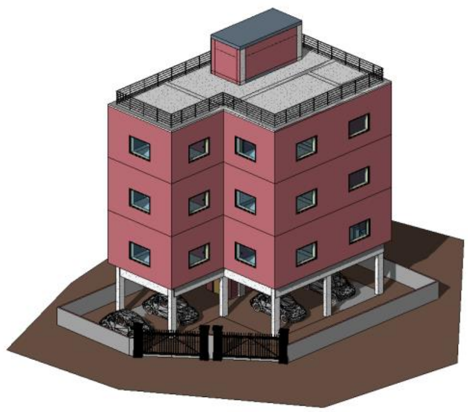

Figure 4.5-1 Model 1 in Revit

2. Model 2

This model was used under the permission of a Construction Management graduate student at the University of Washington. The building is designed to be used for both residential and commercial purpose. The ground level of the construction is aimed for retail spaces. The residential part of the building itself consists of two masses that intersect with series of terraces. In total, twenty residential units were planned.

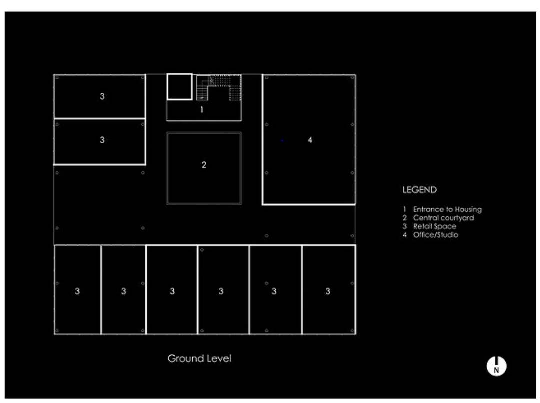

Figure 4.5-2 Ground Level Layout © Yansenlembono.com

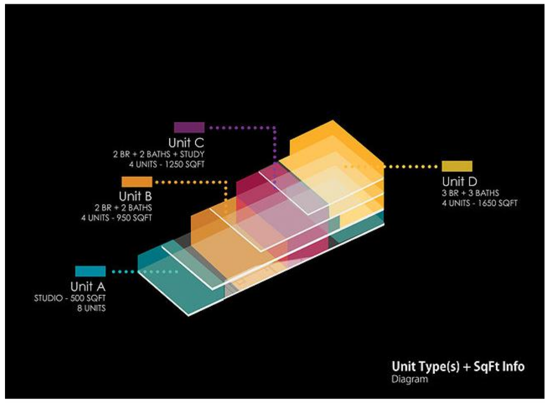

Figure 4.5-3 Detail of Residential Units © Yansenlembono.com

This model was used during the pilot study to address participants' ability to navigate within the virtual space. Due to its complexity, it is not used on the subsequent studies.

In order to translate the model into a format that recognizable by the virtual reality tool, which uses Cryengine 3, it had to be converted into a Sketchup-compatible model. In this study, the models were converted into an AutoCAD drawing (.dwg).

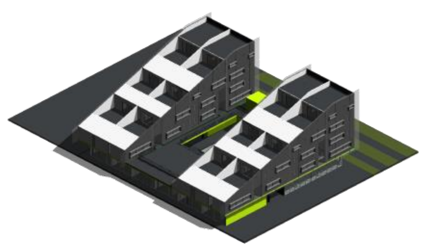

Figure 4.5-4 Model 2 in Revit

Most of the conversion process took place in Sketchup. The advantage of using Sketchup is its convenience in navigating through layers. Additionally, since the model was converted from a Revit model, identification of building components was more convenient because the each building component has been grouped in layers when converted into a .dwg file.

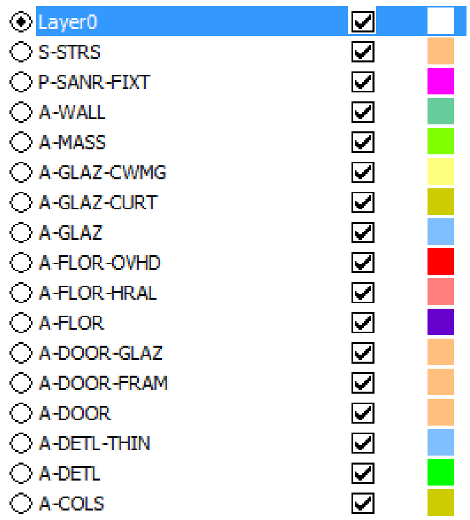

Figure 4.5-5 Layers in Sketchup

Despite the model already having layers that represents major building components, it was still necessary to divide the model into smaller components. When grouping the geometries into smaller components, specific names were given to make identification in Cryengine 3 easier. The list of component naming regulation is described in table 4.5.1-1. Each smaller components were converted into .cgf files which is currently the only format recognized by the Cryengine 3. Files with .cgf extensions were considered as individual geometry that can be assigned as an entity in Cryengine 3. Further explanations regarding Cryengine 3 entity system will be covered in the next section within this chapter.

Table 4.5-1 Naming Convention for Cryengine Geometries

No.	Layer Name	Major Group Function	Individual Component Group	Geometry Name
1	A-STRS	Stairs	Separate components for each level (Level 1-4)	Th_stairs#
2	P-SANR-FIXT	Piping and Plumbing Fixtures	Separate pipes and fixtures	Th_plumbing Th_plumbing_fixt

3	A-WALL	Wall Fence	Separate components for each level (Level 1-4)	Th_wall# Th_wall_fence
5	A-GLAZ-CURT	Curtain Wall	Separate components for each level (Level 1-4)	Th_glaz
6	A-FLOR-HRAL	Handrails	Separate components for each level (Level 1-4)	Th_railings#
7	A-FLOR	Slabs	Separate components for each level (Level 1-4)	Th_slab
8	A-DOOR-GLAZ	Glazings	Separate components for each level	Th_doors#
9	A-DOOR-FRAM	Door frame	Separate components for each level	Th_doorfram#

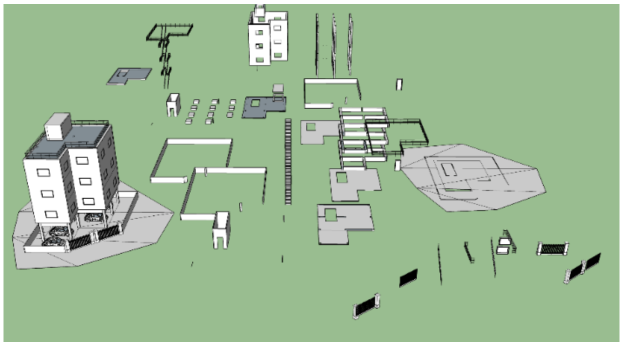

Figure 4.5-6 Separating Model into Smaller Components

Once all components had been converted into Cryengine 3's geometry files, the building geometries must be reassembled from the individual geometry components within Cryengine 3 environment.

It should be noted that materials from Revit do not carry over to Cryengine 3. All materials must be redone and exported using a plug-in supplied by Cryengine 3. The chart below illustrate the 3D geometries aspects that must be considered.

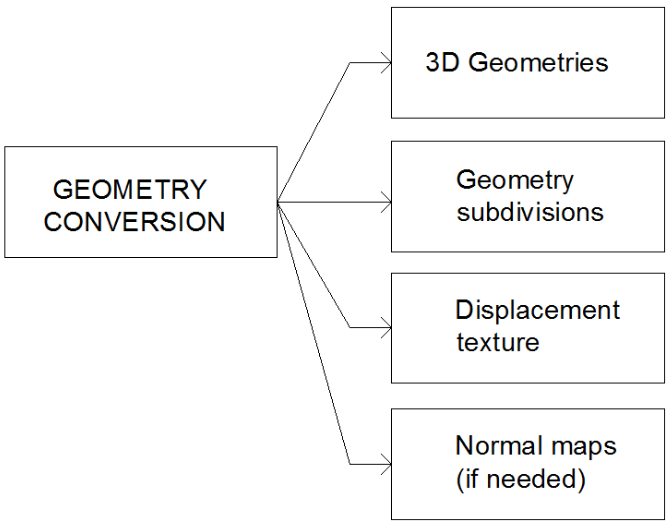

Figure 4.5-7 3D Geometries Conversion Aspects

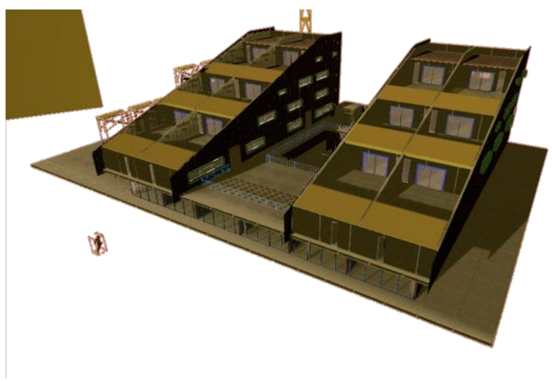

Figure 4.5-8 Model 2 in Cryengine 3

4.5.2 Translating construction schedule into a game logic

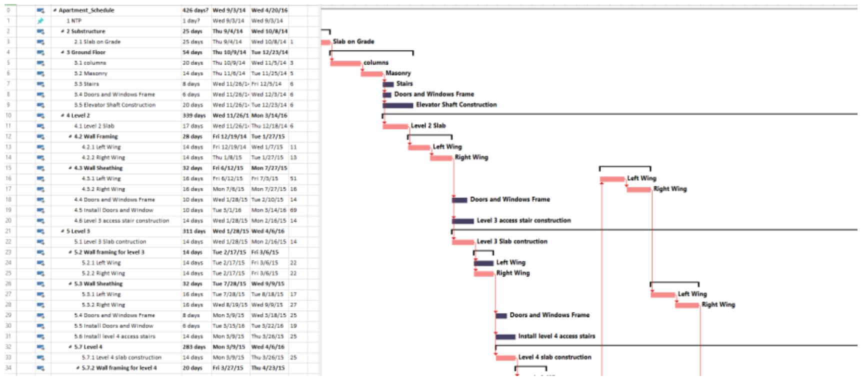

Figure 4.5-9 Construction Schedule in common Construction Application

A construction schedule which consists of 69 activities developed in Microsoft Project had been developed as part of the 4D model development. After the schedule had been developed, all activities within the schedule will be translated into Cryengine 3’s visual scripting. Similar to other 4D CAD tools, developing a 4D CAD model in Cryengine consists of associating the schedule with every geometry of the building.

4.5.3 Simulating the 4D Sequence

At the beginning of the simulation, all building geometry are hidden. As the construction progresses, each geometry that corresponds with its activity will be shown. This can be achieved by linking the geometry with the “hide” and “unhide” ports of Cryengine 3’s flowgraph system. The construction sequence will proceed based on an input made by the participant. The input can be a button press, a gesture, or a voice command.

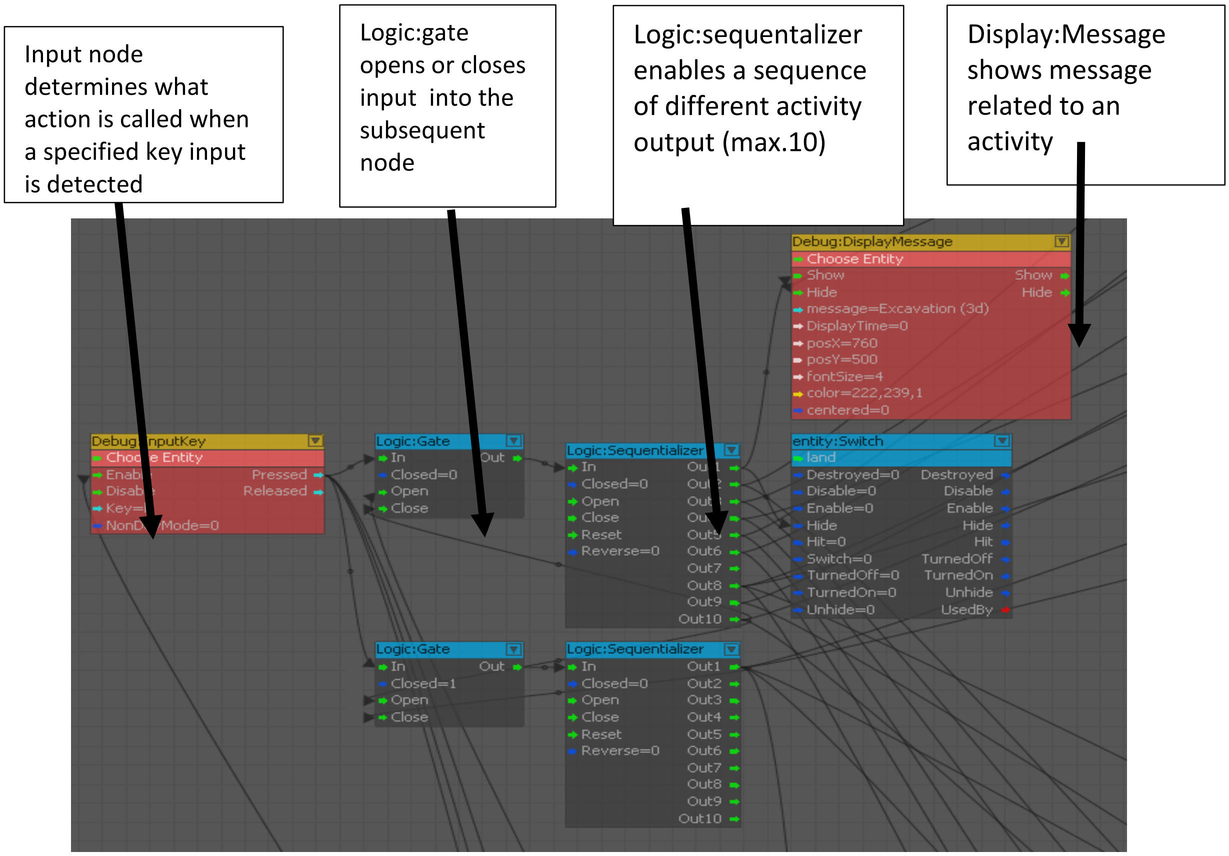

Figure 4.5-10 Typical Flow Graph Structure for a Construction Sequence

In the first few iterations of the tool, the logic:sequentializer flow graph nodes were used as a system to represent each activities on the CPM schedule. Each node's output represents construction activities and will show either building components or name of the construction activities. Each building component such as column, beam, or wall, is represented as a single entity flow graph node. The "hide" and "unhide" are the functions that let the program control whether building component must be shown or hidden.

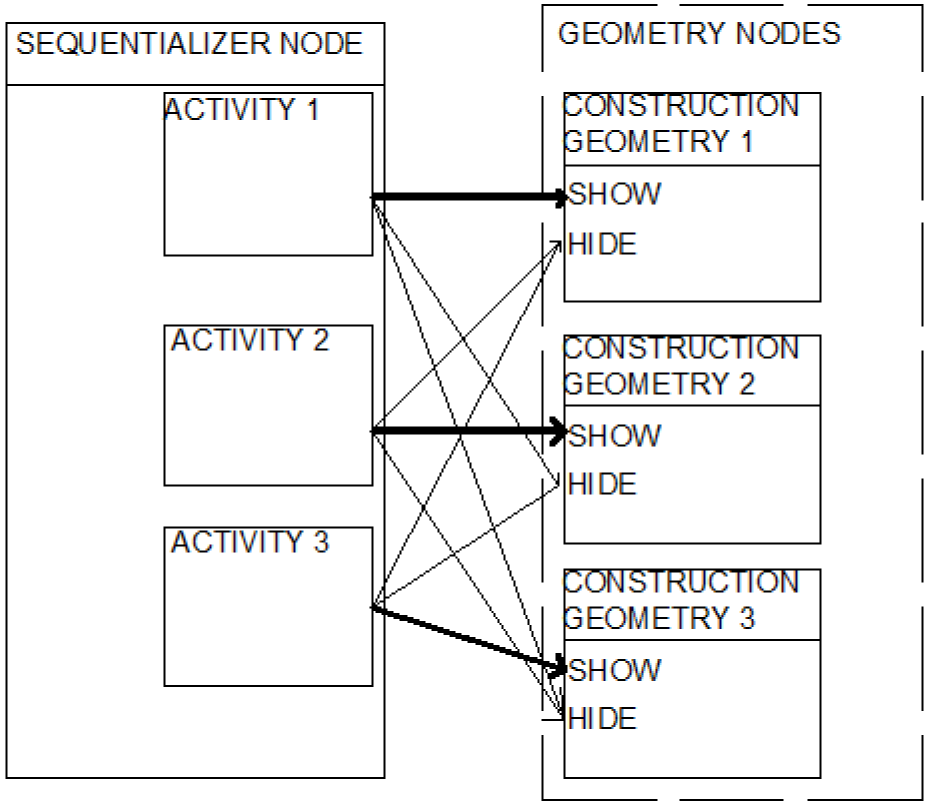

Figure 4.5-11 Building Components as Switch Entities in Cryengine 3 Flowgraph

Upon program start, all building components will be hidden. Input from a button is relayed to the *sequentializer* node. Each *sequentializer* nodes has a maximum of ten output whereas each output represents the construction activities. Each of the *sequentializer* output will show the hidden building components and display a message containing information of current activity and duration of that activity. The sequence was tailored to mimic Navisworks mechanism in showing the construction phases. To increase sequentializer node's capacity, multiple Logic:sequentializer nodes were used and linked by a logic:gate flow graph node The first logic:gate node will block any input towards current logic:sequentializer node while the second logic:gate node will open the input towards the next logic:sequentializer node.

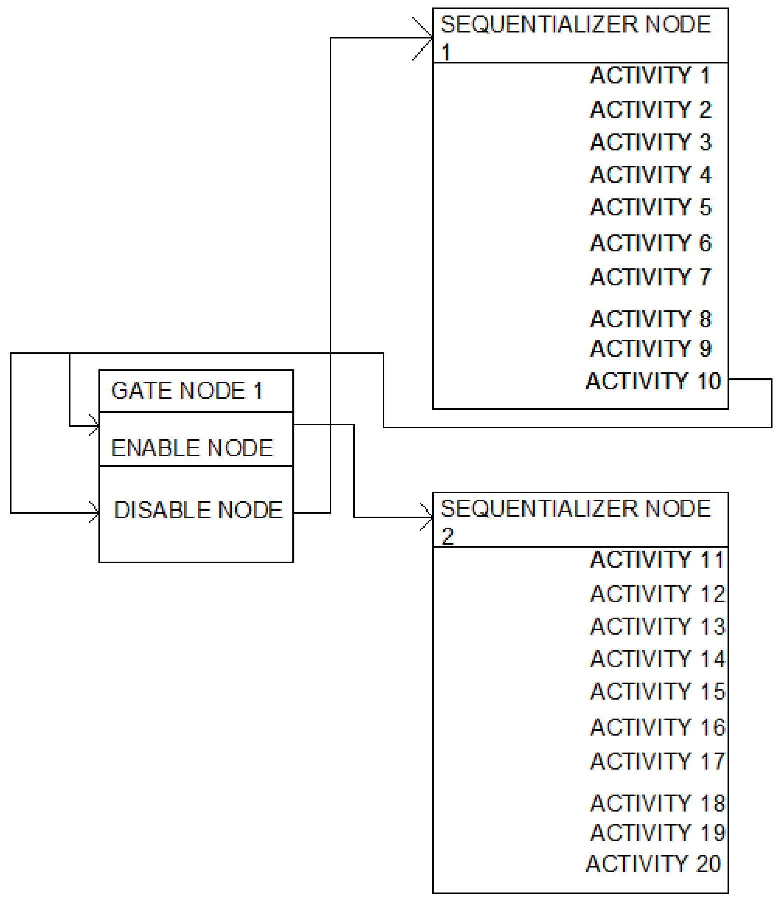

Figure 4.5-12 Combining Several Logic:Sequentializer Nodes to Allow More Output

However, this method had a flaw. The user will only be able to play the construction sequence forward and the only way to rewind the construction sequence is to play the sequence all the way until the end of the schedule. The last input will hide all construction geometries to restart the sequence and the next input will start from the first logic:sequentializer node. Modifying the construction sequence takes a large amount of time since the output has to be manually reassigned to all building geometries and the visual layout can be confusing as shown in the figure below. This method was used during the pilot studies until a more flexible method was devised.

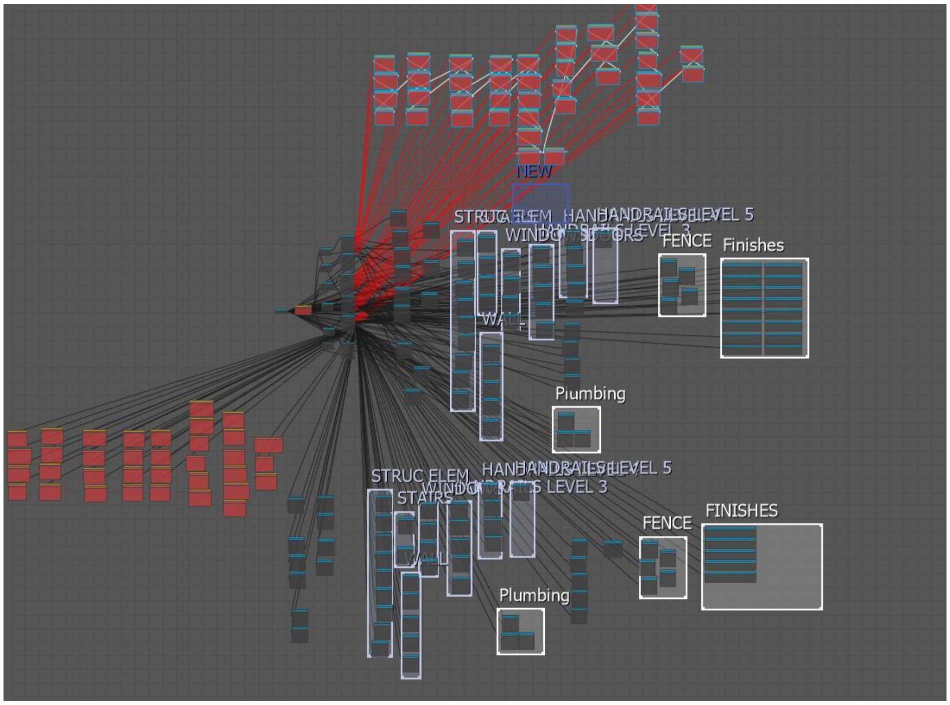

Figure 4.5-13 Overall Visual Programming Components in the VR Prototype

Chapter V Test Phases and Analysis

5.1 Tests and Prototype Update

The first phase the study produced a set of error scenario to be tested with the VR tool. The VR tool were used with participants from different level expertise, starting from those unfamiliar with the technology.

This chapter explains the second and third phases of the research. The explanation will cover the test results and the subsequent development of the prototype. The tests are divided to pilot tests and actual tests. As the name suggests, the pilot tests involved various build of the prototype and was mainly aimed to fine tune the prototype and study the stability of the hardware. The actual tests

Table 5.1-1 Test Timeline

Phase 2			
Tests	Participants	Timeline	Hardware
Pilot Studies	Students	September 2014	OculusRift DK1 + Game Controller
		October 2014	Oculus Rift DK2 + Kinect
Phase 3			
Industry I I	Professionals	December 2014	Oculus Rift DK2 + Kinect
			Oculus Rift DK2 + Hydra
Industry Test II		February 2015	Wireless Oculus Rift DK1 + Wiimote

5.2 Second Phase: Pilot Tests

1st batch of Pilot study

The first batch of the study was conducted in Indonesia, with eleven undergraduate students of Construction Engineering Management who has had no previous experience in 4D modeling and virtual reality. The pilot study acted as a stress test platform to determine whether the model is appropriate and easy to navigate in. The model used for the first pilot study was model 2. A scenario was also prepared in which the construction activity is not sequenced properly.

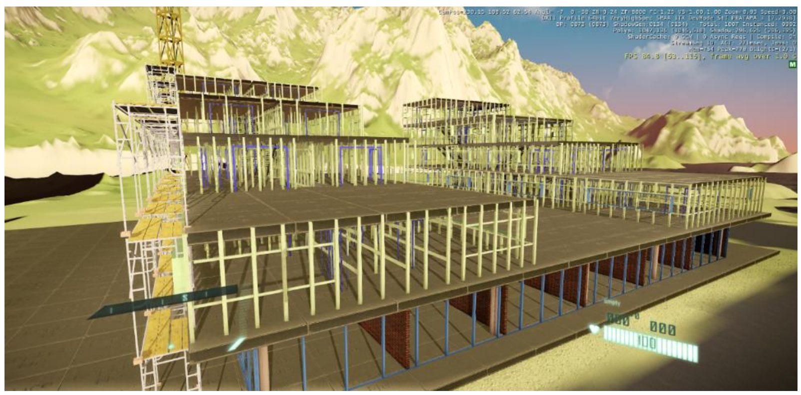

Figure 5.2-1 Visualization of a Construction Activity in the immersive virtual reality environment

In the pilot test, participants were allowed to explore the virtual construction environment, participants may choose either "walk on foot" or "free camera" mode. After the test, participants were tasked to fill in an assessment form to address the mistakes in the construction sequence.

Figure 5.2-2 1st Batch of Pilot Test

Few participants managed to wear the headset for more than ten minutes. Most of the participants mentioned that they experienced headaches and motion sickness after removing the VR headset.

Out of eleven participants, only one participant felt normal after using the VR prototype. Most of the time, participants found themselves “trapped” inside the building due to the complex layout of the building. The lack of ability to quickly move between several important viewing points such as aerial camera, building interior, and building exterior further contributed to the confusion of participants.

Since the test was conducted using a wired video game controller, participants felt that it was not effective to use virtual reality yet. Regardless of the drawbacks, participants were able to identify errors with the model and provided feedback used for further development of the tool.

As demonstrated in figure 5.2-2, the result of the first batch test varies greatly with only sixty percent of participants were able to identify errors on the floorings activity, but ninety percent of participants were able to identify error in the framing activity.

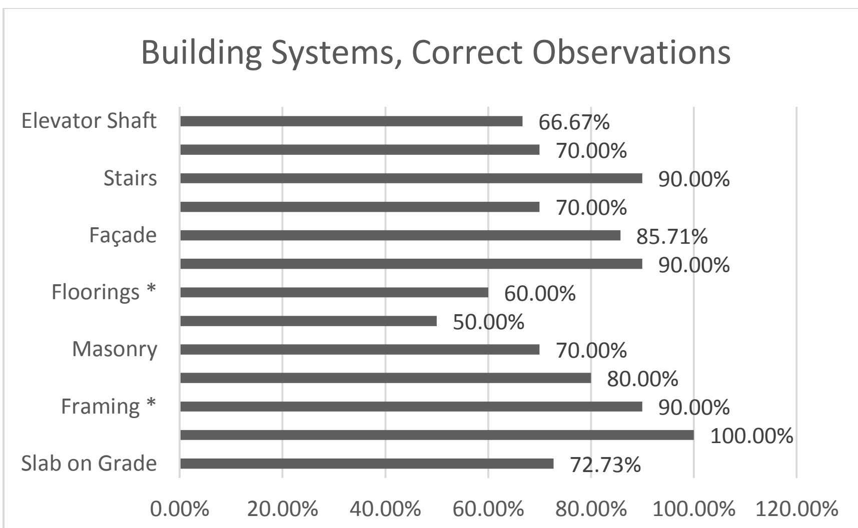

Figure 5.2-3 Correct Observations by Participants

2nd batch of Pilot study

The pilot study conducted earlier in August 2014 showed that, given the state of the tool at the time, only a number of participants were able to identify errors in the sequence. Ten out of eleven students experienced motion sickness after using the virtual reality tool. This may be attributed to their minimal experience with moving in 3D virtual world and seeing 3D images.

Additionally, the complexity of model 2's layout increased the difficulty significantly. Therefore, model 1 with simpler layout and less activities was used to accommodate the test time.

Figure 5.2-4 Model 1

The second batch of the pilot study was conducted on September 27, 2014. In this batch, two students were selected as participants to test the virtual reality tool with updated control and newer hardware. In the updated tool, a higher resolution VR goggles and a motion tracking device were added.

The goal of this second batch of experiment is to study whether the updated virtual reality tool could eliminate problems faced by participants of the first batch of the study. The virtual reality tool was updated with training session to familiarize with the control. Participants were given three sets of tasks:

1. The first set of task was to navigate the avatar within a straight corridor to reach the "finish" line and return to the starting point three times.
2. The second task set the training session aimed to test the basic functionality of the tool. Participants were given a simple 4D model of a house consisted of wall, roof, and window. In this sessions, participants were asked to play the construction sequence three times, change their viewpoints to inside the building, and mark a certain part of the building.
3. The third set of tasks let player navigate inside and out of a more complicated building. A basic model of a four-story building was used as the "level". To complete this sessions, participant must go inside the building, reach the top level of the building, and return to starting point outside of the building.

The results showed that both participants had minimal trouble after using the virtual reality tool. Both participants did not report experiencing motion sickness when asked. Interestingly, both participants demonstrated different levels of maneuverability within the immersive virtual environment despite both demonstrating generally equal maneuverability using a videogame controller.

Table 4.3.3-2 Comparison of Time Spent Using Non-Immersive and Immersive VR

Pilot Test Participant	Experience with VR/4D	Training 1		Training 2		Training 3	
		Videogame Controller	Goggles + Motion Tracking	Videogame Controller	Goggles + Motion Tracking	Videogame Controller	Goggles + Motion Tracking
1	N	1:50	0:57	0:52	2:39	2:04	1:52
2	4D	1:11	1:07	1:04	3:00	2:24	5:12*

Later, it was found that the second participant had difficulties navigating in the VR environment due to the tool's limited motion tracking capabilities. Especially during the third training session, the second participant often made incorrect gestures and sometimes moved outside the motion tracker's tracking coverage. Both participants reported having trouble maneuvering within the VR tool because they could not walk slowly.

3rd batch of Pilot study

Addressing problems identified on the second batch of experiment, the tool was revamped with increased sensitivity and capability to move slowly. The third training session was updated with a 4D model. The 4D model used the same model 1. In the third session, participants are tasked with identifying error in the model.

Two scenarios were developed. In one scenario, a structural element was removed from the sequence, leading to an incomplete schedule. The second scenario moved the construction of stairs after the construction of masonry wall, leading to an incorrect sequence. Two participants were selected for this experiment. Both participants has limited experience in the construction industry, but one participant mentioned having experience using virtual reality device (CAVE-like system). Participant #3 has a civil engineering background while participant #4 has background in architecture.

Participants reported the same difficulties when moving, especially when navigating inside a building. One participant was found to be having some disorientation when using the VR tool which caused the participant to physically move outside the motion tracking range. However, participant #4 was able to identify an error compared to participant #4 who could not point out the exact error. Participant #3 often focused on criticizing the physical representation of the building. Participant #3 criticized that the beam system was incomplete despite being actually present in the 4D model, but participant #4 overlooked the fact that one activity was actually missing. Despite having an experience with a CAVE-like system, it took slightly longer for participant #3 to complete the first two training sessions. Participant #3 failed to identify all errors in the third training session and it took the participant approximately 13 minutes before dropping the test .

Figure 5.2-3 Usage duration between participants in pilot studies

Participant	Experience with VR/4D	Training 1		Training 2		Training 3	
		Videogame Controller	Goggles + Motion Tracking	Videogame Controller	Goggles + Motion Tracking	Videogame Controller	Goggles + Motion Tracking
3	N	3:01	2:28	2:05	2:06	12:00	13:53
4	BOTH*	1:09	1:53	1:35	1:42	2:05	1:05

**did not finish the test*

A demonstration in which people were allowed to try the prototype was made during University of Washington's open house at Sand Point on October 2014. Additional demonstration was also conducted at the University of Washington's Capital Project Office on the following week. No data was collected during this demonstration, the demonstration was aimed to raise people's awareness of how the VR technology can be implemented for construction industry.

5.3 Phase Three: Industry Tests Part 1

Two tests were conducted on December 17th and 18th on two groups of participants from different companies. Each groups consists of three participants. In one group, the participants used the immersive virtual reality tool and in the other group, participants used the non-immersive virtual reality tool. Table 5.3-1 below lists the equipment used in the two tests.

Table 5.3-1 System Setup for Non-Immersive and Immersive VR

	Non-Immersive VR	Immersive VR
Input device	Motion controller (Razer Hydra) Motion controls for advancing the construction sequence. Controller buttons and analog stick for controlling movement,	Motion sensors (Kinect and Kinect v2) • Kinect v1 detects upper body gestures (turning, advancing construction sequence, cycle viewpoints, make wall transparent, marking building components) • Kinect v2 detects lower body gestures (walking)
Display	Normal flat-screen display 32 inch, 1920 x 1080 LED Display	Virtual reality goggles (Oculus Rift DK2) 960x1080, 75 Hz
CPU	Laptop (2.7 GHz Quad-Core CPU, 12 GB DDR3L SDRAM, 2500 MHz GPU memory clock, 8GB GDDR5)	

Table 5.3-2 demonstrates usage duration from both companies. The duration is measured from the beginning of the test until participants identified the first error. In general, it takes longer to identify using conventional methods.

Table 5.3-2 Usage Duration between Participants

Participants	Duration of usage		Level of Experience in Construction Industry	Experience with 4D CAD Software
	VR Prototype	Conventional		
1	6:47	15:25	1-5 years	Y
2	4:46	5:17	1-5 years	Y
3	2:53	5:51	1-5 years	Y
4	5:00	11:10	1-5 years	Y
5	6:29	N/A	6-10 years	Y
6	5:39	N/A	5-8 years	Y
7	4:38	N/A	< 1 year	Y
Average	5:10	9:25		

Despite taking shorter amount of time, participants tend to express concern regarding the duration it takes to set the equipment. Due to time concern, participants 5, 6, and 7 did not take the conventional tests. These participants were involved in the non-immersive VR test using normal display monitor.

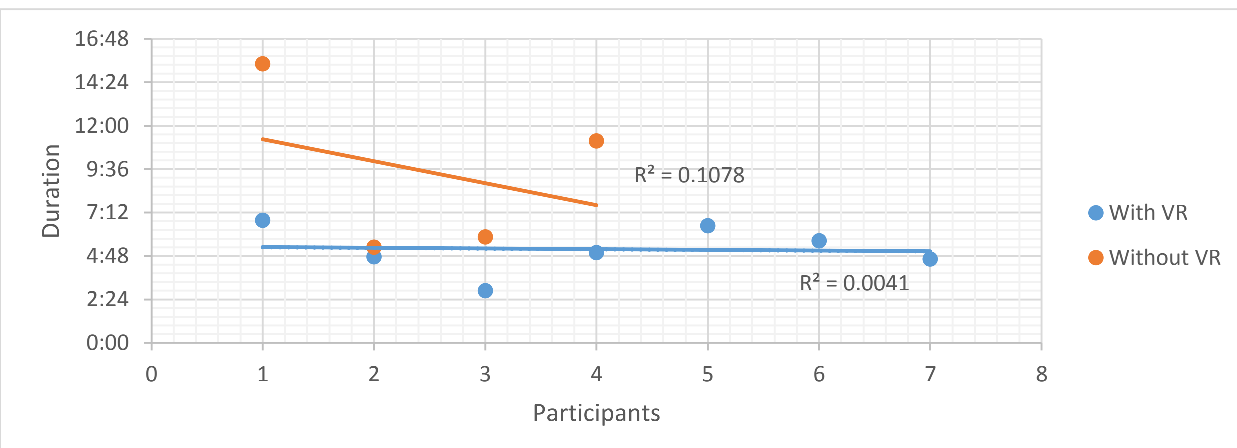

Figure 5.3-1 Usage Pattern

Both teams, despite having been given training in navigating the immersive and non-immersive virtual reality environment, faced difficulty in identifying an error within the sequence.

Generally, participants from both of the VR groups only played the construction sequence once and were able to identify the error sooner than using Navisworks. However, within time spent on Navisworks and VR tool, participants were able to identify more errors in Navisworks than the VR tool. When using the Navisworks tool, participants tend to spot more errors that is not intended for the scenario they were assigned with. Participant 7, for example found two other mistakes in the sequence prior to identifying the error in the scenario (stairs, illogical sequence). Instead, the participant spotted error that the fence posts should be done earlier before construction the fence walls.

The same pattern occurred with other participants when they were using Navisworks. The fixed view point in Navisworks aided them in viewing the overall construction site. In the VR prototype used for the experiment, participants spent most of their time inside the building. Therefore, when there was an activity that was supposed to take place outside of the building, the participants could not see the activity. However, when it comes to viewing specific building element such as MEP, the virtual reality helped the participants identifying the problem faster than Navisworks.

5.4 Phase Three: Updates

Questionnaires were distributed among participants in the second phase of the study. From the results, several problems were identified and solutions were developed to overcome them. Table 5.4-1 shows the solution for each problems experienced by the participants. The biggest problem participants faced during the test was the inability to rewind the construction schedule. The problem came from the game engine's inability to index the flowgraph entities using its default flowgraph nodes. To solve the problem, the sequence controller flowgraph must be rebuilt. Details on the updated construction sequence controller will be described in the subsequent section.

Table 5.4-1 Problem and Solution Table

Number	Problem	Solution
1.	Inability to rewind the construction schedule.	Rebuilt the flow graph system
2.	Frequently falling to the ground when cycling viewpoints.	Added movement constraints at each view points
3.	Inability to view the overall construction site.	Added a fixed camera position, the tool will start in a fixed camera position.
4.	Inability to view construction schedule.	Added a schedule viewer system within the tool.
5.	Navigation control, difficulty while turning, and cluttered wires	Increased sensor sensitivity, devise a wireless virtual reality setup.
6.	Disorientation when using the immersive VR	Use normal controller.

Changes on the following aspectes were made after the tests with the first two construction firms:

1. Ability to control the sequence
2. Ability to automatically play the construction sequence.
3. Visual aid to identify newly construction building elements
4. Ability to view the CPM schedule

5.4.1 Hardware Updates

On the hardware aspect it was decided that participants need to have an impression of not connected to a computer. Therefore, it is paramount for the VR hardware worn by participants to be wirelessly connected to the PC.

The VR goggles were modified to run wirelessly through wireless internet connection. Generally, the Oculus Rift is made of two systems: display adapter and headtracking data which are connected through HDMI and USB connection. It is possible to use wireless HDMI adapter and wireless USB emitter to eliminate the requirements for wired connection to the PC. Two battery packs are used to power the device, as demonstated in the figure below.

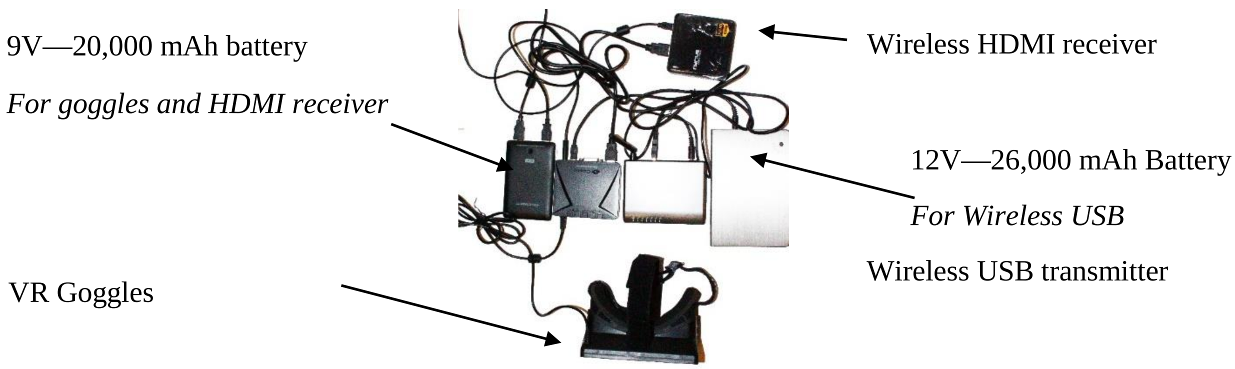

Figure 5.4-1 Wireless VR Goggles Modification

In order to make the device wearable, all components but the goggles are put in a backpack. Since the system's performance relies on Wi-Fi reception. Therefore, performance may vary depending on the location it is used.

5.4.2 4D System Update

Since the game engine does not initially support a flexible input sequence, it was decided that development abandon the logic:sequentializer node. As a replacement, a separate system comprised of a number of switch entities was devised. Each switch entity in this system relates to one activity in the construction schedule. To remotely activate the switch entities, a group of proximity trigger entities are placed on the virtual world and linked to each switch entities. A proximity trigger entity will be activated when an object or entity is within its area. Therefore, a trigger object is also created. This trigger object is a geometric entity that will be beamed to the a proximity trigger next to it when a key input is detected. Table 5.4-3 outlines the entities used for the system.

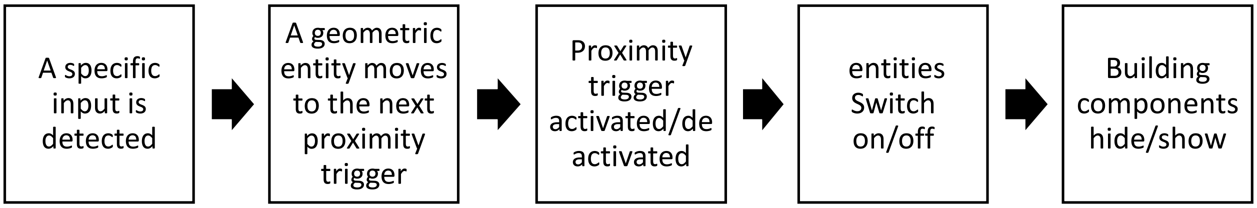

Figure 5.4-2 Logic for updated sequence controller system

There are two flowgraph groups that control the switch system as outlined in figure 5.4-4 and 5.4-5. The switch system is made of several physical entities that can be controlled (figure 5.4-3). It is comprised of 49 entities that act as marker, at each markers, a proximity trigger (4) is placed. These proximity triggers will activate each activities when an object is within its vicinity. Therefore, a primitive geometry that acts as a trigger object (1) is created. The trigger object will move to the next or previous proximity trigger when a key L or R is pressed. To optimize space in the virtual world, the proximity triggers are configured in several lines. Proximity triggers on (4) position will beam the trigger object to the next position (3).

Table 5.4-2 Entities descriptions for sequence controller system

Number	Name	Entity Type	Function
1	Control Box	Geometry Entity	Control box, will move between proximity triggers.
2	Trigger Box	Proximity Trigger	Triggers the switch that corresponds with each construction activities.
3	Beamer Box	Proximity Trigger	Change the control box position to box #4
4	Beamer Box	Proximity Trigger	Change the control box position to box #3

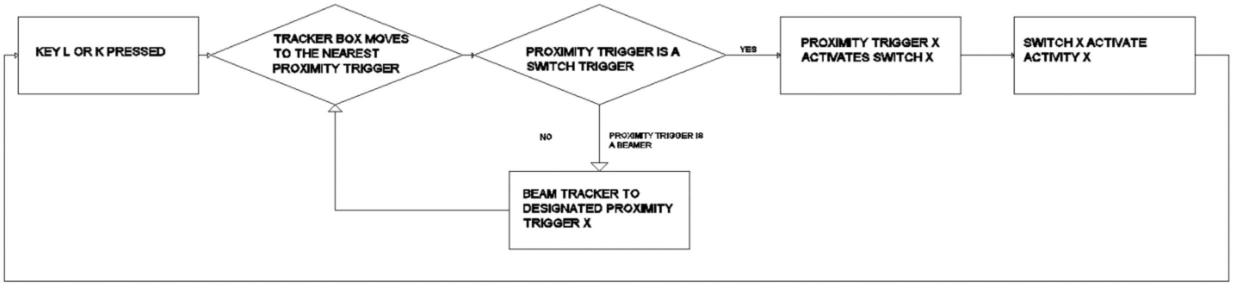

Figure 5.4-3 Logic for Construction Sequence Module

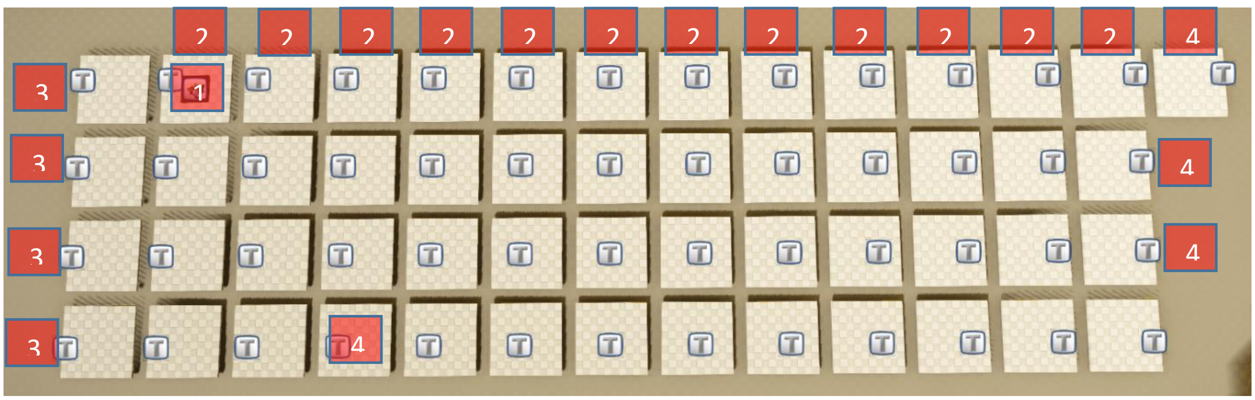

Figure 5.4-4 Controller box system in game engine

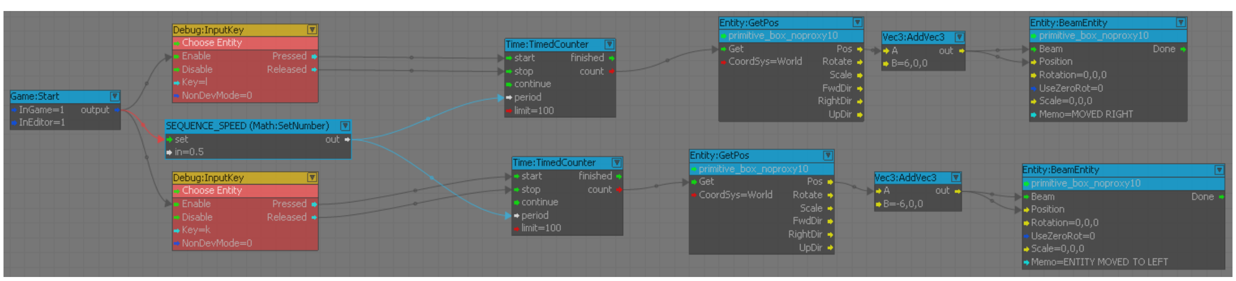

Figure 5.4-5 Control Box Flow Graph

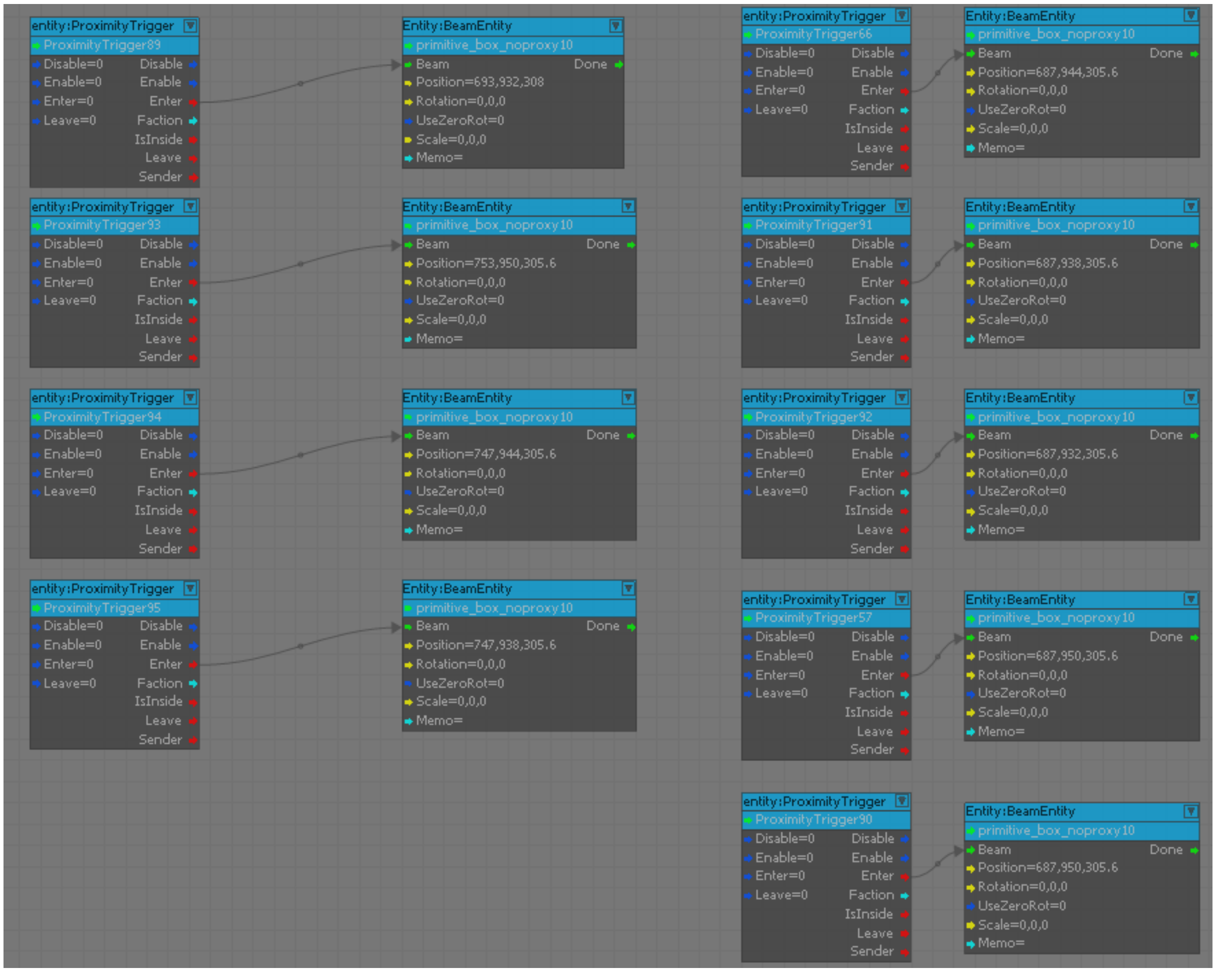

Figure 5.4-6 Teleporter Box Flow Graph

The switches are embedded into the flowgraph system, and each switch is linked to one construction activity. Each activity module contains identical flow graph nodes composition that represents every building geometries, material information, and schedule components but will have different link depending on which building components will be displayed or hidden. The amount of activity modules equals to the amount of activity on the schedule. A typical breakdown of activity module is shown in figure 5.4-6.

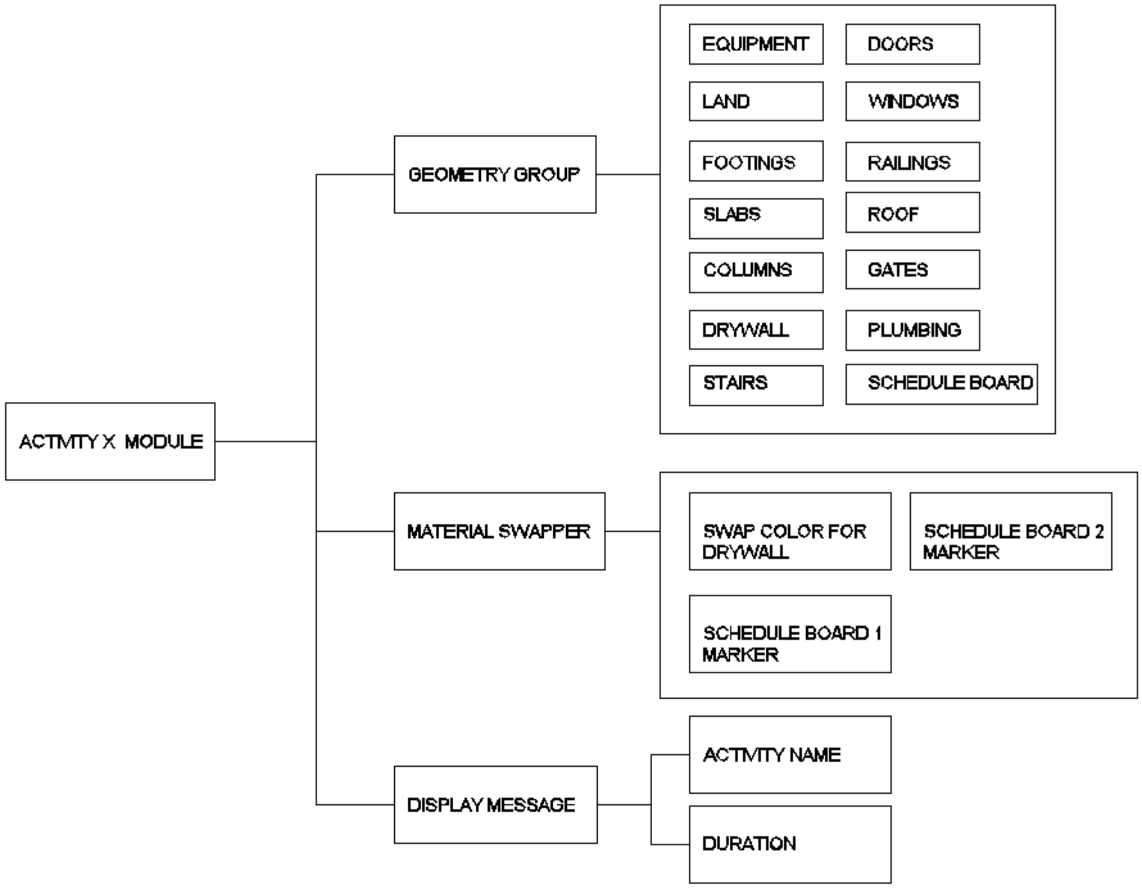

Figure 5.4-7Activity Module Breakdown

Interpreting the module into Cryengine 3's flowgraph system requires grouping every building geometry flowgraph nodes, material swap flowgraph nodes for building geometries and schedule boards, and display message flowgraph node. Every group represents one construction activity and will be triggered by the corresponding trigger entity.

By using this method, the problem with rewinding construciton sequence is eliminated. Furthermore, adding or removing activities becomes more flexible because every activity has its own flow graph node groups. The overalll final flowgarph configuration is illustrated in Figure 5.4-8

Figure 5.4-8 Final 4D System Flowgraph

5.5 Phase Three – Industry Tests Part 2

Due to the limited time and available equipment, a different approach is taken. Instead of involving participants individually evaluate a 4D model, four participants of different experience were put in a group. Coincidentally, each member represented three out of five Dreyfus' model of learning stages.

Table 5.5-1 Collaborative Participants Demographics

Participants #	Experience in company	Learning Stage	Role
1	>10 years	Expertise	Leader
2	5 years	Proficiency	Member

3	3 years	Competence	Member
4	1 year	Competence	VR Navigator

None of the participants fall in the first second group because they have similar background. All of them have construction management degree and done scheduling prior to joining the company.

The leader, who fell under Dreyfus' fifth group, is a scheduler with extensive experience. His duty is to lead the 4D model evaluation and to provide suggestions on what should be seen by the 4th member. On the other hand, the youngest member with the least experience was appointed as the "navigator" who control and navigate within the virtual reality application.

The combination of knowledge from various member's experience improved the test results. Previous studies with only one person navigating the VR and evaluating the 4D model showed that people were focusing only to find a specific error. However, with the help of team members outside the virtual environment and the expertise level of the leader, the participants found several errors not only related to the schedule, but also safety issues and flaws on the model.

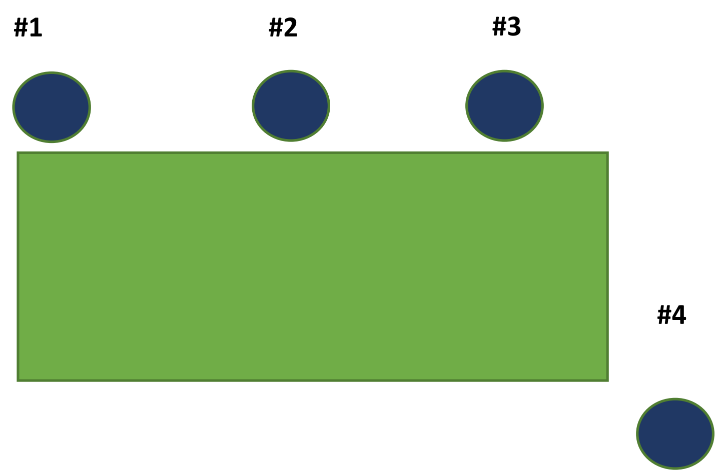

Figure 5.5-1 Group Based 4D Evaluation Model

The study was conducted in two parts. In the first part, participants evaluate a 4D model on Navisworks and in the next part participants use the VR to evaluate 4D model. A 15 minutes time-limit was given to participants. However, participants are allowed to call off the evaluation once the leader feels that they have found all errors.

The results were different in which a discussion takes place between the team members. The team did not only manage to find designated errros in the model but also give feedback on the model such as incorrectly placed slab on grade and the finishing activity should be separated into interior and exterior finishes.

Table 5.5-2 Error Identification in Navisworks and VR Prototype

Industrial Study	Rate of Error Identification		Errors identified
	Normal	VR	
#1 (Company 1 and 2)	1	1	• Scheduling error (incorrect sequence and missing activities)
#2 (Company 3)	10	18	• Scheduling error • Safety concerns

The collaborative study group produced a different result when compared to the results from the individual study group. Participants in the individual study group spent shorter time on both Navisworks and VR evaluation. It took almost twice long for the collaborative group to evaluate the error in Navisworks. The collaborative group was able to complete the evaluation much faster in VR than Navisworks.

However, in terms of error identifications, the collaborative group was able to identify more errors than the individual groups.

5.6 Influence of Virtual Reality on Identifying Construction Activities

Based on the response provided by nine participants throughout the industry studies, the immersive virtual reality might be effective to identify specific construction activity. Figure 5.6.1 and 5.7.2 illustrates that main structure components (beam, slab, columns), roofing, doors and windows, and MEP are relatively easier to identify in virtual environment than non-virtual environment. However, when it comes to substructures and finishes, participants generally prefer non-virtual reality visualization.

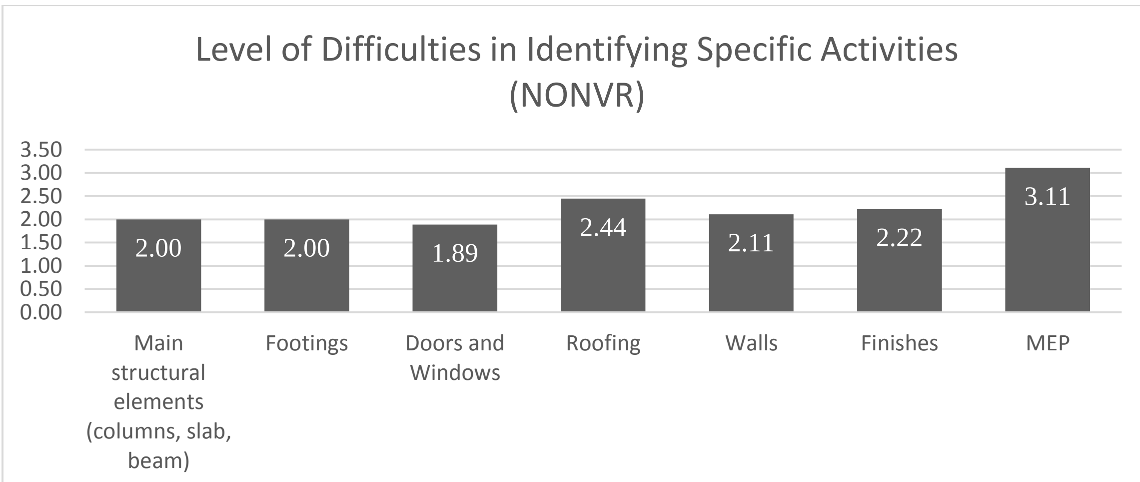

Figure 5.6-1 Level of Difficulties in Non-VR Environment

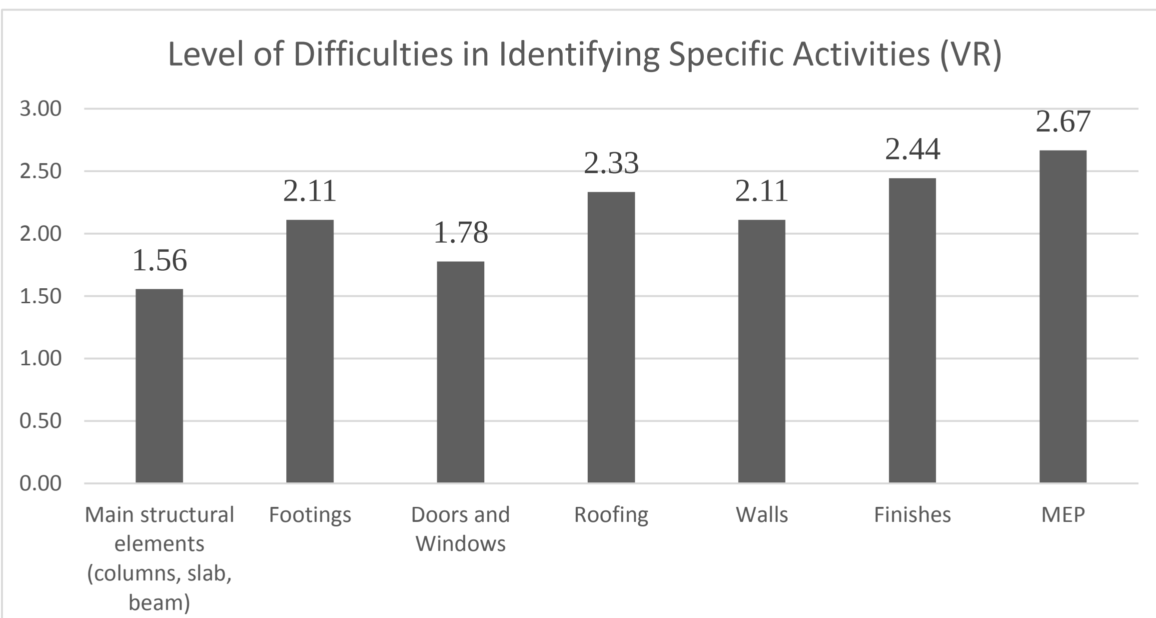

Figure 5.6-2 Level of Difficulties in VR Environment

5.7 Important Aspects of 4D modeling in Virtual Reality

Another post-experiment survey was distributed to the participants after each test about important aspects of 4D modeling. Exclusively for the test on final phase, only the participant who used the immersive VR prototype was given the post-experiment survey. It should be noted that the result may apply only to the prototype used in the research. Figure 5.7-1 through 5.7-3 summarized the responses received from participants.

Most participants thought that ability to control sequence are the most important features with 57% of participants' response indicating sequence control is a very important feature. Navigation becomes the second mos important features with 57% of participants indicating that navigation is a very important aspect, while 14% thinks that navigation is not so important after all. However, participants seems to be having mixed opinions regarding ability to access activity information.

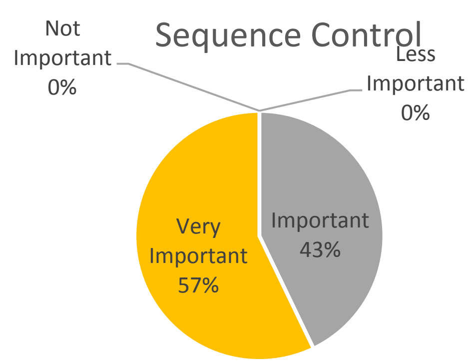

Figure 5.7-1 Participants' Opinions on Sequence Control Aspect

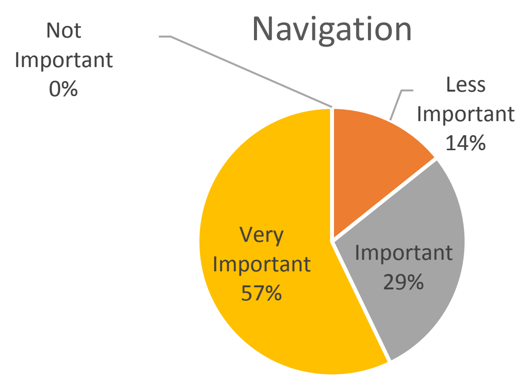

Figure 5.7-2 Participants' Opinions on Navigation Aspect

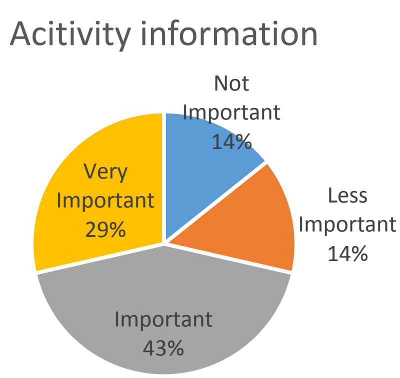

Figure 5.7-3 Participants' Opinions on Activity Information Aspects

Chapter VI Conclusions

6.1 Research Summary

Developing a Videogame Engine-based Immersive 4D Virtual Reality System

Currently, videogame engine is the most viable platform to develop a virtual reality application. The engine used in this research provided a visual programming solution that enables people with the least programming experience to conduct the programming. From the research, it can be concluded that the following components are needed for developing the system:

1. Conversion tool to convert 3D geometries from CAD software application into a format recognized by the videogame engine
2. The main construction simulation sequencer
3. The study also showed an interesting phenomenon in which people wearing the VR headsets tend to process information presented in 2D planes such as schedule information and charts slower than 3D geometries.

Different level of proficiencies

In conducting the research, several people of various experience and background had participated and almost all participants can be associated with the five levels:

1. Novices who has no background on 4D modeling

Most of student participants from Indonesia had no experience at all related with 4D modeling. The results vary greatly for each participants.

The 4D model scenario presented on the participants was a 4 story mixed use wooden structure on a podium slab. Errors were intentionally placed on the construction schedule to be analyzed by each participant. Due to participant's lack of experience with the real construction industry, they identified the activity errors as a domino effect that influence the next step.

One student commented that "since the third floor framing was placed incorrectly, all subsequent activities are considered error as well" and they called off the evaluation. Had they been familiar with the visualization of 4D modeling, they would identify each error independently. The lack of experience in virtual reality also hampered participant's ability to make sound and logical decision as most of them were struggling with navigation.

2. Advanced beginners and Competence

Participants of the second phase were the CM students of the University of Washington. Most of them had an established background in either civil engineering or architecture. The different interpretation was found whereas student with architecture background tends to comment on the model quality such as "the room should not be looking like this" while student with Civil Engineering background had the tendency to comment on the structural element of the model. Regardless of that, they were unable to identify errors in the activity.

3. Proficiency

The third stage, competence starts to set itself from theoretical knowledge and more into intuition. This stage is best represented by industry people with one to five years of experience in relevant field.

4. Expertise

The highest stage of learning, according to Dreyfus et al (1986). Individuals within this category see and solve problems by making spontaneous decision, but accurate due to their experience solving similar problems and skills they have acquired in their career lives. They have transcended the novice's tendency to make deliberate decision and often no longer need to be aware of it.

Two participants from different general contractors that were studied fall under this category. In the 4D model study, the two experts were observed differently. One expert was using a non-immersive virtual reality prototype while the other leads a team with virtual reality operator. Aside from different approach, both experts were the one who found the most mistakes on the test.

User Perception of 2D Symbols and Geometries in Immersive Virtual World

The immersive virtual environment represented in the prototype virtual reality tool contains both geometric for buildings along with 2D symbols and text as visual aid to describe construction activities and duration.

However, there is a tendency for the user to focus on the 3D geometries instead of 2D information. There are several factors that contributed to this phenomenon:

1. The 3D representation technique of immersive virtual reality goggles gave the feeling of cross-eye which is not comfortable for the users that made them disregard the 2D information altogether.
2. Current virtual reality goggles driver software adds an overlay to simulate pitch and roll movement of the head. This overlay, in fact, narrows the area of the display despite having a wider field of view. In this case, the wider field of view doesn't provide more advantage on showing 2D information.

Viability of Immersive Virtual Reality

The research has explored various method in representing immersive virtual reality for application in the construction industry, particularly in the evaluation of a 4D model. For the time being, button input navigation method is still considered as the most viable navigation method due the minimum time it takes for the users to familiarize with the control. Button input is also more precise than gesture control given from the industry tests, the results showed that this alternative caused the least troubles on the participants.

Motion sensing alternative such as Kinect is more useful for limited movement in immersive virtual world. However, when it comes to interactions, motion sensing combined with gesture just become more cumbersome and inefficient due to the inconsistent sensor precision and the need to remember multiple gesture for simple commands.

6.2 Contributions to the Construction Industry

1. *Alternative method for constructability review*

As addressed earlier in this thesis, the recent emergence of virtual reality devices opens up new possibilities at a more affordable prices. Even though many studies had explored many possibilities for practical uses of VR, not much of this devices had been used outside of architectural visualization. By adding more content to the prototype such as 4D simulation, it can be used by general contractors to visualize construction sequence. This prototype also allows the scheduler to collaborate with designer to evaluate the model and construction phasing. It presents a possibility of an alternative constructability review method. As presented by the data of this research, this tool could be appropriate for identifying several activities related to the roofing, plumbing, and other interior elements. For a better result, it is advised to use this tool in collaboration with other party members who have experience in CAD modeling, especially during the translation of the 3D geometries into virtual world.

2. *Affordable VR setup*

A number of virtual reality devices were tested during the course of this research. The latest build of the prototype can be used as a reference by general contractors or VR startups for developing their own affordable VR setup for construction industry. It should be noted that the most important factor in setting up the VR devices is the level of comfort in using the device. Developing a VR setup with 1:1 positional tracking without providing users freedom to move and alternative method to navigate through the whole model could diminish the benefit of the tool.

6.3 Limitations

The study was limited to a small sample pool which made the results exclusive to specific case. Larger samples would make it possible to clarify which aspects of 4D modeling would be better in immersive virtual reality than conventional non-VR methods. This was also attributable to the studies being more focused on developing the prototype than actually comparing the immersive VR with conventional non-VR method.

6.4 Future Studies

The prototype development was focused on a non-commercial version of videogame engine. Should the prototype be used for a commercial, a licensed version of the engine must be used to avoid violation of the software license agreement. Recent emergence of virtual reality technology would also benefit future studies since more options will be available in terms of navigation and visualization.

Several future themes can be extracted from this research:

1. Development of a Conversion tool for 4D modeling in virtual environments

The prototype itself is developed using Cryengine 3's visual programming tool which is limited and involved elaborate efforts in order to simulate the 4D technology. Using the programming logic described in this research, it is possible to develop a script for use with another videogame engine that is more stable than the one used for this research.

2. Development of BIM Interface

Future studies could involve the integration with other BIM elements such as CoBie on a more powerful hardware. In this research, the building geometries did not contain any information about the construction. What was shown in the prototype (schedule and duration) was the result of manually interpreting the CPM schedule into on-screen information.

3. Construction Industry Readiness in adopting Innovative Technologies for Project Delivery

An in-depth study could be done about industry readiness on adopting innovative technologies. The research could branch into several topics which may be conducted through case studies or by experiments using the tool developed in this thesis.

4. In-Depth Study of Immersive Virtual Reality influence on Collaborative Effort

The final study phase involved a study of how the immersive virtual reality can affect collaborative work. Further development of the prototype could integrate multi-user elements which enables several users to utilize immersive virtual reality in collaborative problem solving such as identifying the mistakes in a model and creating a report based on their observations. Better hardware would also open the possibility of using computer-based video capturing methods rather than capturing the tests on a separate camera.

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Appendix 1: Interview Questions

Preliminary Interview

This interview will be conducted in order to acquire data on how much detailed the 4D model should be developed.

Name:

Date of interview:

Age:

1. How long have you been working for the company?

2. What types of construction project are commonly conducted by the company you are currently working for?

3. In your company you are currently working for, what position is responsible in planning a project schedule?

4. Does your company conduct a constructability review during the pre-construction phase? If yes, what steps are taken to ensure that the design is correct?

5. Does your company utilize the use of 4D model to review the construction schedule? If the answer is no, how does your company determine feasibility of the schedule?

6. In your opinion, how important a 4D model is in reviewing the construction schedule?
    a. Very Important
    b. Important
    c. Not so important
    d. Not important

7. What software does your company use to develop a 4D model?

8. When developing a 4D model, how detailed the 4D model should be? Please elaborate on what component is typically present in the 4D model your company has developed.

9. Please rank the importance of these following components visualization in developing a 4D model

	Not Important	Less Important	Important	Very Important
Sitework				
Main structural elements (columns, slab, beam, footing)				
Groundwork				
Doors and Windows				
Roofing				
Walls				
Paints				
MEP				
Furnitures				
Scaffoldings				
Formworks				
Heavy equipment (crane, excavator, etc)				
Other, please specify…..				

10. What are the type of errors frequently found when assessing the construction sequence?

	Never Happened	Less frequent	frequent
Omission			
Illogical sequence			
Others			

Appendix 2: Preliminary Survey

Preliminary Research Survey

The objective of this survey is to collect preliminary information regarding the participant candidates. No personal information will be published and the participant's participation in the following research is voluntary.

CODE:_________________

DATE:_________________

AGE: __________________

GENDER:_______________

Q: How long have you been working for this company?

a. Less than a year
b. 1-5 years
c. 6-10 years
d. More than 10 years
e. Prefer not to answer

Q2: What type of construction project does your company typically involved in? Please circle all that apply

a. Mixed-Use
b. Residential
c. Commercial
d. Healthcare facilities
e. Educational facilities
f. Others, please specify …

Q3: What is your current position within the organization?

A:

Q4: Are you involved in developing project construction schedules? If yes, please specify:

a. Less than a year
b. 1-5 years
c. 5-10 years
d. 10-15 years
e. More than 15 years

Q5: Have you used a 4D modeling software such as Navisworks or Synchro? If the answer is yes, what 4D modeling software are you most familiar with?

A:

Q6: If you are using a 4d modeling software, how long have you been using that software?

a. Less than a year
b. 1-4 years
c. 5-8 years
d. 9-12 years
e. More than 12 years

Q6: What do you/your company use the 4D models for?

a. Helping with visualization of the schedules
b. Assessing the construction methods
c. Showing the construction visualization to clients (marketing purpose)
d. Others, please specify …

Q7: Have you used a Virtual Reality equipment (Oculus Rift, Sony VR headsets, etc.) or watched a 3D movie prior to this testing?

A:

Q8: Based on your experience, please rate the difficulty of identifying errors in these following activities without 4D CAD models

	Very Easy 1	Easy 2	Moderate 3	Difficult 4	Extremely Difficult 5
Sitework					
Main structural elements (columns, slab, beam, footing)					
Groundwork					
Doors and Windows					
Roofing					
Walls					
Finishes					
MEP					
Heavy equipment (crane, excavator, etc)					
Other, please specify…					

Appendix 3: Post-Experiment Survey

1. Please rate the degree of importance of these following interaction that you think helped in identifying errors in the construction sequence:

Important Aspects	Not Important	Less Important	Important	Very Important
Ability to control the sequence				
Ability to access information about the state of construction (duration of activities, relationship between activities, etc.)				
Ability to navigate within the construction area				

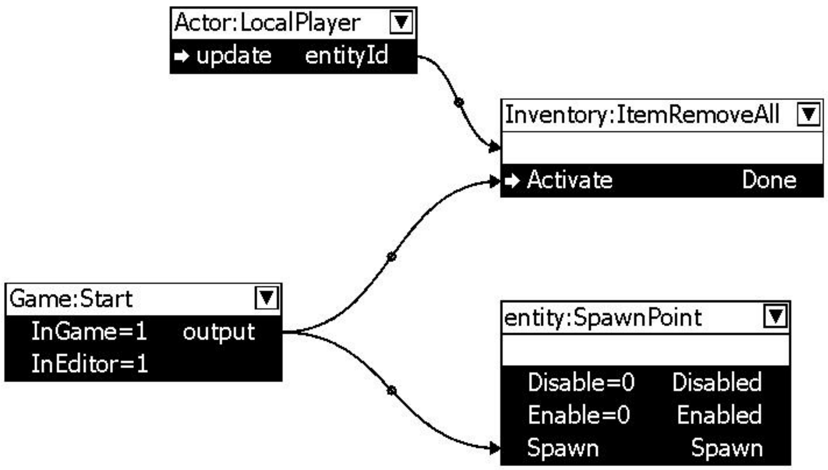
2. Based on your experience, please rate the difficulty in identifying errors of these following construction elements in the 4D model.

	Very difficult		Difficult		Easy		Very Easy	
	N	VR	N	VR	N	VR	N	VR
Sitework								
Main structural elements (columns, slab, beam, footing)								
Footings								
Doors and Windows								
Roofing								
Walls								
Finishes								
MEP								
Other, please specify…..								

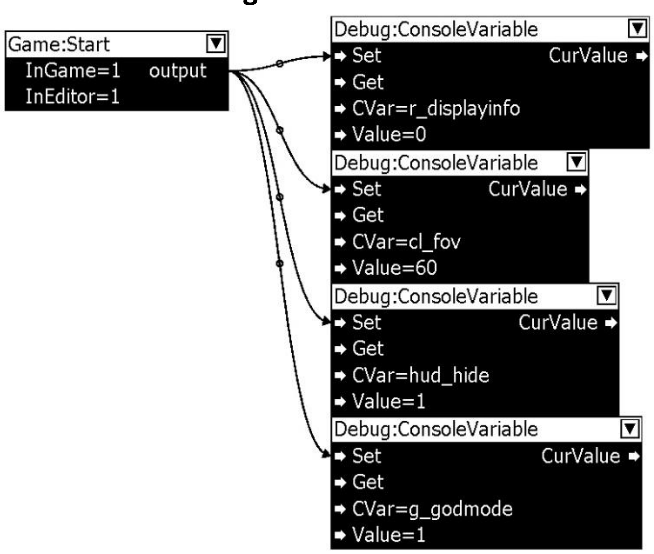
3. Please describe you experience when using the VR Tool.

Appendix 4: Cryengine Flowgraph Node Examples

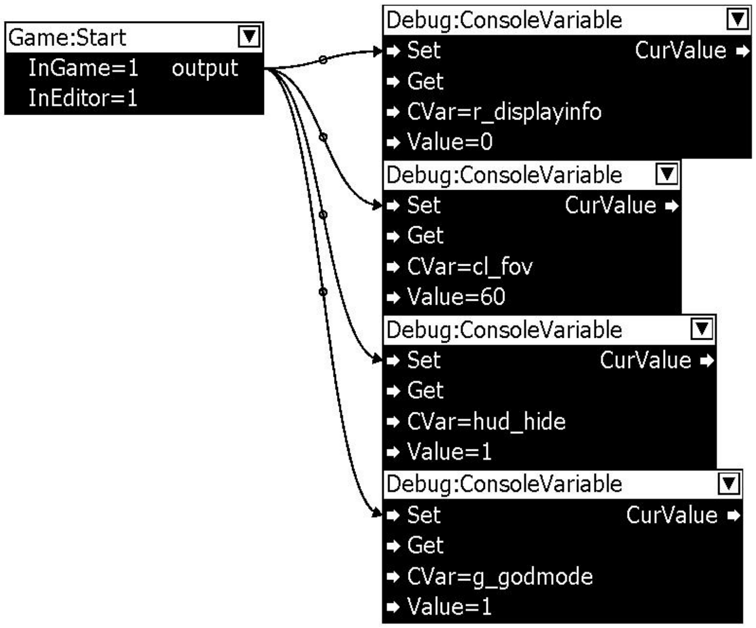
User Starting Point Nodes



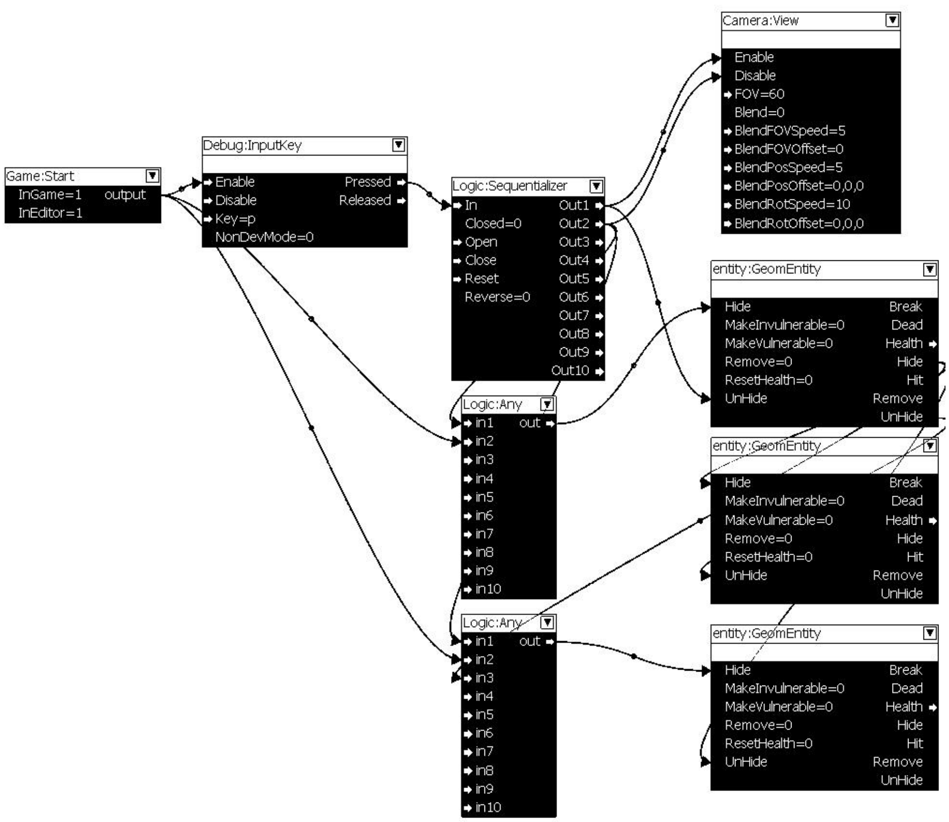
Nodes for Disabling Default Game Behavior



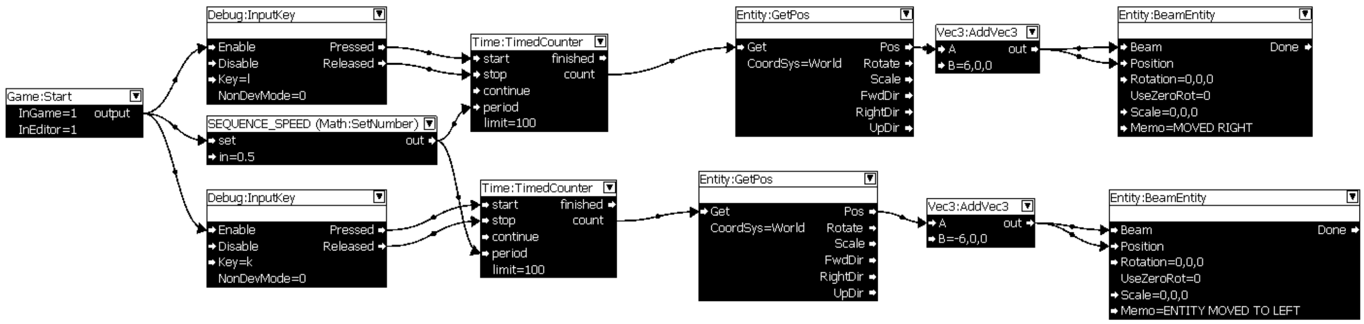
Nodes for Disabling Default Engine User Interface



Nodes for Cycling User Positions between Levels

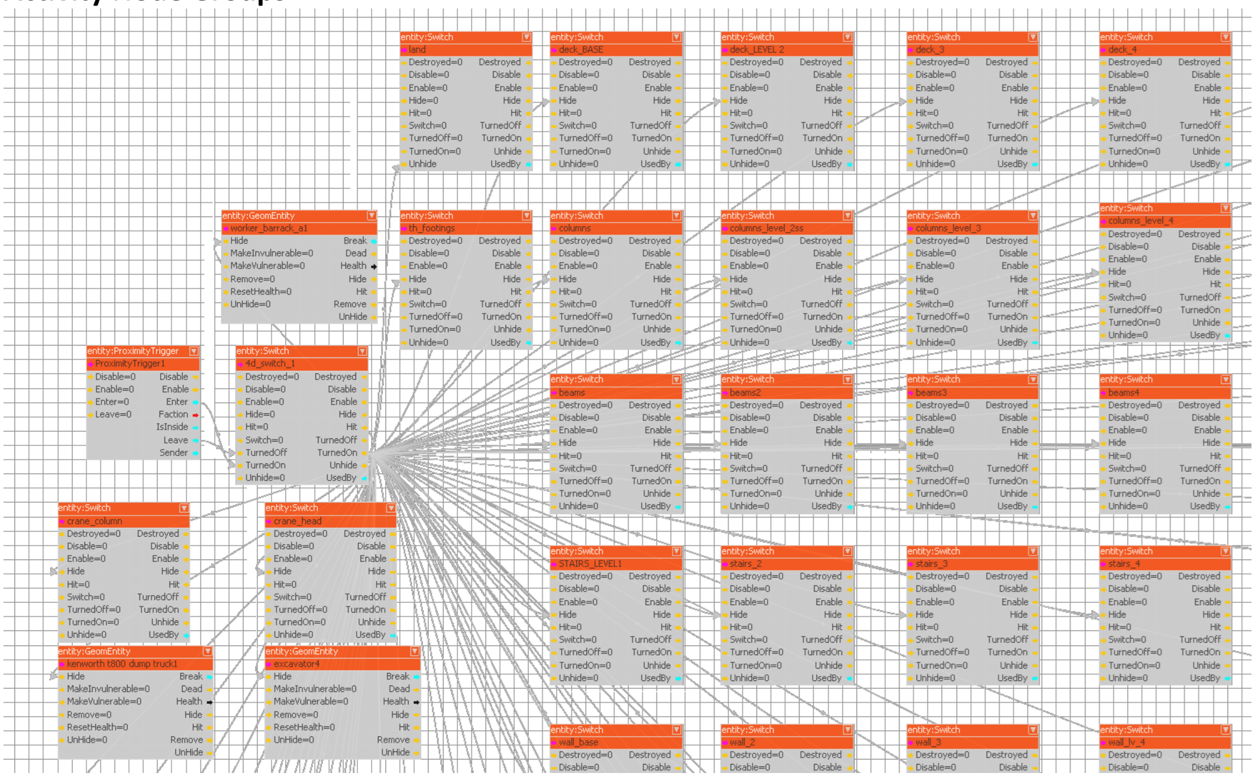


Trigger Object Controller Nodes



Trigger Object Beamer Nodes

Activity Node Groups



Appendix 5 : Cryengine 4D Flowgraph XML Code

Code Example for Trigger Object Movement

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  </Node>
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  </Node>
  <Node Id="48" Class="Vec3:AddVec3" pos="749,-153,0" flags="1">
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  </Node>
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   <Inputs InGame="1" InEditor="1"/>
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Code Example for Trigger Object Beamer

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Code Example for User Starting Position in Virtual Environment


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Code Example for Changing Camera to Schedule Board


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BlendRotOffset="0,0,0"/>
  </Node>
  <Node Id="3157" Class="Game:Start" pos="-392,-148,0" flags="0">
   <Inputs InGame="1" InEditor="1"/>
  </Node>
  <Node Id="3158" Class="Debug:InputKey" pos="-202,-178,0" flags="0">
```

```
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  </Node>
  <Node Id="3161" Class="entity:GeomEntity" pos="288,-58,0" flags="0"
EntityGUID="{67C42A4B-2FED-40A2-8893-7C189DFFF38C}"
EntityGUID_64="40A22FED67C42A4B">
   <Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
  </Node>
  <Node Id="3163" Class="entity:GeomEntity" pos="288,112,0" flags="0"
EntityGUID="{F7E8C42E-2767-4D50-86A9-C08B243F2CD7}"
EntityGUID_64="4D502767F7E8C42E">
   <Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
  </Node>
  <Node Id="3164" Class="Logic:Any" pos="48,72,0" flags="0">
   <Inputs />
  </Node>
  <Node Id="3226" Class="entity:GeomEntity" pos="288,292,0" flags="0"
EntityGUID="{0C1ABAF2-2EA0-4C19-8359-53963B3BCBEE}"
EntityGUID_64="4C192EA00C1ABAF2">
   <Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
  </Node>
  <Node Id="3227" Class="Logic:Any" pos="48,282,0" flags="0">
   <Inputs />
  </Node>
 </Nodes>
 <Edges>
  <Edge nodeIn="3158" nodeOut="3157" portIn="Enable" portOut="output" enabled="1"/>
  <Edge nodeIn="3164" nodeOut="3157" portIn="in2" portOut="output" enabled="1"/>
  <Edge nodeIn="3227" nodeOut="3157" portIn="in2" portOut="output" enabled="1"/>
  <Edge nodeIn="3159" nodeOut="3158" portIn="In" portOut="Pressed" enabled="1"/>
  <Edge nodeIn="3154" nodeOut="3159" portIn="Enable" portOut="Out1" enabled="1"/>
  <Edge nodeIn="3154" nodeOut="3159" portIn="Disable" portOut="Out2" enabled="1"/>
  <Edge nodeIn="3161" nodeOut="3159" portIn="UnHide" portOut="Out1" enabled="1"/>
  <Edge nodeIn="3164" nodeOut="3159" portIn="in1" portOut="Out2" enabled="1"/>
  <Edge nodeIn="3227" nodeOut="3159" portIn="in1" portOut="Out2" enabled="1"/>
  <Edge nodeIn="3163" nodeOut="3161" portIn="Hide" portOut="Hide" enabled="1"/>
  <Edge nodeIn="3163" nodeOut="3161" portIn="UnHide" portOut="UnHide" enabled="1"/>
  <Edge nodeIn="3226" nodeOut="3161" portIn="UnHide" portOut="Hide" enabled="1"/>
  <Edge nodeIn="3227" nodeOut="3161" portIn="in3" portOut="Hide" enabled="1"/>
```

```
  <Edge nodeIn="3161" nodeOut="3164" portIn="Hide" portOut="out" enabled="1"/>
  <Edge nodeIn="3226" nodeOut="3227" portIn="Hide" portOut="out" enabled="1"/>
 </Edges>
 <GraphTokens />
</Graph>
```

Code Example for Switching User Position Between Building Levels

```
<Graph Description="" Group="" enabled="1" MultiPlayer="ClientServer">
 <Nodes>
  <Node Id="3" Class="Actor:LocalPlayer" pos="-417,3,0" flags="0">
   <Inputs />
  </Node>
  <Node Id="7" Class="Entity:BeamEntity" pos="683,-337,0" flags="0">
   <Inputs entityId="0" Position="1113.14,1238.39,310.24" Rotation="0,0,0" UseZeroRot="0"
Scale="0,0,0" Memo=""/>
  </Node>
  <Node Id="18" Class="Debug:DisplayMessage" pos="363,273,0" flags="0">
   <Inputs entityId="0" message="LEVEL 4" DisplayTime="2" posX="750" posY="300" fontSize="2"
clr_Color="0.871367,0.938686,0.00651209" centered="0"/>
  </Node>
  <Node Id="3189" Class="Game:Start" pos="-427,-87,0" flags="0">
   <Inputs InGame="1" InEditor="1"/>
  </Node>
  <Node Id="3190" Class="Debug:InputKey" pos="-207,-117,0" flags="0">
   <Inputs entityId="0" Key="t" NonDevMode="0"/>
  </Node>
  <Node Id="3192" Class="Logic:Sequentializer" pos="93,-127,0" flags="0">
   <Inputs Closed="0" Reverse="0"/>
  </Node>
  <Node Id="3193" Class="Entity:BeamEntity" pos="683,-147,0" flags="0">
   <Inputs entityId="0" Position="1112.7,1240.81,313.81" Rotation="0,0,0" UseZeroRot="0"
Scale="0,0,0" Memo=""/>
  </Node>
  <Node Id="3195" Class="Debug:DisplayMessage" pos="-137,93,0" flags="0">
   <Inputs entityId="0" message="Level 2" DisplayTime="0" posX="750" posY="450" fontSize="3"
clr_Color="1,1,1" centered="0"/>
  </Node>
  <Node Id="3196" Class="Entity:BeamEntity" pos="673,203,0" flags="0">
   <Inputs entityId="0" Position="1113.5,1239.12,321.21" Rotation="0,0,0" UseZeroRot="0"
Scale="0,0,0" Memo=""/>
  </Node>
  <Node Id="3197" Class="Entity:BeamEntity" pos="683,363,0" flags="0">
```

```
   <Inputs entityId="0" Position="1113.3,1239.79,325.36" Rotation="0,0,0" UseZeroRot="0"
Scale="0,0,0" Memo=""/>
  </Node>
  <Node Id="3198" Class="Debug:DisplayMessage" pos="333,-357,0" flags="0">
   <Inputs entityId="0" message="GROUND FLOOR" DisplayTime="2" posX="750" posY="300"
fontSize="2" clr_Color="0.871367,0.938686,0.00651209" centered="0"/>
  </Node>
  <Node Id="3199" Class="Debug:DisplayMessage" pos="353,-147,0" flags="0">
   <Inputs entityId="0" message="LEVEL 2" DisplayTime="2" posX="750" posY="300" fontSize="2"
clr_Color="0.871367,0.938686,0.00651209" centered="0"/>
  </Node>
  <Node Id="3200" Class="Debug:DisplayMessage" pos="353,63,0" flags="0">
   <Inputs entityId="0" message="LEVEL 3" DisplayTime="2" posX="750" posY="300" fontSize="2"
clr_Color="0.871367,0.938686,0.00651209" centered="0"/>
  </Node>
  <Node Id="3201" Class="Entity:BeamEntity" pos="683,43,0" flags="0">
   <Inputs entityId="0" Position="1113.34,1241.95,318.15" Rotation="0,0,0" UseZeroRot="0"
Scale="0,0,0" Memo=""/>
  </Node>
  <Node Id="3202" Class="Debug:DisplayMessage" pos="363,493,0" flags="0">
   <Inputs entityId="0" message="ROOF" DisplayTime="2" posX="750" posY="300" fontSize="2"
clr_Color="0.871367,0.938686,0.00651209" centered="0"/>
  </Node>
  <Node Id="3204" Class="Debug:DisplayMessage" pos="1023,43,0" flags="0">
   <Inputs entityId="0" message="FLYCAM" DisplayTime="2" posX="750" posY="300" fontSize="2"
clr_Color="0.871367,0.938686,0.00651209" centered="0"/>
  </Node>
 </Nodes>
 <Edges>
  <Edge nodeIn="7" nodeOut="3" portIn="entityId" portOut="entityId" enabled="1"/>
  <Edge nodeIn="3193" nodeOut="3" portIn="entityId" portOut="entityId" enabled="1"/>
  <Edge nodeIn="3196" nodeOut="3" portIn="entityId" portOut="entityId" enabled="1"/>
  <Edge nodeIn="3197" nodeOut="3" portIn="entityId" portOut="entityId" enabled="1"/>
  <Edge nodeIn="3201" nodeOut="3" portIn="entityId" portOut="entityId" enabled="1"/>
  <Edge nodeIn="3190" nodeOut="3189" portIn="Enable" portOut="output" enabled="1"/>
  <Edge nodeIn="3192" nodeOut="3190" portIn="In" portOut="Pressed" enabled="1"/>
  <Edge nodeIn="7" nodeOut="3192" portIn="Beam" portOut="Out1" enabled="1"/>
  <Edge nodeIn="3193" nodeOut="3192" portIn="Beam" portOut="Out2" enabled="1"/>
  <Edge nodeIn="3198" nodeOut="3192" portIn="Show" portOut="Out1" enabled="1"/>
  <Edge nodeIn="3199" nodeOut="3192" portIn="Show" portOut="Out2" enabled="1"/>
  <Edge nodeIn="3200" nodeOut="3192" portIn="Show" portOut="Out3" enabled="1"/>
  <Edge nodeIn="3201" nodeOut="3192" portIn="Beam" portOut="Out3" enabled="1"/>
  <Edge nodeIn="3204" nodeOut="3192" portIn="Show" portOut="Out4" enabled="1"/>
  <Edge nodeIn="3202" nodeOut="3198" portIn="Hide" portOut="Show" enabled="1"/>
```

```
  <Edge nodeIn="3198" nodeOut="3199" portIn="Hide" portOut="Show" enabled="1"/>
  <Edge nodeIn="3199" nodeOut="3200" portIn="Hide" portOut="Show" enabled="1"/>
  <Edge nodeIn="18" nodeOut="3202" portIn="Hide" portOut="Show" enabled="1"/>
  <Edge nodeIn="3200" nodeOut="3204" portIn="Hide" portOut="Show" enabled="1"/>
 </Edges>
 <GraphTokens />
</Graph>
```

XML Code for one Activity Example

```
<Graph Description="" Group="" enabled="1" MultiPlayer="ClientServer">
 <Nodes>
  <Node Id="2" Class="entity:Switch" pos="797,840,0" flags="0" EntityGUID="{391712C0-5D4B-
4C54-AF91-00440E9F438B}" EntityGUID_64="4C545D4B391712C0">
   <Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0"
TurnedOff="0" TurnedOn="0" Unhide="0"/>
  </Node>
  <Node Id="6" Class="entity:Switch" pos="797,-130,0" flags="0" EntityGUID="{AA6E755B-3315-
493A-9F95-8501F8755FEC}" EntityGUID_64="493A3315AA6E755B">
   <Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0"
TurnedOff="0" TurnedOn="0" Unhide="0"/>
  </Node>
  <Node Id="8" Class="entity:Switch" pos="797,1310,0" flags="0" EntityGUID="{7F7DCCC7-0AC1-
4121-8075-C31882722B6D}" EntityGUID_64="41210AC17F7DCCC7">
   <Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0"
TurnedOff="0" TurnedOn="0" Unhide="0"/>
  </Node>
  <Node Id="10" Class="entity:Switch" pos="797,1770,0" flags="0" EntityGUID="{3717C131-
CB4B-4A36-B01F-6605D0CD5930}" EntityGUID_64="4A36CB4B3717C131">
   <Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0"
TurnedOff="0" TurnedOn="0" Unhide="0"/>
  </Node>
  <Node Id="12" Class="entity:Switch" pos="797,1550,0" flags="0" EntityGUID="{8AF2F40F-0ECD-
4626-AA6B-BF8422867552}" EntityGUID_64="46260ECD8AF2F40F">
   <Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0"
TurnedOff="0" TurnedOn="0" Unhide="0"/>
  </Node>
  <Node Id="15" Class="entity:Switch" pos="797,340,0" flags="0" EntityGUID="{36ED2D9E-E365-
416A-A399-0E6E38DEA6AB}" EntityGUID_64="416AE36536ED2D9E">
   <Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0"
TurnedOff="0" TurnedOn="0" Unhide="0"/>
  </Node>
  <Node Id="17" Class="entity:Switch" pos="797,100,0" flags="0" EntityGUID="{448AFE9F-CBDF-
4FE2-8D8D-FE0064A12D6C}" EntityGUID_64="4FE2CBDF448AFE9F">
```

<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="19" Class="entity:Switch" pos="1067,-380,0" flags="0" EntityGUID="{77DAD72E-AEF6-4014-83CC-1EFDFBF54C9E}" EntityGUID_64="4014AEF677DAD72E">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="21" Class="entity:Switch" pos="1067,-140,0" flags="0" EntityGUID="{95F96842-7EE0-40BB-BF8B-C844C412B2C9}" EntityGUID_64="40BB7EE095F96842">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="23" Class="entity:Switch" pos="1067,840,0" flags="0" EntityGUID="{A393FECF-0EF6-4079-A9F4-2C6645C977F5}" EntityGUID_64="40790EF6A393FECF">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="26" Class="entity:Switch" pos="1067,340,0" flags="0" EntityGUID="{C1174504-8B3E-4372-84EB-78D1D5F8BB49}" EntityGUID_64="43728B3EC1174504">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="31" Class="entity:Switch" pos="1067,1090,0" flags="0" EntityGUID="{FF820AC1-1055-45B1-9F07-0CEC59F72003}" EntityGUID_64="45B11055FF820AC1">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="33" Class="entity:Switch" pos="1067,1770,0" flags="0" EntityGUID="{B0CC0332-979C-49A9-9863-C2AB560A4166}" EntityGUID_64="49A9979CB0CC0332">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="35" Class="entity:Switch" pos="1067,1550,0" flags="0" EntityGUID="{AAEABD97-9AC3-4D0E-80DB-D637819BC216}" EntityGUID_64="4D0E9AC3AAEABD97">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="37" Class="entity:Switch" pos="797,1090,0" flags="0" EntityGUID="{0E21C44A-8267-4863-893F-27E9625C8BDD}" EntityGUID_64="486382670E21C44A">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>

<Node Id="39" Class="entity:Switch" pos="1067,100,0" flags="0" EntityGUID="{607D91B1-4AE9-4E0D-BF36-9B5B9409006B}" EntityGUID_64="4E0D4AE9607D91B1">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="41" Class="entity:Switch" pos="1317,-380,0" flags="0" EntityGUID="{7491ADCA-CEBE-47B5-9265-B162BAAC1707}" EntityGUID_64="47B5CEBE7491ADCA">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="45" Class="entity:Switch" pos="1327,1770,0" flags="0" EntityGUID="{3E38352D-9129-436F-B760-9B312E28755A}" EntityGUID_64="436F91293E38352D">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="105" Class="entity:ProximityTrigger" pos="-353,60,0" flags="0" EntityGUID="{5BF58F90-5549-4169-A64A-C5A84487C7A4}" EntityGUID_64="416955495BF58F90">
<Inputs entityId="0" Disable="0" Enable="0" Enter="0" Leave="0"/>
</Node>
<Node Id="107" Class="entity:Switch" pos="-143,60,0" flags="0" EntityGUID="{3CAB5146-CA1C-476A-A0CE-79628ED14CED}" EntityGUID_64="476ACA1C3CAB5146">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="135" Class="entity:Switch" pos="537,590,0" flags="0" EntityGUID="{A02E5515-5761-40D5-B11F-6F401AFAF3B7}" EntityGUID_64="40D55761A02E5515">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="137" Class="entity:Switch" pos="537,840,0" flags="0" EntityGUID="{A516CADC-11E9-427D-8932-4386425640EE}" EntityGUID_64="427D11E9A516CADC">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="139" Class="entity:Switch" pos="297,-130,0" flags="0" EntityGUID="{96028C87-F6F7-416E-A559-80EFF8EA5E10}" EntityGUID_64="416EF6F796028C87">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="141" Class="entity:Switch" pos="297,100,0" flags="0" EntityGUID="{C8E12F33-D6FC-4AA5-866D-6C08E89422C4}" EntityGUID_64="4AA5D6FCC8E12F33">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>

</Node>
<Node Id="143" Class="entity:Switch" pos="297,590,0" flags="0" EntityGUID="{7C1FF713-5ECD-4881-9543-2A0CA57E4D66}" EntityGUID_64="48815ECD7C1FF713">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="145" Class="entity:Switch" pos="2057,100,0" flags="0" EntityGUID="{DF518D9C-4E59-4189-91F6-1D68BB2EA2D9}" EntityGUID_64="41894E59DF518D9C">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="147" Class="entity:Switch" pos="297,-380,0" flags="0" EntityGUID="{7B7E5739-E1E6-4891-BB3F-D08010AF2812}" EntityGUID_64="4891E1E67B7E5739">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="149" Class="entity:Switch" pos="2057,330,0" flags="0" EntityGUID="{431E423C-7F28-4D05-B834-715B0C21C3EF}" EntityGUID_64="4D057F28431E423C">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="151" Class="entity:Switch" pos="2057,-380,0" flags="0" EntityGUID="{34F66C16-8C4A-4CDB-BD55-28B7384D6613}" EntityGUID_64="4CDB8C4A34F66C16">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="153" Class="entity:Switch" pos="2057,-140,0" flags="0" EntityGUID="{B8BFCF7D-23F3-4F53-927D-9A79A659E4E3}" EntityGUID_64="4F5323F3B8BFCF7D">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="155" Class="entity:Switch" pos="2057,570,0" flags="0" EntityGUID="{8C05AEB1-0FE9-4403-B26E-2DCE5F8A85C5}" EntityGUID_64="44030FE98C05AEB1">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="157" Class="entity:Switch" pos="87,-130,0" flags="0" EntityGUID="{08B071DE-D526-4E02-9282-8821B0F0394D}" EntityGUID_64="4E02D52608B071DE">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="159" Class="entity:Switch" pos="87,-380,0" flags="0" EntityGUID="{419CFE89-E537-4977-902F-29A082BA035A}" EntityGUID_64="4977E537419CFE89">

<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0"
TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="168" Class="entity:Switch" pos="537,-380,0" flags="0" EntityGUID="{3E63D6C6-
3087-4265-B7B5-47E370D5B75D}" EntityGUID_64="426530873E63D6C6">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0"
TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="170" Class="entity:Switch" pos="297,1310,0" flags="0" EntityGUID="{B4D90168-
CD9B-42A5-BD58-988C7F6E5FEB}" EntityGUID_64="42A5CD9BB4D90168">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0"
TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="174" Class="entity:Switch" pos="537,1090,0" flags="0" EntityGUID="{CA467D19-
FCC0-4DE0-8376-F0CB06D88CA2}" EntityGUID_64="4DE0FCC0CA467D19">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0"
TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="176" Class="entity:Switch" pos="537,1310,0" flags="0" EntityGUID="{2D353556-
A70A-490B-BF24-94736D38E8CC}" EntityGUID_64="490BA70A2D353556">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0"
TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="178" Class="entity:Switch" pos="297,1090,0" flags="0" EntityGUID="{61537283-
DB5D-4AA3-AB63-65AF1F9928FF}" EntityGUID_64="4AA3DB5D61537283">
<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0"
TurnedOff="0" TurnedOn="0" Unhide="0"/>
</Node>
<Node Id="180" Class="entity:Switch" pos="527,1550,0" flags="0" EntityGUID="{CD6C57F1-
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TurnedOff="0" TurnedOn="0" Unhide="0"/>
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TurnedOff="0" TurnedOn="0" Unhide="0"/>
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<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0"
TurnedOff="0" TurnedOn="0" Unhide="0"/>
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<Node Id="346" Class="entity:Switch" pos="1557,-380,0" flags="0" EntityGUID="{F85259A4-E7C6-4638-9E31-C267A76ED3E7}" EntityGUID_64="4638E7C6F85259A4">
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</Node>
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<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
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<Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0" TurnedOff="0" TurnedOn="0" Unhide="0"/>
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<Inputs entityId="0" mat_Material="MATERIALS/THESIS/GENERIC/BRICKS/brick_MASONRY_WALL_DARK_GREY" Serialize="0"/>
</Node>
<Node Id="2876" Class="Material:EntityMaterialChange" pos="2317,-240,0" flags="0" EntityGUID="{857C8B8B-4D8E-4287-AF30-FBC3A4F911EF}" EntityGUID_64="42874D8E857C8B8B">
<Inputs entityId="0" mat_Material="MATERIALS/THESIS/GENERIC/BRICKS/brick_MASONRY_WALL_DARK_GREY" Serialize="0"/>

</Node>
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EntityGUID="{A02E5515-5761-40D5-B11F-6F401AFAF3B7}"
EntityGUID_64="40D55761A02E5515">
<Inputs entityId="0"
mat_Material="MATERIALS/THESIS/GENERIC/BRICKS/brick_MASONRY_WALL_DARK_GREY"
Serialize="0"/>
</Node>
<Node Id="2878" Class="Material:EntityMaterialChange" pos="2317,150,0" flags="0"
EntityGUID="{7C1FF713-5ECD-4881-9543-2A0CA57E4D66}"
EntityGUID_64="48815ECD7C1FF713">
<Inputs entityId="0"
mat_Material="MATERIALS/THESIS/GENERIC/BRICKS/brick_MASONRY_WALL_DARK_GREY"
Serialize="0"/>
</Node>
<Node Id="2879" Class="Material:EntityMaterialChange" pos="2317,-110,0" flags="0"
EntityGUID="{9835C389-091A-4381-B985-1C3F29FE55A1}"
EntityGUID_64="4381091A9835C389">
<Inputs entityId="0"
mat_Material="MATERIALS/THESIS/GENERIC/BRICKS/brick_MASONRY_WALL_DARK_GREY"
Serialize="0"/>
</Node>
<Node Id="2880" Class="Material:EntityMaterialChange" pos="2317,280,0" flags="0"
EntityGUID="{34F66C16-8C4A-4CDB-BD55-28B7384D6613}"
EntityGUID_64="4CDB8C4A34F66C16">
<Inputs entityId="0"
mat_Material="MATERIALS/THESIS/GENERIC/BRICKS/brick_MASONRY_WALL_DARK_GREY"
Serialize="0"/>
</Node>
<Node Id="2881" Class="Material:EntityMaterialChange" pos="2317,410,0" flags="0"
EntityGUID="{B8BFCF7D-23F3-4F53-927D-9A79A659E4E3}"
EntityGUID_64="4F5323F3B8BFCF7D">
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mat_Material="MATERIALS/THESIS/GENERIC/BRICKS/brick_MASONRY_WALL_DARK_GREY"
Serialize="0"/>
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<Node Id="3239" Class="entity:GeomEntity" pos="-393,690,0" flags="0"
EntityGUID="{9653FF23-A020-492A-A711-B45D8C13BD88}"
EntityGUID_64="492AA0209653FF23">
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ResetHealth="0" UnHide="0"/>
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<Node Id="3241" Class="entity:GeomEntity" pos="-83,690,0" flags="0"
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EntityGUID_64="4A8E12FCAF3ED317">
<Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
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EntityGUID_64="41BEAC7435630A07">
<Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
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EntityGUID="{0C295055-2037-42D5-9DB3-ABE4F4B1EAB2}"
EntityGUID_64="42D520370C295055">
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ResetHealth="0" UnHide="0"/>
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<Node Id="3247" Class="entity:GeomEntity" pos="-83,850,0" flags="0"
EntityGUID="{37283D13-D590-4811-88FB-1397D5708232}"
EntityGUID_64="4811D59037283D13">
<Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
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EntityGUID="{74982674-2EA3-4F5F-8255-6C2F1AAC4DE2}"
EntityGUID_64="4F5F2EA374982674">
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ResetHealth="0" UnHide="0"/>
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EntityGUID_64="4F5BE0552A1F983C">
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ResetHealth="0" UnHide="0"/>
</Node>
<Node Id="3253" Class="entity:GeomEntity" pos="-83,1170,0" flags="0"
EntityGUID="{1EDC40CD-4A86-44E6-9A1E-02AC680F3FDB}"
EntityGUID_64="44E64A861EDC40CD">
<Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
</Node>

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EntityGUID_64="46A594DF197CE6B7">
  <Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
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EntityGUID="{055F7487-0000-4740-8209-8AD9BE141DE9}"
EntityGUID_64="47400000055F7487">
  <Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
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EntityGUID="{BC4D0A10-B89D-46AE-BCE3-6686026B7DB9}"
EntityGUID_64="46AEB89DBC4D0A10">
  <Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
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EntityGUID="{32DDFC21-E536-442E-91B4-760BD59E53DC}"
EntityGUID_64="442EE53632DDFC21">
  <Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
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EntityGUID="{54363090-C71D-4A75-8CEA-EEF6DF58779F}"
EntityGUID_64="4A75C71D54363090">
  <Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
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EntityGUID_64="482B208076D42F0D">
  <Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
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EntityGUID="{27057948-1F69-4A29-8AF7-EAAB6BEE4A86}"
EntityGUID_64="4A291F6927057948">
  <Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
 </Node>
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  <Node Id="3269" Class="entity:GeomEntity" pos="-83,1810,0" flags="0"
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EntityGUID_64="42BA8E82EDB3A9A3">
   <Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
  </Node>
  <Node Id="3287" Class="entity:GeomEntity" pos="-393,480,0" flags="0"
EntityGUID="{7C77AB78-C4E8-4576-8A86-46143B2A4185}"
EntityGUID_64="4576C4E87C77AB78">
   <Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
  </Node>
  <Node Id="3289" Class="entity:GeomEntity" pos="-103,480,0" flags="0"
EntityGUID="{3B5C49C3-5C92-454B-8527-8AAC173CD036}"
EntityGUID_64="454B5C923B5C49C3">
   <Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
  </Node>
  <Node Id="3328" Class="entity:Switch" pos="-103,280,0" flags="0" EntityGUID="{31BE365D-
13A1-4E63-9504-D18029C6038C}" EntityGUID_64="4E6313A131BE365D">
   <Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0"
TurnedOff="0" TurnedOn="0" Unhide="0"/>
  </Node>
  <Node Id="3329" Class="entity:Switch" pos="-393,280,0" flags="0" EntityGUID="{92F62DE6-
E57D-42A3-A740-1CB2FF0AB722}" EntityGUID_64="42A3E57D92F62DE6">
   <Inputs entityId="0" Destroyed="0" Disable="0" Enable="0" Hide="0" Hit="0" Switch="0"
TurnedOff="0" TurnedOn="0" Unhide="0"/>
  </Node>
  <Node Id="3335" Class="entity:GeomEntity" pos="177,1830,0" flags="0"
EntityGUID="{E4D6FE88-DF0B-43C9-A633-4670F833714F}"
EntityGUID_64="43C9DF0BE4D6FE88">
   <Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
  </Node>
  <Node Id="3504" Class="entity:GeomEntity" pos="-163,-130,0" flags="0"
EntityGUID="{557CE9EA-790A-4350-A6C7-681D2B9E2E0E}"
EntityGUID_64="4350790A557CE9EA">
   <Inputs entityId="0" Hide="0" MakeInvulnerable="0" MakeVulnerable="0" Remove="0"
ResetHealth="0" UnHide="0"/>
  </Node>
 </Nodes>
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<Edge nodeIn="8" nodeOut="107" portIn="Hide" portOut="TurnedOn" enabled="1"/>
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<Edge nodeIn="15" nodeOut="107" portIn="Hide" portOut="TurnedOn" enabled="1"/>
<Edge nodeIn="17" nodeOut="107" portIn="Hide" portOut="TurnedOn" enabled="1"/>
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<Edge nodeIn="157" nodeOut="107" portIn="Hide" portOut="TurnedOn" enabled="1"/>
<Edge nodeIn="159" nodeOut="107" portIn="Unhide" portOut="TurnedOn" enabled="1"/>
<Edge nodeIn="168" nodeOut="107" portIn="Hide" portOut="TurnedOn" enabled="1"/>
<Edge nodeIn="170" nodeOut="107" portIn="Hide" portOut="TurnedOn" enabled="1"/>
<Edge nodeIn="174" nodeOut="107" portIn="Hide" portOut="TurnedOn" enabled="1"/>
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<Edge nodeIn="188" nodeOut="107" portIn="Hide" portOut="TurnedOn" enabled="1"/>
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<Edge nodeIn="332" nodeOut="107" portIn="Hide" portOut="TurnedOn" enabled="1"/>
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