# Virtual Reality in the Architecture, Engineering and Construction Industry

# Master thesis

**International Master of Science in Construction and Real Estate Management**

**Joint Study Programme of Metropolia UAS and HTW Berlin**

Submitted on 01.07.2019 from

**Omar Mabrouk**

S0562620

Prof. Dr.-Ing. Jens Liebchen, HTW Berlin

M.Sc. Olli M. Salo, Pöyry Finland Oy

| | |
|---|---|
| **Thesis title** | Virtual Reality in the Architecture, Engineering and Construction Industry |
| **Universities** | Berlin University of Applied Sciences<br>Metropolia University of applied Sciences |
| **Program title** | International Master of Science in Construction and Real Estate Management |
| **Thesis committee** | |
| **First supervisor** | Prof. Dr.-Ing. Jens Liebchen, Professor at HTW Berlin |
| **Second supervisor** | M.Sc. Olli M. Salo, Department Manager at Pöyry Finland Oy |
| **Author** | Omar Mabrouk |
| **Submitted on** | 01.07.2019 |
| **Student ID** | S0562620 |

htw Hochschule für Technik und Wirtschaft Berlin
University of Applied Sciences

Berlin University of Applied Sciences
Wilhelminenhofstraße 75A, 12459 Berlin, Germany
Tel. (030) 5019 - 0
Fax: (030) 5090 134
www.htw-berlin.de

Metropolia University of Applied Sciences

Metropolia University of Applied Sciences
Myllypurontie 1, 00920 Helsinki, Finland
Tel. +358 40 193 7758
www.metropolia.fi

PÖYRY

Pöyry Finland Oy
Jaakonkatu 3, 01621 Vantaa, Finland
Tel. +358 10 3311
www.poyry.fi

*[Acknowledgement]*

*Without the support of the following people, institutions, and companies, this accomplishment would not have been possible.*

*I would first like to express my great appreciation to my thesis advisor Olli M. Salo, the Department Manager at Pöyry Finland Oy, for his precious and constructive suggestions during the planning and development of this research work. He consistently allowed this paper to be my own work, but steered me in the right direction whenever he thought I needed it.*

*I would like to offer my special thanks to Prof. Dr.-Ing. Jens Liebchen and Prof. Mika Lindholm for their highly appreciated input on this thesis and their enthusiasm that guided me through the process of writing and researching.*

*I would also like to extend my thanks to Pöyry Finland Oy and my colleagues at the department of infrastructure, especially Heikki Vanne, for offering their assistance, expertise, and resources that helped me to conduct my studies, tests, and researches.*

*Most importantly, I wish to thank my parents for their support and encouragement throughout my study.*

*Finally, special thanks to Tabea Schmidt for her support and continuous encouragement through the process of researching and writing.*

*Omar Mabrouk*

Metropolia

Hochschule für Technik
und Wirtschaft Berlin
University of Applied Sciences

**International Master of Science in Construction and Real Estate Management**
**Joint Study Programme of Metropolia Helsinki and HTW Berlin**

**Conceptual Formulation** Date 20.05.2019

**Master Thesis for Mr. Omar Mabrouk**

**S0562620**

**Topic: Virtual Reality in the Architecture, Engineering and Construction Industry.**

Virtual Reality (VR) has rapidly developed in the last decades and has been implemented in several industries sectors; however, its application in Architecture, Engineering, and Construction industry (AEC) is still limited. Nowadays, projects are becoming more complex and multidisciplinary. Infrastructure projects such as tunnels, bridges, and railways are considered a complex projects that involve multidiscipline engineers and stakeholders with various backgrounds. Therefore, communication, coordination, and decision-making has become challenging in such projects. Consequently, there is a need for enhancing the process of the design and construction. In the design, VR has potentials for improving the understanding of the design, engagements of stakeholders and clients into design, making earlier decision, and approving the design earlier. In the construction, VR could connect the design and construction processes, improving the site planning, visualizing the construction simulation and procedure, and providing training for workers.

The planned research methodology consists of literature study, case studies and a workshop done in Pöyry Finland Oy. Besides case studies, interviews and questionnaire with professionals from the AEC industry and software developing companies could be used if needed.

The goals related to the research will be:

- Analyze the benefits of using VR in the design and construction process
- Provide guidelines and workflow for the implementation of VR in the design process of the company.

The research will try to find a sufficient answer to the following questions:

What benefits VR can bring to the design and construction process in the company's infrastructure department?

1. How VR can be implemented in the design and construction process?
2. Does the use of VR improve the design and construction process?
3. Does the use of VR increase the engagements of client and stakeholders into design?
4. What are current practices and needs for developing use of VR in the company?
5. What could be the workflow and procedures of applying VR in the design process in the company?

Signature of the 1st Supervisor
Prof. Dr.-Ing. Jens Liebchen

## Abstract

The Architecture, Engineering, and Construction (AEC) industry and particularly infrastructure represent the main artery of the country; therefore, there is a growing demand for mega-infrastructure projects. Despite the importance of infrastructure projects, it consumes a considerable amount of time and budget. It also involves multi-disciplined engineers, clients, stakeholders, and end-users. As a result, the management of infrastructure projects faces challenges that require different solutions and techniques to enhance communication and collaboration among all parties. Over the last few decades, many studies show that the Virtual Reality (VR) technology has potential in the AEC industry. The aim of this research is to analyze the contribution of VR in the design and construction processes with focusing on the infrastructure. In addition, it provides a procedure for applying VR in the infrastructure department of Pöyry Finland Oy. The research is based on reviewing previous researches, investigating former case studies, and the author's participation in a workshop in the company. The research presents guidelines that cover the framework and workflow for implementing VR in the company's infrastructure projects.


**Keywords:** Architecture, Engineering, and Construction (AEC), Virtual Reality (VR), Infrastructure Projects

# Table of Contents

**Abstract** ..... **IV**

**Table of Contents** ..... **V**

**Table of Figures** ..... **VII**

**List of Tabulations** ..... **IX**

**List of Abbreviations** ..... **X**

**1. Introduction** ..... **1**

1.1 Overview ..... 2

1.2 Research Goals ..... 3

1.3 Research Questions ..... 4

1.4 Research Methodology ..... 4

**2. Overview of Virtual Reality** ..... **6**

2.1 Development of Virtual Reality ..... 6

2.2 Mixed Reality ..... 9

2.3 VR System Components ..... 11

2.4 CAVE ..... 12

2.5 Predicted Market Size of Virtual Reality in the AEC Industry ..... 13

**3. Virtual Reality in Design of Infrastructure Projects** ..... **15**

3.1 Design Review and Design Approval ..... 16

3.2 Earlier Decision Making ..... 21

3.3 Engagements of Stakeholders and End-Users into Design ..... 25

3.4 Spatial Arrangements and Virtual Prototype ..... 27

3.5 Case Studies ..... 30

**4. Virtual Reality in Construction of Infrastructure Projects** ..... **39**

4.1 Construction Safety Training and Planning ..... 39

4.2 Construction Process Simulation ..... 45

4.1 Construction Site Planning.................................................................... 47

4.2 Case Studies ............................................................................................ 50

**5. Current Practices of VR in Infrastructure Department, Pöyry Finland Oy.... 58**

5.1 Case Study: Engagements of End-users and Stakeholders into the Design in Raide-Jokeri Project, Helsinki, Finland ......................................................... 58

5.2 Workshop: Immersive 3D Design in a Virtual Environment .......................... 63

**6. Conclusion ............................................................................................... 72**

6.1 Limitation ................................................................................................ 73

6.2 Recommendations and Future Work ........................................................... 74

**Declaration of Authorship.............................................................................. 75**

**7. Appendix ................................................................................................... 76**

7.1 Appendix A: Guidelines of Using VR in Pöyry’s Infrastructure Projects......... 76

**List of Literature ............................................................................................ 77**

# Table of Figures

Figure 1: Flowchart shows the thesis methodology. .... 5
Figure 2: Sensorama Simulator. .... 7
Figure 3: Ivan Sutherland's first VR headset, The Sword of Damocles .... 7
Figure 4: Interactive virtual tour with the Aspen Movie Map. .... 8
Figure 5: The Super Cockpit. .... 8
Figure 6: The Virtual Interface Environment Workstation (VIEW) developed by NASA. .... 9
Figure 7: Range of Mixed Reality wherein the left side is the real world and in the right side is the virtual world. .... 10
Figure 8: Mixed Reality range, from the reality on the left to the virtuality on the right. .... 10
Figure 9: The left pictures show the VR system of the Oculus Rift and the right shows the system of HTC Vive. .... 12
Figure 10: CAVE system included walls and floor screens, video projectors, speakers, and tracking cameras. .... 12
Figure 11: From left: nVisor SX60, HMD, Oculus Rift HMD, and Google Cardboard. .... 13
Figure 12: Predicted market size of VR/AR software for different use cases in 2025. .... 14
Figure 13: Plan view for level one and showing the conference room within a red box. .... 20
Figure 14: The left picture shows the virtual meeting room and scaled models above the table. The right picture shows multiple views for the model (architecture, structure, and sections). .... 20
Figure 15: Information availability vs. uncertainty in a project. .... 22
Figure 16: Availability of Information vs. lack of information for D-Ms. and their effect on goal, budget, and time of the project. .... 23
Figure 17: Relation between design effort/ effect and project phases curve by Patrick MacLeamy. .... 28
Figure 18: Train operators drive the train in VE; Real terrain mixed with the model using 3D laser scanning .... 31
Figure 19: Train driver gave advice for moving the signal for achieving better visibility .... 32
Figure 20: Design process and workflow of the data and information for MK3 project. .... 34
Figure 21: Same participant performing the experiment in non-immersive in the left picture and full immersive in the right picture. .... 36
Figure 22: Workflow of both the immersive and the non-immersive system. .... 37
Figure 23: Workflow of the experiment .... 38
Figure 24: Null and non-null PMIs results of the two techniques. .... 38
Figure 25: Percentage of fatal and non-fatal accidents by workplace in the EU, 2015. .... 40
Figure 26: Two workers communicating in a safety-training platform. .... 42
Figure 27: View for operating a crane from two different computers at the same time .... 43
Figure 28: Workflow of modelling the VR for safety training. .... 44
Figure 29: Traditional, incremental, and cantilever bridge construction methods. .... 46
Figure 30: 3D model shows potential collisions between cranes at the construction site. .... 49
Figure 31: Longitudinal section for the bridge. .... 50
Figure 32: Construction sequence. .... 52
Figure 33: Screenshots from the virtual model shows the sequence of construction. .... 52
Figure 34: The average of students and teacher’s answers .... 53
Figure 35: The selected construction site. .... 54
Figure 36: 2D site plan for scenario 1 .... 55

Figure 37: 2D site plan for scenario 2 ..... 55
Figure 38: 3D site plan for scenario 1 ..... 55
Figure 39: 3D site plan for scenario 2 ..... 55
Figure 40: Comparison between the answers of professionals in 2D, 3D, and 3D within VR. 57
Figure 41: Raide Jokeri light railway and the stations with the expected population growth. 58
Figure 42: The urban model in the south park area in the city of Tampere. ..... 59
Figure 43: Extracted from the Kruunusillat project model at a different times of day and in various weather conditions; sunny, dark, post-raining, and snowy conditions. ..... 60
Figure 44: Picture from the VR model for the driver's sight. ..... 62
Figure 45: Picture from inside the VR model done by laser scanning. ..... 65
Figure 46: ALIENWARE M17 gaming Laptop ..... 66
Figure 47: VIVE Headset. ..... 66
Figure 48: VIVE Controllers. ..... 67
Figure 49: VIVE Base Station. ..... 67
Figure 50: Design Space software main tools. ..... 68
Figure 51: In the beginning of workshop two teams at the same room. ..... 68
Figure 52: Workflow of Design Space Software. ..... 69
Figure 53: The participant is using the software’s tools to draw and edit a new pipe. ..... 70

# List of Tabulations

Table 1: ALIENWARE M17 gaming laptop. .................................................................... 66
Table 2: VIVE VR system. ........................................................................................................ 66
Table 3: Features of Design Space Software ............................................................................ 70

# List of Abbreviations

| | |
|---|---|
| 2D | Two Dimensions |
| 3D | Three Dimensions |
| AEC | Architecture, Engineering and Construction |
| AR | Augmented Reality |
| BIM | Building Information Modeling |
| CAD | Computer Aided Design |
| CAVE | Cave Automatic Virtual Environment |
| CVE | Collaborative Virtual Environment |
| EU | European Union |
| GIS | Geographic Information System |
| HMD | Head Mounted Display |
| HVAC | Heating, Ventilation, and Air Conditioning |
| JHA | Job Hazardous Area |
| MR | Mixed Reality |
| VE | Virtual Environment |
| VR | Virtual Reality |

# 1. Introduction

During the last decades, the size of cities is expanding as well as the number of inhabitants; therefore, the demand for complex and mega-infrastructure is increasing. The Architecture, Engineering, and Construction (AEC) industry and especially infrastructure facilities are the major force of country development. However, complex construction projects, such as infrastructure, absorb a considerable amount of the country's capital. Also, it comprises multi-disciplines such as structural, architectural, road, and geotechnical engineering, as well as the involvement of high influence stakeholders; clients, municipalities or transportation agencies. In addition, the pressure to carry out projects of this scale rises significantly, as the expectations of end-users are higher.

In such complex projects, it becomes difficult to maintain a sufficient level of communication, collaboration, and coordination within the project team. With a high level of detail, the design review and design approval consume a significant amount of time and effort. Besides that, clients without engineering background face challenges in understanding the different aspects of the design's components. The lack of design understanding can lead to imprecise decisions with negative consequences such as cost or time overrun. Infrastructure projects involve many stakeholders with different interests and backgrounds. Although the satisfaction of end-users is a vital factor, it is difficult to engage them in the design using the traditional communication approach.

The challenge is not only during the design phase but also in the construction phase. According to (Eurostat, 2018), the construction industry is one of the most dangerous workplaces that cause serious and deadly accidents. Most of the accidents at the construction workplace are due to lack of safety planning and/or training. Infrastructure projects usually extend over a vast area and implement special equipment and techniques. As a result, construction managers face challenges to plan the construction sequence and to define the construction method. Infrastructure construction site involves a big number of equipment and resources; therefore, poor site planning causes clashes and interruptions, which affects the productivity and utilization of available resources.

On the other hand, many studies have indicated that Virtual Reality (VR) can provide better solutions to enhance the design and construction processes. VR can work as a communication and collaboration platform among the design team. The level of visualization, immersion, and interaction in the Collaborative Virtual Environment (CVE) can increase the designer's understanding of the model. Within a Virtual Environment (VE), the client can participate in regular design review meetings with the designers. A better understanding by the client of design components enhances the quality of his/her decisions related to the design. In addition, stakeholders and end-users can visualize the facility and take part during the design by giving feedback and ideas. On-site, safety planners can use VR to provide safety sessions for workers and improve the safety plan. Construction managers are able within a VE to simulate the construction method and detect future collisions or clashes. Finally, site planners can simulate dynamic activities with the resources within a VE to create an efficient site plan.

## 1.1 Overview

This research contents and considers the following:

Chapter 1 Introduces the thesis and briefly shows the challenges that face the AEC industry with a focus on infrastructure projects and refers to the thesis's goals, questions, and methodology.

Chapter 2 It discusses a general overview of VR development through the last decades. In addition, it explains the levels of MR, the VR components for both HMD and the CAVE system, and refers to the VR market size in the near future.

Chapter 3 Investigates the integration of VR in the design process in the AEC industry and especially the infrastructure projects and explains how VR is implemented. Besides focusing on VR and its contribution with design review and design approval, decision-making, engagements of stakeholders and end-users, and understanding the spatial arrangements. The chapter presents three different case studies.

Chapter 4 Explores the integration of VR in the construction process in the AEC industry projects and presents its contribution. The focus here is on the VR integration with construction safety planning and training, construction methods simulation, and planning the construction site. In addition, two case studies are presented for more clarification.

Chapter 5 Shows two cases from the current practices of VR in the design process of Pöyry Finland Oy:

- Case Study: explains how VR could involve end-users and stakeholders in the design of tramline in Helsinki, Finland
- Workshop: explains the application of VR as a tool for communication and collaboration with the client. The author took part in this workshop and the information provided is based on his participation.

Chapter 7 Provides a brief conclusion and the outcomes of the research.

## 1.2 Research Goals

The main goals of this research are:

- Analyzing the benefits of VR in the design process
- Investigating VR support for the construction process
- Studying previous practices of VR in Pöyry Finland Oy
- Provide guidelines and workflow for the possibility of implementing VR in the design process in the infrastructure department of the company.

## 1.3 Research Questions

The research attempts to find answers to the following questions:

- What benefits can VR bring to the design and construction process in the company's infrastructure department?
    - How VR can be implemented in the design and construction process?
    - Does the use of VR improve the design and construction process?
    - Does the use of VR increase the engagement of client and stakeholders into design?
    - What are current practices and needs for developing use of VR in the company?
    - What could be the workflow and procedures of applying VR in the design process in the company?

## 1.4 Research Methodology

The research methodology consists of;

- Literature review
    - Studying previous researches related to the implementation of VR in the design and the construction processes
- Case studies
    - Design review and approval of Ulriken Tunnel, Bergen, Norway
    - Decision-making in MK3 Plant, Malmberget, Sweden
    - Understanding the spatial arrangements, School of Architecture and Design, Brazil
    - Construction simulation of a bridge in Rodental, Germany
    - Site planning for a campus building in Famagusta, Cyprus
- Recent practices at Pöyry Finland Oy
    - Engagements of end-users and stakeholders into the design of tramline project in Helsinki, Finland
    - Workshop for using immersive 3D design in a VE in Vantaa, Finland.

- Outcomes
    - Creating guidelines and workflow for implementing VR during the design of infrastructure projects.

Figure (1) shows a flowchart for the thesis methodology

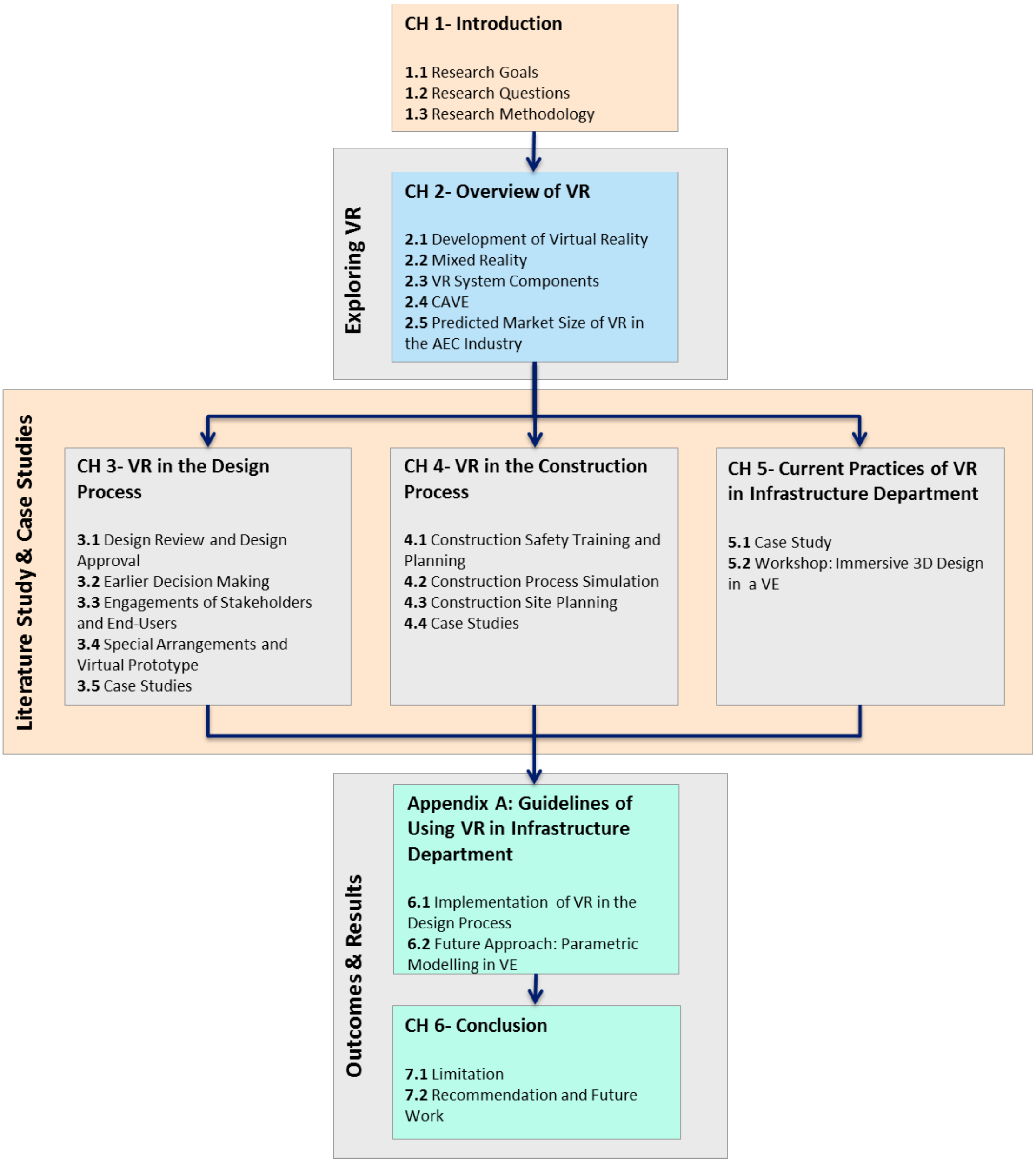



Figure 1: Flowchart shows the thesis methodology. Source: the author

# 2. Overview of Virtual Reality

This chapter discusses a general overview of Virtual Reality (VR) development through the last decades. In addition, it explains the levels of Mixed Reality (MR), the VR components for both Headsets and Cave Automatic Virtual Environment (CAVE) system, and refers to the VR market size in the near future. It is expected from this chapter that the reader forms a general overview about VR history, technologies, and market size.

In order to understand the meaning of VR, it is necessary to define both terms. According to (Oxford, 2019) virtual is "Almost or nearly as described, but not completely or according to a strict definition" in addition, reality is "The state of things as they exist, as opposed to an idealistic or notional idea of them" when adding the two terms together VR means any actions near the real experience of human beings. To experience the VR, there is a need for a Virtual Environment (VE) that closes enough to the physical environment; therefore, there was the engagement of the computer to create this VE. According to (Collins Dictionary, 2019) VR is "the computer-generated simulation of three-dimensional images of an environment or sequence of events that someone using special electronic equipment may view, as on a video screen, and interact with in a seemingly physical way".

## 2.1 Development of Virtual Reality

### 2.1.1 Sensorama Simulator

The term virtual reality might be new but the history of virtual reality back to the 1950s. In 1957, Morten Heiling created a big machine called Sensorama, which was like a large kiosk see figure (2). The purpose of the machine was to combine several technologies to give the sense of being fully immersed in a 3D environment. Heiling added effects such as sound, smell, vibrations, and wind to enhance the feeling of immersion in the virtual environment. In 1960, Heiling developed his invention with the first head-mounted display in the world, but the project remained frozen because of lack of financing. Thereafter, Heiling's invention was considered the foundation of the development of VR (Dormehl, 2017).

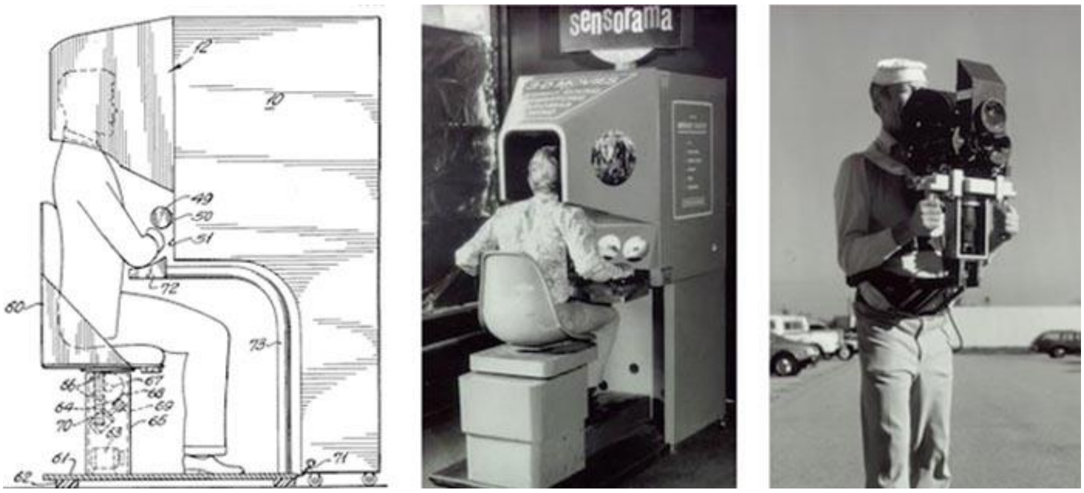



Figure 2: Sensorama Simulator. Source: (The VR Headset, 2018)

### 2.1.2 The Sword of Damocles

In 1968, the computer scientist Ivan Sutherland developed the first Head Mounted Display (HMD) that was the first headset to be connected to a computer instead of a camera see figure (3). While not only was the headset heavy and unpractical but also the computer was producing very simple (Virtual Reality Society, 2019).

Figure 3: Ivan Sutherland's first VR headset, The Sword of Damocles. Source: (Ismail & S. Pillai)

### 2.1.3 The Aspen Movie Map

In 1978, MIT developed “the Aspen Movie Map” which was a virtual tour based on a video taken by a driver thought Aspen, Colorado giving the ability of interactive for the user through a touch screen display see figure (4). Running the system required a computer, a touch screen display, and several laserdisc players. The Aspen Movie

Map was a revolutionary invention that time, as it opened the mind for the ability of VR to transport people to other places in a virtual environment (Dormehl, 2017).

Figure 4: Interactive virtual tour with the Aspen Movie Map. Source: (Aspen Movie Map, 2010)

### 2.1.4 The Super Cockpit

In 1986, Thomas Furness, a military engineer, developed a simulator for training the pilots for controlling the aircraft using sensors with hand signals, a speaker, and an eye tracking. The project called “Super Cockpit”, see figure (5), and could generate 3D maps from the computer, radar and infrared figuring (Barnard, 2018).

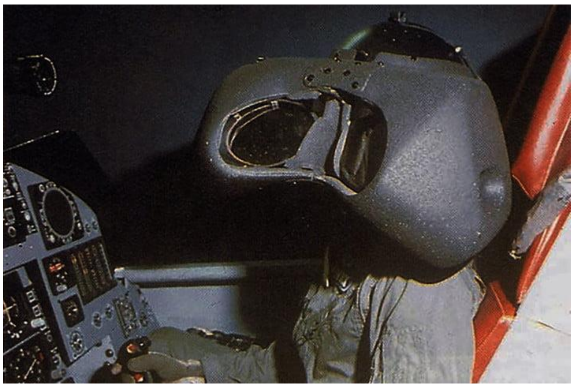


Figure 5: The Super Cockpit. Source: (Dormehl, 2017)

### 2.1.5 NASA

In 1989, NASA started to develop a workstation using a virtual environment for simulating space trips and training the astronauts. The system compromised headset and gloves see figure (6). The gloves had sensors and fiber optic wires that enable the user to interact with the virtual environment. In 1991, NASA scientists developed a computer simulator system that allows the astronauts to control and drive a robot on Mars at real time (NASA, 2018).


Figure 6: The Virtual Interface Environment Workstation (VIEW) developed by NASA. Source: (NASA, 2018)

### 2.1.6 Sega VR

In 1991, Sega, one of the biggest video games companies that time, announced a development project to produce a VR headset. The company planned to launch the new product in 1993 with a competitive price of $200. The system formed a VR headset with LCD screens in the visor, headphones, and sensors. The sensors were supposed to track the user's head movements. Unfortunately, the company could not release the product for unknown reasons (Wiltz, 2019).

### 2.1.7 Oculus Rift

In 2010, Palmer Luckey, a young entrepreneur, launched the first prototype of Oculus Rift. The headset was designed to provide a 90-degree vision, low latency, and built-in haptic feedback (Morgan, 2017).

## 2.2 Mixed Reality

Mixed Reality (MR) combines the physical world and the VE. MR can be divided into two main environments see figure (7). The first environment is Augmented Reality

(AR) where the user exists in the real world and uses an interface device to visualize and interact with a virtual model. One example for AR is using glasses when performing maintenance of a road by bringing the model of pipes and manholes to place them virtually on the road. Augmented Virtuality (AV) is to bring the real environment into a virtual world. When considering the same road example, the actual road will be modeled and combine with pipes and manholes in the VE, therefore the user can manipulate between virtual and real elements.

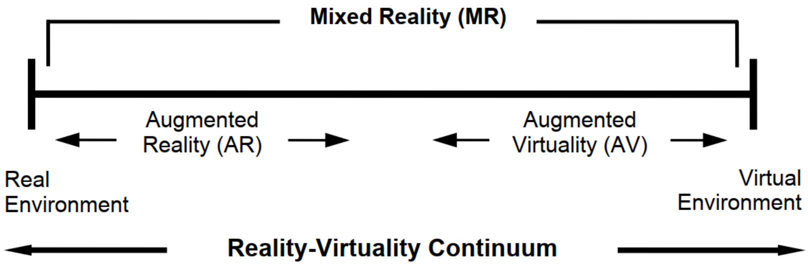



Figure 7: Range of Mixed Reality wherein the left side is the real world and in the right side is the virtual world. Source: (Wang & Schnabel, 2009)

According to (Wang & Schnabel, 2009), MR is extended from the real world to the virtual environment. Figure (8) shows the order from the real to a virtual world and some of them are described as following:

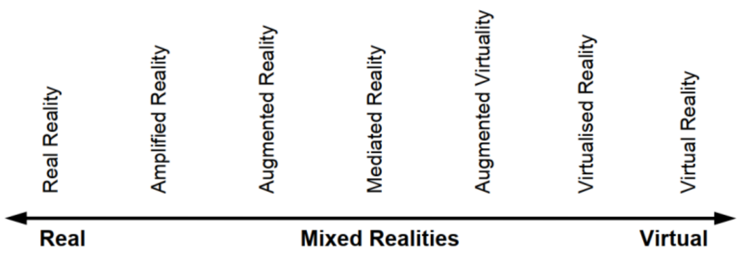



Figure 8: Mixed Reality range, from the reality on the left to the virtuality on the right. Source: (Wang & Schnabel, 2009)

**Reality** is on the left side of figure 7 and refers to the real world and things that already exist. In the AEC industry, reality refers to all elements such as buildings, roads, bridges, space, and solid.

**Augmented Reality (AR)** combines virtual elements and the real world. The user can interact between the virtual elements and the real world by using glasses, mobile phones, tablets, etc. Earlier, AR has implemented in scientific visualization and gaming. Recently, AR is used in the AEC industry for collaboration and visualization purposes. Many types of research have argued that AR has great potential in architecture, urban design, decision-support, and planning.

**Mediated Reality** represents the artificial alteration in the real world from human perception. For instance, adding or removing information from the real world scene when the user is visualizing through glasses. MR is useful in many applications; For example, when designing an urban area, the user can remove/add a building or landscape to check how it will look like. Such a tool is important especially at the early stage of design and planning.

**Virtual Reality (VR)** represents computer-simulated environments, which allows the full immersion for the user into this virtual environment. VR can help designers to facilitate communication, visualization and collaboration in the design.

## 2.3 VR System Components

### 2.3.1 Hardware

The VR system consists of a gaming computer with a high processor connected with a Head Mounted Display (HMD), trackers, and base station. HMD is a helmet provided with glasses and headphones that allows the user to experience a virtual environment. HMD can be provided with eye- or head-tracking sensors, which enrich the feeling of immersion. Trackers are joysticks that enable the user to control inside the environment. By using the trackers, the user can walk, fly, draw, or manipulate with virtual elements inside the virtual environment. The base station is responsible for defining the manipulation area and the user has to calibrate them with the HMD and trackers. There are two positions to experience VR. First is while moving in a scaled room and in this case a base station such as in HTC Vive can be used. The other position is static while setting on a desk and using touch controllers, and the Oculus Rift is an example for that. Figure (9) shows the HTC Vive and Oculus Rift for the VR system.

Figure 9: The left pictures show the VR system of the Oculus Rift and the right shows the system of HTC Vive. Source: (Oculus, 2019) and (HTC Corporation, 2019)

### 2.3.2 Software

VR uses gaming engines such as Unity and Unreal Engine for providing a virtual environment. Unity, for instance, is developing some applications in the AEC industry for visualization, design review, safety training, and marketing. Beside these gaming engines, there is other software, which are concerned only about the AEC industry such as 3D Space, IrisVR, InsiteVR , Fuzor, Enscape.

## 2.4 CAVE

Cave Automatic Virtual Environment (CAVE) is a virtual environment consists of projected screens on walls and floors, video projectors, speakers, and tracing cameras see figure (10). The user is able to manipulate with the virtual environment with the help of 3D glasses and controllers. The glasses and controllers are connected to the system by trackers. CAVE system is implemented in the AEC industry for visualization of the design model, walking through to check clashes, and study the construction methods. According to (Visbox, 2019) CAVE is more convenient than HMD for experiencing the VE, but the cost is higher.

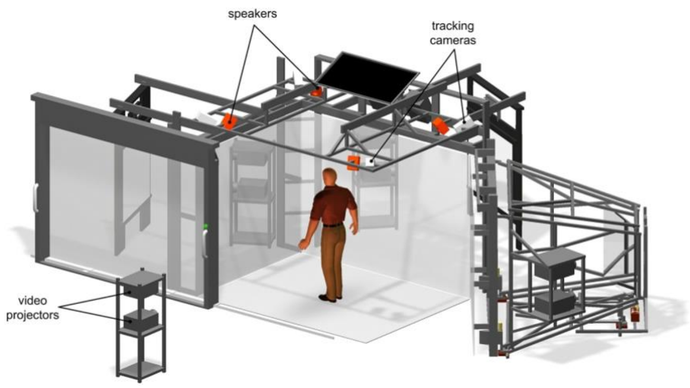



Figure 10: CAVE system included walls and floor screens, video projectors, speakers, and tracking cameras. Source: (Schröder & Dirk, 2010)

## 2.5 Predicted Market Size of Virtual Reality in the AEC Industry

However, VR is not a new concept, but recently it became involved in the AEC industry. The main reason behind is the price, for instance, the cost of “nVisor SX60” Head Mounted Display in 2003 was $24,000 and it had a 60-degree view field with a weight around 1Kg (Engadget, 2017) see figure (11). When comparing the price by today, “Oculus Rift” HMD is available with a touch bundle, high-quality resolution and optimum control with a cost of around $350 (Oculus, 2019). Another product is “Google Cardboard” which costs $15 and is accessible with mobile-phone use (Google , 2019). Therefore, there is almost over 65 times reduction in the price over 15 years that encourages the AEC firms to look for implementing VR in the construction industry.

Figure 11: From left: nVisor SX60, HMD, Oculus Rift HMD, and Google Cardboard. Source: (Engadget, 2017) (Oculus, 2019), and (Google , 2019)

In addition, giant companies such as Facebook, Microsoft, and Google are investing a huge amount of money in VR solutions. In 2017, Facebook purchased Oculus for $2 billion (Business Isider Nordic, 2017). In the same year, Microsoft announced Windows Mixed Reality as a VR platform (Medium , 2017). One year earlier, Google launched the Daydream VR platform for Android users to download VR applications besides the investment in the Google Cardboard (The Motley Fool, 2017).

It is known that construction is always the last industry sector to adopt up-to-date technology, as construction projects are unique, complicated, and not repetitive processes. Nowadays, the development of VR software for construction is giving new potential to the AEC industry. According to a future prediction (Statista , 2016), the VR/AR software will contribute by around $4.70 billion in the engineering sector by 2025, and when combining the real estate sector, the number will raise up to $7.30

billion which means it would be the biggest sector adopting VR after video games see figure (12).

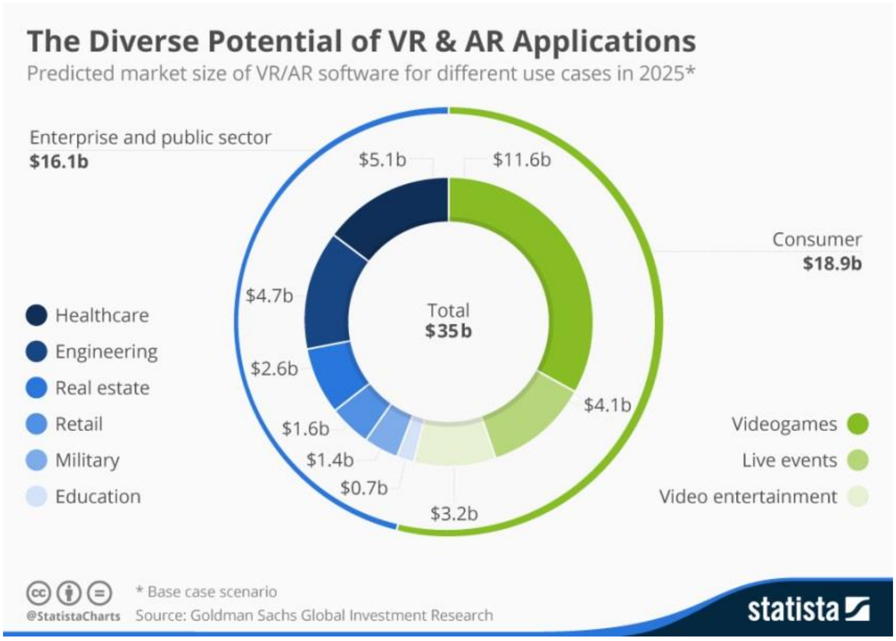



Figure 12: Predicted market size of VR/AR software for different use cases in 2025. Source: (Statista , 2016)

# 3. Virtual Reality in Design of Infrastructure Projects

This chapter discusses the integration of VR in the design process within the AEC industry and especially the infrastructure projects and explains how VR is implemented in the design process. It focuses on the VR and its integration with design review and design approval, decision-making, engagements of stakeholders and end-users, and understanding the spatial arrangements and virtual prototypes. This chapter provides the reader with an overview of VR contribution in the design process.

Infrastructure projects represent the economic growth of the country. The more the country is developing, the more the need for improving the infrastructure. Therefore there is sometimes a need for large-scale infrastructure projects to overcome the city or the country’s growth. However, mega infrastructure projects consume a huge amount of capital (Omar;Trigunarsyah;& Wong, 2009). In infrastructure projects, not only the clients, architects and engineers are involved but also the municipalities, end-users, and citizens living in the surrounding area of the project. Moreover, mega infrastructure projects usually involve multidiscipline engineers such as architecture, structure, geotechnical, road engineering, railway engineering, and rock engineering. Each discipline has a different engineering background and understanding. Therefore, in case of mega projects, design review and approval consumes a big effort and time, the client is taking more time to deiced about the design and different alternatives, the stakeholders and end-users may find difficulties to understand the design, and designers themselves could struggle to understand the spatial arrangements because of the project complexity.

Therefore, there was a need for different tools that could improve the design process of infrastructure projects. Many researchers believe that VR can contribute positively in this approach. VR can be a tool to facilitate the design review and design approval by increasing the visualization and involving not only engineers but also the operators and facility management team during the design review. In addition, VR could be used to enhance communication with the client during the design and provide them with the latest design achievement while setting at the office. During the design development, it is possible to use VR to communicate with stockholders and end-users and show them the future situation after the project completion that can positively change their opinion about the project or bring more innovative ideas that help facility users. The engineers and by the help of VR could be able to understand more the space inside the design when they are immersive and gather a correct and complete picture about the dimensions and model elements.

## 3.1 Design Review and Design Approval

The main purposes of the design phase are achieving the client's objectives for the project, guaranteeing the safety during the construction and operation phases, and keeping the project within the budget. Although the design process only accounts for about 5% of the typical construction project, it affects the quality and the cost of the remaining 95%. Design review involves many disciplines for coordination and cash detection (Tizani, 2011). For example, if a structure engineer wants to review a design part for a tunnel project, the structure engineer has to take in consideration not only the structural elements but also the road design, the MEP system, the ventilation system, and the geotechnical specifications. In such a situation, coordination and communication is required with road engineers, MEP engineers, ventilations specialists, and geotechnical engineers. However, using communications tools such as emails, 2D drawings, or even 3D shared models, there is still some gap for sharing and understanding the design between multiple disciplines.

Design review is part of the project management procedure and carried on frequently for preventing or reducing construction delays by solving the design clashes or redesigning based on the clients' wishes. Misunderstanding and ineffective collaboration can lead to an overrun of time and budget. Increasing collaboration and information flow and ensuring that stakeholders are working together can achieve the development for project time, cost and quality. Therefore, the project management held a design review meetings to smoothen the project execution, solving existing problems and addressing the future. Currently, engineers use CAD and BIM in the design review meetings for visualizations and study the suggested design. BIM allows to bring and sharing data between different disciplines and detect the clashes in the design. However, the BIM ability still limited regarding the interaction within the project team to brainstorm the design ideas and explore different design alternatives when facing a design problem (Fernando;Wu;& Bassanino, 2013).

### 3.1.1 Collaborative Virtual Environment (CVE)

CVE is a virtual environment with multiple users communicating and collaborating in real time and from the different location. The user can experience CVE as fully immersive with using a headset and controllers or non-immersive when using big screen for instance. Users can communicate in the CVE by speaking, texting, or manipulating with the virtual elements. According to (Fernando;Wu;& Bassanino, 2013) most of BIM software such as Autodesk, Graphisoft and Trimble focuses more on the design and not the design review. A possible solution could be the implementation of Collaborative Virtual Environment (CVE) into design process where it can allow involving multiple users in design review in the real-time. Within the VE, collaboration is possible through text, voice, and interaction with the design elements. VE in design review meeting can provide real-time collaboration and interaction within the design, ability to investigate the design, test design alternatives and even simulate the construction method. They argued that CVE could have strengths such as:

| | |
|---|---|
| Rendering in Real-Time | Rendering in CVE with adding texture, shadows, and shading to the model characteristics increase the realistic visualization to the user. |
| Walkthrough in Real-Time | Real-time walkthrough in the model gives the reviewer the sense of being in the reality with the ability to move upstairs, downstairs, out from the window etc. Adding shades, shadows and colors with instant control in the 3D model increase this feeling of presence. The client or the owner can feel the property and its function and picture real expectations for the outcomes. |
| Interactivity | Interaction between the user and computer can be by changing views, voice and type commands, mouse or keyboard control, etc. The more the user interacts with the virtual model, the more feeling of reality. |
| Multi-Users | Dummies and avatars are used to represent each user and to increase the way of communication. Multiple design reviewers can take part in real time inside the |

| | |
|---|---|
| | same virtual space. Communication is by text chat, voice chat, and interaction with the model element. |
| Lighting | It is important that the VE has lighting resembles the real world. It increases the feeling of confidence and security. Two types can be used in the VE static and dynamic lighting. |
| Collision Detection | Collision detection is an important feature, and it can be by default for solid elements such as walls, windows, the doors. In addition, reviewers can walk through the model and detect clashes manually. |

### 3.1.2 CVE in Design Review Meetings

During the design review meeting (Van Den Berg;Hartmann;& De Graaf, 2017) has argued that CVE enable the communication between client and designers inside the virtual model and in the real time beside the client can provide instant feedback about the design. Using a CVE can have positive impacts on the client. While walking through the design model, the client can be able to detect design problems or undesired issues. Moreover, the client can visualize the facility function and have a picture of how it will look like in real life. Through using this approach, the client will not be only reviewing the design but can be a part of finding solutions for the design problem.

In order to experience the CVE in real projects (Van Den Berg;Hartmann;& De Graaf, 2017) used two real projects as case studies to study how it could add value to the design review process. The first project was a conceptual design for parking building, and only 2D CAD drawings were available. The researchers implemented CVE directly from the beginning of the preliminary design phase and engaged two of the clients out of three. The second project was two water production plants, and they were concerned about the definitive phase, while in this project BIM with 3D CAD drawings were available. The researchers organized design review meeting for both projects and recorded the meeting sessions. They also performed a questionnaire and interviewees for the participants and for some people who did not take part.

After using the CVE, engineers and specialists who used the VE could comment and detect some design problems regarding the garage ramp slope and conflicts between pipes in the plants. Clients commented that they experienced the projects as reality with the technical specifications, colors and function that they could not receive from 2D drawings. The ability of the client to leave comments in the VE while walking through the design increased their feeling of presence and they become participations in finding solutions for the design problem. The clients and designers who participated were able to provide feedback, which was helpful in optimizing the design. One client did not feel comfortable using VE in a big group meeting session and they suggested it could be more helpful if the sessions are performed individually (Van Den Berg;Hartmann;& De Graaf, 2017).

The ability to combine different views (architecture, structure, and 3D sections) at the same time and in the same space can enhance the design analysis. Sometimes, there is a need for viewing the model in different scales, which can be more inclusive (Read, 2017). Engineers are used to build a scaled physical prototype to show the client and stakeholders how the projects will look after completion, and this process consumes time and money. However, when implementing CVE, it can be used as an immersive prototype where the user is able to check all the details. Designers themselves could use the model for combining different views and sections at the same time. The following is an example to show how CVE used in a review meeting for normal building can.

The main idea from this example is to show how CVE can be used in design’s review , however this case add that the user (s) will have two options to review; first is walking thought the model and second is to bring scaled models inside the VE and check them together. The BIM model was created by Autodesk Revit and different views and sections were prepared. The building comprised two levels: the ground floor contains a conference meeting room, which will be used for the review session see figure (13). After the views were ready in Revit see figure (13), the user exported them to 3D DWG format with applying the true color function on the software. BIMception, a plug-in tool inside Revit, was used to combine between the main model and the scaled ones. In addition, the user can control the exported level of details (Read, 2017).

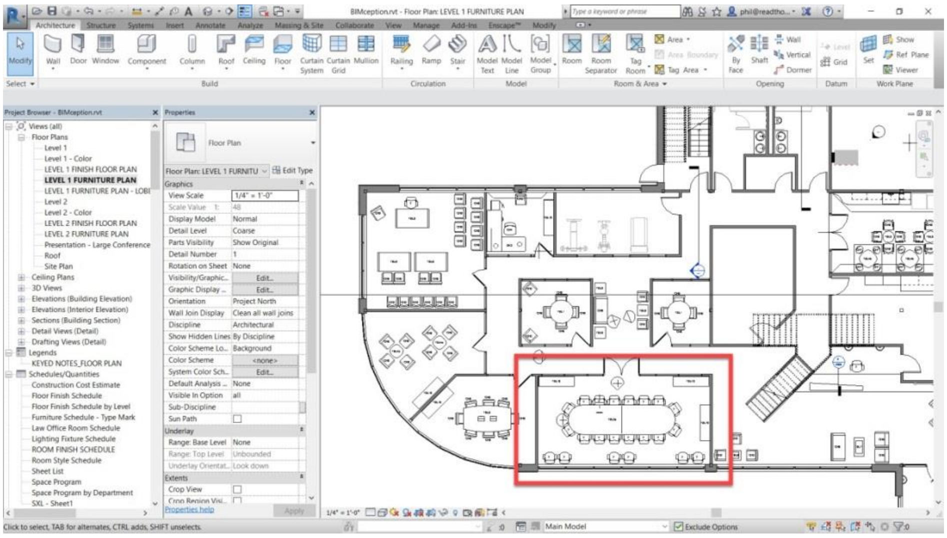


Figure 13: Plan view for level one and showing the conference room within a red box. Source: (Read, 2017)

In the CVE, the user imported the scaled views to the conference room and placed them on the meeting table. Through using such an approach, it is possible to review the scaled models inside the VE by a simple walk around and check the model. The process could be simple and effective; the reviewers can select multiple views based on the meeting agenda see figure (14). In addition, the design review team can navigate easily in the model, sharing ideas and brainstorming about the design. Such a procedure in design review will help designers and customers to communicate immediately no matter where their location (Read, 2017).

Figure 14: The left picture shows the virtual meeting room and scaled models above the table. The right picture shows multiple views for the model (architecture, structure, and sections). Source: (Read, 2017)

### 3.1.3 Results and Discussion

- Design only share 5% of the project cost but affects the remaining 95%
- The design review process is complicated and involves many disciplines
- BIM is an effective tool for sharing data but still limited regarding design review, especially when coordinating between multiple disciplines
- CVE could fill the gap in BIM for collaboration and coordination
- Clients without an engineering background can better understand the design within VE than 2D or 3D CAD models
- Clients can take part in finding design alternatives and solutions when understanding the design
- Some clients do not feel comfortable using VE within a large group.

## 3.2 Earlier Decision Making

At the early design phase, the decision-makers will have more flexibility and a greater impact on the outcomes of the projects. Therefore, to achieve the desired quality within the budget and the time, there is a need for paying more attention to the preliminary design phase (Woksepp;Olofsson;& Jongeling, 2005). Many factors can cause uncertainty during the project phases, especially in the initial phase because of lack of information. The higher the level of uncertainty is, the more difficult it is for decision makers to make reliable decisions see figure (15). At the initial phase, it is more flexible for decision makers to take a decision; however, the available information at this phase is very limited, which complicates the decision-making process. While the project proceeds, the information increases but in become costly and difficult to make amendments, which also limited the decision-makers choices (Samset, 2009).

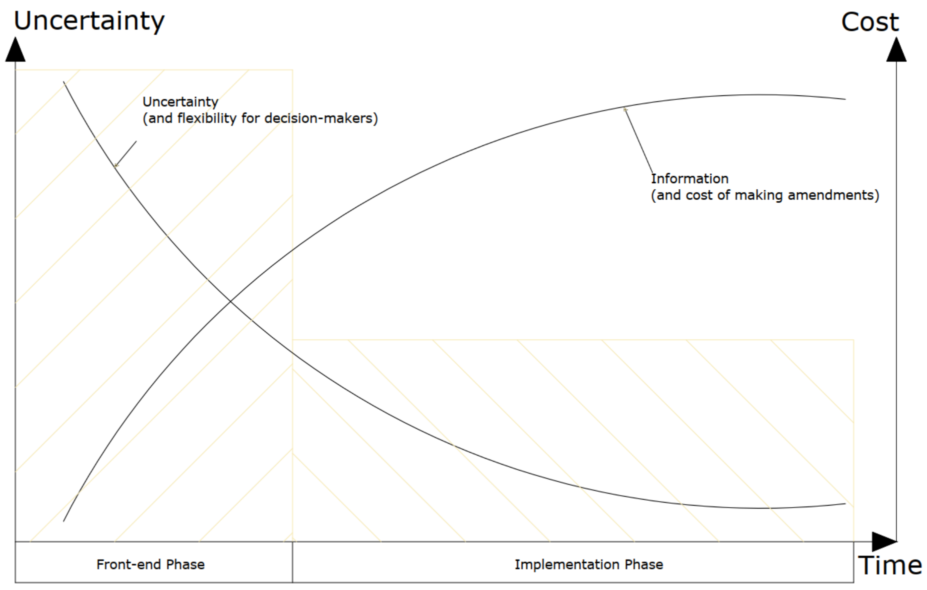



Figure 15: Information availability vs. uncertainty in a project. Uncertainty is the highest at the initial phase and decreases as the project proceeds. The information is less at the initial phases and increases while the project proceeds. Adapted from: (Samset, 2009).

The project is a unique and temporary process aiming for creating a product, result, or service. The project has a goal and completed by achieving this goal within the specified time and quality. To reach this goal, knowledge, skills, and tools are required. Each project passes through five phases: starting, planning, executing, monitoring and controlling, and closing (PMBOK, 2013). The decision is one of the vital skills made in the entire project stages; the project starts with a decision and ends with a decision. Making wise decisions is vital for the success of the project; however, poor and wrong decisions could lead to unclear outcomes with negative consequences.

### 3.2.1 Access to the Right Information

According to (Project Management Institute, 2015), *"nearly half of unsuccessful projects are impacted by poor decision making".* Deciding wisely leads to an effective organization; however, there are some challenges related to culture, people, and processes, which complicate the ability to make effective decisions. One of the most challenging challenges for decision-makers is the availability of accurate information in the right time and how they visualize this information.

Availability and accessibility to the right information increase the reliability of decision-makers to make effective decisions meeting the organization's strategy. It is claimed that in 81% of the organizations, decision-makers have difficulties accessing the needed information. Such a situation leads to a shortage of important information such as available resources, risk assessments, and project requirements. When the right information is available for the decision-makers, 78% of the projects meet the aim compared to 49% when the information is difficult to access. In addition, 67% are completed within the budget compared to 37% and 63% are completed within the time schedule compared to 36% see figure (16) (Project Management Institute, 2015).

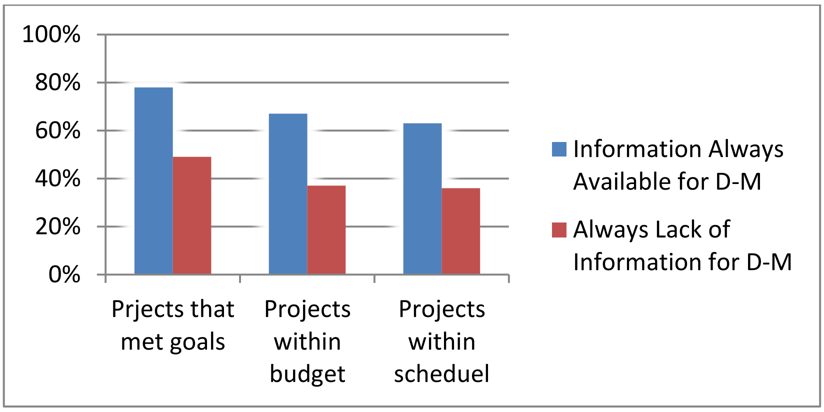



Figure 16: Availability of Information vs. lack of information for D-Ms. and their effect on goal, budget, and time of the project. Source: (Project Management Institute, 2015)

### 3.2.2 VR in Decision Making

The more the project is complex; the more difficult is to sustain communication and coordination. This situation can lead to inefficient information and knowledge flow within the stakeholders. Information losses in the traditional work technique are frequently because of the lack of trust or inadequate communication tools. Two important factors can increase the communications and remove the technical and social barriers: increasing the trust within the involved stakeholders and increasing confidence and reliability of data exchange. VR could fill the communication gap between the design team and the client (Woksepp;Olofsson;& Jongeling, 2005).

To support the decision makers for urban planning, a group of researchers (El halabi;El Sayad;& M. Ayad, 2018) studied the possibility of combining VR and Geographic Information System (GIS). The goal from the research was to determine how VR together with GIS could provide solutions and ideas for urban planning designers and authorities in the Gaza District, Palestine. To provide new practices from existing tools that could support decision-makers. The authors claimed that using VR in urban planning could enhance how that engineers, designers, and decision-makers understand the project. They could experience in the real-time the effects of the design in the surroundings of the project. They can experience different scenarios and compare them within a short time.

The researchers used a case to testify the concept of using VR with GIS. The case study was planning a railway to connect between multiple cities in Gaza District. They created several models as design alternatives of the railway without focusing on details of the railway itself. Together with the case study, the researchers arranged a questionnaire for a group of designers, urban planners, and the responsible for decision-making in the district. The questionnaire was divided into three parts: the personal information of the participants, what is the adding value of GIS as an information source, how was the knowledge level of participants about VR before and after (El halabi;El Sayad;& M. Ayad, 2018).

The results of the case study and questionnaire show implementing of VR with GIS increased the understanding and satisfaction of the participants. For instance, 90% of the participants declared that the tool is beneficial to show or add an opinion. In addition, the question regarding making decision using the traditional way compared to VR with GIS, 63% of the participants indicated that they prefer the VR with GIS than the traditional way. The results specify that there are potential for VR in urban planning and especially if it is combined with GIS. It increases the ability of the designer to illustrate the design ideas. When the participants experienced the city model on VR, they could easily identify the city and be familiar with its streets and neighborhoods. There were some participants faced problems to handle and manipulate inside the VE and some of them mentioned that there was a need for training before using the system (El halabi;El Sayad;& M. Ayad, 2018).

### 3.2.3 Results and Discussion

- There is a need to pay more attention to decisions at the early design phase
- The project starts and ends with a decision
- Access to the right information increases the decision reliability
- Combining VR and GIS is a useful tool for visualizing different design alternatives
- VR with GIS could support decision-making as it enhances the contributions of decision-makers
- However, most of the people tend to use advanced technology; some people still prefer the traditional way of doing the work.

## 3.3 Engagements of Stakeholders and End-Users into Design

Frequently, construction projects and especially the infrastructure meet claims from the residents during design and construction because of misunderstanding the project scope. Such claims may lead to delays in the project and sometimes stop it, which causes a huge loss for investors. Therefore, the project can proceed faster if satisfaction for the inhabitants and stakeholders increases. The project might seem as understood for the residents and stakeholders, but as soon as the construction started, they may think the construction differs from what they have thought. This problem mainly happens because the professional uses 2D drawings and reports for communication with ordinary people (Yabuki, 2011).

The opinion and feedback of users or inhabitants of a facility could affect positively or negatively on the quality of the project and it can cause extra cost in case of amendments. Therefore, their concerns must be taken into consideration during the design. It is difficult and time consuming to collect stakeholders’ feedback before or during the design. There is a need for communication tool during the design to present the designs/ alternatives for the users and stakeholders and involve their feedbacks and concerns in the final design (N. Mohammadi & E. Taylor, 2019).

### 3.3.1 VR for Stakeholders and End-users

According to (Yabuki, 2011), VR can be an effective communication tool between engineers, residents, and stakeholders, where they can take part in the design, provide their opinions, asking questions, and leave feedback. Using CVE for engaging stakeholders or end-users in the design could be an effective tool as it offers multiple users at the same time with the ability to take part remotely no matter where is the location. Besides visualization, the CVE could be augmented with sound, smell, touch, and taste effects. In addition, CVE provides the capability of sharing and exchanging the data therefore, the designers can present and explain them to stakeholders and residents and gather the feedback in the real time.

To test the contribution of VR in engaging the stakeholders and gather their feedback about a future building performance, (N. Mohammadi & E. Taylor, 2019) performed a study on a campus building. The researchers used four different techniques for the evaluation VR, AR, panorama 360°, and 2D pictures. Following preparing the building model and setting up the system for the four methods, the researchers collected 129 participants from different genders, ethnicities, and educational backgrounds. The main job of the participants is to testify the building performance from different aspects such as energy, degree of comfort, place etc. by exploring the building with the different methods, then answers the required questions.

After the researchers collected all responses from the participants, they performed the hypotheses method to check the results. The overall results indicated that VR is more effective in visualization and presentation of the building than the other three techniques AR, panorama 360°, and 2D pictures. However, in the energy visualization, VR could not add value to the participants. In contrast, 2D pictures the most ineffective tool for providing information for the participants (N. Mohammadi & E. Taylor, 2019).

### 3.3.2 Results and Discussion

- Infrastructure projects can meet claims from stakeholders or end-users before or during the construction because of misunderstandings
- Stakeholders or inhabitants could provide feedback about the project, which could bring benefits to the projects and prevent future problems
- VR can be used as a communication tool with stakeholders and end-users to show how the project will look like
- Stakeholders and end-users could add comment/opinion/feedback inside the VE and designers take them in consideration
- Within the VE, people without an engineering background will can see the facility function and operation before even the construction begins.

## 3.4 Spatial Arrangements and Virtual Prototype

In early design phases, the influence of changing the quality of the construction is higher and decisions related to the cost, quality, and time are being made. When the project is proceeding, the influence on the design becomes limited and the cost of changing the design becomes higher. Therefore, it is cost efficient to optimize the project design as early as possible. This could be achieved when there is enough related information and a decent understanding of the project. The famous architect Patrick MacLeamy draw a graph to show this relationship see figure (17). The graph compares between the traditional and the integrated design process. In the traditional way, most of the design changes are applied either in the construction phase or slightly before the construction begins. If project managers provide more effort with integrated tools, this can lead to optimum design changes in the early design phases. With such an approach, the design quality can be higher and design changes will cost less. Therefore, there is a need not only to provide more effort at the early design phase but also to use innovative tools (BuildingSMART UK, 2010).

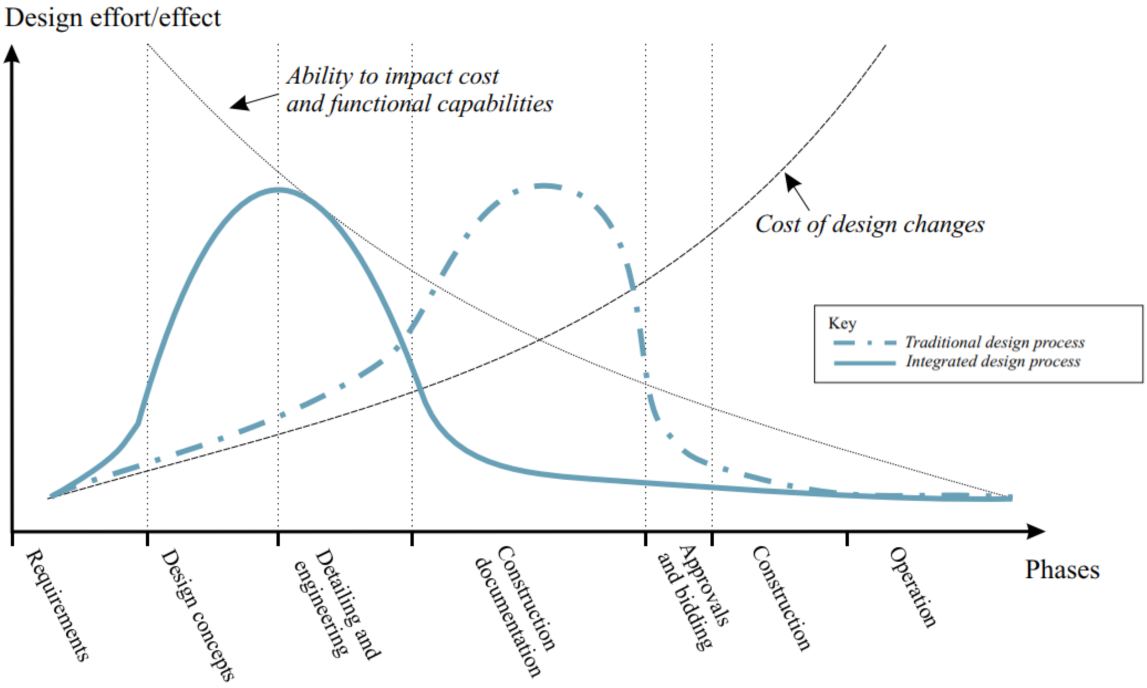



Figure 17: Relation between design effort/ effect and project phases curve by Patrick MacLeamy. Source: (BuildingSMART UK, 2010)

### 3.4.1 VR for Representing the Physical Environment

For integrating the design, there is a need for achieving the highest understanding of the design, which requires an innovative tool with adaptive workflow. These tools should enable completing the conceptual planning phase in the pre-defined time, cost, and quality. Implementation of BIM in the design process has a great impact on the results of the design. BIM enables the designer to have a better understanding for the design and smooth sharing for the information data. However, it is believed that BIM models are still limited in terms of representation and understanding of the spatial arrangements especially in the conceptual design phase. VR has a great ability regarding the visualization and representing the physical environment. In the VE, the user can walkthrough and interact with the model elements within fully immersive environment, which increase the understanding of the spatial perception (Daniel;Eduardo;& Irizarry, 2017).

The major difference between the VE and the traditional approach using a 3D model is the level of presence inside the model. When the user has more ability to interact within the VE, the feeling of presence increases and reflects on the total understanding for the model elements and space. Presence is believed to be a combination of personal leanings and environmental aspects. However, it is assumed that presence improves spatial perception in the immersive environment; it is not necessary to have a high presence to achieve high spatial perception (Daniel;Eduardo;& Irizarry, 2017).

VR provides the ability for the user to interact with the design elements through actual human scale. Besides, it is possible to enhance and augment VR with much information related to visualization and interaction. In recent years, virtual prototypes are widely adapted in the AEC industry. One of the most common features of virtual prototypes is the ability to present different 3D models with different scales. The less cost and short time to produce virtual prototype have proven the advantages of virtual prototypes over the traditional physical mockups in the AEC industry (Castronovo;Nikolic;Liu;& Messner, 2013).

To compare the virtual prototype and physical mockups, (Majumdar;A. Fischer;& R. Schwegler, 2006) have used an actual court room project. The physical mock-up was made from plywood and CAVE has been used to simulate the virtual prototype. They conclude the differences that the time consumed for reviewing the design with virtual prototype was 3 hours and in physical mock-up was 8 hours. In addition, the court judges could use the virtual prototype to check his/her future position while the rest of the participants are watching and he participants could suggest modifications and see the results in real-time. Finally, with a physical mock-up, there is a need for full shop drawing. This is unnecessary for a virtual prototype because it is possible to change in the model.

### 3.4.2 Results and Discussion

- Putting more effort with using innovative tools at the conceptual design phase enhance the project cost, time, and quality
- Increasing the design understanding and especially on the early design phases has a great impacts on the outcomes
- VR increases the understanding for spatial perception
- VE provides more integration with the 3D model elements compared to traditional workstation computers
- Using prototypes can reduce the time and cost of design review

## 3.5 Case Studies

This section highlights three different case studies reflecting how VR is implemented within the design process:

- Case study 1: explains how VR used during the design review and the design approval for a railway tunnel projects in Norway
- Case study 2: explains how VR implemented as a decision-making tool in pelletizing plant in Sweden
- Case study 3: explains how VR used for understanding the spatial arrangements in university project in Brazil.

### 3.5.1 Case Study 1: Design Review and Approval of Ulriken Tunnel, Bergen, Norway

Ulriken Tunnel is a part of a 500 km railway road between two big cities in Norway, Oslo and Bergen. The tunnel locates at the end of the railway road between Arna and Bergen. There is an old tunnel in the same location that was built in 1964, but recently it became one of the most crowded tunnels in Norway. In 2010, the Bane NOR, who is responsible for railways infrastructure in Norway, wanted to double the tunnel's capacity by building a parallel new tunnel. The project's main challenge was to construct the new tunnel without disturbing the trains flow in the old tunnel beside the commitment of the project time and budget (Autodesk, 2018).

With a big budget and tight schedule, the project became more complex and risky. There were many challenges not only in the technical part but also in the administration bureaucracy regarding the review and approval of the design. Traditional design review and approval for such a project could be critical tasks that consume a long time to achieve, which could lead to budget and time overrun. For instance, approval for signs and signals for the railways in tunnels is critical because the whole operation system depends on these signs and signals. Therefore, the design team in Ulriken Tunnel was looking for an alternative solution to facilitate and speed up the design approval (Autodesk, 2018).

The design team of the tunnel adopted BIM from the beginning of the project to enhance coordination between multiple disciplines. BIM Models of the tunnel and the train stations were created using AutoCAD, Civil 3D, and Revit. In the traditional design, the method of testing and approving the signaling system requires a long time after the signals are installed. Therefore, the design team implemented VR and combined it with the BIM model to enable the train operators to drive and test trains in the VE and before even the tunnel being built see figure (18). The design team created the animation form the BIM model by the assist of 3D Max and for giving more realistic to the model, the team used laser scanners for scanning the surrounding area and combining it with the virtual model (Autodesk, 2018).


Figure 18: Train operators drive the train in VE; Real terrain mixed with the model using 3D laser scanning. Source: (Autodesk, 2018)

In the VE, the train operators could drive trains while civil engineers used their simulation to assess the design of signs and signals in the tunnel. When using design iteration and collaboration between the designers and the operation team, it was possible to correct and optimize the design of the signaling system see figure (19). In addition, the designers gained a better understanding of the operation system when watching the drivers experience trains in the VE. Besides the design optimization, Bane NOR used the same VR model for studying the evacuation in case of emergency through. For this purpose, the model was enriched with the natural surrounding environment. The surrounding terrain environment was created using a drone and then combined with the VR model. The combined model used to watch the emergency exits and simulate different emergency scenarios. Similar simulations could help the facility management team achieve a better maintenance plan (Autodesk, 2018).

1 

Figure 19: Train driver gave advice for moving the signal for achieving better visibility. Source: (Autodesk, 2018)

There were many benefits achieved from implementing the VE simulation. First, adjusting the regular approval process and reducing the time needed to approve the design. Second, it reduces the cost of construction by detecting design errors and correcting them before the construction begins. By the help of such an approach, the tunnel could achieve the highest performance after the construction. The company used a similar approach later on another project for gathering feedback from tram drivers about emergency vehicles and bike lanes (Autodesk, 2018).

**Results and Discussion**

- Improving the design process will reflect positively on the construction
- Using VR for simulating operation on infrastructure projects could facilitate and speed up design approval
- Design engineers could understand the infrastructure operation better when watching simulating the operation process
- Involving the operation team could help in enhancing the design and finding better alternatives
- The maintenance team could simulate infrastructure maintenance plan even before the project completion.

### 3.5.2 Case Study 2: Decision-Making in MK3 Plant, Malmberget, Sweden

In the north of Sweden, the Swedish mining company LKAB was planning to build a pelletizing plant called “MK3”. The client wanted an extension for an old pelletizing plant in the same location for increasing the production. The client involved an investment of €290 million in the project. Two years was the timetable from making the investment decision to the completion of the project, which was a limited period, compared to similar projects. Therefore, a short time was available for making the preliminary study and the preliminary design; together were the fundamentals for making the investment decision (Woksepp;Olofsson;& Jongeling, 2005).

The client’s objectives were to achieve the plant with the required capacity, within budget and within the time schedule. The client’s priority for the design and planning was the manufacturing process then the layout with the surroundings and finally the construction of the plant, which lead the project team to focus more on the manufacturing process as a priority than the real construction. Because of the complexity of the project and the need to meet the client’s requirements, the contracting between all parties formed as Partnering and the project team used CVE in the design process. The CVE implemented directly from the beginning in the design process aiming for improving the communication between partners, reducing the risk, and achieving the goals of stakeholders (Woksepp;Olofsson;& Jongeling, 2005).

The project manager divided the designers into different design teams such as structural, electrical, HVAC, and process. Each team was free to use favorite 3D CAD software as long as they could export it to a DWG format. Each team is responsible for development of the 3D CAD models and the availability of the last updated version. The client appointed a consultant for VR to handle all 3D CAD models from different disciplines and to transfer them to FTP server, where all the information is restored, then convert them to VR models. The combined VR model of the plant covered many data including structural elements, machines, HVAC, electrical systems, and surroundings. The project team produced different VR models for multiple reasons For instance, there were models for planning the spatial space, understanding the facility and machines inside, training the workers, and simulating the production process (Woksepp;Olofsson;& Jongeling, 2005).

**Workflow of the CVE in MK3**

Because of the critical timetable, the project team chose VR models as the main communication and coordination tools within the project meetings. Subsystem such as structural, HVAC, electrical and equipment processing were the responsibility of the design teams (*Design team from 1 to n*) while the overall design procedure is the responsibility of the client. The VR consultant is managed by the client and responsible for correcting and updated models and giving access for the people involved in the design and management. In the formal meeting, the project team used VR models (*VR from 1 to n*) for design review. The formal meeting took place every two weeks, where representatives of the client and the design team carried out design review (*Design review from 1 to n*). When errors or clashes were detected there were two approaches either to deal directly with and solve in the meeting or forward to the responsible person (*Person from A to n*) see figure (20). Main modifications and decisions carried out after measuring the risk impact on the goals of the project; the quality, the time, and the cost (Woksepp;Olofsson;& Jongeling, 2005).

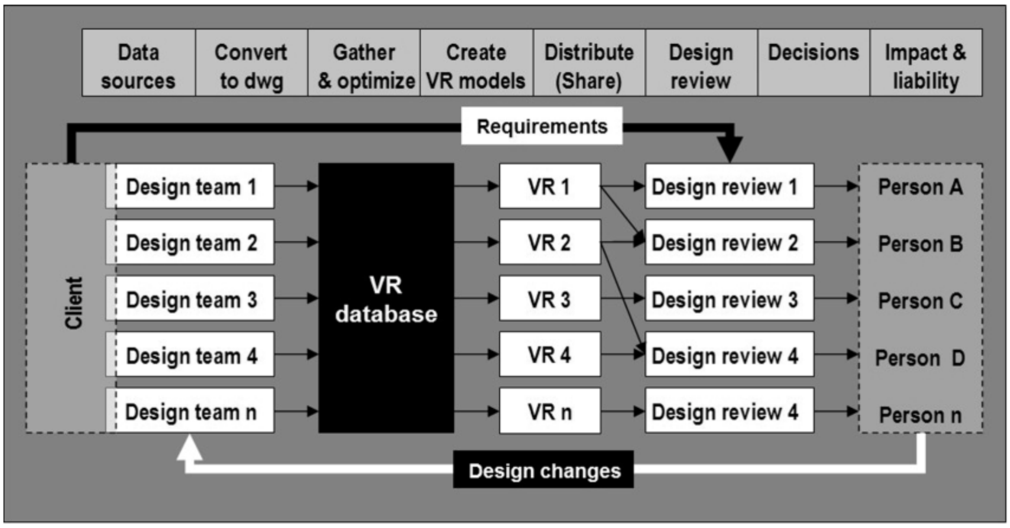



Figure 20: Design process and workflow of the data and information for MK3 project. Source: (Woksepp;Olofsson;& Jongeling, 2005)

**Decision-Making in MK3**

For decision-making in the MK3 project, the project management considered VR models as the foundation of information in addition to 2D drawings and paper documents. Using VR models increased the understanding of information during communication. One example about the use of VR model during the design; sometimes a design team needed to take a decision quickly regarding the design, but the timetable was limited to consult the other teams, as an alternative they could use VR to see exactly the consequences of their design decision on the other discipline. In addition, the main concern for the client was the manufacturing process design and other designs such as structural, HVAC and electrical had to support the manufacturing process. Therefore, the client was able to simulate the manufacturing process and at the same time the structure, HVAC, and electrical designs supporting this goal. VR models involved the client in the daily design activities and enabled access to up-to-date information that brought out reliable decisions during the project time (Woksepp;Olofsson;& Jongeling, 2005).

**Results and Discussion**

- Access to correct and up-to-date information facilitates client's decision process and positively influences outcomes
- Efficient data exchanging tools such as VR can lead to precise earlier decisions
- Team working, sharing responsibility and trust within a CVE increase transparency and clarity
- Involving clients in daily design activities through VR models reduces the time needed for making decision.

### 3.5.3 Case Study 3: Understanding the Spatial Arrangements, School of Architecture and Design, Brazil

The case study was performed in the School of Architecture and Design UFMG, Brazil. The main goal of the study was to identify whether the use of VR increases the user understanding of the 3D model or not. The study method was to measure the users' level of understanding for the spatial space in the 3D model within two different environments: Non-Immersive Virtual Environment (nIVE) and Immersive Virtual Environment (IVE). Then compare the results from nIVE, and IVE with the results from the Physical Environment (PE). The researchers used a hall in the school and created a 3D model with all architecture details. In the nIVE, the researchers used traditional workstation computer with a mouse and keyboard as data entry and in the IVE, they used the same computer besides glasses with the same mouse and keyboard see figure (21) (Daniel;Eduardo;& Irizarry, 2017).

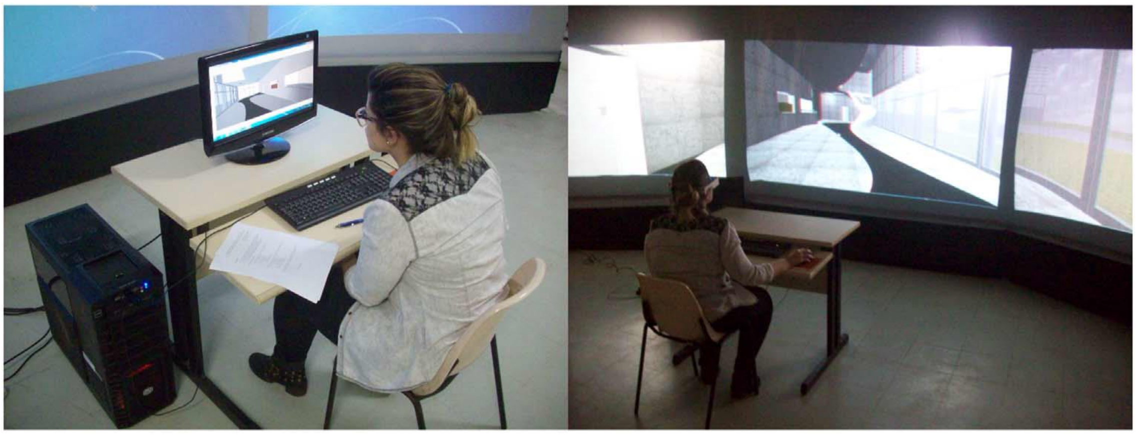


Figure 21: Same participant performing the experiment in non-immersive in the left picture and full immersive in the right picture. Source: (Daniel;Eduardo;& Irizarry, 2017)

**Evaluation Method**

To evaluate the results, the researchers performed a survey with a questionnaire. The number of participants in the study was 120, and they were divided into four smaller groups. The participants have different professional and educational backgrounds. For instance, the sample included civil engineers, architects, engineering professionals, undergraduate students, and lay people. The experiment was built on the concept that each participant should complete two different questionnaires. The first questionnaire module was about the personal information and the second one was about the special perception for the 3D model such as vertical and the horizontal distances, areas, shapes, positioning, etc. The participants had to perform the same tasks within three different environments: Non-Immersive Virtual Environment (nIVE), Immersive Virtual Environment (IVE), and Physical Environment (PE) (Daniel;Eduardo;& Irizarry, 2017).

**Experiment Workflow**

They used inferential statistics analysis as a statistical method to calculate the confidence interval. A 95% confidence interval was assumed to prove that the experiment was true. The study was divided into nine steps, as shown in figure (23), and as following:

1- The researchers selected the lobby of the school and created a 3D model
2- The plan was created with AutoCAD, then was exported to Sketchup for creating the 3D model, and after that was exported as .3ds to Unity for creating the VE see figure (22).

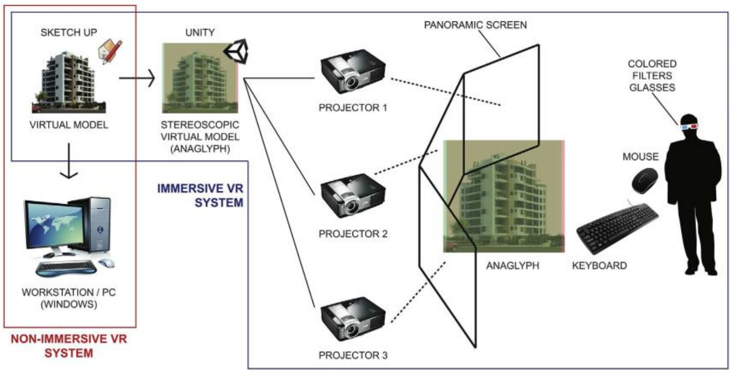



Figure 22: Workflow of both the immersive and the non-immersive system. Source: (Daniel;Eduardo;& Irizarry, 2017).

3- The researchers prepared the two modules questionnaires
4- For performing trial tests to make sure about the right positions of the equipment
5- The supervisors selected the participants and organized them in groups
6- The participants experienced the model in the nIVE
7- The participants experienced the model in the IVE
8- The participants experienced the model in the PE
9- The researchers analyzed the data by comparing the answers from nIVE and IVE with the answers from PE. When the answer from nIVE or IVE was identical to the answer in PE, they called it "*NULL*", and when it was not identical, they called it "*NOT NULL*".

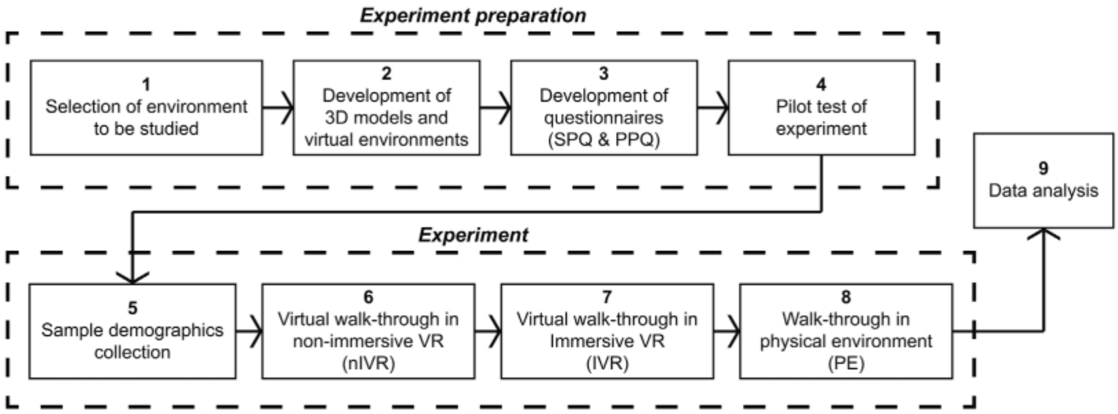



Figure 23: Workflow of the experiment. Source: (Daniel;Eduardo;& Irizarry, 2017).

## Results and Discussion

When comparing the answers gathered from the participants' experience for the 3D model using the workstation computer with the answers from the physical experience for the building, 60% of the answers was identical "*NULL*". When they compared the participants' answers from the VR model, 71% of the answers were identical to the answers from the physical experience see figure (24). The difference between the identical values when experiencing the model with a workstation computer and the VR environment was 11%. When the researchers applied the t-test for the two results, they achieved a p-value equal to 0.018. Since that, p-value differs significantly from the assumed 0.05 with the confidence interval of 95%, which means that there is a significant difference between the nIVE and IVE regarding understanding the spatial perception (Daniel;Eduardo;& Irizarry, 2017).

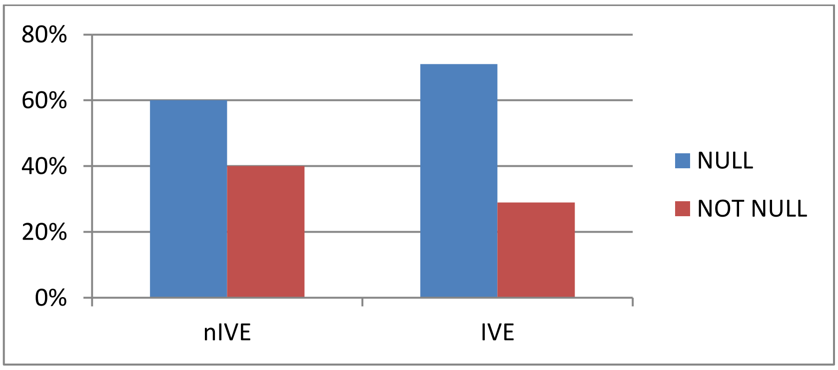



Figure 24: Null and non-null PMIs results of the two techniques. Source: (Daniel;Eduardo;& Irizarry, 2017).

# 4. Virtual Reality in Construction of Infrastructure Projects

This chapter discusses the integration of VR in the construction process in the AEC industry projects and explains how VR is implemented in the construction process. It focuses on VR integration with construction safety planning and training, construction methods simulation, and planning the construction site. It is expected from the reader after reading this chapter to form a brief idea of how VR contributes in the construction process.

Each project is unique, which means it is not a repetitive process and what was applied in one project might not be possible in a similar project. Construction is a complex process that involves many people with different education, culture, and engineering backgrounds. For instance, infrastructure projects include workers, operators for equipment, drivers, technicians, civil engineers, geotechnical, and transportation engineers. Beside all these different people, there is a large number of special equipment. It is essential that every person in the construction site is familiar with the safety regulations and the possible hazardous area before being involved in the construction site. For construction managers, it is important to define the construction methods and the construction sequence before the beginning of the execution. In addition, there is a need to plan the site itself and locate the equipment and resources in the workspace. Therefore, there is a need for new tools to visualize more the construction site and increase the ability to interact with its components.

## 4.1 Construction Safety Training and Planning

An accident at work can be defined as *“a discrete occurrence during work, which leads to physical or mental harm”*. The result could be fatal or non-fatal accidents. The fatal is when the accident causes a death for the victim within one year from the accident’s occurrence. Non-fatal is the accident, which causes absence from the work for at least four calendar days. Sometimes non-fatal accidents can be dangerous and lead to permanent disability or inability to continue for the same job, besides a tangible economic lost for the company and the country. In 2015 in the European Union (EU), the numbers of non-fatal accidents that lead to four days’ absence or more were around 3.2 million besides 3,876 for fatal accidents that caused death of the victim (Eurostat, 2018).

The number and the type of accidents at work associated with the workplace. For instance, in 2015 in the EU countries, the construction industry accounts for more than the fifth (21%) of the total fatal accidents and over one in ten 12% for non-fatal accidents. Manufacturing industry comes next after construction regarding the fatal accidents 17% and exceeding it in the no-fatal accidents with around 19% (Eurostat, 2018), see figure (25). These statistics show that the construction industry is one of the most hazardous workplaces. However, the strict safety regulations in the EU members, many workers are still victims for the unsafe construction workplaces or lack of safety training. A healthy and safe work environment is a basic requirement of the human being. In addition, a safe work environment will increase the productivity of the workers and positively reflect on the company and the country.

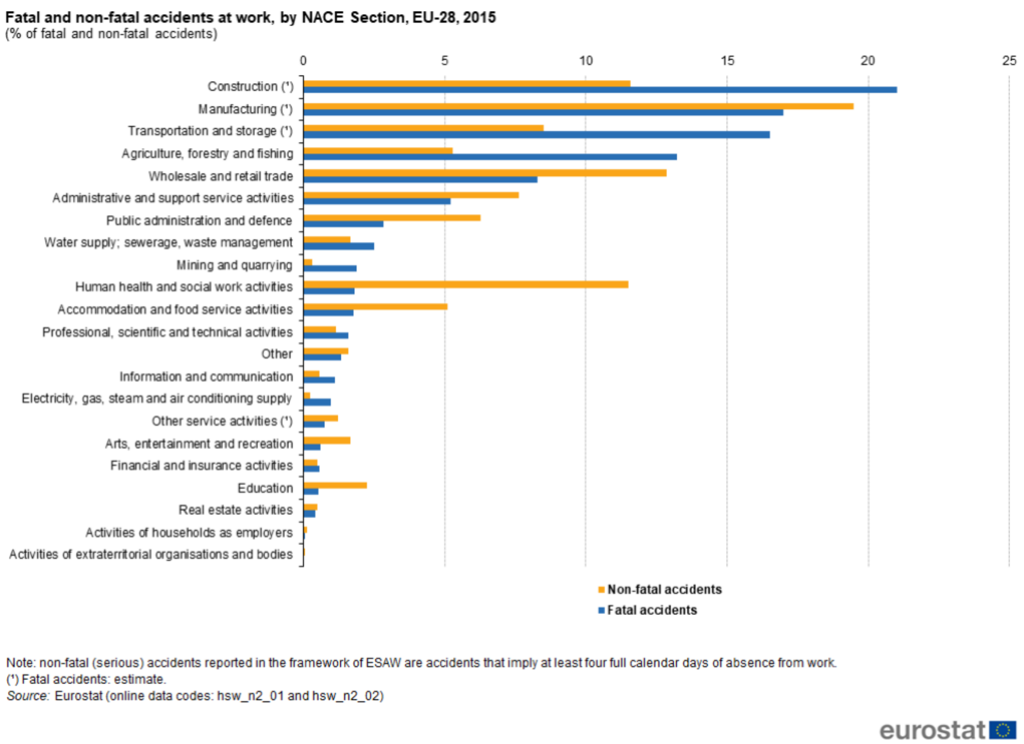



Figure 25: Percentage of fatal and non-fatal accidents by workplace in the EU, 2015. Source: (Eurostat, 2018)

### 4.1.1 VR in Construction Safety

There are two main phases related to the management of construction safety. The first phase is before the start of construction, where safety planning and safety training are needed. The second phase is during the construction, where monitoring the pre-defined safety plan is needed. Many defects lead to accidents in the construction phase, and the mean reasons for these accidents is inadequate safety training and poor safety planning. In the in-door training sessions and before the beginning of construction, trainers usually use 2D drawings and pictures for training the workers. Such a method is not sufficient, especially in complex construction projects, when workers need to be more conscious about the site. Identifying the Job Hazardous Areas (JHAs) is one of the key elements during safety planning. Project managers and safety managers usually define the JHAs based on previous experience and with the help of 2D drawings, time schedule, and safety guidelines. However, their experience and their following of safety standards, many JHAs stay undedicated because of the complexity of the construction. Therefore, visualization technology such as VR could bring benefits in the training and planning of construction safety (Yu;Skitmore;& Guo, 2016).

**VR in Safety Training**

Training construction workers is essential to increase their awareness about potential construction hazards. Training the workers can be divided into two main types: on-site and off-site. On-site training is difficult to apply in the site because it obstructs the construction and causes delays; on the other hand, there is a lack of interaction with the construction environment in the off-site training. Visualization technology such as VR can combine on-site and off-site training by providing interactive training within a VE. Workers could walk through the model and identify the potential JHAs. When the workers interact with the building elements, their safety awareness will increase. Warning messages could appear when workers are walking through the model and becoming close to JHA or equipment. In addition, such an environment can increase the cooperation level among workers before the beginning of construction. For example, in a VE, workers and plant operators can cooperate with each other, which can increase the level of consciousness and reduce the accidents (Yu;Skitmore;& Guo, 2016).

When implementing VR, it is possible to create an online safety-training platform for visualization and interaction between multi-users with the ability to enrich the model using open-source programming. Online virtual platforms allow the interaction between users and the VE through controllers where the user can select, move, or copy the virtual elements. Workers can virtually practice operating the construction equipment and communicate with each other. The VE can provide safety warnings that appear automatically when there is a safety hazard. When the worker is inside the VE, he/she can change their viewpoint to other participant's view that increases the worker's awareness about the space and ability to identify potential hazards. In addition, workers can easily understand safety instructions when being immersive in an environment similar to reality. Workers can communicate more effectively and clearly. For instance, in figure (26), the two workers A and B are inside a virtual environment talking and sharing their perspective (Guo;Li;Chan;& Skitmore, 2011).

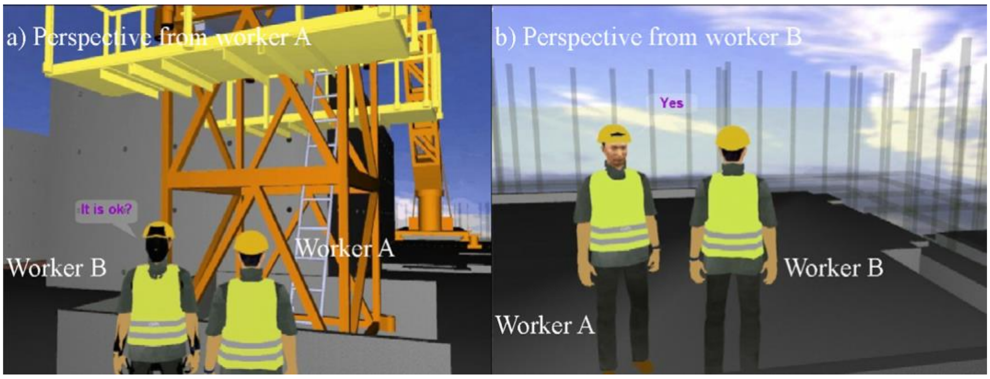



Figure 26: Two workers communicating in a safety-training platform. Source: (Guo;Li;Chan;& Skitmore, 2011)

The online safety platform allows equipment operation with multiple users at the same time. For instance, when a worker performs an activity on his/her computer such as selecting an element the other users can not only observe this activity but also collaborate with it from their own computer. Therefore, plant operators can collaborate in the equipment's operation and easily predict potential collisions. For example, if the construction site has two cranes, two operators one for each crane can manipulate inside the VE, identify the collisions, and prevent any accidents could happen in the real environment. Figure (27) shows the equipment operation from two different computers at the same time (Guo;Li;Chan;& Skitmore, 2011).

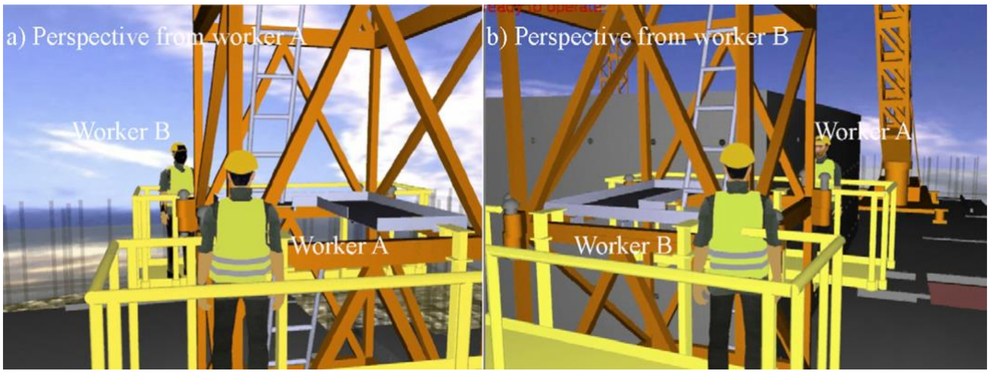



Figure 27: View for operating a crane from two different computers at the same time. Source: (Guo;Li;Chan;& Skitmore, 2011)

The online safety platform can use the information related to the construction equipment, the timetable, and safety instructions to create a smart manipulation system with the ability to response automatically. For instance, it automatically detects collisions and highlights them. For instance, warning messages appear automatically in case of wrong operation or if the operation process is not following the construction timetable (Guo;Li;Chan;& Skitmore, 2011).

**VR in Safety Planning**

Visualization technology such as BIM and VR can reduce the gap between dynamic construction tasks and safety planning (Azhar, 2016). Visualization technology can provide an automatic 3D method to identify the JHA. For instance, safety planners can use VR to identify the JHA in safety meetings. When implementing the VR in the construction simulation, it is simple to identify collisions in the construction process, which might cause problems or accidents. Simulation is also possible for the construction equipment to identify required space in a specific time and location. It is also possible to identify JHA related to the stability of the structure during the construction and temporary structures. Safety planners can simulate potential collapse scenarios and prepare for such a scenario (Yu;Skitmore;& Guo, 2016).

A project for renovation a campus in Auburn University, Alabama, USA is presented as a real case study for how it is possible to implement VR in safety planning. The project goal was to maintain the facade of the building and change insulation and waterproof layers without interrupting the studies at the campus. The reason behind using VR was to provide a VE where users can walkthrough and experience the building and its surroundings. Autodesk Revit was used to create the BIM model to illustrate the building and the renovation at different phases. Constructing plants such as the crane, scaffolding, and construction barriers were imported to the model by the help of SketchUp. For rendering, 3Ds Max was used. The model was exported to Unity 3D for an immersive environment and Camtasia was used to record and produce movies, see figure (28) (Azhar, 2016).


Figure 28: Workflow of modelling the VR for safety training. Source: (Azhar, 2016).

After modeling the building, the team produced a 2D site plan, a 3D site plan, a virtual immersive site plan, and a video showing the VE. The project team created some safety-related scenarios such as unsafe forklifts usage, insufficient safety barriers, and hazards related to electric and tripping. The project team used HMD to visualize the building in a full immersive environment and then provide feedback about the experience. The project team members provided positive feedback about the experience. The virtual environment facilitates identifying the potential hazardous by being immersive in an environment as close as to reality. In addition, it is feasible to use such a technology when investigating an accident to recreate the scene, which can help to prevent similar accidents (Azhar, 2016).

### 4.1.2 Results and Discussion

- The construction industry is one of the most hazardous workplaces with a high number of accidents
- Inadequate safety training and poor safety planning are the main reasons for accidents at the construction workplace
- VR can combine between off-site and in-site training features as it provides training VE similar to the site without need to go the site itself

- During training sessions, workers could identify the JHAs inside the VE and be aware of them in advance
- Operators could collaborate with other workers/ supervisors within a training sessions in the VE
- Safety planners could simulate the construction and identify potential collisions.

## 4.2 Construction Process Simulation

In construction management, it is essential to define the construction method and sequence of the execution at the site. Planning the project process at the early stages of the project is considered a key factor for project success. Therefore, planners at this phase need to design the construction scenario, define the construction methods, outline the construction sequence, and arrange the required resources for the execution (Huang;Kong;Guo;Baldwin;& Li, 2007). Infrastructure projects usually are built over a large area where it is difficult for construction professionals to be familiar with all details in the entire project. Infrastructure projects use heavy and special equipment, and sometimes these equipment needs temporary structures that complicate the construction process.

Bridges are one of the most complex projects in infrastructure projects because they require special construction techniques and equipment. Therefore, a detailed construction simulation could be beneficial to present the construction sequence and the operation of the equipment. The construction method should be prepared as early as possible during the design phase. Sometimes, the construction method influences the selection of the cross section and the structural system. For instance, there are three main construction methods for the bridges: The traditional with a formwork supported the bridge deck on the ground, the cantilever method, and the incremental method. Professionals usually use the traditional method in small size bridges and with height not more than 20m. The cantilever and incremental methods, where usually box girder section is selected, are for the long-span bridges when is not possible to install a formwork such as a bridge over a waterway or natural terrain, figure (29) shows the three different techniques (P. Martins & Z. Sampaio, 2011).

Figure 29: Traditional, incremental, and cantilever bridge construction methods. Source (P. Martins & Z. Sampaio, 2011)

For instance, construction of bridges with an incremental launching method is a complex method; therefore, there is a need for more detail about the equipment and the sequence of construction. The method based on a temporary station where is possible to cast a concrete section (15 to 30m) and push this section along the bridge axis using hydraulic jacks. The method requires a constant height for the cross section over the whole span, and the box girder is the most convenient section for this method. There are two types of pre-stressing reinforcement for tension: first type is placed when casting the station and the other type is placed after the segment become in the final place. This method requires particular equipment such as hydraulic jacks supported on concrete bearing responsible for pushing the segment forward and launching nose for smoothing the deck sliding over piers. Therefore, applying VR in for similar complicated process will help the professionals visualize the construction simulation and equipment functionality and increase the efficiency of detecting and eliminating clashes (P. Martins & Z. Sampaio, 2011).

### 4.2.1 VR for Construction Simulation

The main purpose of applying VR in construction process simulation is to provide a VR model where the construction professionals will manipulate the complex stages of the process. VR could aid the professional visually stimulating the construction sequence and interacting with the model components. The model could work in training sessions where construction professionals can repeat multiple tasks until achieving the required level of understanding. In a VE, it is possible to show the development of the work, the sequence of construction, and details for specific elements (P. Martins & Z. Sampaio, 2011). In the VR model, large groups of participants can interact with the construction elements and communicate smoothly with each other. When adding animation technique to the VR model, it is possible to represent the assembly of the complex equipment in the construction site (Z. Sampaio & P. Martins, 2014).

Virtual prototypes can be used for visualizing the projects assembly when the VR model created with a high level of details related to the construction logic sequence (Rohani;Fan;& Yu, 2012). In addition, by using virtual prototypes, it is possible to mimic the machines function process such as speed, moving area and detect the collision with the other construction elements. Such an approach could save the time needed to build a physical prototype to study space management. It can help connecting the timetable of the project with the dynamic movement of the resources at the construction site. Based on that simulation, the construction managers can apply changes to the site management to be more effective and safe (Martin & Neo K.Y, 2012).

### 4.2.2 Results and Discussion

- Before the beginning of construction, it is important to define the construction sequence and construction method
- Infrastructure projects usually extend over a big area and it is difficult for construction management to be familiar with all site details by traditional ways
- Sometimes when using complex equipment, it is difficult for the project team to understand how it works beside it is dangerous to become close by
- VR can simulate the construction sequence and provide interaction with the construction components
- VR can provide simulation for the construction equipment and allow predicting future clashes in the site.

## 4.1 Construction Site Planning

Planning a layout for construction site is important tasks no matter how is the size of the project. Site planning includes multiple tasks such as planning of materials, accesses and exits, resources, equipment, temporary facilities, and construction scenarios. Therefore, site planning is a difficult task and with poor management, it can lead to time and cost overrun. Because of the unique characteristic of each construction project, the design of site layout is not a repetitive task and changing form project to another. Site managers plan the site to guarantee efficiency during the construction and to achieve the maximum benefit of resources and space. Good site plan should ensure maximum use of the workspace that will save time and cost, provide a safe work environment, and smooth movements for the resources (Muhammad;Yitmen;Alizaedhsaehi;& Celik, 2019).

In the traditional construction methods, the project management teams focus more on scheduling, materials, resources, and construction methods. Insufficient time remains for planning the site, which sometimes complicates the construction process. Each construction site is restricted by multiple conditions, such as location and flow of material. In these traditional methods, site planners usually use 2D drawings together with hand drawings to plan site layout and logistics. This method could lead to poor site planning, which can have negative consequences such as resources loss, inefficient location for temporary facilities, inefficient use of workspace, inadequate access and exists, timetable exceeding, and cost overrun (Muhammad;Yitmen;Alizaedhsaehi;& Celik, 2019).

### 4.1.1 VR for Site Planning

Implementation of VR in the site planning allows foresee the site and predict problems and clashes before it even happen see figure (30). Creating a VE for the site can help the site management and the workers to understand better the site daily activities such as equipment rotes, stockrooms placement, and material location. The availability of a VR model will allow visualization, walkthrough, and manipulation with the model elements. For instance, construction engineers can investigate crane routines and predict any clashes that could happen (Muhammad;Yitmen;Alizaedhsaehi;& Celik, 2019).

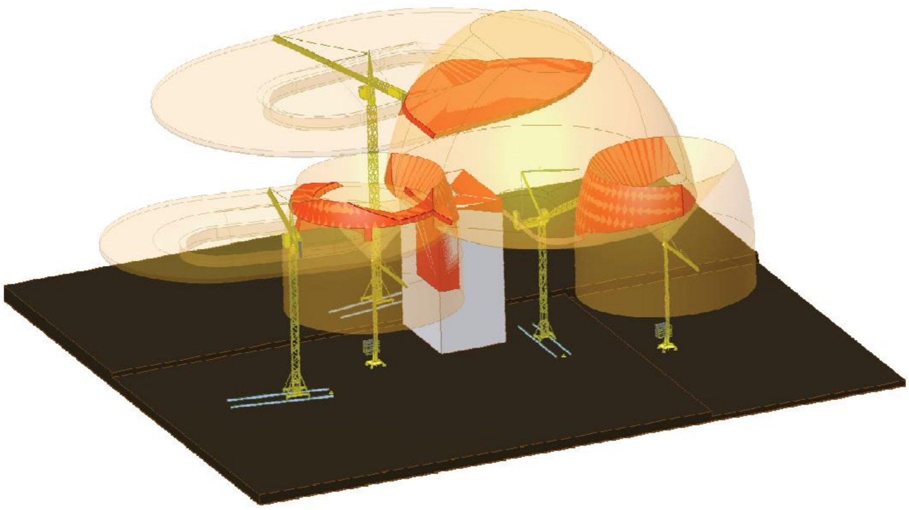


Figure 30: 3D model shows potential collisions between cranes at the construction site. Source: (Ebner;Kammergruber;Horenburg;& Günthner, 2012)

In addition, VR and by the help of lasers canning and photogrammetry technologies can be used for planning the site for the place with hazardous conditions. This technology could be used not only for constructing new facilities but also for reconstructing damaged buildings. In such situations, a VE can be created and the user can experience the model and interact with its elements without being in danger. Therefore, project managers can smoothly identify hazards, and plan based on virtual and interaction experience. One-step further, and when combining tele-operation equipment, it can be possible to remove dangerous obstacles from the site (Pratama;Lin;& Fardhosseini, 2018).

### 4.1.2 Results and Discussion

- Poor site planning can lead to collisions during construction
- Good site plan should maximize the benefits from the workspace and avoid future clashes and collisions
- Applying VR in site planning could help to predict the collisions between construction equipment
- VR with the help of laser scanning and photogrammetry could be useful for investigating hazardous sits
- When conducting the research, the author found that there are many applications of AR in site planning than VR.

## 4.2 Case Studies

### 4.2.1 Case Study 1: Construction Simulation of a Bridge in Rodental, Germany

The case study was performed in a long span bridge near Rodental, Germany. The bridge length is 388m and comprises seven spans (five spans with 58m and two spans with 49m). The bridge has six piers and two abutments, see figure (31). The selected construction method for the bridge was an incremental launching system. The construction team created a VE to show the construction process of the bridge's deck in more detail (P. Martins & Z. Sampaio, 2011).

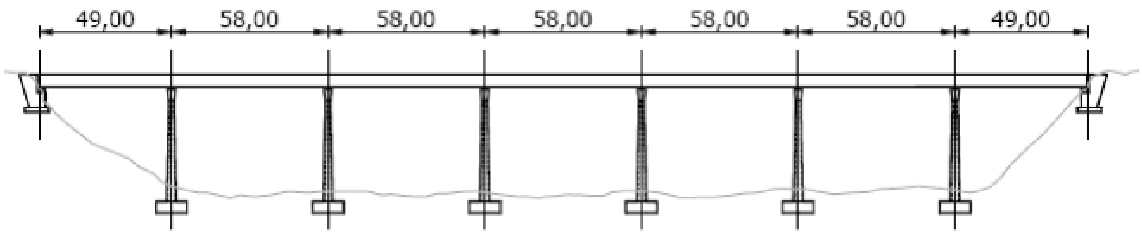



Figure 31: Longitudinal section for the bridge. Source: (P. Martins & Z. Sampaio, 2011)

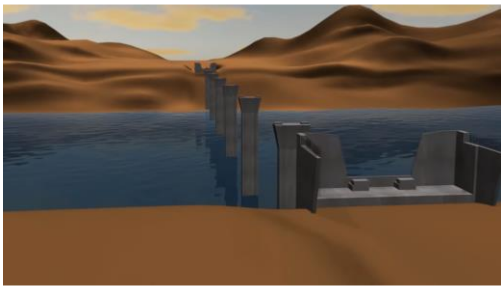
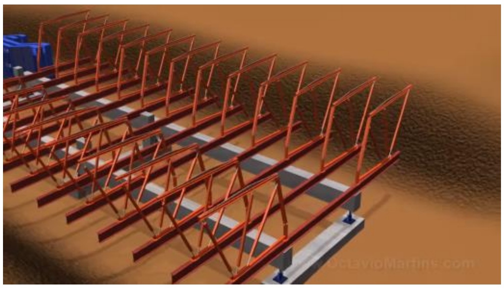
**Bridge Modelling Workflow**

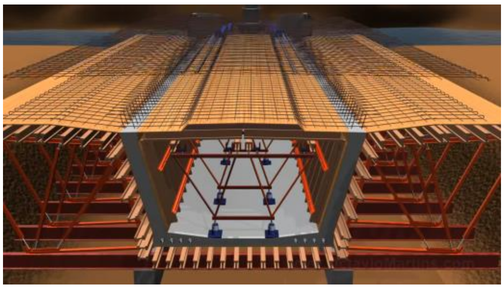
The construction team selected AutoCAD to prepare the 3D model for different components and used specific layers for elements that will move in the simulation. They defined the level of detail for the modeling at the beginning to know which details needed to be presented. For example, assembling of station formwork, the launching nose, and the reinforcement mesh were considered in the model. After they created the model in AutoCAD, it was exported to 3Ds Max for rendering. In 3Ds Max, it was possible to define realistic material and change the material characteristics (color, brightness, roughness, texture, etc.). When the model was created, and each material had its right characteristic and right position, they exported it to EON StudioTM for sequence simulation (P. Martins & Z. Sampaio, 2011).

**Sequence of construction**

The aim of using the VE was to simulate the sequence of construction visually. The team used the counter feature in EON StudioTM for modeling the construction sequence. The counter defines the actions based on the mouse click. The first action is the visualization of terrain, pillars, and abutments. Then (P. Martins & Z. Sampaio, 2011) defined the construction sequence as following:

1- The simulation started when the abutments, piers, and casting yard of the bridge was already installed in their places, including the terrain and the waterway, see figures (32)
2- Visualization of assembling process of the casting station, including temporary foundation, supported steel beams, steel formwork, and wooden plywood
3- The assembling of the steel launching nose begins, including all its parts and connections
4- The placement of reinforcement meshes, pre-stress cables, and the lateral formwork. Casting concrete is shown first for the bottom slab, then walls and finally the top slab
5- The hydraulic jacks hold the deck web and launch it forward in the bridge's axis direction. The process is repeated until the end of the segment (31m)
6- The launching nose arrives to the first pier and pulls the first segment
7- The process is repeated for the rest of the segments for the entire bridge
8- For the last segment, the simulation shows the launching nose arrive to the other side of the waterway and the removal of temporary support
9- Finally, the simulation shows the




finishing for the bridge, such as asphalt and barriers.

Figure 32: Construction sequence.
Source of all pictures: (WVOLF, 2009)

**Similar Technique in Different Bridge**

The Technical University of Lisbon has used the same model together with another bridge model for teaching the student the construction sequence of bridges. The second model used the cantilever method for constructing the bridge see figure (33). The two models used for teaching the construction sequence and methods for the students in the school.  The model was not only available for professionals from the construction industry. The main purpose of using the VE was to provide a clear explanation and assistant tool for civil engineering students. The university team believes that the VR model improved the interaction between all parties involved. Students and teachers could visualize the evaluation of the facility’s construction with a better understanding through better communication (Z. Sampaio & P. Martins, 2014).

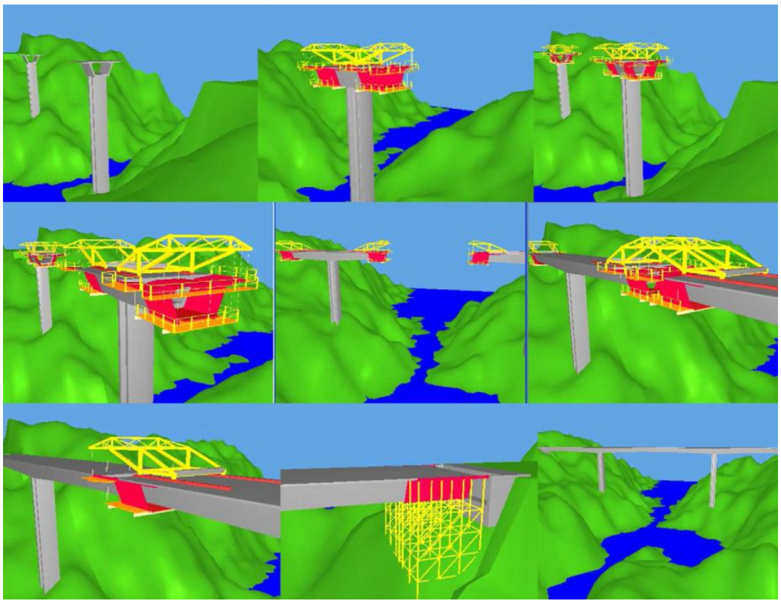


Figure 33: Screenshots from the virtual model shows the sequence of construction. Source: (Z. Sampaio & P. Martins, 2014)

**Results and Discussion**

According to (Z. Sampaio & P. Martins, 2014), one of the main features of using VR in teaching the construction is that it provides access to multiple users at the same time within VE, which enhance the interaction and communication. Students can also manipulate the model's elements. In addition, VR represents the construction work dynamically. Such an approach improves the perception of visualization and interaction not only with the construction components but also with the equipment operation. Within the VE, students and professionals could visualize the construction site with all its dynamic activities.

To compare the VR model and the traditional method, they performed a questionnaire on 25 students. They used a scale in the questionnaire from one that represented *poor* and five referred to *good*. Figure (34) illustrates the average values of participants' answers. The answers show that the VR model enhanced the understanding of the topic. In addition, it increased the level of details and provided a better presentation for the construction activities. On the other hand, the answers were low regarding the probability of replacing the traditional method with the VR model and the ease of using the traditional method compared to VR model (Z. Sampaio & P. Martins, 2014).

| Comparison between VR model and traditional methodology (pictures, drawings, and text) | [1–5] |
|---|---|
| Complements the traditional methodology | 4,2 |
| Replaces the traditional methodology | 2,0 |
| Improves the understanding of the topic | 4,7 |
| *The VR model performance* | |
| Presents the construction activity clearly | 4,3 |
| Presents enough detail | 3,7 |
| *Student's manipulation at home* | |
| Easy to handle | 3,3 |
| Helps to consolidate the learning of the topic | 4,0 |
| *The teacher's experience* | |
| Easy to handle | 3 |
| Correct as teaching material | 4 |
| Effective as educational support | 5 |
| Improves the level of attention of students | 4 |
| Improves the level of understanding of students | 3 |

Figure 34: The average of students and teacher's answers. Source: (Z. Sampaio & P. Martins, 2014).

### 4.2.2 Case Study 2: Site Planning for Campus Building in Famagusta, Cyprus

A group of researchers performed a case study in university building in Cyprus to check the benefits of VR in site planning. The main idea from the case study was to compare three different approaches for site planning; 2D drawing, 3D model, and VR model. The researchers' method was to divide the experiment into three stages: planning, modeling, and data collection and validation. The main purpose of the planning was to define VR application, 3D models format, and define the concerned site activities such as access in the site, crane location, waste location, material location, equipment location, offices location, and site orientation. The last step in planning was to provide a workflow for the VR in this experiment (Muhammad;Yitmen;Alizaedhsaehi;& Celik, 2019).

**Preparing Two Scenarios for Planning the Site**

The researchers selected a construction site that contained the parameters mentioned in the planning phase. The building selected is approximately 9,000 square meters with a budget of $4.5 million and should complete within a tight schedule of 11 months, see figure (35). After the selection of the site, the researchers proposed two different scenarios for planning logistics in the construction. The construction management of the project created the first scenario based on previous experience. For the second scenario, they did some modifications for site access, materials locations, number and location of cranes, waste location, site office, and site orientation (Muhammad;Yitmen;Alizaedhsaehi;& Celik, 2019).

Figure 35: The selected construction site. Source (Muhammad;Yitmen;Alizaedhsaehi;& Celik, 2019)

### Creating the VR Models

The researchers created different models for different scenarios with the help of Autodesk Revit, SketchUp, and Lumion software. Figures (35, 36, 37, and 38) show the two planning scenarios with the 2D plans and with the VR models. Revit used for creating the structural model then the models exported to SketchUp. With the help of SketchUp's warehouse, all necessary equipment brought to the model that increased the sense of reality to the model. Then the model exported to Lumion for final rendering, after that the model was ready for VR experience (Muhammad;Yitmen;Alizaedhsaehi;& Celik, 2019).

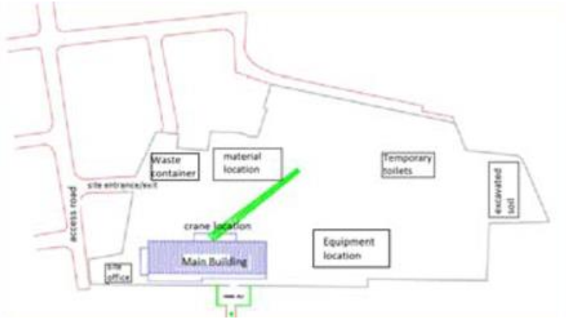



Figure 36: 2D site plan for scenario 1. Source: (Muhammad;Yitmen;Alizaedhsaehi;& Celik, 2019)

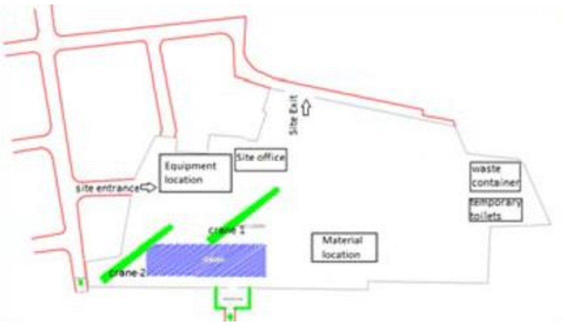



Figure 37: 2D site plan for scenario 2. Source: (Muhammad;Yitmen;Alizaedhsaehi;& Celik, 2019)

Figure 38: 3D site plan for scenario 1. Source: (Muhammad;Yitmen;Alizaedhsaehi;& Celik, 2019)

Figure 39: 3D site plan for scenario 2. Source: (Muhammad;Yitmen;Alizaedhsaehi;& Celik, 2019)

### Collecting and Validation of Data

The final phase of the experiment was data collection and validation. The main purpose of this phase was to measure the reliability of implementing VR in the construction site planning. The researchers used a sample comprising 102 professionals working in the construction industry. They selected participants from different specializations in construction such as construction management, design management, architectural design, and structural engineering. The participants were from different positions such as BIM specialists, site supervisors, site engineers, architects, design managers, construction managers, and structural engineers. The participants were asked to assess, monitor, compare, and rate three different approaches for site planning 2D drawings, 3D model, and 3D in VR. The rating scale was from one (highly ineffective) and five (highly effective). The researchers categorized the overall rating of the participants as high if it was over 80%, medium if it was between 60-79% and low if it was less than 59% (Muhammad;Yitmen;Alizaedhsaehi;& Celik, 2019).

**Results and Discussion**

The participants answered all the questions and provided rates for the site planning for both scenarios in the three different environments: 2D Drawings, 3D Model, and 3D in VR. In 2D Drawings, the average rate was 4.5 out of 5 regarding the ease of using the 2D document. However, the participants provided a rating 1.9 out of 5 regarding the sufficiency of the information in 2D drawings for example the possibilities of collision between the cranes was difficult to detect in 2D drawings only. According to the participants' responses, the 3D model increased the understanding of the site plan. This was clear when comparing the overall rating for 2D and 3D; the 3D model was 3.9; However, the 2D was 3.0. The participants provided an overall rating for the 3D model when using in the VR environment by 4.4, which shows that VR enhanced the understanding of the site planning. The participants rated the ease of using VR by 2.9 out of 5, which shows that training might be needed before implementing such a technology (Muhammad;Yitmen;Alizaedhsaehi;& Celik, 2019).

After analyzing the answers of the questionnaires for the participants of this experiment, the researchers discovered that a 2D drawing in site planning is easy to understand and less time-consuming compared to the virtual environment. However, the participants believe that VR increased the understanding of the site planning, the ability to detect collisions, and predicting the site constraints through better evaluation of different scenarios see figure (40). The researchers recommended that the construction managers have to practice more using the visualization tools, which will help them, visualize better the site planning and increase the level of details for the site space (Muhammad;Yitmen;Alizaedhsaehi;& Celik, 2019).

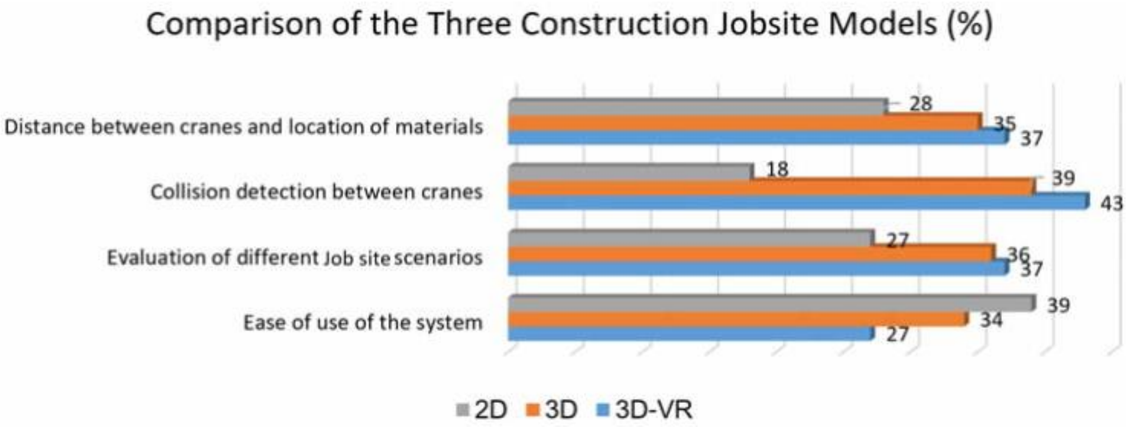



Figure 40: Comparison between the answers of professionals in 2D, 3D, and 3D within VR. Source (Muhammad;Yitmen;Alizaedhsaehi;& Celik, 2019)

- VR is more effective than 3D model and 2D drawings regarding planning the site components and placing materials
- VR is more effective than 3D model and 2D drawings regarding detection of future collisions of construction equipment and testing different site planning scenarios
- VR is difficult to use and handle compared to 2D drawings and 3D models, which means training needs to be considered when using VR.

# 5. Current Practices of VR in Infrastructure Department, Pöyry Finland Oy

This chapter shows two cases from the current practices of VR in the design process in the department of infrastructure:

- Case Study: explains how VR could be used for involving end-users and stakeholders in the design of tramline
- Workshop: explains how VR could be a tool for communication and collaboration with the client. The author took part in this workshop and the information provided is based on his participation.

## 5.1 Case Study: Engagements of End-users and Stakeholders into the Design in Raide-Jokeri Project, Helsinki, Finland

Raide-Jokeri is a tramline connecting Itäkeskus in Helsinki to Keilaniemi in Espoo. The word Jokeri refers to the only HSL bus number" 550" which connecting the east and west of Helsinki region and one of the most crowded buses in Helsinki area. The estimated length of the tramline is 25 km and will serve around 40,000 people after completion, the number expected to rise to 102,000 in 2040 see figure (41). The municipalities aim of the project was to direct the growth of the population to use sustainable transportation like public transport and cycling (Raide Jokeri, 2018).

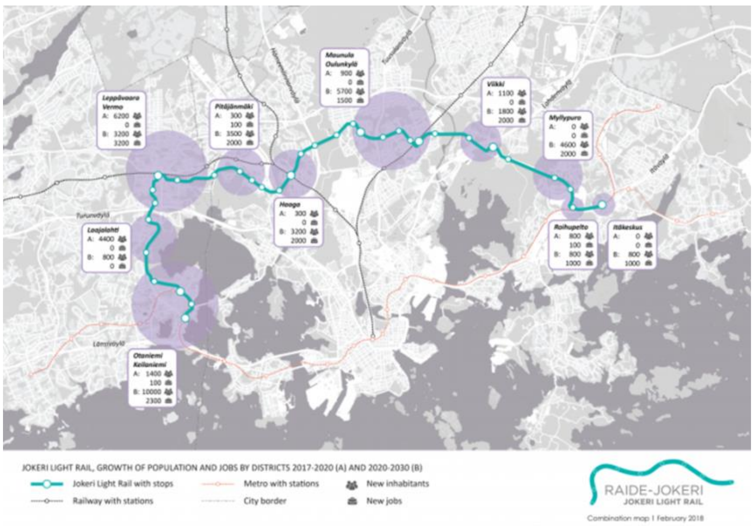



Figure 41: Raide Jokeri light railway and the stations with the expected population growth. Source: (Raide Jokeri, 2018)

### 5.1.1 Proposal for Implementing VR in the Development and Design Phases

Pöyry Finland together with WSP Finland submitted a tender for applying the VR during the development and the design phase. The idea behind this was to create a VR model directly from the BIM model and use it for visualization, coordination, and communication. A similar approach was used before in a previous project in the city of Tampere see figure (42). The model can be available for the project team in the BigRoom and for communicating with future users and inhabitants in the surrounding area of the project. The VR model can be created by the help of Unity and synchronized with the BIM model, therefore any changes in the BIM model will be updated automatically in the VR model. The VR model can be available to the alliance group, the stakeholders, and the citizens of Helsinki and Espoo with the ability of navigation and walkthrough using the computer screen, mobile phones, or VR headset (Vanne, 2017).

Figure 42: The urban model in the south park area in the city of Tampere. Source: (Vanne, 2017).

### 5.1.2 Visualization, Communication, and Interaction

When the level of acceptance for the project increases, the project can proceed smoothly without complaints and damage to the reputation. The best way to increase acceptance of people for a project is to pay attention of their concerns, familiarize them with the future situation, and involve them as far as possible into the design and especially the conceptual planning. It is normal that people always worry about changes, even though the new changes might improve the quality of life and the surrounding environment. It is important to encounter inhabitants face to face. In such situations, it is important to use the most illustrative material and methods. Taking people's opinions in consideration increases integrity, engagement, and acceptance. The VR model is an applicable tool for achieving these purposes (Vanne, 2017).

One of the best features of the VR model is the ability to simulate the day and night time within all weather conditions. When using the VE, the user can easily walkthrough and navigate beside the ability to produce higher resolution images from any desired viewing position. To show the VR model attributes similar to the real world, materials properties in the VR model can be created using the photogrammetry technology. Therefore, the material can perform as closely as possible to the reality within different weather and lighting conditions, see figure (43) (Vanne, 2017).

Figure 43: Extracted from the Kruunusillat project model at a different times of day and in various weather conditions; sunny, dark, post-raining, and snowy conditions. Source: (Vanne, 2017).

The project proposal suggested placing many locations along with Raide-Jokeri line, where the inhabitants could experience the future impact of the project on the surroundings area. The VR model can provide the user with a real experience for the tram within the VE. For instance, the user can travel by the tram, check the platforms, and watch the impact of construction on the surrounding area. The model can provide fundamental features, especially in how residents and future users understand the situation and the progress of the final design. In public planning events, there could be possibilities to provide residents with small-scale planning tasks where they can view and comment on in the design and vote for different design alternatives (Vanne, 2017).

### 5.1.3 Coordination and Clash Detection

When the VR model be created directly from the beginning of the project, it could be used as a multi-disciplinary coordination tool. The up-to-date model from different design disciplines can be shown to assist in coordination sessions. In the VR model, it is possible to look at the results of traffic simulations for project critical sites with traffic signals. When simulating the tram operation, it is possible to ensure that the design solutions allow for an average target speed. For instance, when simulating, consider the relationship between the tram speed and the pedestrian crossings and stops. In addition, it is possible to visualize the model form multiple views, such as an outside viewpoint or an inside perspective of the diver’s control cabin. Actual tram noises in critical points can be brought to the VR model to analyze the noise dampening solutions. The VR model can be augmented with lighting techniques such as special lighting, facade lighting, and colored lights (Vanne, 2017).

For the simulation purposes, the tram model can be inserted into the VR model and if needed the different friction coefficients of the rail and wheel in different weather conditions could be modeled. In the simulations, a section of the tram can placed in front of the tram to show the stopping distance taking into account the climatic conditions (water, snowfall or leaf fall) when the rail lines are slippery see figure (44). They can use this view to observe the effect of the conditions on the stopping distance and to estimate accessibility even in difficult circumstances. The wagon driver's vision could be checked with a vision for constraints caused by vehicles or surrounding buildings. In addition, drivers can use the same system for training during the design until the project completion (Vanne, 2017).

Figure 44: Picture from the VR model for the driver's sight. Source: (Vanne, 2017).

### 5.1.4 Results and Discussion

- The project is crossing through crowded residential areas and expected to serve a high number of people
- Satisfaction for residents and end-users is an important factor for project success
- People will explore the project in public planning events or through the project website on their computers/ phones
- People can try the tram in the VE and check stations how it will look like in the future
- It is possible to simulate the weather conditions in the VR model and see the effects on the project
- Drivers can try driving the train in the VE and provide their opinion on the design
- Integrating VR and Photogrammetry technology will increase the model reality

## 5.2 Workshop: Immersive 3D Design in a Virtual Environment

The main goal of the workshop was to explore and practice the integration between VR, laser scanning, and photogrammetry technologies to enhance the communication and collaboration with the client during the design process. Therefore, the client can be involved in the daily design tasks, which will reflect positively on the time, cost and quality of the project.

### 5.2.1 Description of the Workshop

In this workshop, the author focuses on this part related to applicability of implementing VR in a full immersive 3D design environment to enhance communication, collaboration, and coordination within the project team itself and with the client. Furthermore, and because of the overseas project, there is a need to overcome challenges regarding the project location and possibility to use VR with photogrammetry instead of visiting the actual site. Therefore, the aims of implementing VR:

***Communication:*** Complex projects involving many stakeholders with different backgrounds and interests, which can be a challenge. Therefore, lack of communication between clients and engineers or between project teams will always lead to undesirable outcomes such as time delays and cost overrun. As a result, it is essential to achieve an effective communication way not only within the project multi-disciplines but also with the client. VR can speed up the communication between designers and clients. Within a VE, the client can have access to the VR model from the office and communicate directly in real-time with the designers. The client can visualize the facility elements in real scale similar to the reality without need for engineering background to be involved in the design.

***Collaboration:*** The design process is very complicated and passes through different phases. In infrastructure projects, for example, the design process is divided into three main phases: conceptual design, preliminary design, and detailed design phase. In each phase, the project team commits a different level of collaboration with the client. VR can influence positively on the collaboration within the design process. For instance, it allows multiple users at the same time within CVE where the client can virtually walkthrough with the engineers and influences the design.

***Coordination:*** Design involves multiple disciplines such as architecture, structure, geotechnical, HVAC, and rock engineers. The understanding and background for each engineer differs from the other. For instance, structural engineers can easily understand structural elements, materials, and loads however, for architecture engineers it is easier to understand finishing materials, colors, and facade. VR can visualize the project different details regarding structural elements, architecture finishes, HVAC components etc. that enables engineers to achieve a better understanding for the whole model.

***Project location:*** Project location sometimes can affect the quality of the work. For instance, some projects located remote from the office and required considerable time to visit. Insufficient information about the site can lead to significant delays. Some sites involve hazards issues and materials, which could be dangerous for humans. With the help of laser scanning, photogrammetry, and drones, it is possible to create a VR model where engineers can walkthrough and investigate the site without a need to visit the site in the nature.

In this workshop, the supervisors used an existing plant for the case study. The plant needed maintenance and designing for a new heat exchange. The area of the factory is 1200 $m^2$, and they created the 3D model of the project using a high quality laser scanner see figure (45). The average point density in the high focus area was 3 mm. The specialists scanned the entire plant within six hours using 60 scan stations with 32 hours of processing time to create the 3D model.

Figure 45: Picture from inside the VR model done by laser scanning. Source: (3D TALO, 2018)

### 5.2.2 Description of Participants

The selected number of participants was 18 engineers from different engineering backgrounds, including the author. The participants were from a different company's offices around the world: Finland, Sweden, Norway, Germany, Russia, Brazil, and China. The supervisors divided the workshop into two full workdays. In the first day, they presented five lectures related to the implementation of laser scanning, photogrammetry, point cloud and 3D design, AR, and VR in the construction industry and the possibilities of using such a technology to facilitate the work process and increase the client satisfaction. After finishing the lectures, the participants started to unbox the hardware and set up the system for the next day. On the second day, the contributors started the first steps to learn how to move, measure, draw, and fly in the VE. After the participants became familiar with the environment, the trainers conducted another workshop for explaining the workflow of the system and some advanced techniques.

### 5.2.3 Setting up the System: Software and Hardware

The supervisors divided the participants into six groups each group contained three engineers. Each group had to set up the working area, hardware, and software.

### Setting up the Hardware

Using a full immersive environment requires a high quality computer. Therefore, the supervisors selected a gaming laptop model Dell Alienware M17 supporting VR see table (1).. Then, participants set up the HTC Vive for VR system with the connection of the headset, controllers, and base station to the laptop, see table (2).

Table 1: ALIENWARE M17 gaming laptop. Source: (DELL, 2019)

| | |
|---|---|
| ***Picture*** | <br>Figure 46: ALIENWARE M17 gaming Laptop Source: The author |
| ***Processor*** | 8th Generation Intel Core i7-8750H (6-Core, 9MB Cache, up to 4.1GHz w/ Turbo Boost) |
| ***Operation System*** | Windows 10 Home 64bit English |
| ***Video Card*** | NVIDIA GeForce RTX 2060 with 6GB GDDR5 |
| ***Hard Drive*** | 256GB M.2 PCIe SSD + 1TB 7200RPM SATA HDD |
| ***Memory*** | 16GB, 2x8GB, DDR4, 2666MHz |

Table 2: VIVE VR system. Source: (HTC Corporation, 2019)

| | |
|---|---|
| ***Headset***<br><br>Figure 47: VIVE Headset. Source: (HTC Corporation, 2019) | **Screen:** Dual AMOLED 3.6'' diagonal<br>**Resolution:**1080 x 1200 pixels per eye (2160 x 1200 pixels combined)<br>**Refresh rate:** 90 Hz<br>**Field of view:** 110 degrees<br>**Safety features:** Chaperone play area boundaries and front-facing camera<br>**Sensors:** SteamVR Tracking, G-sensor, gyroscope, proximity<br>**Connections:** HDMI, USB 2.0, stereo 3.5 mm headphone jack, Power, Bluetooth<br>**Input:** Integrated microphone<br>**Eye Relief:** Interpapillary distance and lens distance adjustment |
| ***Controller*** | **Sensors:** SteamVR Tracking |

| | |
|---|---|
| <br>Figure 48: VIVE Controllers. Source: (HTC Corporation, 2019) | **Input:** Multifunction trackpad, Grip buttons, dual-stage trigger, System button, Menu button<br>**Use per charge:** Approx. 6 hours<br>**Connections:** Micro-USB charging port |
| ***Base Station***<br><br>Figure 49: VIVE Base Station. Source: (HTC Corporation, 2019) | **Standing / seated:** No min. space requirements<br>**Room-scale:** min (2m x 1.5m) and max (3.5m x 3.5m) |

### Design Space Software

Design Space Software is software developed by 3D TALO see figure (50). The company locates in Finland and comprises four different companies sharing the same concepts of implementing laser scanning, photogrammetry, augmented reality, and virtual reality in the construction industry. The software enables the user to export CAD model to a VR environment with multiple editing tools. After the user optimizes the project, it is possible to send it back to the CAD model. The software allows combining between different models such as an architectural, HVAC, scanned data, etc. Multiple users from different locations can use the same model with the ability to edit in the real-time. Within the immersive environment, the user can select useful tools such as measuring and scaling, flying and walkthrough, drawing pipes or cubes, writing notes, and taking pictures. In addition, it is possible to adapt the software for multiple purposes.

### Scaling the VR Room

After setting up the hardware and installing the software, the supervisors distributed the groups over three rooms, two teams in each room. The groups started to locate the base stations in the room in which they were facing each other in the diagonal line of the room. The trainees made sure that the distance between the stations was not less than 1.5m and not over 3.5m, as specified in the instructions. Subsequently, the trainees calibrated the controller and the headset. The calibration was done by moving the controllers and headset in the area between the two base stations and locating them on the floor. At the beginning, all teams faced difficulties in setting up and calibrating the tracking area. The problem was because there were two teams in the same room and the base stations were wireless connected that interfered between the two groups. Therefore, and to avoid that problem, the supervisors located each team in one separate room, see figure (51).


Figure 50: Design Space software main tools. Source: (3D TALO, 2018)

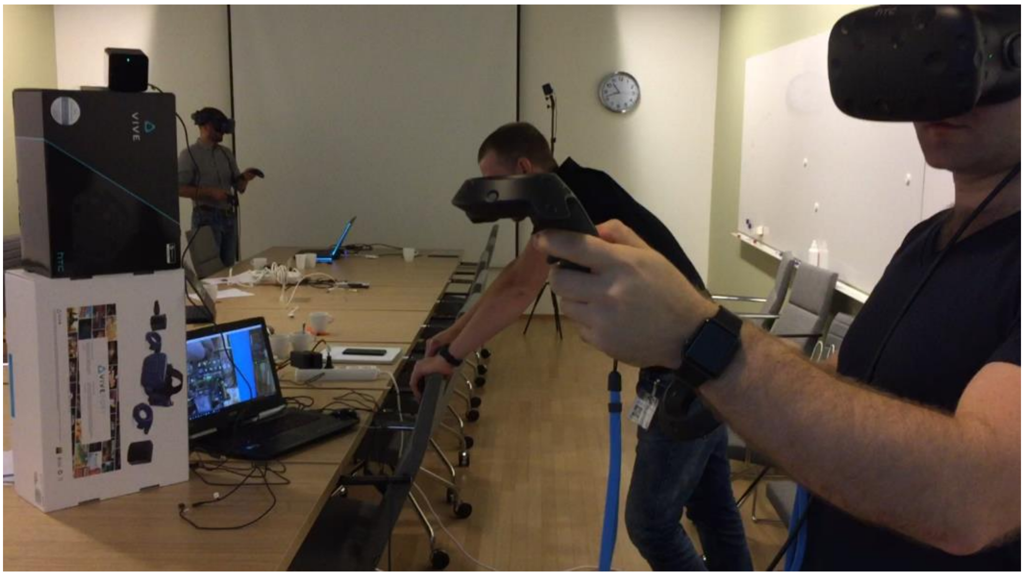


Figure 51: In the beginning of workshop two teams at the same room. Source: the author

### 5.2.4 Workflow of Design Space Software

The software automatically converts 3D-CAD into VR environment using attribute reader. The process and workflow are straightforward and timesaving. The workflow starts by exporting the 3D-CAD data to a polygon model such as exporting from Navisworks as FBX format. When the file is imported into Design Space software, the software automatically optimizes the file. Then the VR model is ready for editing, collaboration, and communication. After finishing the modification and reviewing the model, the software sends the changes back to the CAD model, see figure (52). In addition, drawing drafts, adding safety instructions, and taking pictures are possible while navigating in the VR model.

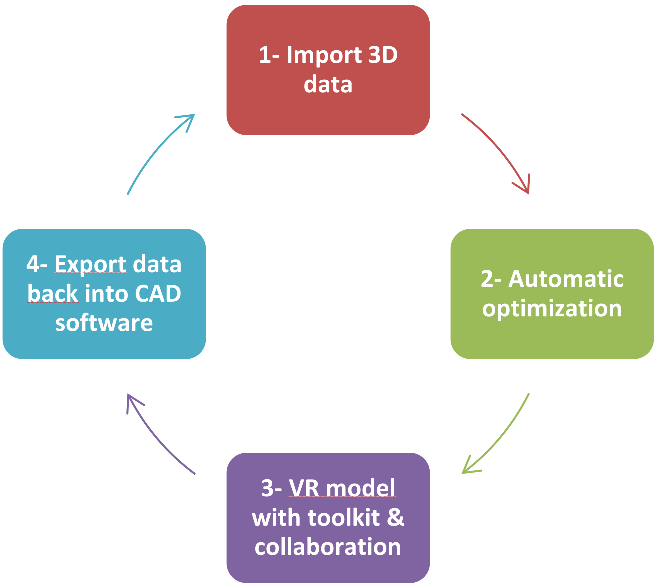



Figure 52: Workflow of Design Space Software. Source: (3D TALO, 2018)

The supervisors instructed each group how to use the headset and the controllers to navigate in the VR model. At the beginning, it was important to learn how to maintain balance while wearing the headset. In the VE, the software provides a network represent the obstacles in the room such as walls so that the user can avoid hitting the wall while being immersed in the VR model. The software contains many features that help the user make changes and to navigate smoothly in the model. Table (3) shows the main features and function. Figure (53) shows a participant while editing in the VR model.

Table 3: Features of Design Space Software  Source: the author

| Feature | Function |
|---|---|
| **Scale Your Own Size** | Increasing or decreasing the scale of the user in the model and ability to reset the scale to the original state (1:1). |
| **Select Object** | Select an object or multiple objects. |
| **Hide Object** | Hide selected objects |
| **Show All Object** | Un-hide all hidden objects |
| **Copy Object** | Make a copy for an object and allow for pasting |
| **Move/ Manipulate Object** | Move the selected object and manipulate with |
| **Draw Pipes** | Draw pipes, select the diameter, and draw elbow |
| **Add Custom Objects** | Insert custom objects such as Avatars, Safety Signs, Exit Signs, Fire Fighting box, etc. |
| **Draw Cups and Cylinder** | Draw cups and cylinders with the ability to change it. |
| **Draw lines freehand** | Using a brush to draw or write notes with a freehand style. |
| **Measure distances** | Measures distances in 3D dimensions. |
| **Take pictures** | Write notes or place safety instructions and take pictures. |
| **Walkthrough/ Fly** | Walkthrough or fly in the model. |

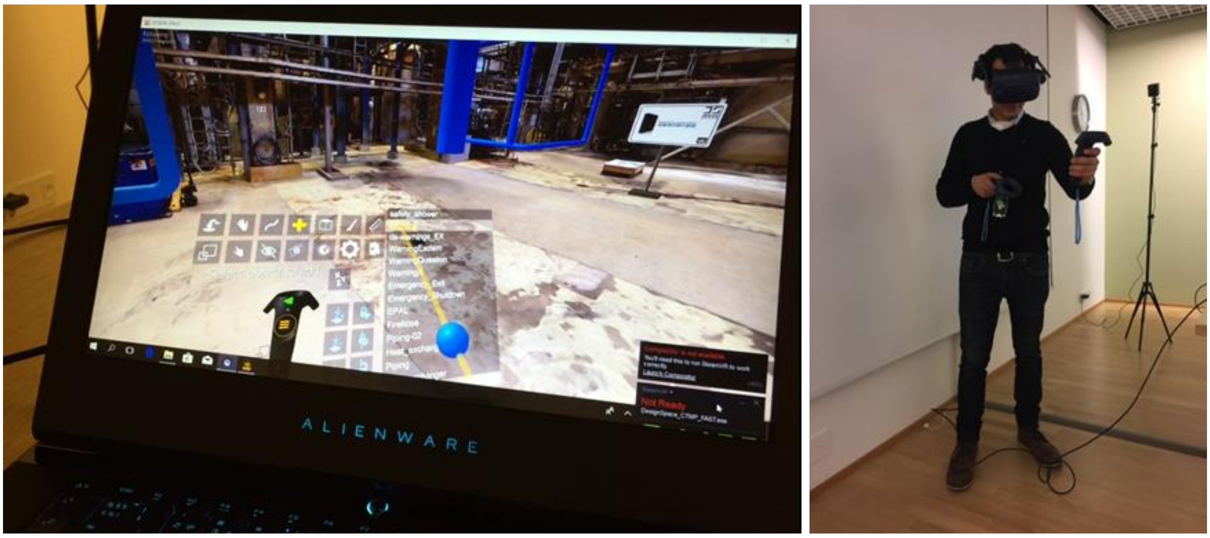



Figure 53: The participant is using the software’s tools to draw and edit a new pipe. Source: the author

### 5.2.5 Results and Discussion

- After the two-day workshop, participants became familiar with the VR and its technical settings
- The level of awareness and consciousness of participants developed with the time while moving and wearing the headset
- When the participants were immersed in the VR model, their feeling of presence increased and they became familiar with the factory as if they were physically there
- The participants learned how to draw, copy, take measurements, walk, and fly inside a VE
- They also learned how to make drafts and placing safety instructions in the VE with the ability to picture, document, and send it back to the CAD model for shop-drawing
- The participants learned how to use multi-users mode and collaborate with each other from different rooms within the VR model
- Some participants were feeling sickness and dizziness while using the VR.

# 6. Conclusion

Over the last seven decades, VR has developed rapidly and has proven its efficiency in many industry sectors; however, its application and implementation are still limited in the AEC industry. The main causes of this limitation are the unique character of the construction projects and the high cost of VR technology in the past. The construction projects and especially infrastructures involve multi-disciplined engineers, stakeholders with different interests and background, clients with high influence, and end-users cautiously looking for the project. Therefore, lack of communication, collaboration, and coordination in such projects generate mistakes and problems during the design and the construction processes. In addition, clients and stakeholders without an engineering background may face difficulty in understanding the design and particularly at the early design phase where the information is still limited. The project can face claims during the construction caused by the misunderstanding of the end-users or stakeholders.

On the other hand, the VR technology has witnessed a huge improvement not only in hardware and in software but also in the technology's cost, which has dramatically decreased compared to 15 years earlier. Therefore, many developers are working on adapting VR in the AEC industry. In the design process, the design team can use VR within CVE to improve the design review and design approval by increasing the communication and collaboration and reducing the revision and approval time. In addition, understanding the space and design elements can increase when the designer becomes immersive in a real scale 3D model. The facility operation and maintenance teams are able within CVE to simulate operation, maintenance, and even evacuation plans with the ability to leave feedback and comments on the design. The client and decision-makers can have access to the right and up-to-date information within a VE, which enables them to take earlier, reliable, and precise decisions. Stakeholders and end-users within a VE can see the future effects of the projects on the surroundings and even walk around trying to use the facility virtually.

A sufficient design should always consider the method and the ability to construct the facility. Before the beginning of the construction phase, VR can be applied to simulate hazardous areas in future sites and provide safety training for workers in advance. In addition, safety planners can identify and correct potential collisions that might cause accidents. Based on construction stage management, designers can simulate the construction elements sequence or order in a VE. Construction managers can simulate the dynamic process in the construction site when preparing site planning and before the beginning of the execution phase. This could maximize the benefits from the workplace and the resources.

Through the literature study, investigated case studies, and participation in a workshop for implementing the VR in the design process, the author has provided a framework and workflow to show the benefits and challenges from applying this technology in the infrastructure department in Pöyry Finland Oy. It can be concluded that implementation can bring many benefits for the department. The VR model can be used for communicating with the client within the VE, where the client is able to see the up-to-date design and select between multiple alternatives. Meeting sessions can be recorded in the VE with the ability to take notes and comments, which can represent the meeting minutes. In mega-infrastructures projects, the VR model can be applied to engage the stakeholders in the design and increase the satisfaction of end-users. Designers and modelers could understand and manipulate better with the design components and communicate with each other within a CVE. Finally, the model can be used for planning the operation, maintenance, and as-built documentation.

## 6.1 Limitation

The real implementation of VR still faces challenges regarding technology limitations or cultural aspects. VR still needs traditional modeling tools and cannot work independently from 3D modeling software. Creating a CAVE requires a permanent place and high cost, which limited the application only for high budget projects. The implementation may not cost efficient with simple and small size projects where traditional 3D models can be sufficient. In addition, some people feel sickness and dizziness when using VR headsets for a long time. Some clients feel comfortable using the headsets within a big group. Due to the lack of research time, there was a shortage in investigating the future approach proposal. Therefore, a case study may be needed to verify this future approach and analyze the results.

## 6.2 Recommendations and Future Work

This research drew a big picture for implementing VR in the design and in the construction processes. It also provided a framework for the infrastructure department for a preliminary implementation within the infrastructure projects. However, researches are still needed to be done in this field with focusing on:

- Perform a study on a real project case to testify the outcomes of using VR in communication with the client
- Study the pros and cons for both VR headset and VR CAVE and identify which technology is more suitable and convenient for design purposes
- Define the scale of projects suitable for applying VR
- Research and investigate the relationship between VR, photogrammetry, laser scanning, and AR and their possibility to enhance in the design process
- Investigate the potential of VR in the design process after the launch of the fifth generation cellular network (5G).

There is a need to maximize the use and implementation of BIM technology in the design process besides some training for:

- Familiarizing the modeler and designer with parametric modeling methods and software
- Setting up the VR system and experiencing the VE
- Exchanging the knowledge about VR between employees for increasing acceptance for the technology and removing the barrier.

## Declaration of Authorship

I hereby declare that the attached Master's thesis was completed independently and without the prohibited assistance of third parties, and that no sources or assistance were used other than those listed. All passages whose content or wording originates from another publication have been marked as such. Neither this thesis nor any variant of it has previously been submitted to an examining authority or published.

1st July 2019

Date

Signature of the student

# 7. Appendix

## 7.1 Appendix A: Guidelines of Using VR in Pöyry's Infrastructure Projects

(Content of this chapter is confidential)

# List of Literature

3D TALO. (2018). *Factory planning and industrial solutions in Virtual Reality*. Retrieved March 6, 2019, from 3D TALO: https://3dtalo.fi/en/industrial-solutions.html

*Aspen Movie Map*. (2010, 3 18). Retrieved 2 27, 209, from Inventing Interactive: http://www.inventinginteractive.com/2010/03/18/aspen-movie-map/

atBIM. (2018, August 11). *Parametric bridge made width Dynamo BIM*. Retrieved June 16, 2019, from Youtube : https://www.youtube.com/watch?time_continue=2&v=k0wnpEJW0FU

Autodesk . (2018, Augost 02). *Revit Products* . Retrieved June 10, 2019, from Autodesk : https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2018/ENU/Revit-Customize/files/GUID-F45641B0-830B-4FF8-A75C-693846E3513B-htm.html

Autodesk. (2018). *Infrastructure innovators use VR games to streamline Scandinavian tunnel design*. Retrieved April 16, 2019, from Autodesk: https://www.autodesk.com/customer-stories/norconsult-vr-gamification

Azhar, S. (2016). Role of visualization technologies in safety planning and management at constuction jobsites . *Elsevier*, 215-226.

Barnard, D. (2018, August 11). *History of VR -Timeline of Events and Tech Development*. Retrieved March 10, 2019, from Virtual Speech: https://virtualspeech.com/blog/history-of-vr

Benford, S., Greenhalgh, C., Rodden, T., & Pycock, J. (2001). To what extent is cyberspace really a space? Collaborative Virtual Environments. *COMMUNICATIONS OF THE ACM*, 79.

Boehning, J. (2015). *Programming Revit MEP? Say it Ain't Dynamo.* Autodesk university .

BuildingSMART UK. (2010). *Constructing the business case: Building information modelling.* London: British Standards Institution .

Business Isider Nordic. (2017, January). *Mark Zuckerberg reveals that Facebook paid more than we thought for Oculus VR*. Retrieved February 2019, from nordic.businessinsider.com: https://www.theguardian.com/technology/2014/jul/22/facebook-oculus-rift-acquisition-virtual-reality

Castronovo, F., Nikolic, D., Liu, Y., & Messner, J. (2013). An Evaluation of Immersive Virtual Reality Syatems for Design Reviews. *International Conference on Construction Applications of Virtual Reality*, (pp. 22-28). London.

Collins Dictionary. (2019). *Definision of Virtual Reality*. Retrieved June 20, 2019, from Collins Dictionary: https://www.collinsdictionary.com/dictionary/english/virtual-reality

Coppens, A., Mens, T., & Gallas, M.-A. (2018). Parametric Modelling Within Immersive Environments-Building a Bridge Between Existing Tools and Virtual Reality Headsets. *Research Gate* , 721-726.

Daniel, P., Eduardo, A., & Irizarry, J. (2017). Immersive environment for improving the understanding of architectural 3D models: Comparing user spatial perception between immersive and traditional virtual reality systems. *Elsevier*, 1-10.

DELL. (2019). *Dell*. Retrieved 05 22, 2019, from https://www.dell.com/de-de/shop/cty/pdp/spd/alienware-m17-laptop?~ck=mn

Dormehl, L. (2017, 11 13). Retrieved 10 30, 2018, from Digital Trends: https://www.digitaltrends.com/cool-tech/history-of-virtual-reality/

Ebner, A., Kammergruber, F., Horenburg, T., & Günthner, W. (2012). Logistics and Layout Planning of Construction Equipment on a VR-Multi-Touch-Tablet. *12th International Conference on Construction Application of Virtual Reality*, (p. 558). Germany.

El halabi, A. S., El Sayad, Z. T., & M. Ayad, H. (2018). VRGIS as Assistance Tool for Urban Decision-Making. *EL Sevier*, 1-8.

Engadget. (2017). *Road to VR - A Look at 4 Virtual Reality HMDs Before Oculus*. Retrieved February 2019, from Engadget: https://www.engadget.com/2016/11/27/road-to-vr-a-look-at-4-virtual-reality-hmds-before-oculus/

Eurostat. (2018). *European statistics on accidents at work.* European statistics.

Fernando, T., Wu, K.-C., & Bassanino, M. (2013). Designing a Novel Virtual Collaborative Environment to Support Collaboration in Design Review Meetings. *Journal of Information Technology in Construction*, 373-392.

Flaticon. (2019). Retrieved 2019, from Flaticon: https://www.flaticon.com/

Google . (2019). Retrieved 2019, from store.google.com: https://store.google.com/us/product/google_cardboard?hl=en-US

Grasshopper. (2019). *The Grasshopper Primer Third Edition V3.3.* Retrieved June 12, 2019, from Modelab: https://www.modelab.is/grasshopper-primer/

Guo, H., Li, H., Chan, G., & Skitmore, M. (2011). Using game technologies to improve the safety of construction plant operations. *Elsevier Ltd*, 204-2013.

Hernandez, C. R. (2005). Thinking parametric design:introducing parametric Gaudi. *Elsevier Ltd*, 310.

HTC Corporation. (2019). *Vive*. Retrieved 05 22, 2019, from https://www.vive.com/uk/comparison/

Huang, T., Kong, C. W., Guo, H. L., Baldwin, A., & Li, H. (2007). A Virtual Prototyping System for Simulating Construction Processes. *Elsevier B.V.*, 1-19.

Ismail, A., & S. Pillai, J. (n.d.). *The Sword of Damocles* . Retrieved 2 27, 2019, from D'source: http://www.dsource.in/course/virtual-reality-introduction/evolution-vr/sword-damocles-head-mounted-display

Kron, Z. (2014, January 9). *Dynamo Bridge Layout to Revit Structural Elements*. Retrieved June 10, 2019, from Youtube : https://www.youtube.com/watch?v=aLA6iA2S4IA

Majumdar, T., A. Fischer, M., & R. Schwegler, B. (2006). Conceptual Design Review with a Virtual Reality Mock-Up Model. *Joint International Conference on Computing and Decision Making in Civil and Building Engineering*, (pp. 2902-2911). Montreal .

Martin, S., & Neo K.Y, L. H. (2012). The use of Virtual Prototyping to rehearse the sequence of construction work involving mobile cranes. *Construction Innovation : Information, Process, Management*, 429-446.

Medium . (2017, November ). *Microsoft's Windows VR is a good move, but the tech giant still has to play catch up*. Retrieved February 2019, from medium.com: https://medium.com/omnivirt/microsofts-windows-vr-is-a-good-move-but-the-tech-giant-still-has-to-play-catch-up-21293c177fa7

Morgan, J. (2017). *Exploring Oculus Rift: A Historical Analysis of the Virtual Reality Paradigm.*

Moubile, M. (2018). *Towards real-time parametric structural modeling in Virtual Reality using a game engine.*

Muhammad, A. A., Yitmen, I., Alizaedhsaehi, S., & Celik, T. (2019). Adoption of Virtual Reality (VR) for Site Layout Optimization of Construction Projects. *Research Gate*, 1-16.

N. Mohammadi, S. H., & E. Taylor, J. (2019). Exploring Future Stakeholder Feedback on Performance-Based Design Across Virtuality Continuum. *Springer Nature Switzerland* , 423-428.

NASA. (2018). *The Virtual Interface Environment Workstation*. Retrieved June 19, 2018, from NASA Gov: https://www.nasa.gov/ames/spinoff/new_continent_of_ideas/

Nicole, R. (n.d.). *Project Management in Civil Engineering.* Retrieved 02 16, 2019, from HTW Berlin: https://moodle.htw-berlin.de/

Oculus. (2019). Retrieved 2019, from www.oculus.com: https://www.oculus.com/

Omar, F., Trigunarsyah, B., & Wong, J. (2009). INFRASTRUCTURE PROJECT PLANNING DECISION MAKING: CHALLENGES FOR DECISION SUPPORT SYSTEM APPLICATIONS. *QUT Digital Repository*, 146-151.

Oxford, D. (2019). *Oxford Dictionary*. Retrieved 2 27, 2019, from Oxford Dictionary: https://en.oxforddictionaries.com/definition/virtual

P. Martins, O., & Z. Sampaio, A. (2011). Bridge Launching Construction Visualized in a Virtual Environment. *The International Journal of Virtual Reality*, 49-55.

PMBOK. (2013). *A Guide to the Project Management Body of Knowledge.* Pennsylvania: Project Management Institute, Inc.

Pratama, L., Lin, K.-Y., & Fardhosseini, S. (2018). An Overview of Generating VR Models for Disaster Zone Reconstruction Using Drone Footage. *Research Gate*.

Pridto, R., & J. Cansas, J. (2000). Are visual programming languages better? The role of imagery in program comprehension. *Idealibrary*, 805.

Project Management Institute. (2015). *Capturing the Value of Projrct Management Through Decision Making.* August.

*Raide Jokeri*. (2018). Retrieved 10 20, 2018, from Raide Jokeri: http://raidejokeri.info/in-english

Read, P. (2017, May 26). *BIMception: Virtual Design Reviews Inside of the Virtual Design*. Retrieved April 11, 2019, from Linkedin: https://www.linkedin.com/pulse/bimception-virtual-design-reviews-inside-project-phil-read/

Rohani, M., Fan, M., & Yu, C. (2012). Advanced Visualization (Simulated) Techniques for Modern Construction Management . *Indoor and built Environment*.

Samset, K. (2009). Projects, their quality at entry - and challenges in the front-end phase. In K. Samset, T. Williams, & K. Sunnevåg, *Making Essential Choices with Scant Information* (pp. 18-31). London: Palgrave Macmillan.

Sanderink, C. (2017). *Virtual Reality, Augmented Reality Hype? Or Serious Business?* Tilburg: Brabant Developement Agency.

Schröder, & Dirk. (2010). Virtual Reality System at RWTH Aachen University. *Proceedings of the International Symposium on Room Acoustics, ISRA 2010* , 1-7.

Statista . (2016, April). *The Diverse Potential of VR & AR Applications*. Retrieved February 2019, from www.statista.com: https://www.statista.com/chart/4602/virtual-and-augmented-reality-software-revenue/

Statista. (2019). *Forecast augmented (AR) and virtual reality (VR) market size worldwide from 2016 to 2022 (in billion U.S. dollars)*. Retrieved 2 28, 2019, from Statista: https://www.statista.com/statistics/591181/global-augmented-virtual-reality-market-size/

Tekla Software. (2017, January 10). *Grasshopper Tekla Live Link Beta Bridge Demo Pt2*. Retrieved June 12, 2019, from Youtube : https://www.youtube.com/watch?time_continue=246&v=CGoYN7F60iQ

The Motley Fool. (2017, July). *Google Is Aiming to Bring VR to the Masses*. Retrieved February 2019, from www.fool.com: https://www.fool.com/investing/2017/07/29/google-is-aiming-to-bring-vr-to-the-masses.aspx

The VR Headset. (2018, November 11). *Historical Development of Virtual Reality*. Retrieved 3 10, 2019, from The VR Headset: https://thevrheadset.com/historical-development-of-virtual-reality-vr/

Tizani, W. (2011). Collaborative Design in Virtual Environments at Conceptual Stage . *Springer Science*, 67-75.

Van den Berg, M., Hartmann, T., & de Graaf, R. (2017). SUPPORTING DESIGN REVIEWS WITH PRE-MEETING VIRTUAL REALITY ENVIRONMENTS. *Journal of Information Technology in Construction*, 306-318.

Van Den Berg, M., Hartmann, T., & De Graaf, R. (2017). Supproting Design Review with Pre-Meeting Virtual Reality Environments. *Journal of Information Technology in Construction*, 306-318.

Vanne, H. (2017). *Helsingin kaupungin liikennelaitos–liikelaitos ja Espoon kaupunki, Raide-Jokerin suunnittelun hankinta.* Helsinki.

Virtual Reality Society. (2019). *History Of Virtual Reality*. Retrieved March 10, 2019, from https://www.vrs.org.uk/virtual-reality/history.html

Visbox. (2019). *CAVE vs HMD*. Retrieved June 5, 2019, from Visbox: http://www.visbox.com/technology/cave-vs-hmd/

W. F. Lau, W., & H. K. Yuen, A. (2015). *Encyclopedia of Information Science and Technology, Third Edition.*

Wang, X., & Schnabel, M. A. (2009). *Mixed Reality in Architecture, Design, and Construction.* Sydney: Springer Science and Business Media B.V.

Wiltz, C. (2019, March 01). *The Story of Sega VR: Sega's Failed Virtual Reality Headse*. Retrieved May 19, 2019, from Design News: https://www.designnews.com/electronics-test/story-sega-vr-segas-failed-virtual-reality-headset/74451237860349

Woksepp, S., Olofsson, T., & Jongeling, R. (2005). DESIGN REVIEWS AND DECISION-MAKING USING COLLABORATIVE VIRTUAL REALITY PROTOTYPES; A CASE STUDY OF THE LARGE-SCALE MK3 PROJECT. *Proceedings IGLC-13*, (pp. 145-151). Sydney.

WVOLF. (2009, May 11). *Bridge construction - Incremental Launching - 3D Animation*. Retrieved March 20, 2019, from Youtube : https://www.youtube.com/watch?v=S3Kf9e6JgF4

Yabuki, N. (2011). Impact of Collaborative Virtual Environments on Design Process . *Springer Science*, 103-110.

Yu, Y., Skitmore, M., & Guo, H. (2016). Visualization technology-based construction safety management: A review. *Automation in Construction*, 136-141.

Z. Sampaio, A., & P. Martins, O. (2014). The application of virtual reality technology in the construction of bridge The cantilever and incremental launching methods. *Automation in Construction*, 58-67.