Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Computer Science

Mikael Mathisen
Sondre Løvhaug

Visualizing Key Performance Indicators in Sustainable Neighbourhoods

Master's thesis in Databaser og Søk
Supervisor: John Krogstie, Dr Aoife Houlihan Wiberg, Ekaterina Prasolova-Førland, Eirik Resch

June 2019

NTNU
Norwegian University of
Science and Technology

Mikael Mathisen
Sondre Løvhaug

Visualizing Key Performance Indicators in Sustainable Neighbourhoods

Master's thesis in Databaser og Søk
Supervisor: John Krogstie, Dr Aoife Houlihan Wiberg, Ekaterina Prasolova-Førland, Eirik Resch
June 2019

Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Computer Science

NTNU
Norwegian University of Science and Technology

Sammendrag

Denne oppgaven følger Design Science Research metoden og utforsker hvordan virtuell virkelighet-teknologier (VR) kan bli benyttet for å visualisere utslipps-data i nullutslippsområder. For å oppnå dette ble en virtuell virkelighet-applikasjon, kalt ZENVR, utviklet. Denne ble evaluert gjennom semi-strukturerte ekspert-intervjuer. De innsamlede dataene ble strukturert og analysert ved å delvis anvende prinsippene fra Grounded Theory. Systemets brukervennlighet ble evaluert gjennom brukertester med et tilhørende spørreskjema.

Resultatene indikerer at virtuell virkelighet er en egnet plattform for å kommunisere og gi kontekst til komplekse data, og at ZENVR er et egnet verktøy for å visualisere Key Performance Indicators (KPIs) i nullutslippsområder. Resultatene viser også at ved å utnytte de altoppslukende egenskapene til virtuel virkelighet er det mulig å skape en opplevelse for brukeren som kan gjøre et vedvarende inntrykk. Flere bruksområder for ZENVR har blitt oppdaget: Engasjere innbyggere, promotering og reklame for nullutslippsområder, verktøy for tverrfaglig kommunikasjon og samarbeid mellom profesjonnelle.

Abstract

This project follows the Design Science Research methodology and explores how virtual reality technology may be utilized for visualizing emission data in Zero Emission Neighbourhoods (ZENs). The project involved developing a virtual reality application named ZENVR, which were evaluated through semi-structured expert interviews. The data collected was structured and analyzed by partially applying Grounded Theory. Furthermore, the usability of the system has been evaluated through user test with an attached questionnaire.

The results indicate that virtual reality is a suitable platform for communicating and contextualizing complex data and that ZENVR is an appropriate tool for visualizing Key Performance Indicators in ZENs. The findings also show that by utilizing the immersive properties of virtual reality, it is possible to create an experience for the user and subsequently making a lasting impression. Several areas of use for ZENVR were discovered, including citizen engagement, promotion and the advertisement of ZENs, tool for interdisciplinary communication and collaboration between professionals.

Preface

This project has been defined and completed with the guidance of our supervisors; professor John Krogstie, Dr Aoife Houlihan Wiberg, professor Ekaterina Prasolova-Førland and Student Scholar Eirik Resch at the Norwegian University of Science and Technology (NTNU). We want to thank them all for the continuous support and guidance during this project.

A special thanks to Dr Aoife Houlihan Wiberg for always meeting us with a smile and a hug, and giving us the opportunity to visit the Fraunhofer Institute in Singapore. We would also like to thank the Research Center for Zero Emission Neighbourhoods in Smart Cities (FME-ZEN) for funding the expedition.

Thank you to Ekaterina and Mikhail at IMTEL and Frank at IDI for supplying us with the equipment needed to realize this project.

Thanks to Marius Erdt and Benedikt Tschoerner at Fraunhofer. Thank you for welcoming us with open arms and giving invaluable support during the development of ZENVR.

We also would like to thank Jan Håvard and Eystein for giving us feedback on our report.

A special thanks to our good friends BlockBoys for the unforgettable times these last years at Gløshaugen.

And last, but not least, we wish to thank our incredible partners, Tiril and Kristine, for putting up with us during the last year and for the endless love, support and encouragement.

Mikael Mathisen & Sondre Løvhaug

Contents

List of Tables

List of Figures

Abbreviations

Symbol	=	definition
AR	=	Augmented Reality
BIM	=	Building Information Modeling
CO2eq	=	Carbon Dioxide Equivalent
DoF	=	Degrees of Freedom
DVAS	=	Discrete Visual Analogue Scale
EPD	=	Environmental Product Description
ERD	=	Entity Relationship Diagram
FME-ZEN	=	Research Centre for Environmentally Friendly Energy
FoV	=	Field of View
GHG	=	Greenhouse Gas
GWP	=	Global Warming Potential
HMD	=	Head Mounted Display
IDE	=	Integrated Development Environment
KPI	=	Key Performance Indicator
LCA	=	Life Cycle Assessment
MR	=	Mixed Reality
NSD	=	Norsk Senter for Forskningsdata
SUS	=	System Usability Scale
VE	=	Virtual Environment
VR	=	Virtual Reality
ZEN	=	Zero Emission Neighbourhood
ZEB	=	Zero Emission Building
XR	=	Extended Reality

Chapter 1

Introduction

1.1 Context and Relevance

As the complexities of societies are increasing, municipalities face new challenges for addressing this. To have well-functioning cities, one relies on using resources efficiently and engaging with technology in new ways. The concept of "smart cities" are defined as urban areas which rely on technology to gather data and use it to manage assets and resources [17]. It aims to use technology for reducing costs and consumption, enhancing well-being and performance, and engaging more actively with their citizens.

The Research Center for Zero Emission Neighbourhoods in Smart Cities (FME-ZEN), together with its partners, is working towards creating sustainable neighbourhoods in smart cities [18]. To enable the transition to a low carbon society, ZEN has developed a set of Key Performance Indicators (KPIs) to measure the performance of a sustainable neighbourhood [5]. Today, there is a challenge with increasing complexity and decreasing usability when dealing with the level of detail required to model a zero emission neighbourhood. Therefore, visualization becomes beneficial in order to better understand and communicate complex data to a variety of stakeholders [19].

In the context of visualization, virtual reality (VR) is an emerging technology which has shown potential for improving learning, motivation, understanding and information recall [20][21][22][23][24][14]. A number of studies and projects who utilize VR for visualizing data have exist today, however, most of these concentrate on either visualizing numerical data [14] or building information models (BIM) [12][25][11][26]. After researching the field of interest, the lack of a application which can visualize BIM models with the associated KPIs became apparent.

1.2 Problem Definition

This thesis aims to research the data visualization possibilities and engagement factors of virtual reality and use these properties in favour of communicating complex data to diverse stakeholders.

1.3 Research Questions

Based on the problem description, the following research questions were formed and helped guide the research:

1. *How can Virtual Reality be used to visualize Key Performance Indicators in sustainable neighbourhoods?*
   (a) *Which form of data visualization is most beneficial for comprehending the Key Performance Indicators for different user groups?*
   (b) *How can Virtual Reality be used to improve stakeholder participation in sustainable neighbourhood projects?*

Stakeholders, in this context, span from citizens wanting to know more about the work of ZEN, to experts and professionals working with building- and city planning/development. Data visualization is a presentation of data in a way where users can put it into context within the virtual environment.

1.4 Project Description

This project is structured as a design science research (DSR) project [27] and relies on the development and evaluation of artefacts. This project has been completed as a three-step process, including the research of the application domain, development of the application, and evaluation of the application.

The preliminary study explored the potential of both extended realities (XR), such as augmented- and virtual reality, and traditional desktop applications. As a result, three prototypes were created and evaluated. The potential and limitations of each technology were mapped and resulted in using virtual reality for further development.

The development of the application has mainly been conducted at the Fraunhofer Institute in Singapore [28]. The application has been developed in Unity [29] for the HTC Vive [9] VR system with the bLCAd-tool [30] as the data source for building emissions.

For evaluating the result, a qualitative approach of semi-structured expert interviews has been used for data collection. When analyzing and drawing theories from the data sets, the principles of grounded theory [31] have been partially applied. Additionally, data was gathered through user tests with an associated questionnaire. It was conducted on subjects without expert knowledge of the technology or the field of architecture.

The result of the project is twofold; a practical virtual reality application with the possibility to visualize greenhouse gas emission (GHG) data from an online database, and an evaluation of the application with research on visualizing data in virtual reality with suggestions for further improvements to the application.

This research has been reported, reviewed, and accepted by the Norwegian Centre for Research Data (NSD).

1.5 Report Outline

This project report is structured as follows.

Chapter 2 - Background provides the reader with the necessary context needed when reading this paper. It contains a presentation of Zero Emission Neighbourhood and the pilot area of Sluppen in Trondheim, Norway. It also presents the relevant hardware, software and database used in this project.

Chapter 3 - Related Work presents research conducted which are relevant to this project. It is comprised of related research in data visualization in VR, user interface design in VR, usability design and virtual reality as a tool for learning. It also presents related projects that, to some degree, try to accomplish something similar with technology.

Chapter 4 - Research Method presents the research method and theories for evaluating the system.

Chapter 5 - Research Approach presents how the theories from Research Approach are applied in this project.

Chapter 6 - Presentation of ZENVR is a presentation of the developed application. It also contains a short presentation of the developed prototypes, which were a part of the study of the application domain. Furthermore, an overview of the technical details of the system is provided.

Chapter 7 - Findings contains the data collected. First, the data gathered through a questionnaire are presented, after which the data from interviews are provided.

Chapter 8 - Discussion are the discussion of the findings and the limitations of this study.

Chapter 9 - Conclusion & Further Work presents the conclusion in light of the research questions. It also contains a section describing further work.

Chapter 2

Background

This chapter provides the reader with the context necessary for understanding this thesis. The research organization behind this project, the Research centre for zero emission neighbourhoods in smart cities (FME-ZEN) [18], will be presented, and their pilot projects, which this thesis revolve around. Furthermore, the chapter will go into detail about the XR technology relevant for this project and explain the main differences between augmented- and virtual reality. State of the art is presented, followed by relevant software for this project. Lastly, an explanation of the building LCA database-tool, which are the source of emission data, will be presented.

A summary may be found at the end of this chapter.

2.1 Zero Emission Neighbourhood

This thesis is a collaboration with the ZEN centre, which was established in 2017 by the Research Council of Norway. Researchers, municipalities, industry, and governmental organizations cooperate in the ZEN Research Center to plan, develop, and run neighbourhoods with zero greenhouse gas emissions. The ZEN Center has nine pilot projects spread over all of Norway that encompass an area of more than 1 million m^2 and more than 30000 inhabitants in total. The goal of ZEN is to enable the transition to a low carbon society by developing sustainable neighbourhoods with zero greenhouse gas emissions. From their report *The ZEN Definition - A Guideline for the ZEN Pilot Areas* [5] they list the following pointers to achieve this goal:

- A clear definition of the goal, i.e., what is a zero emission neighbourhood
- Key performance indicators, which will help to plan and design the neighbourhood and to monitor its actual performance
- Tools to monitor the performance of a planned or existing neighbourhood with different ambition levels (equivalent to the Zero Emission Buildings(ZEB)-tool)
- A guideline for how the definition of ZEN and its KPIs could be assessed and implemented into the planning, design, construction, and operational phases of planned and existing neighbourhoods (ZEN pilot projects).

The ZEN Research Centre defines a neighbourhood as a group of interconnected buildings with associated infrastructure, located within a confined geographical area. Furthermore, the ZEN Research Centre has provided a definition report containing assessment criteria and key performance indicators. These are grouped into seven categories: Greenhouse gas emissions, energy, power/load, mobility, economy, spatial qualities, and innovation. Each of these categories is divided into several assessment criteria. The assessment criteria are then divided into several key performance indicators.

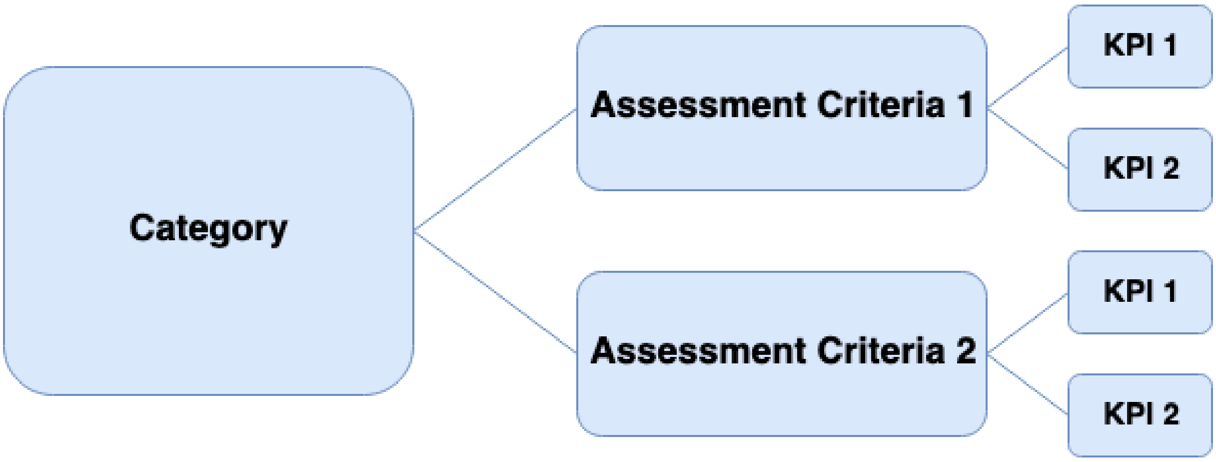


Figure 2.1: System of category, assessment criteria, and KPIs within the ZEN definition guideline. From [5]

2.1.1 Key Performance Indicators

The ZEN centre has created a set of *Key Performance Indicators*. As mentioned, these KPIs are a part of seven categories and associated *assessment criteria*. Assessment criteria are requirements that name different aspects within a category which are essential to assess the performance of a neighbourhood within the category. They may be interconnected, meaning the fulfilment of one depends on the other. One or several KPIs assess each assessment criterion.

The Key Performance Indicators are a set of quantifiable performance measurements which define sets of values based on measured data from a ZEN project, making it possible to track a neighbourhoods performance over time. The categories, assessment criteria, explanation and calculation of the different KPIs can be found in figure 2.2.

2.1.2 Pilot Projects

ZEN pilot projects [32] are neighbourhoods geographically limited to areas in Norway where new solutions for the construction, operation, and use of buildings are tested to cut the total greenhouse gas emissions to zero on a neighbourhood scale. These neighbourhoods will function as role models, inspiring others to build zero emission neighbourhoods and offering explanations as to how the best possible results can be achieved. Various stakeholders will have different influences on the ZEN pilot area at different times during

Category	Assessment Criteria	Key Performance Indicators (KPIs)
GHG Emission	• Total GHG Emissions • GHG emission reduction	• Total GHG emissions in tCO_{2eq}: $\frac{tCO_{2eq}}{m^2}$ heated floor area $\frac{(BRA)}{yr}$; $\frac{kgCO_{2eq}}{m^2}$ outdoor space $\frac{(BAU)}{yr}$; $\frac{tCO_{2eq}}{CAPITA}$ • % reduction compared to a base case
Energy	• Energy efficiency in buildings • Energy carriers	• Net, gross and total energy need in $\frac{\frac{kWh}{m^2}}{\frac{BRA}{yr}}$ • Energy use, generation, delivery, export and colour coded carpet plot in $\frac{kWh}{yr}$ • Self-consumption & self-generation in %
Power/Load	• Power/Load performance • Power/Load flexibility	• Net-load yearly profile in kWh; Net-load duration curve in kWh; Peak-load in kWh; Peak export in kWh; Utilization factor in % • Daily net-load profile in kWh
Mobility	• Mode of transport • Access to public transport	• % share • Meters; frequency
Economy	• Life cycle cost (LCC)	• NOK; $\frac{NOK}{m^2}$ heated floor area $\frac{(BRA)}{yr}$; $\frac{NOK}{m^2}$ outdoor space $\frac{(BAU)}{yr}$; $\frac{NOK}{CAPITA}$
Spatial Qualities	• Demographic needs and consultation plan • Delivery and proximity to amenities • Public space	• Qualitative • Number of amenities; Meters (Distance from building) • Qualitative

Figure 2.2: ZEN assessment criteria and KPIs covered in ZEN definition guideline. From [5]

the development of the area [5]. There are nine ZEN pilot areas included in the ZEN Research Center:

- Campus Evenstad
- Fornebu, Bærum
- Furuset, Oslo
- Knowledge Axis, with NTNU Campus
- Knowledge Axis, with Sluppen, Trondheim
- Lø, Steinkjer (former NRK site)
- Nyby, Bodø
- Ydalir, Elverum
- Zero Village, Bergen

2.1.3 Nidarvoll Pilot Project

The pilot site Nidavoll in Sluppen is located in the larger ZEN pilot project called "The Knowledge Axis", as shown in figure 2.3. It starts at the harbour to the north of the city centre and ends up in Sluppen, a mainly commercial area that is planned to be developed into a multi-functional neighbourhood [33]. Key stakeholders include Trondheim municipality and the project owner NTNU and other stakeholders [34].

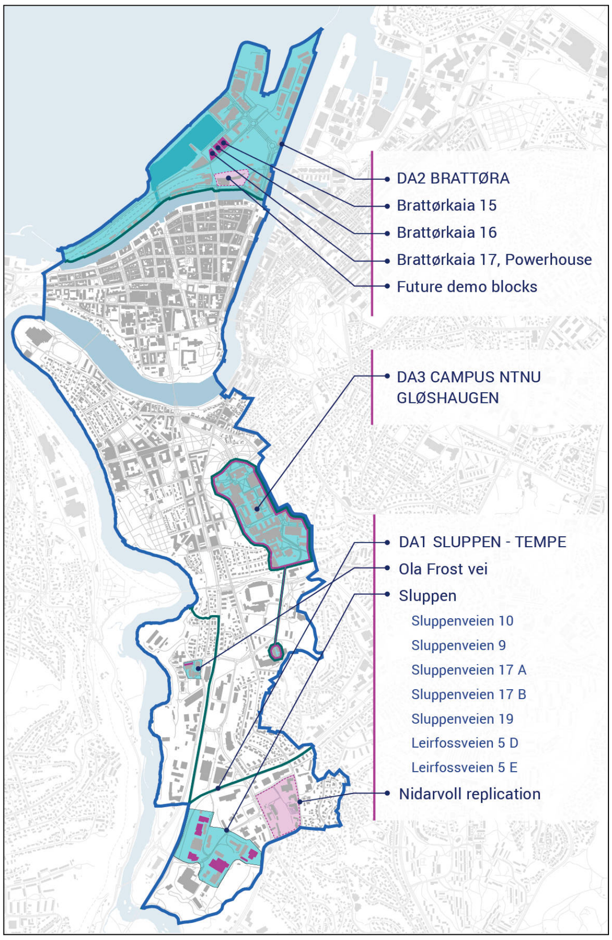


Figure 2.3: The Knowledge Axis. From [6]

The focus area of this paper and VR application is the ZEN pilot project Nidarvoll School in this Sluppen area in Trondheim, Norway [34][35]. The school area consists of several buildings which were added to the site during the 60s, '70s and '80s. The study focuses on "The Yellow House" ("Gulhuset"), a wooden building from the early 1900's [36].

2.2 Hardware

This section focuses on the tools and technologies relevant to developing the developed application. Since the development process has included prototypes for other technologies that were used for the application, the tools and technologies used both in the end product and prototype phase will be included. However, the main focus will be the technologies involved in the end product.

The technologies researched in this thesis for displaying data to the user and creating an experience, all fall under the umbrella term *Extended Reality*. XR covers most technologies for creating a real-to-virtual combined environment such as *augmented reality* and *virtual reality*. In contrast to XR, one finds the more traditional user interfaces for displaying data such as regular desktop applications. These applications have the advantage when working with large quantities of text-based data, whereas XR is more suitable for making an impact and creating an experience for the user.

Solutions span from showing information on a tablet (AR) to the user wearing a haptic suit with a head-mounted display (VR). The main differences between AR and VR are that AR supplements reality, while VR completely replaces it [37]. Due to the immersive effect of head-mounted displays, the user can interact with the data in a way that is limited in desktop-applications. In recent years the primary focus for VR has been set around the entertainment industry. This focus has driven the innovation in the field where different manufacturers promise better and cheaper solutions and have also made the technology available for consumers. There has been a significant increase in technologies allowing for users to interact and alter a virtual environment, and technologies suited for immersive experiences.

2.2.1 Augmented Reality

In 1990, the term "Augmented Reality" was coined by Tom Caudell and David Mizell, referring to use cases that involved displaying information to pilots on their visor, and drawing on top of television footage [38].

Augmented reality has a use case beyond just showing information on a screen. Potentially, AR can be applied to all senses, including hearing, smell and touch. Some AR applications have the ability to remove real objects from the perceived environment, in addition to adding virtual objects [39]. The technology also has the potential to be used for visualizing data on buildings in the real world, or by showing 3D models of buildings on a flat surface.

AR has gained popularity in the growing market of smartphones. Since most AR applications rely on using a camera to capture the real-world-environment and other sensors such as gyroscope and accelerometer to layer information on top the real world, smartphones provide all required elements right out the box. With the rise of applications such as Pokémon Go [40] and filters in Snapchat [41] AR has become a part of daily life. These types of AR apps capture the real world through a camera lens and use surface- or face-detection algorithms to place objects and elements on top of the image.

Figure 2.4: Example of AR used in Pokémon GO

In the last couple of years, augmented reality has gained much traction in the construction industry, much due to the increasing popularity and possibilities of the Microsoft Hololens [42]. The Hololens shares many similarities with early AR-systems and is essentially a pair of glasses the user can wear, which allows for rendering graphics on top of the real world. After the release of the Hololens in 2016, other companies have made competing technologies, such as the Magic Leap [43] offering a better field of view and resolution than the Hololens.

2.2.2 Virtual Reality

Ivan Sutherland, the creator of one of the world's first VR systems in the 1960s, stated [44]:

> *"The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal."*

Oxford dictionary further defines virtual reality as:

> *"The computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors."* [45]

However, this definition only focuses on the physical sensations of VR. In its pure form, VR is *communication*. A virtual reality system communicates to the user how the virtual world works, how objects are controlled and the relationship between user and content. A well designed VR experience can be thought of a collaboration between human and machine where both software and hardware work harmoniously together to provide intuitive communication with the human [46].

The History of Virtual Reality

What today is perceived as VR-technology began in the early 1800s with the creation of stereoscopes, invented by Sir Charles Wheatstone[46]. This device uses mirrors to reflect images and gave the pictures a depth which resembles modern 3D-visualization. It was further developed by David Brewster, who used lenses to make smaller, hand-held stereoscopes [46]. The success of the stereoscope resulted in a 3D-craze, and various forms of the stereoscope were produced. Among these were a self-assembled cardboard version, which is conceptually the same as the Google Cardboard.

Figure 2.5: Image of an early stereoscope

Figure 2.6: Image of the Google Cardboard [7]

During the 1900s, the use of the concept of the stereoscope was further developed. One patent, which closely resembles today's VR-technology, was Morton Heilig's Sensorama from the 1950s [47]. This device was created for immersive film viewing with a large field of view (FoV). In 1961, Philco Corporation built the first working HMD with head tracking [46]. When the user moved their head, a camera in another room simultaneously moved to provide a feeling of being in another location.

In 1982, Atari Research, led by Alan Kay, started researching new ways of interacting with computers [46]. They began designing technologies which soon were essential for commercializing VR systems. The research and work that were put in during the 1980s resulted in a new VR era in the 1990s. Several new companies started work on location-based entertainment. Existing companies, like Sega, Disney and General Motors as well as universities and military, started to do more extensive research on how to utilize VR. The VR industry had its peak in the mid-'90s, but the technology could not keep up with the rapid development of the area. By the end of the 1990s, most VR companies went out of business.

The following years are known as the "VR winter", and there were close to no media coverage on the subject. VR was no longer a subject with the public population, but the research continued in several corporate, government, academic and military research laboratories. The VR-community started to switch its approach from technology-centred to human-centred design, and there was an emphasis on user studies. This change in direction led to the conclusion that a large field of view was paramount to achieve the "magic" feeling of presence. In 2006, Mark Bolas of UMCs MxR Lab and Ian McDowall from Fakespace Labs created a 150-degree field of view head mounted display (HMD) called the Wide5 [46]. They researched the effect of field of view on the user behaviour and experience, and as a result, they created a low-cost Field of View To Go (FOV2GO) [48]. It was part of the MxR Labs Open Source project and became the precursor to most of the consumer HMD of today.

One of the researchers at the MxR Lab, Palmer Luckey, started at this time to share his prototype online at a forum. Here he met John Carmack, and together they formed Oculus VR.[49] Luckey left the MxR Lab and launched the Oculus Rift Kickstarter, and popular media once again became interested in VR.

State of the Art

VR is a combination of creating a stereoscopic image, tracking position and registering input for creating an immersive experience through a head-mounted display. The HMDs position and orientation is tracked, which is essential since the computer-generated image has to be updated accordingly to the user's movement. In the real world, when one turns their head, objects are stable in space, and the same rules have to apply to the virtual world. Another challenge is updating the computer generated images fast enough, known as latency. If the latency is too high, the user will get dizzy and motion sick [46]. The stereoscopic images are achieved by rendering two independent images, one for each eye. It gives the illusion of depth in the image.

Today there exist many companies, some more established than others, all trying to deliver the best possible VR experience. Some of the more proven companies, such as Oculus and HTC, are targeting the entertainment business with their HMDs pushing better resolution and interaction for their users. Some companies are trying to solve other problems or deliver new functionality. For instance is FOVE [50] using infrared cameras to track eye movement, opening up for a whole new way of interacting with applications. Others, such as StarVR, are expanding the field of view for their HMDs, opting for an even more immersed experience [51]. On the other side of innovation, Google is trying to make VR more accessible and cheaper by offering high-quality headsets for mobile phones, namely the Google Daydream [52]. In 2016, Antes et al. [8] wrote a paper on the state of the art of virtual reality. In figure 2.7, one may observe how the most popular HMDs compare to each other with regards to functionality, screen resolution, the field of view and price.

	ResVert	ResHor	FOV	Tracking	Head	Eye	Touch	Vibration	Wind	Smell	Audio	Weight	Price	Available
Cardboard				3	X								$10	X
VirtualVizor				3	X								$54	X
Wearality SKY			150	3	X								$49	X
Samsung Gear VR V1			96	3	X		X							X
Samsung Gear VR V2			96	3	X		X						$99	X
Zeiss VROne			100	3	X								$129	X
Gameface Mark V	2560	1440	140	X	X									
Auravisor	1920	1080	100	3	X						X		$260	P
HTC Vive	2160	1200	110	X	X									
Oculus DK1	1280	800	110	3	X							380	$300	X
Oculus DK2	1980	1080	100	X	X							440	$350	X
Oculus - The Rift	2160	1200		X	X						X	380	$599	P
PlayStation VR	1920	1080	100	X	X									
FOVE	2560	1440	100	X	X	X						400		
HDK OSVR	1920	1080	100	X	X								$300	P
Sulon Cortex					X									
Avegant Glyph			45	X	X							450	$599	P
VRVANA Totem					X									
AntVR	1920	1080	100		X							370		
StarVR	5120	1440	210x180	X	X	X								
TeslaSuit								X						
Subpac M2								X					$399	X
ARAIG								X			X			
KOR-FX								X					$135	X
VirWind									X					
Feel Three								X						
FeelReal									X	X			$299	P
Nirvana Mask				3	X				X	X	X		$799	P

Figure 2.7: Comparison matrix of different VR HMDs. From [8]

Stationary Versus Mobile VR

Stationary and mobile VR can be compared to the difference between mobile applications and more detailed, high-powered desktop applications. Mobile VR has its strengths in that a user can, at any time and place, be immersed almost instantaneously and that it can be a social experience because of its availability and ease of use. Usually, all that is needed is a form of head-mount, such as the Google Cardboard [7], see figure 2.6, which makes the applications easy to distribute because of the low price tag for a headset and the fact that smartphones are widely available. Stationary VR requires a larger set of components and a computer powerful enough to run VR applications. It also takes time to set up and requires a large area of movement. However, Stationary VR has the potential to be higher quality and offers the most immersive experience since it can utilize high-end equipment and tracking technologies. [46]

Interaction in VR

> *"Human-centered interaction design focuses on the human side of communication between user and machine–the interface from the user's point of view. Quality interactions enhance user understanding of what has just occurred, what is happening, what can be done, and how to do it. In the best case, not only will goals and needs be efficiently achieved, but the experiences will be engaging and enjoyable."*
>
> \- *Jason Jerald* [46]

Unless a VR application is entirely one-way communication, some form of input from the user is required. An input device is a physical tool or hardware used to interact with the virtual environment. The physical devices them-self can differ much from each other and are often categorized by their characteristics. Most common is using a controller for user input to the program. Controllers are often categorized by their degrees of freedom (DoF), meaning the number of dimensions the device is capable of manipulating. 1 DoF would be a trigger or button, while 6 DoF is necessary to measure full 3D translation. Newer controllers, such as the HTC Vive controller, supports full 6 DoF tracking, multiple input alternatives through buttons, triggers and touch, and haptic feedback. For most applications, this is sufficient for creating an intuitive way of communication between user and machine.

The input device for an application is often decided after the needs and purposes of the application. For instance, more nontraditional ways of registering user input are through full-body tracking where the application uses depth cameras for registering the user movements and inputs. For solutions where technology is limited, or controllers are unavailable, such as the mobile VR platform, other means of registering inputs are necessary. Here it is common to use head tracking input, meaning that the user controls the application only by looking at interactable objects in the application. The solution is often a reticle or pointer in the middle of the screen that is trigger by a button press (if available) or timer. In more advanced HMDs, seen in figure 2.7, eye tracking is possible. It allows for registering where the user is focusing, unlocking a new level of interaction.

Figure 2.8: HTC Vive Controller

HTC Vive

The HTC Vive is an HMD developed by HTC and the Valve Corporation. It was released in 2016 and is one of the most popular VR solutions, much because of the large number of supported games. The headset has a refresh rate of 90Hz and a 110-degree field of view. There are two OLED displays, one for each eye, with a resolution of 1080x1200 pixels each. The headset uses two base stations known as the *Lighthouse*, emitting timed infrared pulses at 60 pulses per second which are then picked up by the headset and the controllers resulting in sub-millimetre precision [53]. It gives the user an approximately 5x5 meter radius to move freely.

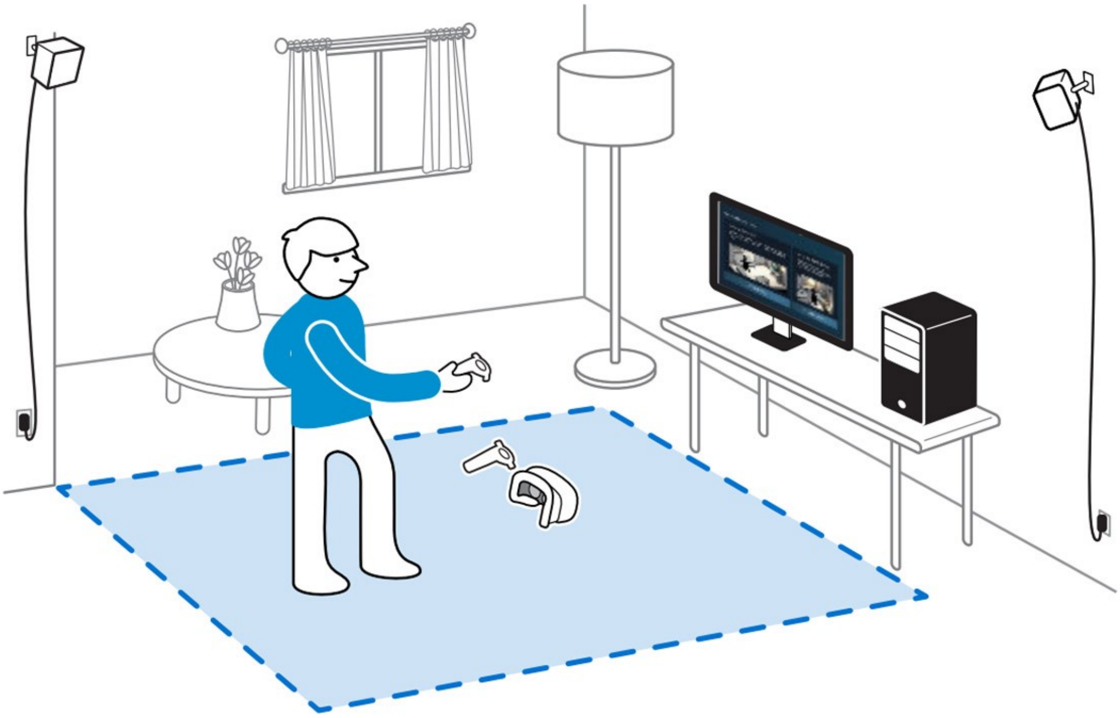


Figure 2.9: Example of HTC Vive Room Setup. From [9]

2.3 Software

2.3.1 Unity 3D

Unity is a cross-platform game engine with support for 27 platforms [54], developed by Unity Technologies for creating both 2D and 3D applications. The game engine is supported on macOS and Windows and has limited support for Linux. Nowadays Unity uses only C# for scripting, but earlier it had support for JavaScript and Boo. C# is an object-oriented programming language developed by Microsoft [55]. Unity uses the Mono platform for development. Mono is based on the .NET Framework, is open source and allows developers to build cross-platform applications. Unity has excellent documentation and a large user group [56], which makes developing and troubleshooting much easier.

2.3.2 Microsoft Visual Studio

Microsoft Visual Studio is an integrated development environment (IDE) from Microsoft. Visual Studio supports eight different programming language but is primarily used for developing C# applications. The Visual Studio code editor has support for IntelliSense (code completion) in addition to code refactoring. When developing with Unity and Visual Studio, the IDE uses the Mono platform and libraries. Unity's documentation is linked in when developing applications through Visual Studio, making it easy to access.

2.3.3 Autodesk Revit

Autodesk Revit [57] was first released in 1997 by Charles River Software and later acquired by Autodesk in 2002. Revit is a building information modelling software, centred around a BIM-model with the idea that all involved in the project can contribute to the same model. The software allows for editing and manipulating of whole buildings, assemblies or individual 3D shapes. From Revit, the user can export the model or whole scene to a variety of formats for other use cases. For instance, does Revit support exporting to .fbx for use in most software for rendering 3D models.

2.3.4 Autodesk Maya

Maya is a 3D modelling software released in 1998 and later acquired by Autodesk in 2005. Maya has support for Windows, macOS and Linux and is used to design, model, alter and animate 3D models. Maya has become one of the most popular modelling software in the animation industry, also since it been developed side by side with input from animators from Walt Disney to make the most efficient work-flow for animators [58].

2.4 Building LCA Database-tool

The data visualized in the developed application are based on the work of Eirik Resch and Inger Andresen [30]. They published an article during 2018, which tackles the issues concerning the growing body of research on embodied emissions of buildings. The results and methods for such calculations remain inaccessible and incomparable due to the lack of reported information and the variety of existing systems, methods and data used. The paper presents a tool for comparison of results across digital systems, which enables a higher degree of transparency and reproducibility of assessments. Thus it makes utilization of the results in statistical applications possible.

In their paper, the Resch and Andresen argue that the relative share of life-cycle emissions, in new or refurbished buildings, gets shifted from operational emissions towards the production and transportation of building materials and other emissions related to the construction, maintenance and end-of-life processes. In order to compare life cycle assessments with different system boundaries, Resch and Andresen state that the results need to be stored with the highest available resolution for all building parts and materials, including life cycle stages.

The building LCA database-tool (bLCAd-tool) is a relational MySql database, which stores results from existing, in addition to having the ability to calculate new, process-based LCAs of buildings. The entity relationship diagram for the database may be found in Appendix H. The tool consists of three main components:

A *building* component which stores the attributional data regarding the building and study. It contains information specific to the building; typology, construction type, location, energy ambition level and floor area, to name a few. It also contains information regarding the study, which includes calculation method, primary data source, study type, year of assessment, study lifetime period, built status and yearly GHG emissions results.

The *material* component is independent of the buildings and store information about the materials and products which make up the buildings. This background data is typically gathered from LCA databases such as Ecoinvent [59], or Environmental Product Declarations (EPDs).

The *results and inventory* component contains modules for string, calculating and aggregating LCA results for the building. Each building has a global warming potential (GWP) results from an LCA connected to it, and the results are stored in a hierarchical building elements tree-structure. The structure follows the hierarchical structure given in the Norwegian standard NS3451 Table of building elements [10]. It is shown in figure 2.10.

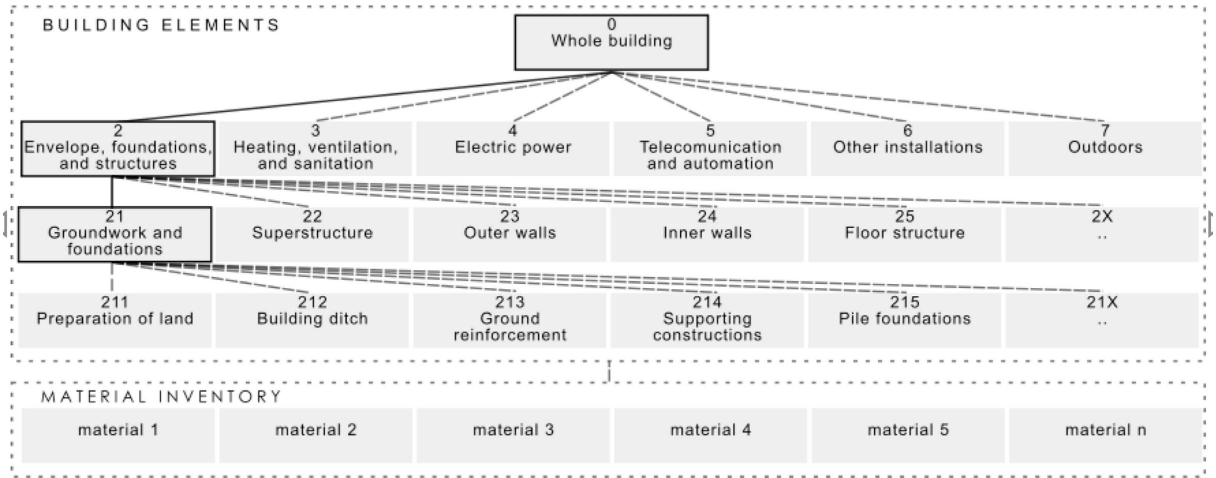


Figure 2.10: The hierarchical structure of building elements. From [10]

The embodied carbon calculation is done in two parts: First, the material quantities are included in the material inventory, and the embodied emissions are calculated using emission factors for each material. Secondly, an aggregation of the inventory emissions is carried on through the hierarchy of the building parts. These are organized according to the European standard EN 15978 [60] for life cycle assessment. The database tool focuses on the modules that are most often observed in building LCAs, namely A1-A3 (material production), A4(transportation to the building site), and B4 (material replacements throughout study lifetime period). The LCA method builds upon that created in the ZEB-tool, created by Houlihan Wiberg et al., during the period 2010-2015. A user guide describing further development is included in [61].

The data collected in their study, and subsequently used in the ZENVR-application, are gathered from 11 studies from various sources. Five of these studies are from the Research Centre on Zero Emission Buildings [62], the predecessor to Zero Emission Neighbourhoods [18]. The remaining six are gathered from two different Norwegian consulting firms.

Chapter summary

In this chapter, the research organization behind this project; The Research Center on Zero Emission Neighbourhood has been presented. ZEN has created a set of Key Performance Indicators which are quantifiable performance measurements which define sets of values based on measured data from a ZEN project, making it possible to track a neighbourhoods performance over time. ZEN currently has nine pilot projects which are limited areas in Norway where new solutions for the construction, operation, and use of buildings are tested to cut the total greenhouse gas emissions to zero in a neighbourhood. The pilot project on which this thesis revolves around is the Sluppen area with a focus on the Nidarvoll school.

Extended reality is an umbrella term covering most technologies of creating a real-to-virtual combined environment. This chapter presents two XR technologies; Augmented reality and virtual reality . The main differences between AR and VR are that AR supplements reality, while VR completely replaces it [37]. A prevalent VR solution is the HTC Vive. The Vive is a high-quality head mounted display offering full tracking of the user and is the HMD used for this project. The data source for the VR application is a MySQL database created by Eirik Resch and Inger Andersen [30] at NTNU.

Chapter 3

Related Work

This chapter presents the theory and relevant work for this project. It starts by introducing concepts for visualizing numerical data and presents a selection of articles where building model data are visualized and how this was achieved. When designing user-friendly applications, it is crucial to have a user-centred design. Therefore this chapter includes theory about user interfaces and usability. Since this project will be used for communicating data and teaching its users about emission data and other variables, research on virtual reality in learning environments are included. Lastly, a selection of projects which have inspired the development, and are similar to the developed application, will be included.

3.1 Data Visualization in Virtual Reality

With the emergence of new technologies like VR, disciplines like interaction design, human-computer interaction, user experience and user interface-design have an increasingly more significant focus on useful data visualization[63]. It is in many ways, the bridge between quantitative content and transitioning it into becoming knowledge and understanding. At the same time, there are limitations to how much information the human eye can process when reading text from a screen. By immersing the user in a virtual environment, enabling them with a 360-degree field of vision, movement in 3D-space and interaction with data, it should be possible to increase the available bandwidth of the human brain[63]. This section presents related research on both the visualization of numerical data and building information models in VR.

3.1.1 Numerical Data

> *"It's easy for eyes to start glazing over when looking at a bunch of numbers, it is very different when you bring the data to life ... Essentially you are putting a real face to your data. It is much harder to ignore your metrics when someone has a deeper level of understanding, or even emotional attachment to the data."*
>
> \- *Tullis, T. & Albert, W.* [64]

Donalek et al. in their paper *Immersive and Collaborative Data Visualization Using Virtual Reality Platforms* [65], researched the use of visualization methods in VR in order to comprehend data. They argue that one cannot really understand or intuitively comprehend anything that one cannot visualize in some way. They further state that one of the key methodological challenges of the 21st century may be the ability to perform effective and flexible visual exploration of data. VR has been shown to lead to a higher degree of discovery in domains where the original dimensions are spatial. It is demonstrated that immersion helps scientists more effectively investigate a wide selection of fields [66][67][68][69][70]. When it comes to the exploration of large data-sets, many researchers tend to look to visualization for support. Donalek et al. concluded in their study that effective data visualization remains a bottleneck on the path between data and discovery. Furthermore, by utilizing immersive technologies, scientists may be equipped with visual data exploration capabilities at easy access and low cost.

In this particular project, metaphors and semiotics have been used in order to achieve an exploratory and visual representation of emission data. The essence of metaphors is described as *"... understanding and experiencing one kind of thing in terms of another"* [71]. The motivation for this is that users may transfer existing knowledge to the application domain in order to ease the transition to an unfamiliar software [72].

3.1.2 Visualizing Building Information Models

This thesis revolves around visualizing numerical data on building models, and this section presents articles regarding the use of building information models in virtual reality. The papers presented in this section explores solutions for exporting building models (BIM) to a format readable for virtual reality applications. They also address interaction with these models in a virtual environment.

Low-cost virtual reality environment for engineering and construction

Low-cost virtual reality environment for engineering and construction, written by Thomas Hilfert and Markus König in 2016 [11], presents a *"way to build a low-cost, highly immersive virtual reality environment for engineering and construction applications"*. Hilfert and König utilize the Oculus Rift Development Kit 2 HMD [49] paired with a Leap Motion hand-tracking device [73], see figure 3.1, for natural interactions within a virtual space. To stitch everything together, they use the game engine Unreal Engine 4 [74].

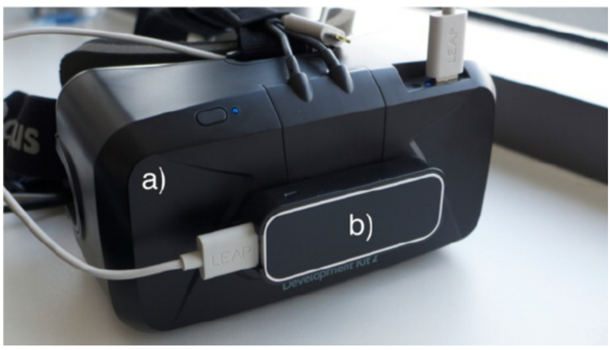


Figure 3.1: Oculus Rift DK 2 with a Leap Motion controller mounted. From [11]

Their goal was to view and interact with

BIM-models to create a proof of concept for streamlining models into Unreal Engine 4. They used BIMServer [75] for hosting the models and a plugin [76] for exporting these to a readable format in Unreal. They conclude that HMDs are getting more useful for a wide range of applications in construction and engineering while costing less than in the past. They also show the feasibility of automating significant parts in the VR creation process from BIM as a starting point.

Extending Building Information Models into Game Engines

Written by Ross Bielle, Shamus P. Smith, Kim Maund and Graham Brewer, *Extending Building Information models into Game Engines* [12] is a paper which explores a pipeline for using building information modelling with game engines. The paper focuses on exporting BIM-models from Autodesk Revit [57] to the game engine Unity 3D [29]. Their motivation is the possibility for collaboration with BIM-models to simultaneously co-generate this information in a virtual environment. They explore the process of moving from an accurate building model to an interactive virtual environment.

Autodesk Revit has *out of the box* export functionality to the .fbx-format, which Unity prefers for its' 3D models. However, Bielle et al. realized that by exporting directly from Revit, the model loses some information, primarily in the form of 3D-materials. Thus it results in a 3D model which has all the geometry but is missing the colours and textures. The paper suggests a pipeline that uses Autodesk 3DS Max [77] as an intermediary between Revit and Unity for the inclusion of materials to solve this issue. This pipeline is also supported by Ben Dalton and Maxwell Parfitt the year before, in their paper *Immersive Visualization of Building Information Models* [25]. They explore different ways of exporting building models for usage with CAVE [78], a system from 1992, but the pipeline from Revit is the same.

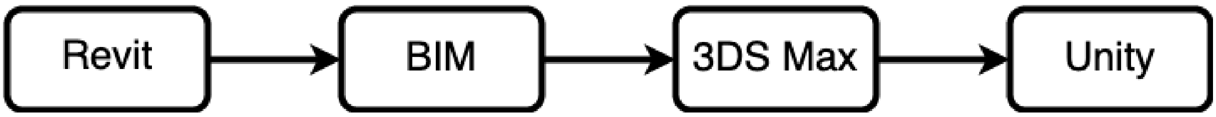


Figure 3.2: Suggested pipeline for exporting BIM models from Revit. From [12]

3.2 User Interface Design in Virtual Reality

When developing a user interface for VR the rules somewhat changes from traditional GUI-design, since a single screen viewed in 2D is replaced with a 360°screen presented in 3D. When researching GUI-design for VR, this thesis' primary source has been the work of M. Alger [79]. In one of his proceedings; *Visual Design Methods for Virtual Reality*[13] he states that an important concern is the field of view and work-zones. As one may observe from figure 3.3, the *main content zone* is the field in front of the user and is where one want to put information which will be presented. Furthermore, when using the hands as a form of interaction, the general user tends to explore the area nearby for ways to interact with a menu or equivalent. It is based on the work of Alex Chu who, in a presentation at Samsung[80], presented a study regarding the comfortable and maximum head rotation when using a test application.

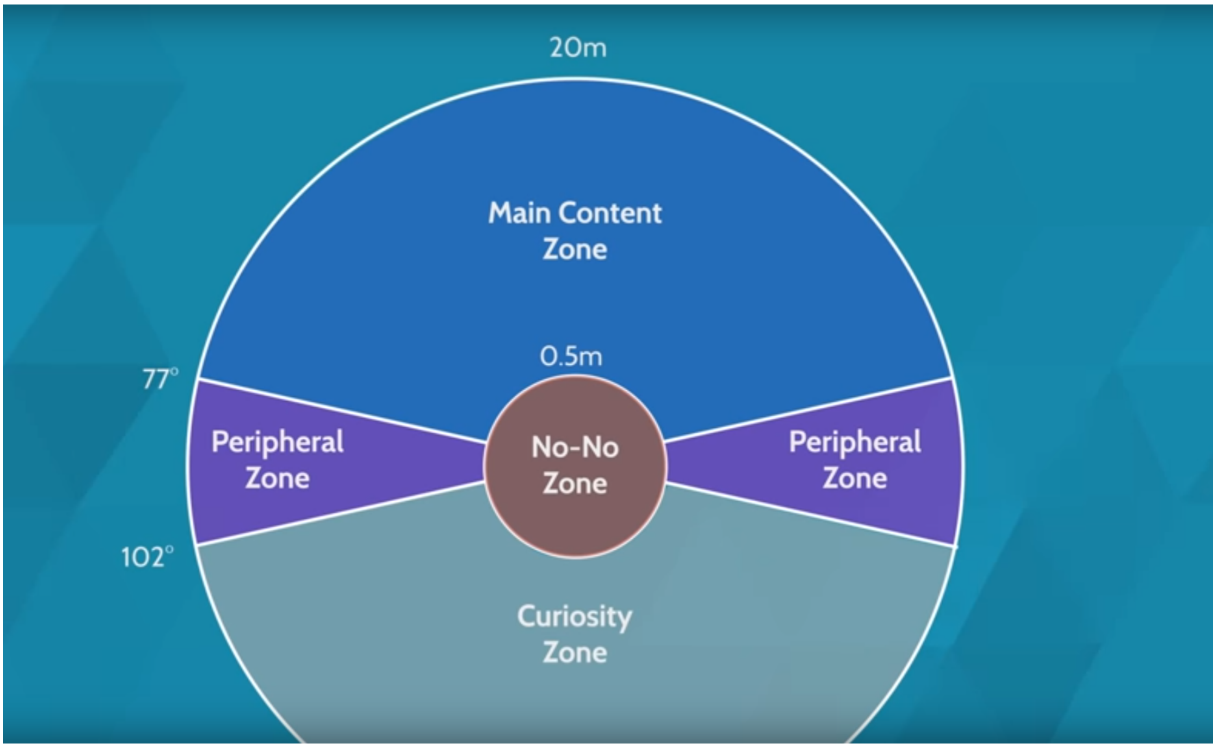


Figure 3.3: Field of View Work zones. From [13]

However, Sutcliffe and Gault[4] argue that when designing user interfaces for virtual environments, the purpose of the interface is not limited to the user reaching the goal. Equally important is equipping the user with the tools that they can work intuitively. Norman[1] has presented in his book *The Design of Everyday Things* a set of design principles in order to design an intuitive user interface. These are presented in table 3.1 and how these principles are addressed and followed in regards to the development of the application can be read more about in chapter 6.

Principle	**Description**
Affordances	Affordances define which actions are possible and how something can be interacted with by the user. Good interaction design focuses on creating the right affordances in order to make the desired actions doable with the technology used.
Signifiers	A signifier is a perceivable indicator which communicates the purpose, structure, operation and behaviour of an affordance. A good signifier informs the user what is possible before interacting with said object.
Constraints	Constraints are the limitation of actions and behaviours of the user. With the proper use of constraints, the interaction with the software may be simplified, and the accuracy, precision and user efficiency may be improved.

Feedback	User feedback communicates the results of an action, which helps to aid the understanding of the state of the object that is interacted with.
Mappings	Mapping is the relationship between two or more objects. The relationship between a control and the result of an action is most natural to learn when there is a distinct and understandable mapping between the controls, the action and the result.

Table 3.1: Normans design principles. From [1]

3.3 Designing for Usability

Rubio-Tamayo et al. [14] concludes in their study *Digital Data Visualization with Interactive and Virtual Reality Tools. Review of Current State of the Art and Proposal of a Model* that "*In the entire process of data adaption, the concept of usability must be prioritized...*". Normans' guidelines are used to produce a result which aims to satisfy the definition of usability. Generally, usability is described as the ease-of-use or user-friendliness of a system. The formal ISO 9241[81] definition of usability is as follows:

"The extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use."

Whitney Quesenbery [82] has criticized this approach for being too focused on well-defined tasks and goals. It has also received criticism for being too focused on efficiency as the most crucial attribute. Quesenbery thinks that this is not a universal truth for all IS-projects. She also highlights the use of the term *satisfactory* used in the definition. Quesenbery says that while this term may work in an enterprise and work-related context, it does not cover the view of the consumer. As a result of this, Quesenbery have proposed the 5Es to define the word usability further. These principles are based mainly on Jakob Nielsen approach given in *Iterative User Interface Design* [83]. Quesenberys 5Es are as follows:

- Effective - The completeness and accuracy with which users achieve their goals.
- Efficient - The speed (with accuracy) with which this work can be done.
- Engaging - How pleasant, satisfying or interesting an interface is to use
- Error Tolerant - How well the product prevents errors and helps the user recover from any that do occur
- Easy to Learn - How well the product supports both initial orientation and deeper learning

What is interesting with her approach is the focus on applying these principles in line with the context of the product and user personas. In a user interface developed in an enterprise-context efficiency and error tolerance might be of greater importance than engaging the user. In a VR-project, however, there are other more important aspects. The different principles need to be weighed up against each other, depending on the nature of the project. These are balanced in figure 3.4.

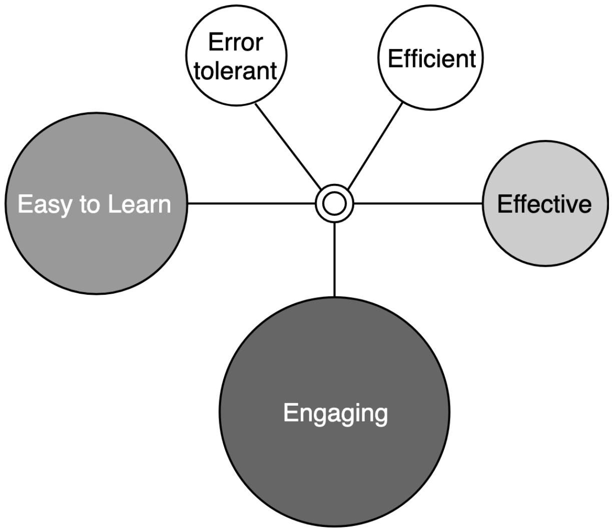


Figure 3.4: Quesenberys 5Es balanced for this project.

As one may observe from figure 3.4, the systems engaging attributes have been given top priority. The choice of technology largely explains the background of this. The main argument for choosing VR as the platform for development is the immersive and engaging attributes. The second priority is the fact that the system must be easy to learn. VR is a type of technology that most people do not necessarily have much experience with, and it was reasoned that in order to fully exploit the immersive experience it offers, the system must be experienced without encumbrances. The third most prioritized principle is that the system would be effective. Since the application first and foremost is meant to be a platform for exploration and visualization, the need for effectiveness must give way to the principles mentioned above. The same applies to the degree of efficiency in the system, as it is not a data processing tool rather than an experience. Error tolerance has neither been prioritized because of the narrow scope of this project. However, in the case of further development and increased complexity of the system, this should be given higher priority.

3.4 Virtual Reality for Learning

Virtual Reality solutions gain popularity due to decreased prices and increased computer processing power, utilizing virtual reality in a learning environment becomes a closer reality than before. In the future, VR equipment might be trivial in the classroom, but today, the benefits of using this technology in a learning aspect are still researched. However, research suggests already that more information from participating in virtual reality exercise are retained rather than traditional learning methods. Researchers at the

University of Maryland conducted one of the first in-depth analyses on whether people learn better through an immersive virtual environment. Their result showed an 8.8% improvement overall in recall accuracy using VR [20]. In addition to recalling information, virtual reality is an excellent medium for building empathy, helping people understand situations and events they otherwise would never encounter [21].

Lee et al. [22] explored in 2010 how virtual reality enhances and influence learning . They hypothesize that VR features have an indirect effect on learning outcomes, which are mediated by the interaction experience and learning experience. Better cognitive benefits such as better memorization, understanding, application and overall view of the lesson learned in the virtual environment were observed, as claimed by the authors. Their results show that motivation was a significant psychological factor, positively related to learning outcomes. It is similar to findings by Youngkyun Baek, Jaeyeob Jung and Bokyeong Kim [23] who found that by using technology in education, teachers experience increased attention, excitement and motivation which resulted in students paying more attention. Lee et al. also discovered that reflective thinking was another important antecedent to learning outcomes.

> *"... VR-based learning environment could engage learners in a deep approach of learning where they could actively search for information from the learning material to resolve their doubts, to understand the lesson and link it to previous knowledge and experiences to construct new knowledge. Through reflective thinking, the learners' mental models to explain their worlds will become more complex and enable them to reason more consistently and productively about the phenomena they are observing."*
>
> \- *Lee et. al.* [22]

It corresponds with findings from Merchant et al. [24]. Through a meta-analysis, it was discovered that the effectiveness of game-based learning in virtual reality was the same whether students were assessed immediately or after some time. It indicates that students learning in VR games have retention level beyond short-term learning.

In a study by J.L. Rubio-Tamayo, M. Barro and H. Gómez [14], the authors explore the role of immersive tools and technologies for educational processes and citizen empowerment. They also provide the reader with a base for generating models which allows one to optimize representation of information, see figure 3.5. Also, they present a conceptual design of a series of scenarios that highlight the interrelation between open data, data mining, information management, data visualization and representation and interactive environment design. The proposed model has followed the lines of, among others, the work of Chi and Riedl [84]. It is based on theories of knowledge management as a way to illustrate different steps of data and knowledge.

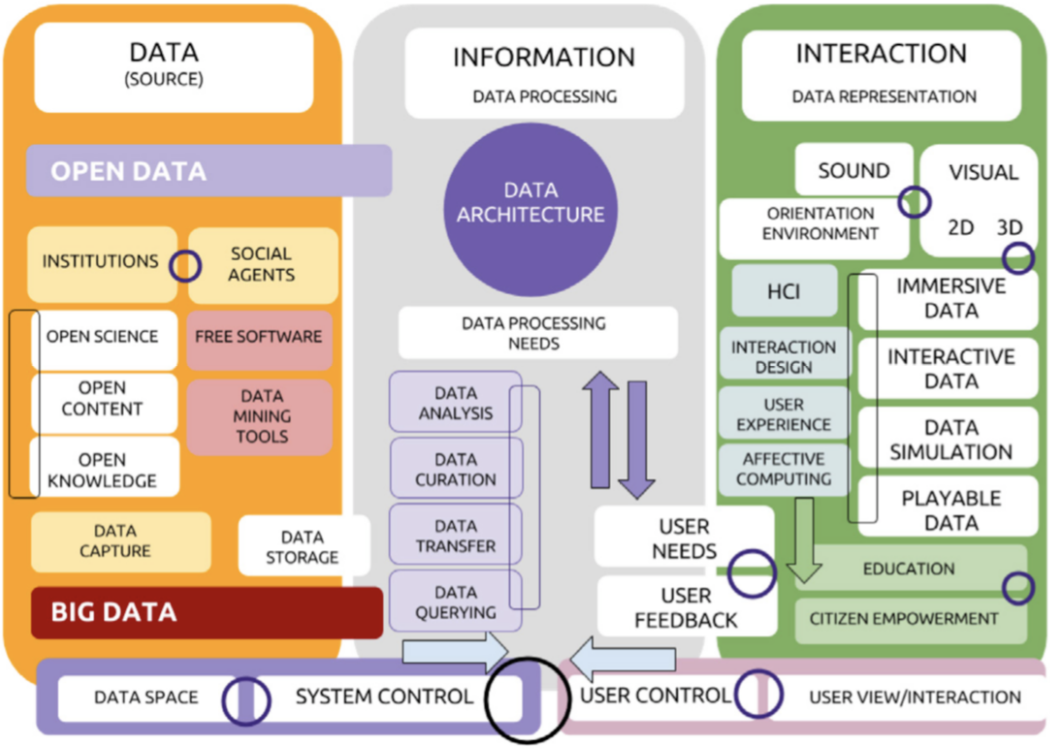


Figure 3.5: Proposed model for optimal representation of information. From [14]

The processes in the model presented in figure 3.5 are explained as follows:

- Data mining/search process - The data is at this stage raw and difficult to interpret.
- Structuring/processing phase - This phase involves sorting the data logically in order for it to be structured, in addition to looking for patterns for optimal data representation.
- Representation/visualization process - This phase seeks to optimize the transmission of information to groups which are not familiar with the subject matter.
- Development of interaction processes - This aspect relates to immersive technologies. Tamayo et al. state that this is an emerging field of research which involves disciplines such as affective computing and human-computer interaction.

The study concludes with, in regards to education, data is just one of the multiple components of educational processes. The proposed models seek to reflect the many ways in which the phases of the process may be applied in educational dynamics. In regards to citizen empowerment, the model design seeks to find new gaps and challenges to foster citizen empowerment due to the accessibility of information through it becoming interactive.

3.5 Projects

This section accounts for projects which have had a significant or direct impact on the development and concept behind this project.

3.5.1 ZEB Tool

The work in ZEN builds upon the previous work conducted in the ZEN research Centre which ran from 2009 to 2017, and part of the work within ZEB included the development of The ZEB tool [61]. The main use of the ZEB Tool is to assess environmental impacts associated with all the stages of the LCA. This information was then used to improve the process, support policies and to provide a sound basis for informed decisions early and throughout the design process. The greenhouse gas emissions are calculated by multiplying the material quantifies with their respective emissions factors depending on the specified system boundary [61]. The ZEB Tool is a basis for all further research related to the development of visualization of Key Performance Indicators currently being led by Houlihan Wiberg within ZEN [85].

3.5.2 Visual LCA in ZEN

In the master thesis *Visual LCA in ZEN*, Aukland and Slake, under the supervision of Houlihan Wiberg [86], explore a ZEN dashboard for architects and planners that aims to support decision making in the early design of Zero Emission Neighborhoods. The project is a 'proof of concept' dashboard, which considers scaling up from building scale to a neighbourhood in terms of material use and material associated GHG. Aukland and Slake created a dashboard tool which takes data from the ZEB Tool and the material inventory from the ZEB Living Lab project [87]. The data is used to create various neighbourhood configurations by utilizing Rhinoceros 3D, and Grasshopper linked together via a Flux server and controlled by a Flux dashboard [86].

This dashboard approach gives the user a visual representation of the neighbourhood and calculated emissions as a consequence of the configuration. However, the application functionality is minimal and only accounts for adding or removing rows or stories for a two-building complex. What the dashboard excels at is giving the user a visual representation of GHG emissions related to transport and materials used in the buildings, and showing this data on a map or in a graph for the user [86].

3.5.3 CityBES

CityBES [15] is a web-based platform created by Cheng And Hong at The Lawrence Berkeley National Laboratory LBNL, University of California. It is used for analyzing and visualizing the energy performance of a district, from a small cluster of buildings to all buildings a city. It gives stakeholders insight into where and how to implement new energy technologies and retrofit strategies. The visualization is done by colour coding scheme to the 3D city model, including data for site energy use intensity, source energy use intensity, energy star score and benchmark status. The interactive interface allows detailed visualization of information on the building stock, such as an address, type, year built, number of floors, total floor area and baseline situation for different years. This information can be filtered and visualized on a dashboard to make it better for evaluation [85]. CityBES uses CityGML 3D-models layered together with data from the simulation software EnergyPlus [88].

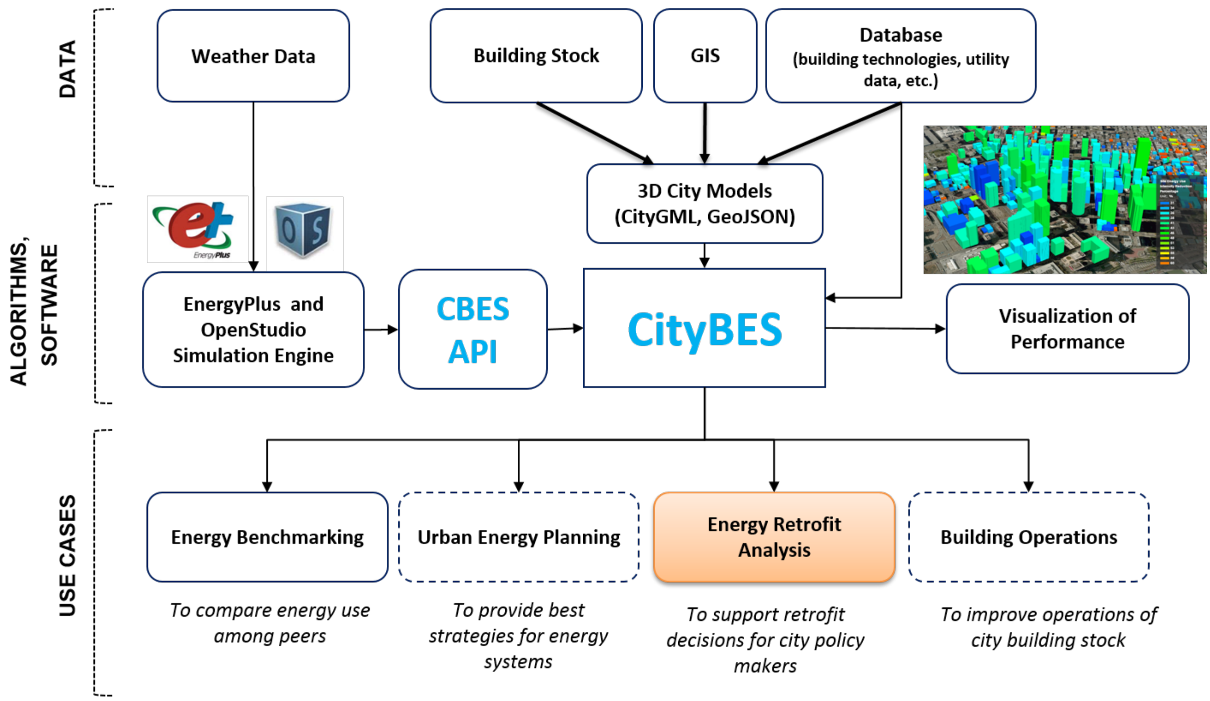


Figure 3.6: Software Architecture of CityBES. From [15]

The colour visualization of CityBES is an excellent way of quickly identifying buildings that stand out from the norm. This type of visualization has inspired the method used in ZENVR and allows users with little to no foreknowledge to put values into context and compare them with others. The addition of the embodied carbon parameter in the LBNL tool included in 2018 through a collaboration between Houlihan Wiberg, Chen and Hong at LBNL[89].

3.5.4 Projects at Fraunhofer Singapore

Fraunhofer at the Nanyang Technological University in Singapore is a research centre focusing on interactive digital media innovations, working closely with industry [28]. They have developed two different systems applicable to VR, where building interaction and planning is the main aspect. The first one is a planning tool made to assist the building and construction industry in Singapore. The UI of the VR-application consists of three different interaction modes targeted for different stakeholders, which are intended to support the decision-making several steps in the process.

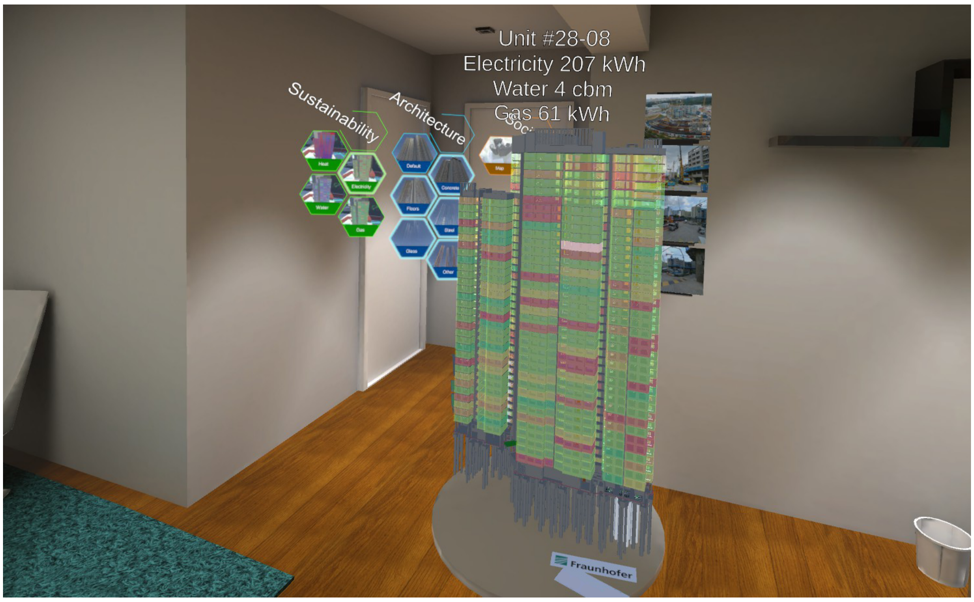


Figure 3.7: Fraunhofer Emission Demo

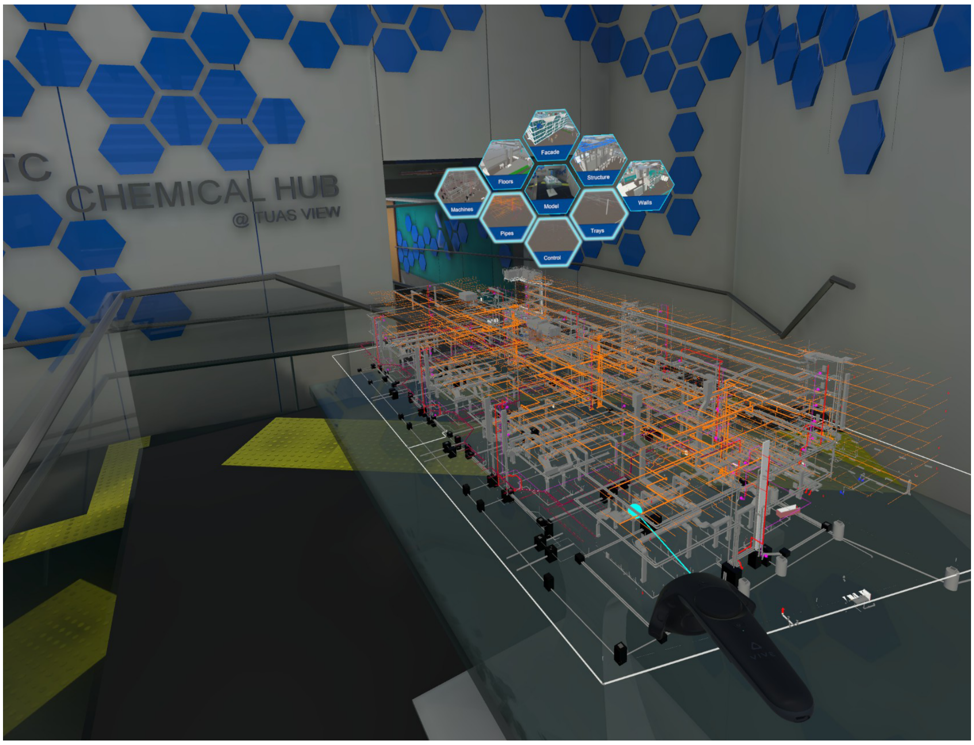


Figure 3.8: Fraunhofer Chemical Plant Demo

The initial concept was focused on the building and construction industry to find errors in their BIM models and give them the ability to explore them in an immersive way. The user can visualize different categories of objects or choose the visualization based on materials to be able to focus on the relevant parts, see figure 3.7. Further interest from different stakeholders leads to the development of a data overlay with the focus on sustainability where electricity, water, gas data and a heat-map can be displayed over the building. For the potential buyer, the model is located in an actual apartment in the building which is rendered realistic and shows the potential of replacing show-flats with the actual apartments at any position in the building including correct outside view, surrounding, sun path and precise layout. A map mode gives users the ability to see the building in its broader context.

The other software developed is a model of a chemical plant, see figure 3.8, where the user can toggle on and off different parts of the building model in order to acquire the relevant information. It resembles the data-presentation view from the first application, but the parameters are different. Here the user can toggle between showing pipes, machinery, walls, building structure et cetera. Both applications enable the user to point at any part of the small model-sized building to teleport to this location. The user is then at the chosen position in a 1 to 1 scale and experiences the building as if it was real. At this point, the user can freely move around by pointing and teleporting or switching back to the model-sized view. This simple movement concept enables rapid exploration of any model with the advantage of being always aware of their relative position.

3.5.5 VirtuaView

In 2018 the Norwegian companies Veidekke [90] and Statsbygg [91] collaborated with the company Dimension 10 [92] to create a Virtual Reality collaboration tool for inspecting BIM-model [26]. The application made by Dimension 10 is called *VirtuaView*. The collaboration tool allows for online collaboration by connecting multiple users to a "virtual meeting room" where they can import BIM-models to inspect together.

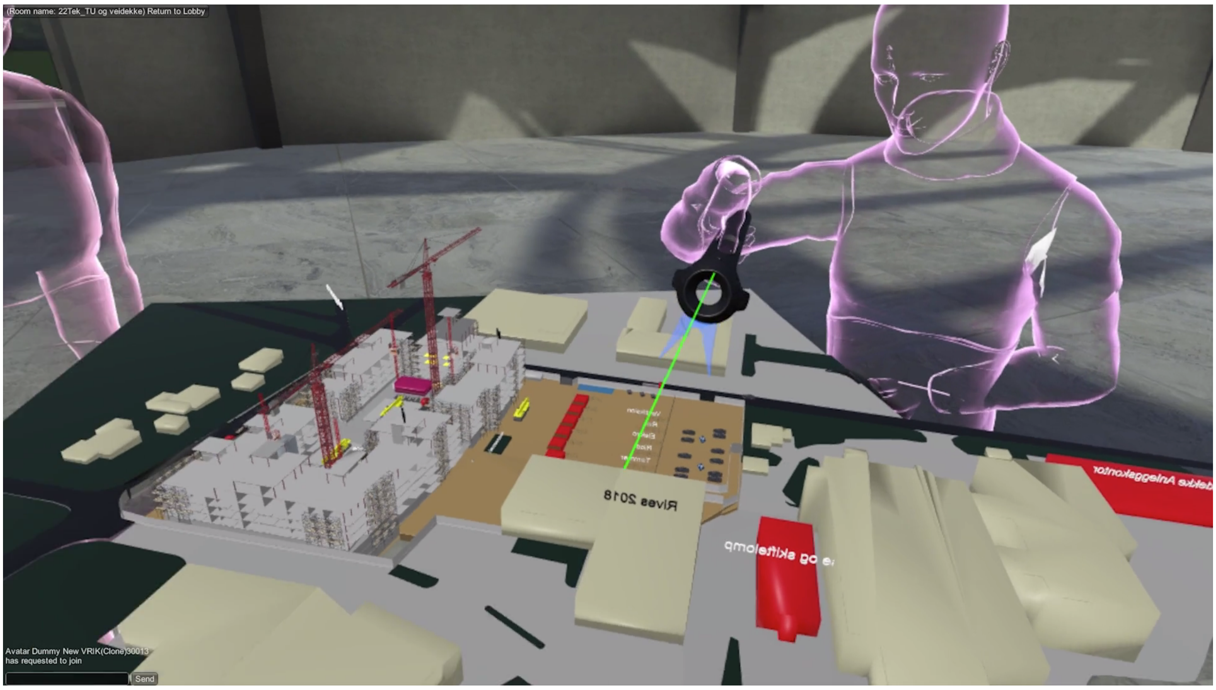


Figure 3.9: VR Collaboration tool by Dimension 10

The users have access to tools for movement and scaling in order to alter the model. It is also possible to view the model in a 1:1 scale, meaning that the users can walk and teleport around the model. The application allows for less travelling and makes meetings location independent. They state that the programme supports well-known BIM-formats such as .obj, .fbx and .ifc. This application achieves a lot of the same things as ZENVR but is solely focusing on inspecting and discussing the model.

3.5.6 Other Relevant Research

This section presents research relevant to this project, but not prioritized due to the difference in scope. However, it might be relevant when further developing the application.

The article *Exploring Urban Data Visualization and Public Participation in Planning* by Hammersam et al. [93] discusses how visualizing data from the Planning and Building Permit Archive may extend the available repertoire for the public. The article highlights the fact that only pinhole access by the public is enabled. It states that the archives, in its current form, denies the public distribution of information in planning and urban development beyond individual building and planning cases. This article was not included as it is limited to looking at how data may be generally visualized for the public.

The article *A critical review of virtual and augmented reality (VR/AR) applications in construction safety* by Li et al. [94] presents a state of the art research of VR and AR. Li et al. develops and research several VR/AR prototypes in order to identify which technologies may be used to improve the current situation of potential hazards that may occur at a construction site. They have an extensive in-depth study of the technology, but the utilization of said technology differs from ZENVR.

Virtual reality-based cloud BIM platform for integrated AEC projects by Goulding et al. [95] displays a game environment supported by a web-based virtual reality cloud platform for integrated architectural, engineering and construction projects. They claim their research is a stepping-stone for developing relationship models in collaborative environments. This article is from 2013 and was not included because the work by Dimension10 [92] appeared to have the same scope.

Abbas et al.[96] presents in their article *A Platform Agnostic Solution for Inter-Communication between Virtual Reality Devices* a VR application prototype for multiple online users that is hardware agnostic. The concept is to connect users regardless of the virtual reality system they are using. To achieve this, they utilize a library called VRTK for Unity. This article was not included in this research because it focuses on multiple users where ZENVR is, at the time of writing this paper, only operated by a single user.

Chapter Summary

By immersing the user in a virtual environment, enabling them with a 360-degree field of vision, movement in 3D-space and interaction with data, it should be possible to increase the available bandwidth of the human brain [63]. Donalek et al. [65] argues that VR leads to a higher degree of discovery in domains where the original dimensions are spatial. It is demonstrated that immersion helps scientists more effectively investigate a wide selection of fields [66][67][68][69][70].

Typical for the previous research looked at is using Autodesk Revit [57] for creating a building model, export this model to the .fbx-format, alter it in a third party application before importing it into the software used for creating a VR application.

When designing a VR application it is essential to focus on where information is displayed and use scenarios from the real world which the user is familiar with, e.g. put information in front of the user like one would on a regular table. In a VR-application, usability principles need to be weighed up against each other, depending on the nature of the project. How this project is balanced can be seen in figure 7.3.

Research suggests that users retain more information from participating in virtual reality exercise rather than traditional learning methods. Research from the University of Maryland [20] showed an 8.8% increase in information recall in virtual reality, compared to traditional learning methods.

The main inspiration for this project comes from the institution Fraunhofer in Singapore, where they use BIM-models in VR and layered information on top of these models. Other solutions which influenced development were the ZEN projects *Visual LCA in ZEN* and the *ZEBTool*.

Chapter 4

Research Method

Design science research [27] are used as the framework for researching while being evaluated through semi-structured expert interviews. The principles of grounded theory have partially been applied, and its use is limited to the analysis and processing of the data obtained. Design science is a well-established research paradigm [27] in disciplines involving the creation and evaluation of artefacts. Semi-structured interviews enable the combination of open-ended and more specific questions and are suitable when researching the applicability of newly established technologies. This approach has been supplemented by user testing and a questionnaire, with the purpose to provide further insight into the usability and design choices of the developed application. Grounded theory [31] are another well established theoretical framework [3], which enables its users with the tools for analysing and categorising data obtained through qualitative methods. This chapter presents the theories that are the foundation for the research conducted. How these are applied will be presented in chapter 5.

4.1 Design Science Research

Design science is first and foremost a problem-solving paradigm. It seeks to widen the boundaries of human and organisational capabilities through the creation of new and innovative artefacts, which were conceptualised by Herbert Simon [97]. Design science research combines a focus on the IT artefact with a high priority on relevance in the application domain [27].

Design science research can be viewed as a process consisting of three cycles, as presented by Alan Hevner in [2]: The relevance cycle, rigor cycle and design cycle.

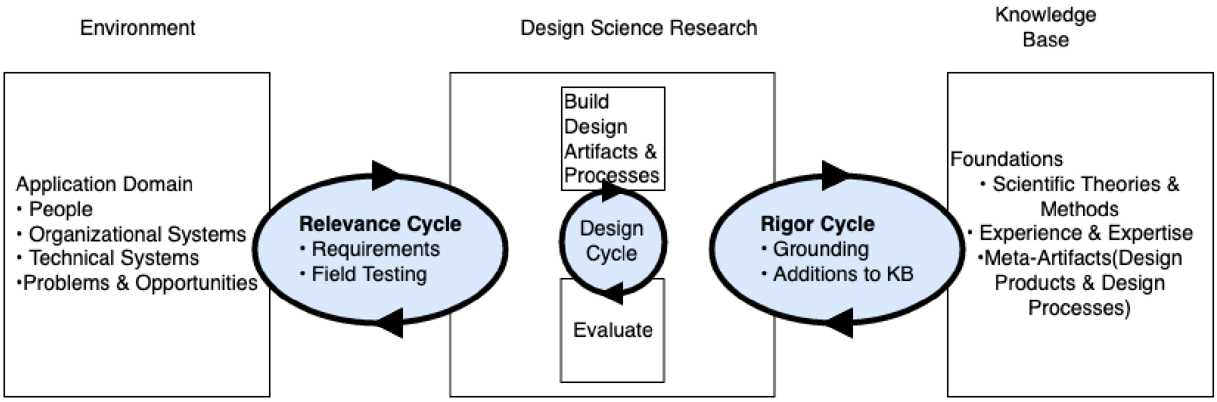


Figure 4.1: Alan Hevners three cycle view. From [2]

One of the pillars of DSR is the desire to improve existing processes and environments with the introduction of new and innovative artefacts. The application domain of the artefact consists of an existing framework of people, technical and organisational systems in which the artefact is to function and contribute. Hevner states that *“"Good design science research often begins by identifying and representing opportunities and problems in an actual application environment".”*

The relevance cycle aims to initiate the design science research with an application context. It provides both requirements of the problem to be solved and acceptance criteria for the final evaluation of the results. Important questions in this cycle are, for example "Does the design artefact improve the environment and how can this improvement be measured?". The result of a design science project must be returned and tested in the real-life environment in order to evaluate it. The results of these tests determine whether there are needed several iterations to achieve the desired solution.

When using design science, one uses a vast knowledge base consisting of scientific theories, engineering methods, state of the art and existing artefacts in the application domain. The aim of the rigor-cycle is to ensure that past knowledge is passed to the research project in order to ensure innovation. Thus it hopefully will lead to an addition to the existing knowledge base in the application domain, consisting of additions to the original theories and methods made during the research.

The design cycle is considered the heart of any design science research project and iterates rapidly between construction, evaluation and feedback of the artefact. Herbert Simon describes the nature of the design cycle as creating design alternatives and evaluating the alternatives to the requirements until one reaches an acceptable design. Hevner highlights the importance of balancing the effort spent in constructing and evaluating the evolving design artefact. These activities must be based on both the relevance- and rigor-cycle.

4.1.1 Hevners Seven Guidelines

This research has followed the seven guidelines for design science research, as presented by Hevner et al. [27], in order to ensure that it is conducted and evaluated soundly. The guidelines are summarized in table 4.1.

Guideline	**Description**	**Execution**
Guideline 1: Design as an Artifact	Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation.	In this project the artifact is the ZENVR tool.
Guideline 2: Problem Relevance	The objective of design-science research is to develop technology-based solutions to important and relevant business problems.	The motivation section of the introduction in this report elaborates the need for visualising data in environmental and architectural planning.
Guideline 3: Design Evaluation	The utility, quality, and efficacy of a design artefact must be rigorously demonstrated via well-executed evaluation methods	The developed software has undergone continuous user testing during development. Chapter 5 elaborates on how the feedback have shaped the end product.
Guideline 4: Research Contributions	Effective design-science research must provide clear and verifiable contributions in the areas of the design artefact, design foundations, and/or design methodologies.	The application and its evaluation are the contribution of this project.
Guideline 5: Research Rigor	Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artefact.	In section 4.4, the method for developing and evaluating the user interface of the designed software is presented. The user interface has been developed with the principles of usability design in mind.
Guideline 6: Design as a Search Process	The search for an effective artefact requires utilising available means to reach desired ends while satisfying laws in the problem environment.	The research of this topic and the development of the software are the result of a constant search of existing research in the problem domain. The design decisions are based on this retrieval of information.
Guideline 7: Communication of Research	Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.	The results of this project are communicated through this report and a conference proceeding [19].

Table 4.1: Alan Hevner's seven guidelines and its applicability to this project. From [2]

4.2 Grounded Theory

When collecting, analysing and working with the data, grounded theory has been used as the theoretical foundation. That being said, grounded theory has only been applied in the evaluation phase of this project, a period of approximately three months. The fact that true grounded theory studies may be very time consuming, the principles have been applied, but not to the letter. Supplied with the fact that this mainly is a design science research project, grounded theory have mainly been applied in the coding of the data and generation of categories.

Glaser and Strauss originally described grounded theory in the book *The Discovery of Grounded Theory* [98], where the goal is to generate theory applicable to the particular study instead of testing and validating existing theories. Over the years, several different varieties of grounded theory have emerged. This thesis has used the "straussian" approach to grounded theory, as described by Strauss and Corbin [31]. This approach differs from the "glaserian" or "classic" grounded theory, as described by Stol et al. [3]. A selection of key points to the straussian approach are summarized in table 4.2, but are presented in its entirety in [3]. It was decided that the straussian approach was the most fitting for this particular research project, mainly because of the strategy for coding the data.

Research questions	RQ is often broad and open-ended
Litterature	The litterature may be consulted throughout the process
Coding	A three step approach: Open coding, axial coding and selective coding
Questions when analysing	Whom, when, where, how, what consequences

Table 4.2: Straussian approach to Grounded Theory. From [3]

Strauss and Corbin have defined the grounded theory approach in the following way:

> *"The grounded theory approach is a qualitative research method that uses a systematic set of procedures to develop and inductively derive grounded theory about a phenomenon" [31]*

where the purpose is building theory that illuminates the area which is studied. A grounded theory is one that is discovered, developed and verified through systematic collection and analysis of data in a specific field of study. One can, therefore, argue that data collection, data analysis and theory are in a mutually dependent relationship with each other.

There exist two primary strategies when developing grounded theory [98], one of which is the constant comparative method. It is explained as a method in which the researcher codes and analyses data in order to develop concepts. These concepts are refined, and both its properties and relationships are explored. Figure 4.2 pictures this.

In order to obtain the concepts, Strauss proposes a three-step coding process.

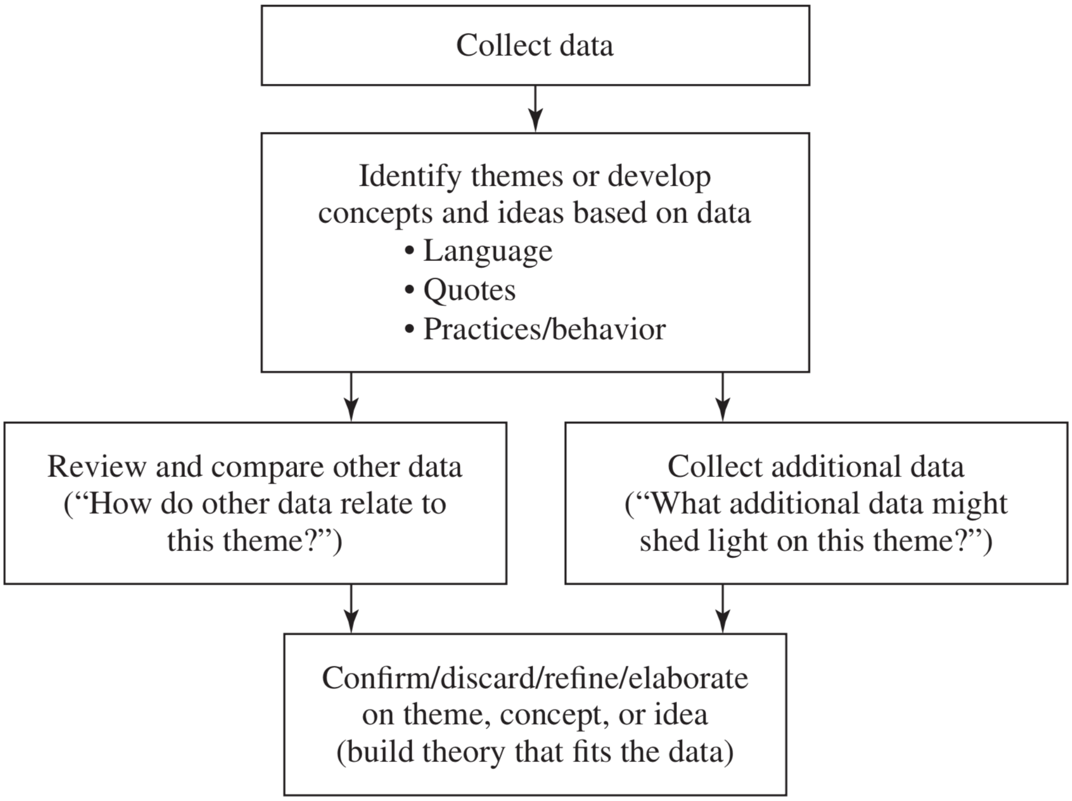


Figure 4.2: Constant comparison method. From [16]

- Open coding:
  The first step of coding is discovering categories by examining the data, line-by-line and paragraph-by-paragraph. As Strauss and Corbin [31] states: *"It is like beginning to work on a puzzle, and the first step is to get organised."*

- Axial coding:
  When the categories are determined, one begins to put the pieces together. By examining the data after the first iteration, one can put the data where it belongs to the relationship between categories.

- Selective coding:
  The final step is to determine a central category that all major categories can link to and the filling in of categories that need further development.

4.3 Interviews

When conducting quantitative data collection, Taylor et al. [16] state that it is necessary to determine a set of basic paths as to how one wishes to conduct a study. The general methodology used when conducting this study have been semi-structured expert interviews. There exist several kinds of interview types which span from structured to unstructured interviews. Structured interviews are described as a more rigid type of interview with a set of predefined questions — unstructured interviews the opposite. The interviewee is the source of both the questions and answers. By using semi-structured interviews, Seaman[99] state that one gets the chance to ask the informant specific questions, but it also allows for unexpected turns.

An expert is in this research defined as an interviewee with relevant education or profession in the field of interest. There were three participants in each of the interviews; The informant and the two authors of this paper. It allowed for one leading the interview and the other taking notes on essential parts of the interview. However, the main collection of data were audio recordings that later were transcribed. To make sure this project was in compliance with GDPR [100], the study has been registered with the Norwegian centre for research data. The interviews were guided by the use of an interview guide, which Taylor et al. [16] states should serve as a list of general areas which are to be covered. It may be found in Appendix E.

The strategy for obtaining informants used was primarily the snowball technique[16], which involves getting to know some informants and having them introduce you to others. The potential drawback of this technique is that the diversity of informants may be limited. However, it was decided that by identifying the key roles which are relevant for the use of the application and talking with informants in these roles, the diversity were adequate. Glaser and Strauss[98] state that the number of studies is relatively unimportant, and the focus should instead be the potential of each case to aid the researcher. As the researcher constantly compares the results, one reaches the point where new interviews additional people yield no genuinely new insights.

4.4 Designing the Questionnaire

To evaluate the user interface and ascertain the degree of usability when using the system, a questionnaire was designed. The questionnaire was designed after the principles of a Likert scale, developed by Rensis Likert [101]. In order for a questionnaire to fulfil the requirements of a proper Likert-scale, John Uebersax [102] list the following criteria:

1. The scale contains several items.
2. Response levels are arranged horizontally.
3. Response levels are anchored with consecutive integers.
4. Response levels are also anchored with verbal labels which connote more-or-less evenly-spaced gradations.
5. Verbal labels are bivalent and symmetrical about a neutral middle.
6. In Likert's usage, the scale always measures attitude in terms of the level of agreement/disagreement to a target statement.

However, the scales used to measure the usability of the system are not genuine Likert scales, but rather a *discrete visual analogue scale (DVAS)*. The scales in the questionnaire contain a set of numeric labels but are only anchored with verbal labels at the upper and lower bounds. As criteria number four for a true Likert scale states, every level is required to have a verbal label as well as numeric labels. It is something that has been discussed by O'Muircheartaigh et al. [103], who concluded that verbal labelling may be preferable in terms of variance explanation, but it is a general assumption that verbal anchors should be sufficient in terms of identifying the range of the response space.

According to Allen and Seaman [104], there are four general types of data collected from questionnaires:

- **Nominal Data:** Categories without numerical representation.
- **Ordinal Data:** Ordering or ranking of responses, but no measure of distance.
- **Interval Data:** Integer data where ordering and distance measurement are possible.
- **Ratio Data:** Data with meaningful ordering, distance and fractions between variables are possible.

As stated by S. Jamieson in *Likert scales: How to (ab)use them* [105], Likert-scales falls into the category of ordinal data. Because of the nature of ordinal data, it was decided to calculate the mode and median value for finding the central tendency and inter-quartile range(IQR) to find the deviance. There is a consensus among online courses in statistics [106][107][108] that it is meaningless to evaluate the mean value of ordinal data. The reason for this being looked upon as an invalid measure is that it relies on the assumption that the psychological distance between the scoring points are equal, and similar for each of the subjects. In other words, in a 7-point Likert scale, one needs to assume that the distance between "strongly agree" and "agree" is equal to the distance between "somewhat agree" and "no opinion". Thus, it is not included in the presentation of the data. The IQR is an indication of the degree of consensus amongst the respondents. A low IQR indicates consensus, while a larger IQR indicates that the general opinion is polarised.

4.4.1 System Usability Scale

The evaluation of the general usability of the system is based on the work of John Brooke in *SUS: A quick and dirty usability scale*, but differs slightly. The original SUS is a set of ten specific questions which are a 5-point Likert scale. It is generally applied after the respondents have tried the system, but before any discussion of the system takes place. It also includes a system for scoring the usability of the application, but this is not relevant for this particular questionnaire since it is a 7-point DVAS scale. The difference between SUS and the questionnaire in this research are explained in chapter 5.

4.4.2 Heuristics for Evaluating User Interfaces

Nielsen [83] has proposed ten heuristics for good user interface design, but as noted by Kristina Höök and Nils Dahlbäck (cited in [4]), these standard evaluation methods do not entirely cover the fundamental difference between a desktop application and a virtual environment. Nielsens checklist evaluation method has been adapted to VR [109], and there have been posed a set of new heuristics to fit the nature of a VR application better.

These were formulated by Sutcliffe and Gault [4] and are presented in table 4.3. The method follows Nielsens recommendations for expert evaluation, but with some minor differences. The subjects evaluating the application familiarise themselves with the system and establish a baseline of what the system reasonably can be expected to deliver, after which a set of representative tasks are carried out. After the tasks are completed, they list the problems encountered, and the problems are classified after the heuristics.

Heuristic	**Description**
Natural engagement	Interaction should approach the user's expectation of interaction in the real world as far as possible.
Compatibility with the user's task and domain	The VE and behaviour of objects should correspond as closely as possible to the user's expectation of real-world objects; their behaviour; and affordances for task action.
Natural expression of action	The representation of the self/presence in the VE should allow the user to act and explore in a natural manner and not restrict normal physical actions.
Close coordination of action and representation	Response time between user movement and update of the VE display should be less than 200 ms to avoid motion sickness problems.
Realistic feedback	The effect of the user's actions on virtual world objects should be immediately visible and conform to the laws of physics and the user's perceptual expectations.
Faithful viewpoints	The visual representation of the virtual world should map to the user's normal perception, and the viewpoint change by head movement should be rendered without delay.
Navigation and orientation support	The users should always be able to find where they are in the VE and return to known, preset positions.
Clear entry and exit points	The means of entering and exiting from a virtual world should be clearly communicated.
Consistent departures	When design compromises are used they should be consistent and clearly marked, e.g. cross-modal substitution and power actions for navigation.
Support for learning	Active objects should be cued and if necessary explain themselves to promote learning of VEs.
Clear turn-taking	Where system initiative is used it should be clearly signalled and conventions established for turn-taking.
Sense of presence	The user's perception of engagement and being in a 'real' world should be as natural as possible.

Table 4.3: Evaluation heuristics. From [4]

As Sutcliffe and Gault note, an underlying premise of many of the principles is the assumption that the virtual environment's role is to represent the real world as faithfully as possible. If the assumption does not correlate to the project at hand, heuristics of naturalness needs to be interpreted regarding the fit between the user's model of the task and domain, and the virtual world.

Chapter 5

Research Approach

As stated in the previous chapter, the design science research may be viewed as a three cycle approach; The relevance cycle, design cycle and rigor cycle. The following sections describe how the DSR has been applied in the different parts of this particular project through researching the domain, designing and developing the artefact and lastly evaluating the developed artefact in its domain. When evaluating the application, the principles of grounded theory have been used. In figure 5.1 the project progress are visualized. The rectangles indicate what has been done in each part of the process, while the yellow arrows indicate how the process has been dynamic and not individual entities.

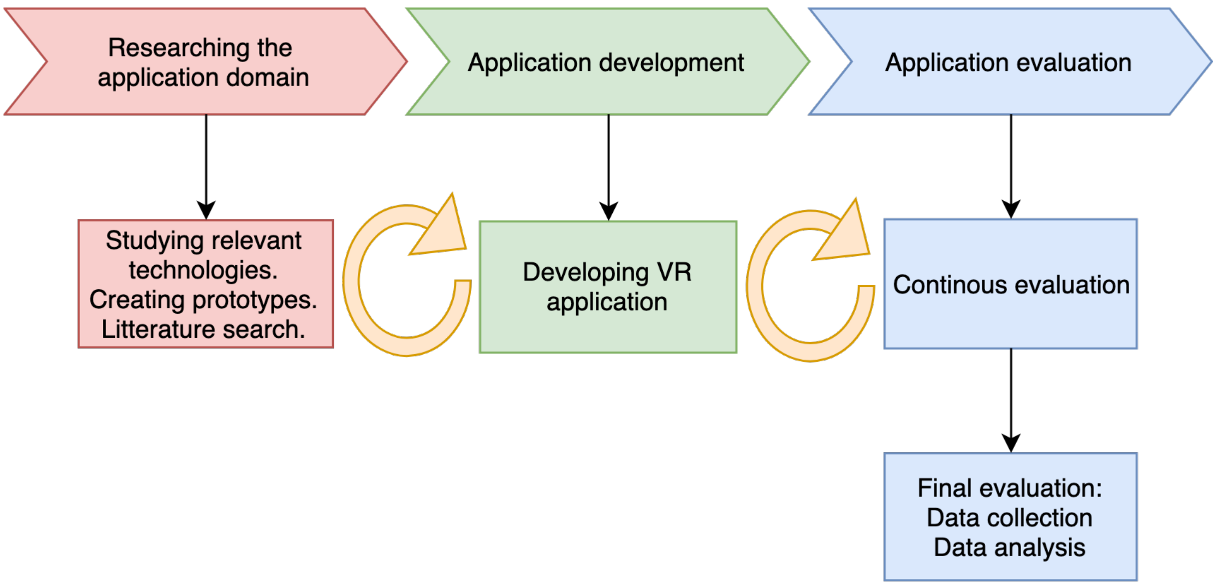


Figure 5.1: Project Progress Description

5.1 Researching the Application Domain

At the beginning of a design science research project, it is crucial to identify and apply a relevance context to which the artefact will operate. During the initial phase of this specific project, there have been taken several steps to understand the problem domain and its workings. In order to understand the workings of ZEN, its structure and related technologies, the authors of this thesis contributed to the *ZEN Work Package 1.3*[85]. It was a study where one of the main goals was to identify and investigate how a selection of tools, emerging technologies and immersive environments may be adapted to improve feedback on building performance and data visualization for the future design of sustainable neighbourhoods. The contribution from the authors of this thesis was primarily on emerging immersive technologies and how they may be used in the problem domain.

After obtaining a clearer picture of the needs in the problem domain, the next step was to develop a set of prototypes as a visual aid tool when discussing a possible end product. An approach to a desktop-, AR- and VR-version were proposed and is described in chapter 6 - *Presentation of ZENVR*. Risk analysis and contribution-matrix were formulated in order to obtain a better understanding of the effects of each technology. These are to be found in *Appendix A* and *Appendix B*.

There were also conducted a search for existing literature and similar projects. This is presented in chapter 3 - *Related Work*.

5.2 Application Development

The design phase of a design science research project relies on the dynamics between construction, evaluation and feedback of the artefact. The application development was conducted in two phases.

The first development phase was completed during the visit at the Fraunhofer Institute in Singapore [28]. This research institute has developed several VR applications which are used in the planning and construction of buildings, and one may find more information in section 3.5.4. During this stay, rapid feedback was received on the application, how to avoid known pitfalls and guidance in regards to the development process. In order to ensure that the result was as expected, the feedback was given once every week from ZEN.

The second development phase was conducted at NTNU in Trondheim, Norway. The feedback given during the first phase contributed to shaping the first version to not communicate the data well enough in non-expert terms. In order to make up for the lack of testing on the general public, a simple user test was conducted. The participants were pedagogy students at NTNU who were given a set of tasks and asked to give feedback on both the usability but also the data visualization. This invaluable feedback set the stage for the second development phase, which was to apply the suggested changes in the system. The changes applied involved contextualizing the data and give them a more visual representation.

5.3 Application Evaluation

This section covers the evaluation phase of the project by providing the reader with insight into the processes involved in respectively data collection and data analysis.

5.3.1 Data Collection

Interviews

The purpose of the interviews was to collect data from subjects with expert knowledge in fields relevant to the application domain. The interview-guide were used as guidance when conducting all of the interviews. However, the individual interviews went in slightly different directions as a result of the different backgrounds of the interviewees.

The interview began by giving the informants some background information about the process and a description of how the data would be used and anonymized. After the subjects had been fully informed, they were asked to sign the "request for participation"-form, as shown in Appendix D. A user test was arranged in order to give the subjects a firsthand experience with the system. Furthermore, the background of the subject and experience both with the work of ZEN and VR-technology were mapped.

The first topic of discussion revolved around the ease-of-use of the application, to obtain insight into the usability and the interviewees first impressions with the technology. Furthermore, the subjects were asked about the use of VR as a tool for visualizing emission data. The third theme discussed was the methods of visualization used; how easy was it for them, as professionals, to understand both numerical data and visualized data. The fourth topic was the potential of usage in order to gain insight into potential paths for further development. The last topic of discussion was how a tool like ZENVR could be used to engage different stakeholders.

Before gathering informants, it was first determined which fields were relevant for this study; architecture, virtual reality and data visualization, urban planning and stakeholder participation. In table 5.1, the informant's titles and fields are presented.

Subject	Field	Title
A	Architecture	Research Assistant of Architecutre and Technology
B	Virtual Reality and Data Visualization	Professor at the Institute of Datatechnology and Informatics
C	Urban Planning	Project-developer and -leader at Trondheim Municipality
D	Sustainable Architecture	Professor at Institute of Architecture and Technology
E	Stakeholder Engagement	Geologist and Scientist at SINTEF Byggforsk

Table 5.1: Fields of interview subjects

Questionnaire

The questionnaire serves the purpose of assessing the systems usability and user interface for users with little or no preliminary knowledge about the field or the technology used.

It is a 7-point DVAS scale and consists of three parts, with a total of 29 questions:

Background information: In this section of the questionnaire, the background of the subject are disclosed. It includes age, gender and experience of both the technology used and the study field.

General usability: The general usability of the software is inspired by the principles of the system usability scale, as presented in 4.4.1. This part of the questionnaire differs from the original SUS by being a 7-point scale. One of the questions were reformulated to fit the nature of the application better. Question number one in the original SUS says *"I think that I would like to use this system frequently"*. It was changed to *"I think this system could be used frequently for promoting sustainable neighbourhoods"*. The reason for this is the fact that the developed application is not a tool which a person often will use, rather than a showcasing tool for promoting sustainable neighbourhoods.

VR-specific usability: This part of the questionnaire measures the usability in terms of the heuristics presented in section 4.4.2. These heuristics were adapted to the developed VR application and formulated into a set of 15 questions. The questions can be found in the questionnaire presented in Appendix G.

The subjects for the questionnaire were gathered from inviting students from NTNU together with employees at Trondheim municipality. Testing the application with non-expert was relevant to asses the application's usability and to see if it was sufficient for average users.

Test subjects were given a short introduction to the HTC Vive controller, seen in figure 2.8, on how to move and control the application, and what to expect of the system. A set of predefined tasks were prepared beforehand, presented in Appendix F, to ensure all subjects got to experience all aspects of the application. The subjects were then asked to put on the HMD and perform the given tasks. After using the application for about fifteen minutes, the subjects had performed all tasks on the list. The subjects all received a questionnaire by email to answer. The questionnaire may be found in Appendix G.

5.3.2 Analysing Data

Data from Interviews

In order to extract the key themes and compare the collected data, the practices of grounded theory were used. It is known as the constant comparative analysis model. After the interviews were transcribed, they went through the coding process as defined by Strauss [31].

The coding process involves a line-by-line and paragraph-by-paragraph review of the transcribed material. Pieces of data were coded labelled with themes or descriptive terms of content. The pieces of data were constantly compared to each other in order to discover similarities and differences.

While coding and creating labels for concepts, models were created to visualize and give an overview of the material. These models enhanced the view of the existing categories and sub-categories. It also established a relationship between the categories.

Nine main categories became apparent after the coding process, with a total of 66 subcategories. The categories explain the main concerns, while the subcategories are different aspects of the theme discussed. In Appendix J, the main category are marked with red, the blue circles are the main categories, and the yellow circles show the subcategories. Two of the categories are connected, which is marked with green.

Questionnaire Data

The number of responses to the questionnaire was limited and is not a reliable representation and evaluation of the usability of the system on its own. Furthermore, demographic diversity is not sufficient in order to make any conclusions from the questionnaire alone. The reader is therefore encouraged not to read the results presented from the questionnaire as a quantitative result, rather than an indication of general tendencies when using the system. That being said, it may shed some light on the user experience when compared to the feedback given in the interviews.

Chapter 6

Presentation of ZENVR

During the early stages of the project, several initial prototypes were developed to explore the possibilities of different technologies and which played a significant role in the final product of the application. This chapter presents these initial prototypes to provide the reader with some context and explanation on how the system works and how the application was developed to address the research questions and system requirements.

Furthermore, the chapter presents the application developed in this project; ZENVR. The different aspects of the application, including system interaction and various levels and features, will be explained.

Lastly, the technical details in regards to the development of the application are clarified.

The source code for ZENVR is available at: https://github.com/sloevhaug/ZENVR

6.1 Prototypes

This section presents the three prototypes created during the research of the application domain.

6.1.1 AR Prototype: Trondheim AR

The AR prototype was created in Unity with the Vuforia Library [110] with support for both iOS and Android smartphones. The Vuforia Library comes with out of the box support for several useful AR features such as surface- and QR-code detection, which allows for a great foundation to build an AR application. The prototype started first by exploring the potential of using CityGML [111] in the application for creating the cityscape, similar to CityBES. However, available tools for converting CityGML to formats readable for Unity were limited, so a tool for converting OpenStreetMap data to .obj-format OSM [112] was used instead.

The application works by using the smartphone's camera to detect a flat surface where it places a model of a map of Trondheim city centre. In the prototype a fictional new housing development area at the peninsula Øya was added, marked in figure 6.1 by green buildings. Emission visualizations were conducted by using columns to indicate the different areas' emissions.

The aspects which made an application of this nature attractive were the cooperative possibilities and general overview it might provide of large data sets. On the other side, AR as a technology lacks some of the immersive and engaging elements which VR provides.

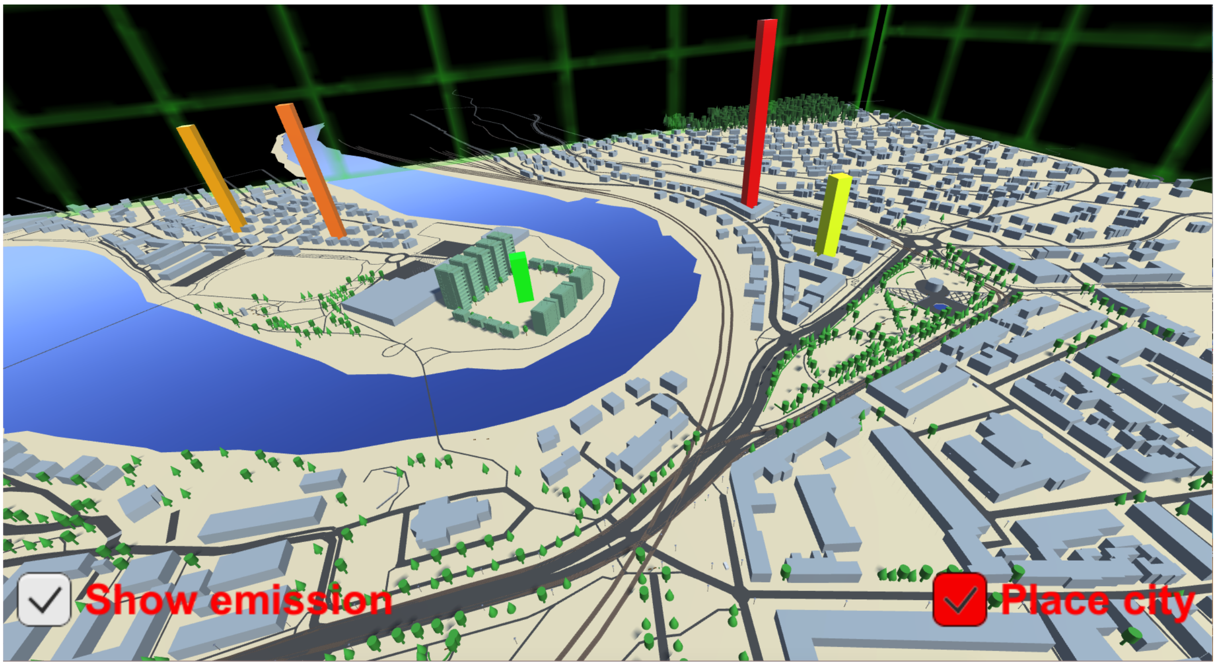


Figure 6.1: Snapshot from AR-application

6.1.2 Desktop Prototype: ZEN Desktop

A desktop application was created for exploring how we could directly continue the work of *Visual LCA in ZEN* [86] by using the database implementation from the *Building LCA Database-tool* by Resch and Andresen [30] presented in Chapter 2. The desktop application retrieves data from the MySQL database to present emissions for the building. This approach of an application resembled more a tool where the user could inspect emissions directly on buildings with the possibilities to compare and explore the use of different materials, see figure 6.2. Since this approach lacked immersion and made it cumbersome to include the general public due to the distribution and installation of the software on peoples computers, it was dismissed.

Figure 6.2: Snapshot from the Desktop Application Prototype

6.1.3 VR Prototype: Nidarvoll VR

The Mobile VR application was created in Unity with the Google VR SDK library [113]. Google VR SDK provides functionality for quickly setting up a mobile VR application for use with the Google Cardboard [7] or other similar mobile friendly head mounts. It contains a series of examples and demo code providing interaction with and navigation of the virtual environment resulting in rapid development. The application was created in two parts. The first part was a proof of concept to test and explore the possibilities and limitations of mobile VR as a platform, see figure 6.3.

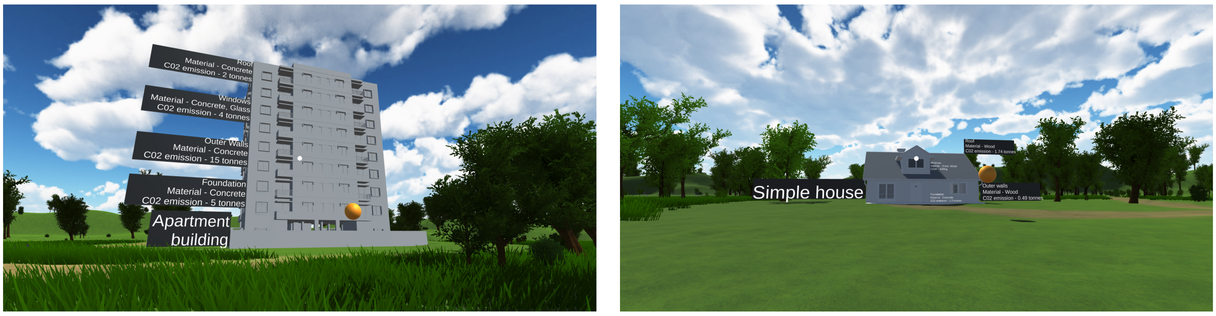


Figure 6.3: Snapshots from Nidarvoll VR Prototype

The second part was a further development where the navigation and interaction from the VR prototype were used in order to showcase and inspect the *Nidarvoll Pilot Project* [36]. The user was able to put on a Google Cardboard [7] and navigate around the project area by teleporting. Since this application was developed for smartphones, it had no input devices connected to it. As a result, the application relied on head tracking input in order for the user to interact with the system. To interact with the buildings, the user had to look at the object of interest, and the application would then automatically interact with the desired object after a time limit.

Figure 6.4: Snapshot from second Nidarvoll VR Prototype

6.2 ZENVR

As a result of the prototyping process, it was discovered that while mobile applications are cheaper and have a higher availability to a general audience, it has its limitations in interaction possibilities. The limitations were so considerable that it compromised the overall functionality with the application, making it only usable for showcasing purposes. In order to develop a product where the user can interact with the environment adequately, it was decided to use stationary VR equipment at the cost of availability for the public.

The most desirable attributes from the prototypes were combined in a single VR-application, in order to keep the overview gained in the AR-prototype, data presentation in the desktop application and the ability to focus on one specific building. The different KPIs have varying granularity and are best presented in different viewing modes. This lead to building the foundation of the application on three different levels to incorporate these requirements best: *Full view* (total view), *ZEN view* (neighbourhood level) and *ZEB view* (building level).

6.2.1 Using ZENVR

As mentioned, the application relies on a hand-held controller for user input. A virtual model of the controller mirrors the users' movement of the real world. The controller emits a laser which functions as a pointer and provides the user with visual feedback. When the laser hits an interactable object, it turns green and gives haptic feedback to signal the user. Likewise, when the laser hits a surface on which the user can teleport, it turns blue. When idle, the laser is red. To interact with an object, the user may click on either the trigger or the touchpad, located on the controller.

6.2.2 Full view

The full view presents the available ZEN pilot projects, at the time being only the Sluppen area. The other non-available projects in the full-view are for showcasing purposes only. The full-view offers data visualizations of aggregated KPI-data belonging to individual projects and provides the user with an overview.

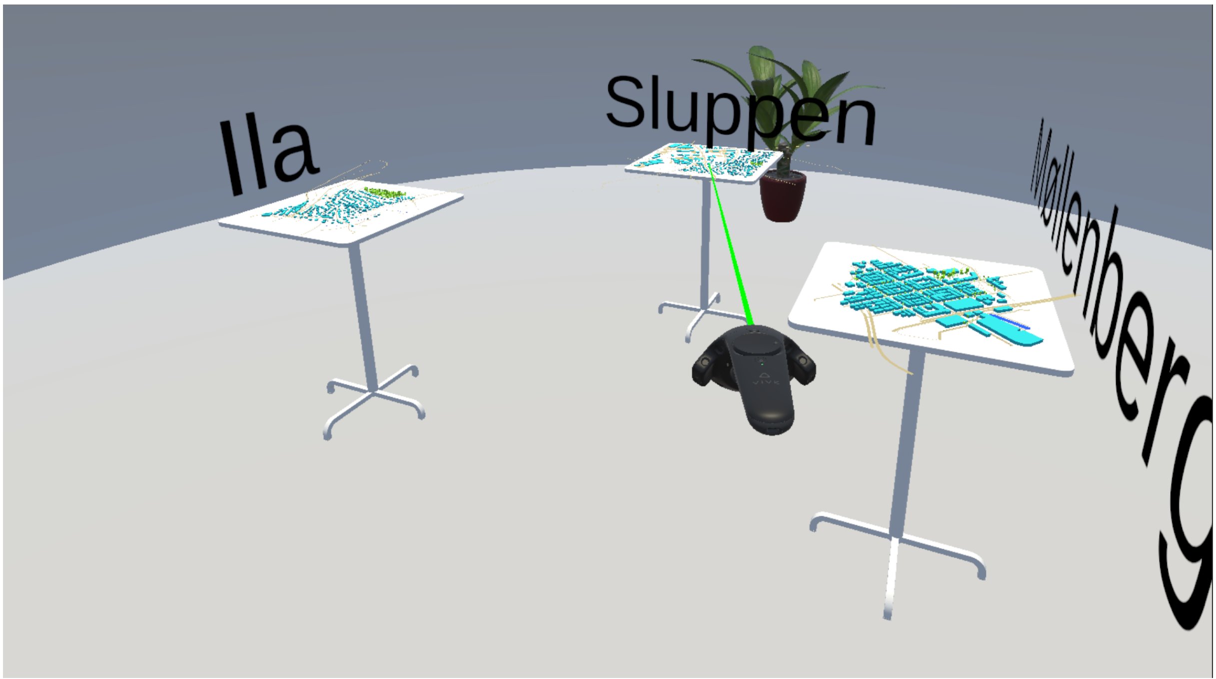


Figure 6.5: Snapshot from Full View in ZENVR

The scene is simple to offer little to no distractions and takes place in a dome with miniature models of the ZENs on tables. Each model can be identified by their project name and have available space on top to allow for aggregated KPI values in the future. In this scene, the user can teleport "down" to the desired neighbourhood by clicking on the model.

6.2.3 ZEN-view

The ZEN-view presents a model of the selected pilot project where the user spawns as a giant in the environment. Buildings that are interactable have distinctive colours and will display data-visualizations when prompted, and others will be rendered in an anonymous colour. The scene contains two large canvases where one is used for explaining the current visualization, and the other is an interactable menu for changing visualization options and KPIs for the whole scene.

Figure 6.6: Snapshot from ZENView in ZENVR

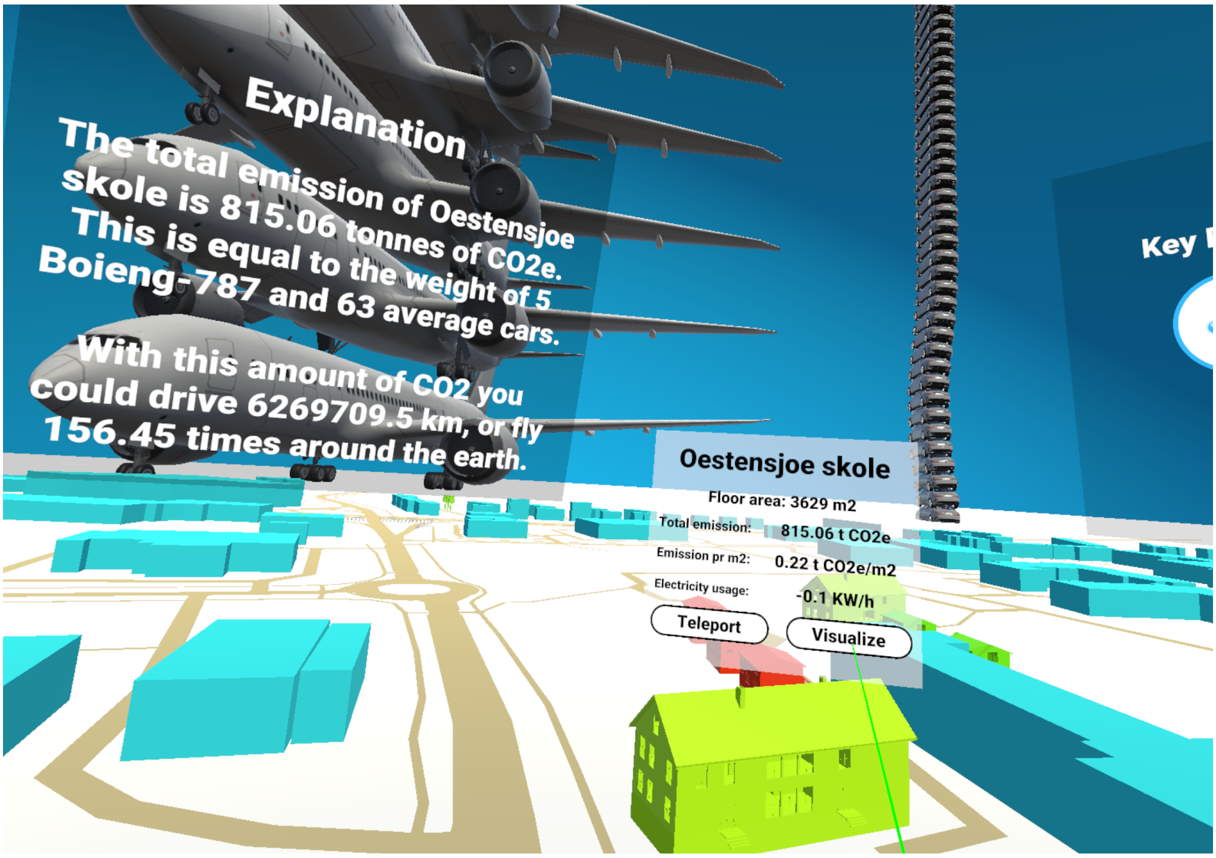


Figure 6.7: Snapshot of Visualizations in ZENView from ZENVR

When clicking on a building, the user is presented with a menu containing detailed emission information regarding the selected building — the canvas containing the explanation text changes accordingly. The menu offers the possibility of visualizing the buildings' emissions in creative ways to provide the user with context. Included today are the possibility to visualize the total weight of the CO_2eq in the form of aeroplanes and cars, and pollution from traffic. To go down to the building level, the user can click the "teleport"-button on the selected buildings' menu.

6.2.4 ZEB-view

When spawning in the ZEB-view, a 1:1 scale model of the selected building is rendered, and a smaller version of the same building is displayed in front of it. The purpose of the large model is to give the user the ability to navigate inside the exported Revit-model on a human scale level to get a feel of the actual model. Also, when hovering with the laser over a building part, a small menu will appear on the hand of the user containing data regarding the emission of building part. Both buildings have their building parts colour coded according to the current visualization type where a red colour would mean high emissions while green indicates lower emissions.

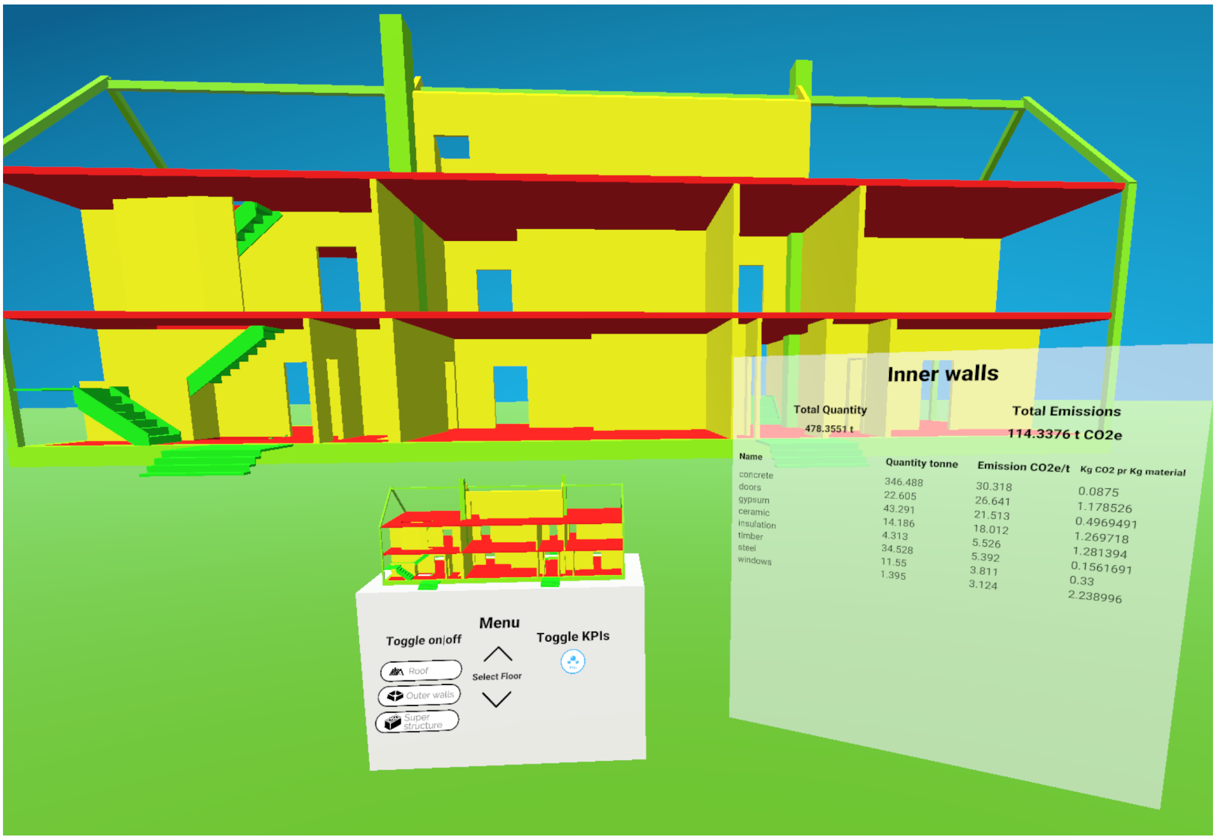


Figure 6.8: Snapshot of building with roof and walls toggled off, from ZEBView.

The scene also contains a large canvas which provides necessary information about the building in addition to explaining the current visualization method.

In front of the smaller model is a menu where the user can alter the building models by toggling on and off rendering of the roof, outer walls and superstructure, to make it easier

Figure 6.9: Snapshot from Inside the building in ZEBView

to inspect visualizations of building parts inside the building. The menu also provides the functionality to change the current visualization method.

The small model is for interacting with the building and inspecting the various building parts. All building parts of the small model are clickable, and when interacted with the user will see a large table being updated showing emissions from the materials in the selected part. In addition, the application visualizes the amount of all materials in the selected build part spawning the actual materials according to their mass. In front of the spawned materials are two columns where the left column is sized and coloured according to the material emission divided by total emission of all materials used in the selected building part. The right column visualizes the *emission intensity* of the material; the amount of kilogram CO_2eq per kilogram of material.

6.3 Technical details

6.3.1 Technology

The application is written in C# for the game engine Unity. For VR support the SteamVR Plugin [114] has been used. SteamVR allows for building VR application with support for most mainstream VR systems and includes demos and example code for fast prototyping. The software architecture is made to be loosely coupled to make a later expansion of the application easier. The online database is a MySQL database, while the local database is SQLite.

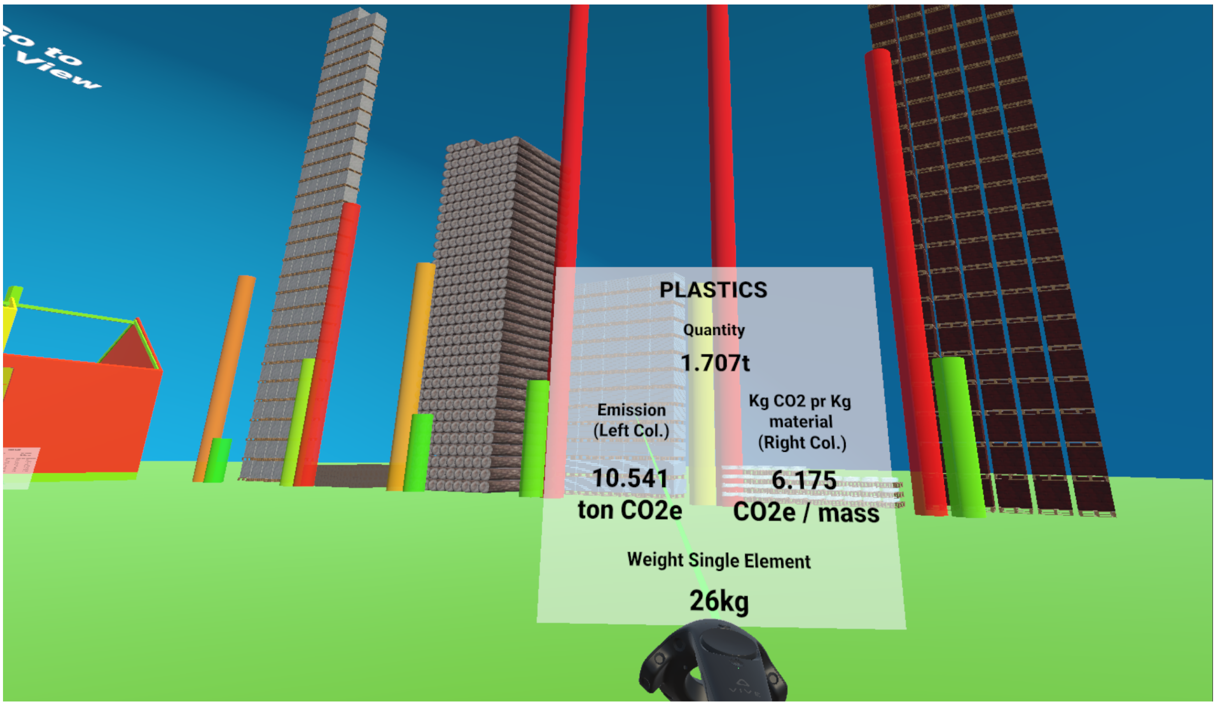


Figure 6.10: Snapshot of material mass and emissions visualized in ZEBView

6.3.2 Software Architecture & Code

During application development, there has been a focus on further development and purpose of building a foundation for expansion. During development, programming principles have been incorporated to make the code base more understandable, maintainable and flexible. The principles by Robert C. Martin [115], known as the SOLID-principles, have been taken into consideration during development. SOLID is an acronym for five design principles; **S**ingle responsibility-, **O**pen–closed-, **L**iskov substitution-, **I**nterface segregation- and **D**ependency inversion principle. To give some examples; classes handling database connection and querying have been separated from the rest of the application to follow the principle of *Single Responsibly* where one class should only have one responsibility, i.e. handling database connection [116]. Next, there has been a focus on the *Interface Segregation Principle* in, for instance, system interaction where objects with interaction functionality extend an interface for handling methods [117]. It is worth to mention that it is difficult to implement classical coding principles to the letter since Unity in itself has a non-traditional architecture and relation between classes and objects. However, they provide a good guideline for architecture-design, and the principles make later expansion easier.

Presented in Appendix I is a UML diagram of the most important classes of the application. There exist other classes, but it was deemed unnecessary to include in the model since they are entirely independent and control minimal parts of the application. Like mentioned earlier, Unity is object-oriented in code and consist of individual objects in the relevant scene in the application. To include all classes would, therefore, result in several classes standing by themselves. The UML diagram is provided in order to give the reader a sense of the relationship between the classes, not for providing a thorough system and architecture description.

6.3.3 Event-Driven Programming

The ZENVR application is an event-driven application. Two forms of interaction mainly determine the flow of the program:

1. OnClick-events, generated when the user clicks an interactable GameObject.
2. OnHover events, generated when the user hovers the laser over an interactable GameObject.

All interactable GameObjects in the virtual environment have a *collider* and a script attached to it. In order to create an OnClick-event, the user has to click the controller. A ray is cast from the controller and registers a hit. It then launches the script attached to the GameObject. The other type of events works in the same way but does not rely on an on click performed by the user.

An interface was created for handling the two types of events. Therefore, each script that are connected to the GameObjects needs to have both a `Hover()` and a `Clicked()` method. In figure 6.11 there is shown an example of an interface which handles the event of a user clicking a building-part in the ZEB-view. It calls on the method `ShowMaterialInformation()` in the class KPIControllerZEB, which among other things fills the table with information about the selected building-part.

```
public class ZEBBuildingPartInteraction : MonoBehaviour, IInteraction{
    public void Clicked()
    {
        //Find script controlling the scene and show material information
        GameObject.Find("KPIControllerZEB").GetComponent<KPIControllerZEB>().
        ShowMaterialInformation("emission", id);
    }
    public void Hover()
    {
        //Not used on this GameObject.
    }
}
```

Figure 6.11: Code snippet describing OnClick events

6.3.4 3D Models

3D models in this application are either .obj or .fbx format. The buildings in ZENVR have first been created in BIM-format with the Autodesk Revit software. From Revit, the model is exported to .fbx-format and imported to Autodesk Maya for cleaning. It is a necessary step since the model exported from Revit can be very heavy in terms of vertices count, due to lack of optimization. In Autodesk Maya, the model is cleaned manually; unnecessary details are deleted, centring of the model is fixed, and correct naming conventions are applied to all building parts. The model is then exported to be used in Unity. In Unity, the correct scale is set, and the model gets a script applied to it containing the information required to identify the building in the database.

The map data is generated by first specifying the desired area in OpenStreetMap [112] and exporting the map data to be downloaded as an OSM-file. The OSM-file is then used to generate a 3D model of the area by using the software OSM2World [118]. The result is a .obj-file which can be imported directly to Unity or modified in Autodesk Maya. It includes removing the placeholder buildings which are to be replaced by BIM-models and unnecessary objects included in the export.

6.3.5 System Interaction

The system interaction is one of the components which was greatly influenced by the fact that the application should be easily ported to a mobile platform. It led to making design choices in regards to the system interaction to support both controllers and, if desirable, head-tracking. Since the head-tracking uses raycasting to detect collisions with interactable objects, it was necessary to have support for the same technique with controller interaction. This was solved by attaching a collider to interactable objects and casting a ray from the position of the controller instead of the HMD. This approach makes it is possible to use the same application with mobile VR should it need to be ported in the future.

6.3.6 Database

The application uses the bLCAd-tool, whose ERD diagram is attached in Appendix H. The functionality for connecting the application to the database is put in the class DatabaseConnection, and the connection can happen in one of two ways. If the online database is not available, it is possible to generate and use a local SQL database containing a backup of the online version of the database; else it connects to the online database.

In order to maintain a loosely coupled application, there is only one class which contains all queries that are sent to the database. In Appendix K, there is an example of a query for retrieving emissions from a building at a certain structure level to show how both local and online database connections are accounted for. Apart from the database connection, there are attached two other parameters, namely the id of the building and which level one wants the data. The levels correlates to the hierarchy defined in NS 3451:2009 [10], presented in chapter 2.4. The method returns a Data Table with the results which may be presented in the user interface.

6.3.7 Design of the User Interface

Chapter 3 presents Norman's design principles for designing UI in VR, and in this section, the applicability to ZENVR will be addressed. This section presents how UI design principles were followed, in addition to a more technical description of different choices made during development.

Affordances
In ZENVR affordances are that the user can interact with neighbourhoods, buildings, building parts and menus by using an input device. The user is also able to interact with the environment by teleporting to a location of choice, and moving in the available space in the real world, reflected in VR.

Signifiers
The application is developed with several signifiers. One example is how the laser is used with the input device. When the laser hits an object which is not an affordance, the laser has the colour red. If it hits something interactable, the laser turns green, and the user gets haptic feedback through the controller. In order to indicate that the user has the option to teleport in the scene, the laser will turn blue when hitting a "teleportable" surface. In addition to this, there are used buttons, labels and icons that indicate the result of an action.

Constraints
The physical limitations in the developed software are, for instance, the limited use of buttons. On an HTC Vive - controller, there are five different buttons [119]. The application is limited to utilizing only two of these, which also performs the same action. It was decided after discovering through user testing that experienced users were in disagreement on what was the standard "click"-button. Another physical constraint is the inability to teleport outside a defined area inside the scene.

Feedback
In the application, the user receives feedback when interacting with an affordance by short haptic feedback in the controller and visual feedback in the application.

Mappings
The applications mapping is indicated by the change of colour on the laser, haptic feedback, and observing results of the actions in the VR environment.

To account for Alger's design principles [79] the ZEN-view has its canvases containing text and menu placed in the main content zone. The use of metaphors has been utilized both when it comes to colour-coding emissions (Red indicated bad performance, green indicates good performance) and visualizing the weight of CO_2eq in planes and cars.

In the ZEB-view, it is a slightly different approach. While the colour-coding has been maintained, interaction with the application has been limited to one specific location. Users may interact with the small building in one of two ways. The building itself may be clicked, and there is a menu for displaying different building parts. It was solved in this way in order to establish a metaphor for a more traditional keyboard-approach. By having the presentation of numbers and interaction placed in one static location, another issue arose. It forced the user to teleport back to the point of origin in order to get the numbers presented. The solution to this problem was to connect a small menu to the controller. If the user hovers the laser on the large-scale building-parts, the numbers are presented in the abovementioned menu.

The effects of the implementations are presented in Chapter 7 - Findings, and later discussed in chapter 8.

Chapter 7

Findings

This chapter presents the findings from both the questionnaire and the interviews. It starts with a presentation of the demographics of the test group and then moves to a descriptive analysis of the responses. The presentation is structured by the main themes of the questionnaire, influenced by the structure of the interview-section. Like mentioned earlier, the findings from the questionnaire are more of an addition to the results of the interviews.

Furthermore, the chapter presents the findings of the interviews. The backdrop for the extraction of information was laid in chapter 4. The interview section is structured after the categories found during the coding process.

These results will be discussed in chapter 8.

7.1 Presentation of Data

7.1.1 Demographics

Table 7.1 shows the demographic profile of the participants of the questionnaire. As one may observe the gender distribution was about equal, but with slightly more male respondents. The ages ranged between 20-59, but the more significant portion were young adults in the range 20-29. The subjects were asked whether they had tried VR-technology of any kind previously, where a larger portion of the respondents answered yes. This question included a comment section where the respondents could elaborate on this subject. The general tendency was that the respondents had tried VR games and early demos of VR applications a few times. Furthermore, none of the respondents had any experience with the visualization of emission data.

Characteristic	Item	N
Gender	Male	7
	Female	6
Age	20-29	10
	30-39	1
	40-49	0
	50-59	2
VR Experience	Yes	8
	No	5
Experience with emission data visualization	Yes	0
	No	13

Table 7.1: Demographic characteristics of participants in the questionnaire

7.1.2 Questionnaire

The respondents rated each item from a scale from 1 to 7, where 1 was *strongly disagree* and 7 *strongly agree*. This subsection is structured by a set of themes in order to easier discuss the data with the findings from the interviews.

Application potential
The answer to Q5 (table 7.2) says something about the potential usage of the application. It varied from "no opinion" to "strongly agree", with a general tendency towards "strongly agree", with a median score of 6.

Item	Median	IQR
Q5: I think this system could be used frequently for promoting sustainable neighbourhoods	6,00	1,50

Table 7.2: Results from questionnaire: Application potential

Ease of Use & Navigation
The respondents answered several questions regarding the ease of use, navigation, consistency of the application, and to what degree the application was intuitive to use. This data are presented in table 7.3. The general tendency was that the respondents felt the system were easy to use (Q7), but at the same time, there is a larger spread when asked if the complexity of the application (Q6). Furthermore, the general tendency was that the system did not feel cumbersome to use (Q12), and the users felt confident while using the application (Q13). When asked about the consistency (Q10) and intuitiveness (Q15), the respondents also answered positively. The subjects managed to distinguish between objects which are intractable and non-interactable (Q17). While most people thought it was easy to understand, three people struggled with it. A little over 80% of the respondents disagreed with the statement that it was difficult to navigate in the application (Q23).

Only three of the respondents answered that they, to some degree, felt lost when navigating inside the virtual environment (Q24). What is interesting is that when asked about navigating between levels (Q25), there is a wide spread of responses, ranging between "disagree" and "strongly agree".

Item	Median	IQR
Q6: I found the system unnecessarily complex	2,00	2,00
Q7: I thought the system was easy to use	6,00	1,00
Q10: I thought there was too much inconsistency in this system	2,00	2,00
Q12: I found the system very cumbersome to use	2,00	0,50
Q13: I felt very confident using the system	6,00	1,00
Q15: I found the interaction mechanism with the application was intuitive	6,00	0,00
Q17: It was easy to understand which objects were possible to interact with	6,00	1,50
Q23: I found navigating in the application difficult	2,00	0,50
Q24: I often got lost when navigating the virtual environment	2,00	2,50
Q25: It was obvious how to navigate between the different levels	5,00	2,50

Table 7.3: Results from questionnaire: Ease of use & Navigation

Need of Support

The subjects also disagreed whether they need support from a technical person in order to use the system (Q8), however, the majority of subjects felt that the application provided sufficient support for understanding the virtual environment (Q27), but with a deviation of 2,00. While the more significant portion felt that they could use the system without any assistance, three of the respondents saw the need, to some degree. At the same time, the subjects were in agreement when asked if most people would learn to use the system very quickly (Q11). The majority of respondents disagreed with the statement that they needed to learn a lot of things before they could use the system (Q14) with a median score of 2. This data is presented in table 7.4.

Item	Median	IQR
Q8: I think that I would need the support of a technical person to be able use this system	2,00	3,00
Q11: I would imagine that most people would learn to use this system very quickly	7,00	1,00
Q14: I needed to learn a lot of things before I could get going with this system	2,00	1,50
Q27: The application provided support for understanding the virtual environment	6,00	2,50

Table 7.4: Results from questionnaire: Need of support

Application Functionality

All of the subjects agreed upon the statement that the possible actions one could perform were well thought out (Q9), with a median score of 6. The same tendency was apparent when asked if the objects behaved as expected (Q16). The feedback given from the system when interacting with objects (Q21) were deemed sufficient, with a median score of 6. One interesting point is the diverse feedback given to the statement that haptic feedback and colour indication made it easy to understand the interaction (Q26). While the median is scored to 6, there existed less consistency between the answers given when compared to Q21. (table 7.5)

Item	Median	IQR
Q9: I found the possible actions I could perform in the system were well though out	6,00	1,50
Q16: I found that the objects behaved as expected	6,00	1,00
Q21: When interacting with objects I received sufficient feedback from the system	6,00	0,50
Q26: Using haptic feedback(vibration) and color indication made it easy to understand the different types of interaction	6,00	2,00

Table 7.5: Results from questionnaire: Application functionality

Exploration

The subjects agreed with the statement that the nature of the system encouraged them to explore (Q19) with a median of 7,00 and a deviation of 1,00. At the same time, there was a larger disagreement when asked if the possible actions felt restricted (Q18). The median answer was 2, but the deviation was 3, indicating that a portion of respondents felt restricted. This data is presented in table 7.6.

Item	Median	IQR
Q18: I found my potential actions to be restricted	2,00	3,00
Q19: The nature of the system encouraged me to explore	7,00	1,00

Table 7.6: Results from questionnaire: Exploration

Discomfort
None of the respondents felt any significant discomfort when using the system(Q20), which may be explained by the fact that all the respondents felt both the head movement (Q22) and physical movement in real life (Q28) were naturally mirrored in the application.

Item	Median	IQR
Q20: I felt discomfort when using the system	1,00	0,00
Q22: My head movement were naturally rendered in the virtual environment	7,00	0,00
Q28: My physical movement felt naturally mirrored in the virtual environment	7,00	1,00

Table 7.7: Results from questionnaire: Discomfort

7.2 Findings from Interviews

7.2.1 VR Technology

This subsection refers to the theme of VR technology in general in addition to some remarks specifically for the use of VR in a project of this nature.

When first asked about their general thought on the technology, three informants started by expressing their excitement for the technology being fun and two pointed out also that the technology in its nature promotes exploration which sparks curiosity end engagement.

When asked about the degree of immersion, four out of five of the subjects stated they became immersed to some degree. The exception was subject B, the expert with a background in VR-research, who understood the concept and purpose of the application but did not feel immersed in the experience. The remaining subjects stated that they reached a higher level of immersion; some even felt "totally immersed". Subject E stated that at some points she felt so immersed that the experience was almost scary and referred to a situation where she was standing on the top floor of a building and felt like she could fall.

When asked about the use of VR as a data visualization tool, Subject A stated that he initially was sceptical of the technology, because he doubted the effect it would have. After testing the application and completing the set of tasks, this opinion changed to a more positive one. Subject B said that VR is a tool which is well suited for this usage, and highlighted how VR is an alternative way to convey information so that it may stick longer with the user. Subject D thought it was a fun experience and that VR seems like a beneficial way of getting people interested and educated in the area, which is something other subjects also pointed out. Subject A said that he felt curious when using the system and wanted to explore. Subject E also stated that VR is a fun and entertaining way of presenting data.

7.2.2 Other Technologies

This category refers to themes discussed regarding other technologies suited for the same purpose as ZENVR.

One of the questions in the interview was if the informants could think of other technologies that might be well suited for the same purpose. Subject E stated that it depends on what the purpose of the application is. She went on to say (Translated):

> *"... areas in ZEN which are under planning and has not yet been built can benefit from this type of technology (VR). On the other hand, are areas which exist today and are being rebuilt, then the question might be if you get easier access by standing in the area and using augmented reality."*

She also states that augmented reality in its nature already is at a human scale, making the connection to the application stronger for her.

Subject B stated that augmented reality is more limited than VR in the way it is limited to the space in which it operates. On the other hand, AR benefits from using a "digital twin" to visualize data in the space where the user is standing, which is already being used in the construction business today.

7.2.3 User Interface

This subsection contains answers which are related to the user interface of the application.

When discussing the user interface, the subjects were asked about how the text-based data were presented to the user. All subjects agreed that they did not read the text, specifically the text in the sky in the ZEN-view. None of the subjects read text when it was large quantities of data placed together, as it seemed overwhelming. Subject C commented that in ZEB view, she preferred when the data were presented on the controller, rather than on the canvas placed in the sky. It is something that subject D agreed upon, and subject E stated that she wanted to have the ability to toggle on and off explanatory text when needed.

7.2.4 Usability

Usability refers to which degree the interaction and use of the system is intuitive and easy to understand.

When asked about interacting with the system, all subjects felt that the controls were intuitive and consistent. After getting explained how the controls work and the meaning of the different colours of the laser, all subjects found the navigation inside the application to be easy and intuitive. They all understood how teleportation in the current scene worked, and all utilized it frequently. However, when asked to teleport between scenes, none of the subjects understood how to accomplish this by intuition. It indicates an inconsistency in the application. Subject B stated explicitly that it was difficult to understand the instruction to "teleport down to" building level. Teleportation in the scene was indicated by a blue laser, being ambiguous to teleporting between scenes, which is performed by a menu interaction.

All subjects, except subject D, highlighted that a tutorial was necessary to use the system effectively. All of the subjects were informed of how the controls worked and made aware of the different colours of the laser pointer. In order to give users of this application a sufficient knowledge regarding the system and its controls, a practical tutorial was proposed.

7.2.5 Data Visualization

All the subjects were asked to give feedback on the different methods of visualizing the emission data.

A critical point of discussion was the use of objects which the user may have a relation to, in order to put the numbers into context. Subject A stated that: *"... even as a professional, it is a little bit difficult for me to understand how much it (one kgCO2eq) actually is"*. He preferred a representable contextualization of the numbers, for example, driving distance in a defined vehicle. Subject B also stated that it is nice to relate the numbers to something that people may have a relationship with. Subject C pointed out that, even though the use of everyday items may be useful for the general public, it adds little to none value in a work situation. It concurs with subject D, who said that the use of planes and cars were a suitable solution for improving the understanding of the numbers.

The subjects with a background in architecture all preferred visualization with columns over colours. Subject A said that he found the columns the most useful because it is easier to compare emission values from different buildings, something that subject C, D, and E agrees with. Subject D highlighted the use of sizes as a way of making an impression on the user, and that when seeing columns that were substantially larger than herself made an impression which stuck. This was something that was well summarized by subject E (Translated):

"... (the planes) made a strong impression, which was on an emotional level and not on a rational level, like colours and columns."

Furthermore,

"... if you want to achieve change, you have to get on an emotional level in order to make people feel, or get a relation to this."

At the same time, both colours and columns have each their use. Subject A and E both stated that by merely using colours, it is possible to identify buildings with high emission in large neighbourhoods quickly.

When discussing the aspect of the application which aims to put the numbers into a visual context, an important topic arose. Subject A stated that when seeing cars and planes, he jumped to the conclusion that it represented the driving and flying distance because it is a well-established metaphor when discussing emission data. In the application, the number of planes and cars are equal to the weight of emissions.

7.2.6 Application Functionality

This category covers both the existing functionality and functionality which the subjects pointed out as something that was missing.

Subject A and B said that they initially were sceptical of the application and its usage. Subject A was sceptical if the application contained enough functionality to give an adequate data visualization experience. Subject B said that his first thoughts when using the system were that it is simple and that he was wondering what the usage would be. He also noted that it became more apparent after some time. Subject A clarified and stated that he was "positively surprised" with several of the features of the application, one aspect being the use of a simplified map of the pilot area. In his opinion, there is a "graphics rabbit hole", meaning that if one start to implement high detailed models, the rest of the experience must have the same level of detail. Moreover, if architects started showing people finished looking rooms or areas, there is a strong possibility that the finished product would not look like the computer model. He remarked the possibility of the application creating false expectations for buyers and users if giving them a realistic as possible experience through the application being a promotional tool. Another interesting point made by subject A was the fact that this type of application could have little or no effect on buyers such as energy labels, referring to an article by Prof. J.O. Olaussen and A. Oust at NTNU [120].

When discussing the use of the application in a work-situation, subject A and D evaluated the current implementation and its functionality not suitable. Subject D said that the VR equipment was impractical for replacing existing tools. Subject A highlighted the amount of facilitation needed for successfully using this kind of application in a dynamic work setting. He specified the substantial amount of information needed in the model in order for it being an interdisciplinary tool, and that a requirement would be having sufficient expertise in the area of BIM-models and visualizing LCA.

Some of the informants pointed out that some data might be too generalized. Subject A stated that it would be interesting to know more details around the travel distance visualization, stating: *"... people can say "ok, this is a Toyota Yaris driving to Oslo""*. Subject C stated that for the application to be used in work-related situations, they would have to know additional information on how the emissions were calculated and if the life cycle of the building was included in the emissions.

7.2.7 Application Potential for Stakeholders

This section addresses the application's potential for diverse stakeholders. The category is divided into two; potential use for the general public, and potential use for experts.

When asked about the potential for the application, all informants had grand visions and ideas on how it could be used in their field. Alike for everyone was pointing out the potential for engaging and including the general public in projects by using VR. Subject B stated that with an application like this, you could communicate the magnitude of emissions to the general public. (Translated):

> *"... if you have a good way of visualizing data, to get people up and aware of the situation, then you should not underestimate the influential force of the general public."*

Subject E, who works with stakeholder engagement, pointed out that a problem with new and green neighbourhoods is that in many cases, it can be hard to sell to the public. She says that in one of their new projects, they are planning buildings without parking spaces to promote using collective transportation. (Translated):

> *"A bit of a problem with ZEN is that people feel like things are being taken away from them, and the question becomes "what does actually ZEN give to the citizens?""*.

She goes on to say that if they were able to visualize how the new districts could look, and give the citizens a feel for and show them what they could use the parking spaces for instead, then it might be an easier sell.

All the interview subjects highlighted the use of the application as a tool for interdisciplinary communication as one of the main attributes. Subject C stated (Translated): *"I struggle to communicate with the people that are with me, even advisors who are experts."*. This is something subject E agrees with when she states that (Translated): *"But I think it would be a helpful tool (the application) for translating the barriers which occur in interdisciplinary cooperation."* Subject B, the subject with knowledge regarding the technology, emphasized that one of the main capabilities with VR technology is the possibility for cooperation across spaces. It enables users located in different parts of the world to gather on one unison platform. In regards to this, Subject E noted that when communicating with another person, non-verbal communication makes up a large part of the interaction. She goes on to suggest that cooperatively there would be a need for an avatar to mimic the person you are working with. Alike for all informants with architecture background was the suggestion of using the already collaborative workflow around a BIM-model, where different stakeholders in projects can all work on the same model, but with different parts of it. This functionality was suggested to implement so stakeholders could communicate around the actual model.

Subject C, who is employed by the municipality of Trondheim, pointed out the applicability for such a tool both in urban planning and building maintenance. She made an interesting point that the application could be used for decision support when choosing whether to retrofit an existing building or demolish it and build a new one. She also states that in a project, you depend on motivating the people around you:

> *"... I have a hard time communicating with those around me, because you have to motivate each and every person, and when everybody is motivated you have to start motivating a new group of people."*

She stated that the capacity of VR is not utilized in either decision- or development-phase of construction projects, in the municipality.

Chapter 8

Discussion

In this chapter, the findings from the data collection will be discussed, in addition to the application itself. The chapter starts by discussing the limitations of the research by pointing out the shortcomings of the questionnaire and the interviews. It then discusses the findings, which are structured in the same way as the previous chapter. Lastly, the application will be discussed and compared to the other projects presented in chapter 3.

8.1 Research Limitations

There are limitations to the conducted research, and in this section, the main shortcomings will be presented.

Firstly, there are significant limitations to the number of respondents and the demographic diversity of the questionnaire conducted. The set is too small to be statistically significant, and can therefore not be considered a result on its own. Furthermore, the main base of respondents are students, which are not representative in regards to the wide diversity of the population. In order to better reflect the diversity of the user group, a broader set of respondents should be sampled, with more considerable diversity in both age and field of work. That being said, the reason for not being able to gather a sufficient number of respondents was the complexity and time constraints of hosting a VR demo. Each demo lasted between 15 - 30 minutes each, and since it was not the primary source of data collection, it was not prioritized.

A limitation with the interviews conducted was the fact that it was not enough time for follow-up interviews. According to Taylor et al. [16], these types of interviews may aid in clarifying the opinions of the interviewees and confirming the statements given in the first interview.

While the system was being developed, the testing and provided feedback were primarily based on the opinions of professionals. An important aspect of the systems' area of usage is the ability to influence the general public, and the opinions of a large user group were not sufficiently voiced. User tests were conducted on non-professionals after returning from Singapore. However, since the foundation of the system was developed before this, the implementation of large portions of the system's functionality was done without the influence of the general public.

There are also limitations to the literature presented in chapter 3. There has been a challenge to find papers that have researched the same topic with the same scope as this thesis. A large part of the existing literature is based on system concepts or more directed at handling BIM-models in VR, and not as much at presenting numerical data in order to create an experience for the user. As a result, the related work-chapter consists of several semi-related topics and projects in order to fit this particular research. The limitations to the technology and application are discussed in section 8.3.

8.2 Discussion of Findings

8.2.1 VR Technology

During the interviews, several of the subjects noted that the experience was a fun and exciting way of communicating data. A common tendency with all subjects, both interviewed and participants of the questionnaire was that they had limited experience with VR. The exception was subject B, who works with VR. One may argue that the first-hand experience with new technology sparks immediate interest and excitement, which not necessarily is anchored to the developed application, rather the technology itself. It corresponds with findings from [22] suggesting the technology has a motivating factor. With this in mind, the highest prioritized principle from Quesenberys' five Es, *Engaging*, is met. However, one can not say with certainty whether this is due to the application functionality or the chosen technology. That being said, one of the main reasons for choosing VR-technology was because of the immersive and engaging capabilities of the technology.

An interesting observation is that the people who felt most immersed were the subjects who had the least experience with VR. Subject E stated that she at times was so immersed in the experience that she felt a bit scared (of falling off a building). In addition, she highlighted that for her to feel safe while using the equipment, she would prefer a "safe space" without any outside distractions. Jerald [46] explains this strong sensation of immersion which subject E experienced as "presence". It is defined as *"..an internal psychological and physiological state of the user.."*, and the feeling of one being present in a physical environment is one of the main parts of presence. Mel Slater [121] further explains it as "place illusion". Place illusion occurs when the user's perceptions of the stimuli presented, behave as they originate from real-world objects. If place illusion becomes a common occurrence for users of ZENVR, one could argue that it is strengthening the *Engaging* principle from Quesenbery. On the other hand, if the users experience a strong place illusion, but do not feel safe, it might result in a negative experience. Furthermore, since this only occurred with a subject who had little experience with VR, the illusion might decrease as experience with the technology increases.

The safe space subject E suggested is an excellent idea to prevent what Jerald calls a *break-in-presence*, which is a moment when the illusion generated by a virtual environment breaks down, and the users find them self where they truly are; in the real world wearing an HMD. It was observed that experience with the equipment and threshold of immersion were correlated. As a result, one question posed were the case of VR-equipment becoming more frequently used. One may argue that as the users experience with the technology increases, the demands of the applications and technologies immersive capabilities rises as well. This is also a natural way of development and can be seen with for instance StarVR [51] who is pushing the boundaries between the virtual- and the real environment by making HMDs with better specifications and introducing new functionality.

8.2.2 Other Technology

When asked about other technology that may suit the same purpose, most informants addressed using augmented reality. It is worth mentioning that AR, in most cases, came up earlier during the interview process, and might be a factor as to why most people thought of it. Besides, AR is becoming a vast spread technology and part of everyday life. In recent years there has also been an increase in the use of AR in construction, mainly due to the Microsoft Hololens [42] and other AR Glasses increasing in popularity. It would be interesting to see if it is possible to achieve the same level of immersion with high-end AR technology such as the Hololens and if that might work just as well for visualizing KPI data.

A good point made by Subject E was that AR is already at a human scale, which might make the connection to the application more imminent. For her, the factors in ZENVR that were at 1:1-scale made a more significant impact. When asked which of the visualizations made the most significant impact, all informants answered planes and cars, which are in a 1:1-scale.

AR is also more available than VR in the sense that all you need is a smartphone, while with VR, a head-mount is required. Although the human scale connection one might get with AR could be a significant limitation as well. Like Subject B said, AR technology is limited to the space in which it operates, meaning, for AR to be at a human scale, it requires a 1:1-scale in real life. Since VR can generate any virtual environment, Subject E stated, it might be more beneficial for the planning phase. On the other hand, AR might be more beneficial in the construction phase of a project when using a digital twin to inspect the building site or visualize information on top of the real world.

8.2.3 User Interface

The perceptual capacity balance may explain the issue with subjects not reading large bodies of text. In order to prevent overloading the mind, the body has evolved to apply more resources to a single area of interest at the same time. One of the methods to ensure this is the deletion filtering, where the mind omits certain aspects of incoming data by selectively paying attention to only parts of the world [46]. As the user in ZENVR is put into an entirely new and unknown environment, one may argue that the users' perceptual load already is at capacity just by getting to know the workings of the system. A possible solution was proposed by subject E, who desired a solution where she could toggle the information on when need be.

Subjects noticed the text and had some issues with the immediate localization of the menu in the neighbourhood view confirms the work of Mike Alger [79]. While the text, which was noticed by the users, was placed right in the centre of the content area, the menu was placed further to the right. It may have caused the menu to cross over to the peripheral zone, which is significantly less noticeable.

Another issue that became clear when testing the application was that by having the text placed in a static location in the scene, the user's position became an important factor. When the user spawns in the scene, the text is placed in the content area with a sufficient distance so it may be read comfortably. This changes when the user teleports inside the scene and the text may get in the "no-no zone" [79], which makes it hard to read or difficult to spot. Another option discussed for text placement was that the text would follow the users head movement, but after testing it were concluded that it might be experienced as annoying. The solution could be to move the menus according to the user's position, but then it might be confusing not to find the menu where it was last; you would not move the menu bar in a desktop application. It became apparent that menu placement in VR is challenging and needs further research and development.

In the ZEB view, some of the same issues arose. When interacting with the small model, i.e., clicking on building parts, the materials were spawned. As the large Revit-model of the building was placed in the content-zone, the materials were placed in the peripheral and curiosity-zone. By observing the user tests, it became apparent that it was hard to detect this information, and most users had to be prompted to turning their head to notice the new information presented.

Another interesting point where the distribution of information in the scene. Several of the subjects expressed that they struggled when the information was scattered across the scene and that they preferred the menu that appeared on the controller as an information display. This may also relate to the work of M. Alger [79], who states that users often tend to explore the area in close proximity for tools for interaction and information, similar to the keyboard location of the computer. A solution to users not noticing the large menu in the ZEN-view might be to put the menu at the same location as the information display on the controller, which multiple informants specifically said they preferred.

8.2.4 Usability

The subjects felt that the controls were intuitive and easy to use, a statement which is supported by the data from the questionnaire. The input devices were configured after a period of user testing, where it was discovered that users tend to use two separate buttons in order to achieve the same result. As a result, both buttons were configured to produce the same result. All other interaction options were disabled in order to remove the element of confusion. When discussing multi-modal interaction, Jerald [46] encourages the use of a single specialized input modality when there is no specific reason for including other modalities.

Like mentioned in chapter 3, it was decided to give less priority to three of Quesenbery's principles; *Effective*, *Efficient* and *Error Tolerant*, seen in figure 3.4. In ZENVR, the user is encouraged to explore the environment, not just complete the visualization of data tasks. As a result, there is no current need for an effective or efficient solution. However, these principles would need a re-evaluation in the case of the application being further developed as a tool for professionals. Furthermore, as the functionality of the application remains rather narrow, there are few to none actions the user may take in order to create a system error.

Functionality which all of the subjects requested was a tutorial for explaining the virtual environment and its functionality. It is also something that relevant literature urges developers to include. Jerald states that *"User should not have to rely on any external explanation"* [46]. However, this was something that was not prioritized because of the time aspect of the project, but should be prioritized in further development. One of Quesenbery 5Es are the principles is that the application is *Easy to Learn*. Although the application does not at the time, include a tutorial for conveying the controls to the user, none of the interview participants needed any further instructions than a simple verbal walk-through of the controller. It corresponds with replies the on Q11 in the questionnaire, where there was a unison agreement that most people felt they learned to use the system very quickly. Furthermore, the respondents did not feel that they needed to learn many things before they could get going with the system (Q14). It could also be related to that the functionality of the application is still quite limited and does not have a pervasive scope.

Another statement where both the interview subjects and questionnaire participants were in agreement was that the navigation felt intuitive and was easy to grasp. None of the subjects felt any discomfort when using the system, and the participants of the questionnaire felt that both the head- and physical movement were rendered naturally in the virtual environment. The implemented functionality relied on teleportation as a method for transporting the user, which is categorized by Jerald [46] as *magical interactions*. These are techniques which makes the users more powerful by equipping them with new and enhanced abilities. There exist several methods for transportation in VR, teleportation being one. Two different and commonly used approaches are locomotion (natural movements that are translated into in-app. movement) or the use of a gamepad (simulate walking by interacting with a controller). It was decided against these as one of the most widely accepted theories on motion sickness is the *sensory conflict theory* [122]. This theory states that motion sickness occurs when there is a conflict between sensations, primarily visual and vestibular. An example of this is if a user pushes a game controller to move forward in the virtual environment, but in the real environment remains stationary. It then exists an inconsistency between the sensations and motion sickness may occur.

The remarks regarding the inconsistency in teleportation methods are well grounded and indicate that there exists an ambiguity in the design of the navigation. Referring to both teleportations inside and between scenes as the same term causes confusion, and is also reflected through the responses in the questionnaire. In future versions, a more clear distinction between in scene- and level teleportation should be communicated to the user.

8.2.5 Data Visualization

All of the interview subjects that have an architectural background stated that they preferred the columns as a method for visualizing emissions, but at the same time that colours were essential to quickly identifying buildings with high emissions. It correlates well with the work of Jerald [46], stating that colours enables us to distinguish between objects and can capture the user's attention. While the colours are more natural to identify buildings quickly, it was remarked that it is hard to distinguish different magnitudes when the colours are similar. It was said that by using columns, one was presented with a difference in size, which is easier to grasp than for example the distance between "light green" to "slightly darker green". It could be solved by grouping values together and having a predefined gradient of, for example, ten colours going from best (green) to worst (red).

Another issue with solely relying on colours as an indication of performance is the cultural differences. This is discussed by Louis Hébert, a professor at Université du Québec à Rimouski, who states that the red/green scale is ambiguous as other cultures have other colours related to bad and good [123]. He also states that there is an individual aspect when seeing a colour represented as a value. He highlights that some people may look at the colour combination red and green as stop or go, but also another meaning entirely. Some people may correlate the green colour as growth or forest.

Since the same ambiguity was discovered when visualizing the emission weight as the equal number of planes and cars, in combination with the fact that the subjects did not read the explanatory text, the need for clear communication becomes apparent. It was a mistake to combine the use of a metaphorical presentation while relying on a text description to make the user fully understand the meaning of the symbolism. The metaphor itself should be so apparent that it is self-explanatory without any additional text information.

The findings of Donalek et al. [65] stated that the ability to visualize the data is the key to understanding them. It became even more apparent when several subjects said that, even as professionals, putting numbers into context can be challenging. At the same time, it is essential to identify the needs of different user groups. As subject E highlighted; it is important to have a different "language" when visualizing to diverse user groups.

Furthermore, subject E also mentioned that the visualization methods which made an impact on her, in turn, led to a strong impression on an emotional level. This is in direct correspondence with Tullis and Albert [64] who said it much harder to ignore the data when someone has a deeper level of understanding or even emotional attachment to them. However, Jerald [46] states that the user of a VR application will remember the experience according to the feeling they have when it is over. It is, therefore, essential to leave the user feeling positive to promote the agenda. Subject D suggested focusing on the positive aspects of an environmentally friendly neighbourhood instead of solely focusing on the negative aspects of embodied emissions. It could further improve the user experience and attitude towards ZENs and see the benefits of investing in environmentally friendly buildings.

8.2.6 Application Functionality

Subject A stated that he was positively surprised with the features of the application but elaborated on some of the potential pitfalls. If the buildings presented are too close to reality, the users may get false expectations for the end result. This would be problematic if the intended use were to sell environmental friendly buildings. On the other hand, by using a rather low level of details on buildings, we achieve more focus on what is important; visualization the of data. It also prevents users from thinking that irrelevant models are of importance. We also avoid a "graphics rabbit hole" of always having to make sure graphics are to the same level of detail. When designing a virtual environment, to resemble the reality as closely as possible, there are higher requirements to the graphics being consistent. If there is a gap in the level of detail, models will look out of place, and users might think they are interactable. One fundamental principle of graphical user interface design is consistency, as users will learn how to use the system faster and avoid confusion [124].

Some developers consider reality the gold standard of what one tries to achieve in VR. Jerald [46] argue that presence does not require photo-reality and states that being close to reality not necessarily means being better. He discusses that there are more important contributing factors for the users level of immersion, that being system responsiveness, motion in the virtual environment and depth cues. In other words; *"Being in a cartoon world can feel as real as a world captured by 3D scanners."*

Subject A referred to an article written by J.O. Olaussen and A. Oust [120], who studied the importance of energy labels in terms of prices in the Norwegian housing market. They concluded that energy labelling had little or no effect on housing prices. Olaussen and Oust further claim that one of the reasons for this is the fact that when people buy a dwelling, they are not much concerned with energy performance. There exist several factors that are considered more critical: availability of garden and outdoor space, location, the neighbourhood and size of the property. If this research is transmissible to our application, the focus should be on providing useful visualizations and showcasing of surrounding areas in ZENs. This was also something subject E envisioned; communicating to potential buyers the positive attributes of living in an environmentally friendly neighbourhood, and show potential buyers that they are not compromising by living there. By using the application as a framework for showcasing in a sales situation, it then again sets higher requirements to the level of detail in the graphical presentation.

Some of the explanations were deemed not detailed enough, for instance, the details behind calculating travelling distance. It led to one of the informants questioning the calculations behind the numbers. One may argue that this is natural scepticism, but on the other hand, not informing users about how we arrived at certain calculations might result in a loss of credibility for the application. In this case, we already received a good suggestion from one informant; clicking an item of interest displays excess information about it.

8.2.7 Application Potential for Stakeholders

All informants were excited about the technology and expressed several ideas for application potential. Regarding the general public, all informants saw this application as a way of engaging and educating people about ZEN, which corresponds to findings by Lee et al. [22]. As stated by subject B, if one has a effecitve way of visualizing emission data and people are aware of the situation, the influential force may be significant. As Rubio-Tamayo et al. [14] states, interacting with the data may be a way to democratize information in order to enhance accessibility and understanding, hence fostering citizen empowerment.

Informants working with architecture and stakeholder engagement wished to use the application as a collaboration tool for interdisciplinary communication to both motivate and get everybody on the same page. This, in addition to the communication barrier even between experts, indicates a need for a better communication platform between different parts involved in a project. For this purpose, VR as a technology is promising since it allows users to work with the 3D models as intended; in 3 dimensions [26]. They all saw the possibility to allow for BIM-model alteration and cooperation within the application, which could be solved by further development of the work of Hilfert and König [11]. This functionality is also being covered by applications such as *VirtuaView* by Dimension 10 [92], and it would be beneficial to use existing software instead of developing an application consisting of the same functionality.

However, ZENVR, in its current state, could still be used for translating barriers occurring with interdisciplinary cooperation. It can be achieved by using two or more monitors where the user of the application explains the visualizations to spectators. By allowing for multiple users in the application simultaneously, one could use the functionality and visualizations as talking points for an explanation which, according to Krokos et al. [20], improves learning ability.

Like subject E stated, a large part of communication is non-verbal, which could be a challenge with two or more simultaneous users of the system (multiplayer). Even though there is a debate in the field in regards to just *how* crucial non-verbal communication is, research concludes that it is significant nonetheless [125][126]. For covering non-verbal communication in ZENVR, the use of avatars could be researched for simultaneous use of the system.

8.3 Discussion of the Application

In addition to the findings from the interviews and user testing, a result of this project is the actual application. This section discusses what makes ZENVR different from other solutions, compares the solution to the other projects introduced in chapter 3, and presents its shortcomings.

First and foremost, what sets ZENVR apart from the other projects looked at is that it combines the essential functionality from the others. Table 8.1 compares all solutions to each other, and here we see that ZENVR is the only solutions which use VR technology, BIM-models, visualizes the data and can access the data from an online source.

Project	**VR**	**BIM**	**Visualization**	**Online Data**
ZENVR	Yes	Yes	Yes	Yes
ZEB Tool	No	No	No	No
Visual LCA in ZEN	No	No	Yes	No
CityBES	No	No	Yes	Yes
Fraunhofer Demo	Yes	Yes	Yes	No
VirtuaView	Yes	Yes	No	Unknown
Low-cost virtual reality environment for engineering and construction	Yes	Yes	No	No

Table 8.1: Comprison of ZENVR with other projects

When comparing ZENVR to other applications only concerning virtual reality, there is not much which sets it apart. ZENVR, like most other applications, uses the third party library SteamVR [114] for virtual reality support. This makes support for the most popular virtual reality solutions very easily since the libraries are created and maintained by Steam [127]. For ZENVR it was decided against using the pre-made teleportation and interaction solutions from SteamVR, because we wanted to make it easier in the future to port it for mobile platforms. One can argue that this might affect the usability of the application. Users who are familiar with other VR applications made with the same library might, upon recognizing the controller functionality, know precisely how to interact with the virtual environment. However, the functionality of ZENVR is still the same as if we used pre-made solutions, but the execution and design are a bit different.

Different from the other projects looked at is that for instance Hilfert and König [11] only presented a method for exporting BIM-models as a proof of concept and not a functioning application for interacting with and inspecting the models. They also use the Leap Motion Controller to interact with the application and writes that it tends to give false positives and misdetection of left and right hand and that it needs to be paired with a Microsoft Kinect [128] for promising results. The result of this is a more complex setup than we aim to achieve, but might be more intuitive for the user to interact with free hands rather than with a controller. However, Dimension10 [92] with their VirtuaView [26] achieves the same results but by using a regular HTC Vive controller, although they are also not visualizing data, only interacting with a BIM-model.

For importing BIM-models to ZENVR almost the same pipeline as presented by Bille et al. [12] is used but without the 3DS Max step. The models used are fundamental, and we are not dependant on realistic and complex 3D-materials. However, we still need to clean up the model a bit, and therefore, we use Autodesk Maya as an intermediary. Autodesk 3DS Max, which Bille et al. use, is also an alternative to cleaning up the model, but it is limited to Windows computers, which makes it platform dependent.

For visualizing data, ZENVR is unique compared to the other projects included in this research. It has similarities with projects developed at Fraunhofer in Singapore, much because they were a great inspiration and help when developing ZENVR. Where ZENVR differs from the projects in Singapore is that it automatically calculates and generates several types of visualizations. ZENVR is also on a neighbourhood scale while the Fraunhofer demos were concentrated on one building. If we exclude that visualizations must be on BIM-models, Donalek et al. [65] present some example software where numerical and spatial data are visualized in VR. Here, the user is standing in a coordinate system with data visualized by sizes and colours all around. This might be a better solution for visualizing data for expert users, rather than using more trivial methods as is being done with ZENVR.

ZENVR contributes to the ZEN Research Center by allowing for a new and intuitive way of interacting with and viewing Key Performance Indicators. ZENVR presents a new way of combining KPIsdata with building information models and allows for users with little to no preliminary knowledge of either ZENs or KPIs to put emission data into context and grasp the size of the numbers presented. It can be used for communication with and between various stakeholders and, like findings showed, translate interdisciplinary barriers.

Where ZENVR falls short is the fact that it still has some limiting functionality and available visualizations, and in its current state, it might be too limited for both stakeholder participation and communication platform. However, as we have stated earlier, it is still just the foundation upon which ZEN can expand and implement new features and visualizations as pleased. The application is programmed to be modular, so new data sources can be connected and new KPIs implemented. User testing revealed that the text-based information is somewhat poorly communicated to the user, and some menus and text will need a redesign. All users also stated that without the initial explanation of how to use the application, they would have a hard time figuring out how to use the application. As a result of this, we see that the application needs a tutorial option before letting the user explore the solution.

To summarize, the way we see it is that ZENVR can take on either one of two directions. It can be further developed for collaboration between stakeholders in the planning phase of a project where two or more users can share an experience and discuss around a BIM. However, this approach is already well covered by alternative applications which are already in use, such as VirtuaView, and to take ZENVR in this direction seems unnecessary. The other direction is to use ZENVR as a communication and showcase platform for informing and educating its user about the benefits of a ZEN. From our findings, we learned that ZENVR, in its current state, provides an engaging experience that can make an impact on the user. By implementing additional KPIs and data sources, ZENVR could still be a communication platform for stakeholders, while also serving the purpose of informing the general public.

Chapter 9

Conclusion & Further Work

This project explored the utilization of emerging virtual reality-technologies as a tool for engaging and interacting with emission data in new and immersive ways. As a result, a VR-application named ZENVR was developed in Unity. The application is connected to a database containing life cycle assessments of 11 projects. Furthermore, the application and its potential were evaluated through the use of semi-structured expert interviews. Usability testing through a questionnaire was applied to supplement the evaluation of the application. The participants of these two methods of data collection all tested the application on the same terms, with a set of predefined tasks. q

> *1: How can Virtual Reality be used to visualize Key Performance Indicators in sustainable neighbourhoods?*

Virtual reality has already been proven to be a promising platform for communicating complex data, but earlier research has been focused on visualizing data for scientists and not the general public. Through ZENVR, it has been proved that virtual reality can be used as a data visualization tool for understandably presenting data by using well-known concepts, metaphors and objects. By utilizing VR technology, one can appeal to emotional factors by creating a presence inducing environment, which subsequently may result in an emotional experience when interacting with the application. Furthermore, ZENVR shows that these principles can be utilized to visualize the Key Performance Indicators from ZEN. These visualization techniques are exemplified through greenhouse gas emissions related to the life cycle of materials, but the principles are transferable to numerical data in general.

> *(a) Which form of data visualization is most beneficial for comprehending the Key Performance Indicators for different user groups?*

ZENVR allows for selecting between several forms of data visualizations. Expert interviews revealed that professionals preferred traditional visualization approach, i.e. columns, colours and numbers when looking at KPIs. It was discovered that in order to make a lasting impression, which ultimately is the goal of ZENVR, one has to use visualizing methods which appeal to emotions. It can be achieved by anchoring the visualizations to emotional aspects by using the principles mentioned earlier, for instance, using sizes to make the user feel small or movement of objects for dramaturgical effects. The visualization type which made the most significant impact on all users was when numbers were put into context by using relatable objects from everyday life at a human scale.

> *(b): How can Virtual Reality be used to improve stakeholder participation in sustainable neighbourhood projects?*

The potential areas where ZENVR can be used to improve stakeholder participation were: citizen engagement, promotion and the advertisement of ZENs, tool for interdisciplinary communication and collaboration between professionals. With its immersive properties, virtual reality has proven to be a suitable platform to spark engagement among its users. Through a well designed virtual environment, highlighting the beneficial parts of an environmentally friendly neighbourhood, all subjects agreed that this has a considerable potential to promote sustainable neighbourhoods. In addition, virtual reality allows for displaying data in new perspectives, making it understandable for different stakeholders, reducing the barriers of interdisciplinary communication and collaboration.

9.1 Further Work

The application in its current state is still experimental and a foundation for further development. It would be interesting to see more KPIs included in the application and what effect this may have on stakeholders. Also, if the application is further developed, user testing might reveal if usability improvement suggestions from the latest iteration and user testing were useful. With a further developed application, interviews could be extended to experts in fields outside the original scope to see if the response differs from the original findings. Furthermore, interviews could be conducted on average users to get insight from a new user group and see if any other potential use cases not accounted for exists.

From a technical point of view, some alterations and features which might benefit the application surfaced from conducting user tests and interviews. These revolve mostly around the user interface and how it might be altered to suit the user's needs and understanding better. It would be beneficial to test the application with other virtual reality systems to see if it is compatible out of the box, or what alterations are necessary.

Literature which was not researched in depth, but could be interesting to look at for further development, are presented in 3. The literature in question explored similar techniques or aspects as this thesis but did not resemble the research enough to be further explored.

. There exist other applications which use BIM-models to showcase buildings, and since many of the informants requested functionality regarding this, the subject should be explored.

Lastly, to gain insight and learn about useful solutions to the challenges faced in this thesis, it would be useful to test similar applications to ZENVR. There exist other applications which use BIM-models to showcase buildings, and since many of the informants requested functionality regarding this, that subject should be explored.

Bibliography

[1] Donald A Norman. *The design of everyday things*. Basic Books, 2013. ISBN 978-0-465-00394-5.

[2] Alan R Hevner. A Three Cycle View of Design Science Research. *Scandinavian Journal of Information Systems*, 19(2), 2007. URL https://aisel.aisnet.org/cgi/viewcontent.cgi?article=1017&context=sjis. [Accessed 23.03.2019].

[3] Klaas-Jan Stol, Paul Ralph, and Brian Fitzgerald. *Grounded Theory in Software Engineering Research: A Critical Review and Guidelines*. IEEE, 2016. URL https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7886897.

[4] Alistair Sutcliffe and Brian Gault. Heuristic evaluation of virtual reality applications. *Interacting with Computers*, 16(4):831–849, 2004. doi: 10.1016/j.intcom.2004.05.001. URL https://www.researchgate.net/publication/222086342_Heuristic_evaluation_of_virtual_reality_applications. [Accessed 04.04.2019].

[5] Fufa S. M. Baer D. Sartori I. & Andresen I. Wiik, M. K. The ZEN definition – a guideline for the ZEN pilot areas. *SINTEF akademisk forlag*, page 80, 2018. URL https://fmezen.no/wp-content/uploads/2019/03/ZEN-Report-no-11_The-ZEN-definition_A-guideline-for-the-ZEN-pilot-areas.pdf. [Accessed 27.03.2019].

[6] CityXChange. Demo projects: Trondheim. Online, 2019. URL https://cityxchange.eu/our-cities/trondheim/. [Accessed 27.05.2019].

[7] Google Inc. Google Cardboard. Online, 2019. URL https://vr.google.com/cardboard/. [Accessed 07.05.2019].

[8] Christoph Anthes, Rubén García Hernandez, Markus Wiedemann, and Dieter Kranzlmüller. State of the art of virtual reality technologies. 03 2016. doi: 10.1109/AERO.2016.7500674.

[9] HTC Inc. HTC Vive. Online, 2019. URL https://vive.com. [Accessed 10.12.2018].

[10] NS 3451:2009. NS 3451:2009 - Table of Building Elements. Standard, Standards Norway, Lysaker, Norway, 2009.

[11] Thomas Hilfert and Markus König. Low-cost virtual reality environment for engineering and construction. *Visualization in Engineering*, 4(1):2, 2016. ISSN 2213-7459. doi: 10.1186/s40327-015-0031-5. URL https://doi.org/10.1186/s40327-015-0031-5. [Accessed 03.10.2018].

[12] Ross Bille, Shamus P. Smith, Kim Maund, and Graham Brewer. Extending Building Information Models into Game Engines. *Proceedings of the 2014 Conference on Interactive Entertainment - IE2014*, page 1–8, Dec 2014. doi: 10.1145/2677758.2677764. URL `https://dl.acm.org/citation.cfm?id=2677764`. [Accessed 23.04.2019].

[13] Mike Alger. Visual design methods for virtual reality. 2015. URL `https://scholar.google.com/scholar?client=firefox-b-d&um=1&ie=UTF-8&lr&cites=14427975336980654438`. [Accessed 30.04.2019].

[14] H. Gómez J.L. Rubio-Tamayo, M. Barro. Digital data visualization with interactive and virtual reality tools. review of current state of the art and proposal of a model. *Revista ICONO14 Revista científica de Comunicación y Tecnologías emergentes*, 16, 07 2018. doi: 10.7195/ri14.v16i2.1174. URL `https://www.researchgate.net/publication/326098388_Digital_Data_Visualization_with_Interactive_and_Virtual_Reality_Tools_Review_of_Current_State_of_the_Art_and_Proposal_of_a_Model`. [Accessed 09.05.2019].

[15] CityBES. City Building Energy Saver (CityBES). Online, 2019. URL `https://citybes.lbl.gov/`. [Accessed 27.05.2019].

[16] Steven J. Taylor, Robert Bogdan, and Marjorie L. DeVault. *Introduction to qualitative research methods a guidebook and resource*. Wiley, 2016.

[17] Albino, V. and Berardi, U. and Dangelico, R. Smart Cities: Definitions, Dimensions, Performance, and Initiatives. *Journal of Urban Technology*, 22:2015, 02 2015. doi: 10.1080/10630732.2014.942092.

[18] FME ZEN. FME ZEN - Homepage. Online, 2019. URL `https://fmezen.no/`. [Accessed 10.12.2018].

[19] Mathisen M. Løvhaug S. Houliman Wiberg, A. and M. Erdt. Visualisation of KPIs in sustainable neighbourhoods for improved stakeholder participation. In *Sustainable Built Environment D-A-CH Conference 2019, Transition Towards a Net Zero Carbon Built Environment*. Graz University of Technology, Austria, 2019. Conference Paper - Under Review.

[20] Eric Krokos, Catherine Plaisant, and Amitabh Varshney. Virtual memory palaces: immersion aids recall. *Virtual Reality*, 23(1):1–15, 2019. ISSN 1434-9957. doi: 10.1007/s10055-018-0346-3. URL `https://doi.org/10.1007/s10055-018-0346-3`. [Accessed 15.03.2019].

[21] Sol Rogers. Virtual Reality: The Learning Aid Of The 21st Century. Online, 2019. URL `https://www.forbes.com/sites/solrogers/2019/03/15/virtual-reality-the-learning-aid-of-the-21st-century/#4f72ff25139b`. [Accessed 12.05.2019].

[22] Elinda Ai-Lim Lee, Kok Wai Wong, and Chun Che Fung. How does desktop virtual reality enhance learning outcomes? a structural equation modeling approach. *Computers Education*, 55(4):1424 – 1442, 2010. ISSN 0360-1315. doi: https://doi.org/

10.1016/j.compedu.2010.06.006. URL http://www.sciencedirect.com/science/article/pii/S0360131510001661. [Accessed 09.05.2019].

[23] Youngkyun Baek, Jaeyeob Jung, and Bokyeong Kim. What makes teachers use technology in the classroom? Exploring the factors affecting facilitation of technology with a Korean sample. *Computers Education*, 50(1):224 – 234, 2008. ISSN 0360-1315. doi: https://doi.org/10.1016/j.compedu.2006.05.002. URL http://www.sciencedirect.com/science/article/pii/S036013150600100X. [Accessed 13.05.2019].

[24] Zahira Merchant, Ernest T. Goetz, Lauren Cifuentes, Wendy Keeney-Kennicutt, and Trina J. Davis. Effectiveness of virtual reality-based instruction on students' learning outcomes in k-12 and higher education: A meta-analysis. *Computers Education*, 70:29 – 40, 2014. ISSN 0360-1315. doi: https://doi.org/10.1016/j.compedu.2013.07.033. URL http://www.sciencedirect.com/science/article/pii/S0360131513002108. [Accessed 13.05.2019].

[25] Ben Dalton and Maxwell Parfitt. Immersive visualization of building information models. *Design innovation research center working paper*, 6(1.0), 2013. URL https://dl.acm.org/citation.cfm?id=129892. [Accessed 09.01.2019].

[26] Eirik Helland Urke. Veidekke og Statsbygg sparer penger med norsk VR-teknologi. Online, Feb 2018. URL https://www.tu.no/artikler/veidekke-og-statsbygg-sparer-penger-med-norsk-vr-teknologi/430743. [Accessed 02.05.2019].

[27] Alan Hevner and Samir Chatterjee. *Design Research in Information Systems: Theory and Practice*, volume 22 of *Integrated Series in Information Systems*. 2010. ISBN 978-1-4419-5652-1.

[28] Fraunhofer Singapore. Fraunhofer - Singapore. Online, 2019. URL https://www.fraunhofer.sg/en/fraunhofer-singapore.html. [Accessed 14.05.2019].

[29] Unity Technologies. Unity 3D. Online, 2019. URL https://unity.com/. [Accessed 30.04.2019].

[30] Eirik Resch and Inger Andresen. A Database Tool for Systematic Analysis of Embodied Emissions in Buildings and Neighborhoods. *buildings*, 2018. URL https://www.researchgate.net/publication/327007193_A_Database_Tool_for_Systematic_Analysis_of_Embodied_Emissions_in_Buildings_and_Neighborhoods. [Accessed 10.05.2019].

[31] Anselm L Strauss and Juliet M Corbin. *Basics of qualitative research*. Sage Publications, 1998.

[32] Research Centre on Zero Emission Neighbourhoods in Smart Cities. *ZEN Pilot Projects - Mapping of the Pilot Projects Within the Research Centre on Zero Emission Neighbourhoods in Smart Cities*. 2018.

[33] The Knowledge Axis Trondheim Pilot Project. Campusutvikling - NTNU. 2019. [Accessed 26.03.2019].

[34] Anne Torres Mollan. Kommunedelplan for Sluppen. 2019. URL https://sites.google.com/trondheim.kommune.no/kdpsluppen/start. [Accessed 15.03.2019].

[35] Randi Lile. Klimasats - støtte til klimasatsing i kommunene. Online, 2018. URL https://www.miljokommune.no/Documents/Klima/Klimasats%20s%C3%B8knader%20og%20tilsagn%202018/Klimasats%20-%20S%C3%B8knad%20om%20st%C3%B8tte%20til%20klimasatsing%20i%20kommunene%202018%20-%20Nidarvoll%20som%20ZEN%20pilot.pdf. [Accessed 28.05.2019].

[36] WikiStrinda. Nidarvoll Skole. Online, 2014. URL https://www.strindahistorielag.no/wiki/index.php?title=Nidarvoll_skole. [Accessed 15.03.2019].

[37] Ronald T Azuma. A survey of augmented reality. *Presence: Teleoperators & Virtual Environments*, 6(4):355–385, 1997. URL https://www.mitpressjournals.org/doi/abs/10.1162/pres.1997.6.4.355. [Accessed 03.10.2018].

[38] Kangdon Lee. Augmented reality in education and training. *TechTrends*, 56(2):13–21, 2012.

[39] R. Azuma, Y. Baillot, R. Behringer, S. Feiner, S. Julier, and B. MacIntyre. Recent advances in augmented reality. *IEEE Computer Graphics and Applications*, 21(6):34–47, Nov 2001. ISSN 0272-1716. doi: 10.1109/38.963459. [Accessed 03.10.2018].

[40] Niantic Inc. Pokémon Go. Online. URL https://www.pokemongo.com/en-us/.

[41] Snap Inc. Snapchat. Online, 2019. URL https://snapchat.com. [Accessed 22.05.2019].

[42] Microsoft Inc. Microsoft HoloLens: Mixed Reality Technology for Business. Online, 2019. URL https://www.microsoft.com/en-us/hololens. [Accessed 27.02.2019].

[43] Magic Leap Inc. Magic Leap. Online, 2019. URL https://www.magicleap.com/. [Accessed 27.05.2019].

[44] Ivan E. Sutherland. The ultimate display. In *Proceedings of the IFIP Congress*, pages 506–508, 1965. URL http://worrydream.com/refs/Sutherland%20-%20The%20Ultimate%20Display.pdf. [Accessed 24.04.2019].

[45] Oxford University Press. Virtual Reality. Online, 2019. URL https://en.oxforddictionaries.com/definition/virtual_reality. [Accessed 24.05.2019].

[46] Jason Jerald. *The VR Book: Human-Centered Design for Virtual Reality*. Association for Computing Machinery and Morgan & Claypool, 2016.

[47] M Heilig. The cinema of the future. *Multimedia: From Wagner to Virtual Reality*, pages 239–251, 01 2001. URL https://www.researchgate.net/publication/313771764_The_cinema_of_the_future. [Accessed 24.04.2019].

[48] USC Institute for Creative Technologies. FOV2GO-project. Online, 2019. URL http://projects.ict.usc.edu/mxr/diy/fov2go/. [Accessed 05.05.2019].

[49] Facebook Technologies, LLC. Oculus Rift. Online, 2019. URL `https://www.oculus.com/rift/`. [Accessed 23.04.2019].

[50] Fove Inc. Fove. Online, 2019. URL `https://www.getfove.com/`. [Accessed 26.06.2019].

[51] StarVR Corp. Starvr. Online, 2019. URL `https://www.starvr.com/`. [Accessed 26.03.2019].

[52] Google Inc. Google VR. Online, 2019. URL `https://vr.google.com/`. [Accessed 26.03.2019].

[53] Ben Lang. Latest HTC Vives Are Shipping with Tweaked Base Stations, Redesigned Packaging. Online, 2017. URL `https://www.roadtovr.com/latest-vive-shipping-with-tweaked-base-stations-redesigned-packaging/`. [Accessed 22.05.2019].

[54] Unity Technologies. Unity Multiplatform. Online, 2019. URL `https://unity3d.com/unity/features/multiplatform`. [Accessed 30.04.2019].

[55] Microsoft. C Programming Guide. Online, 2019. URL `https://docs.microsoft.com/en-us/dotnet/csharp/programming-guide/`. [Accessed 03.05.2019].

[56] VRFocus. Unity CEO: '5.5 million developers' Working with Videogame Dev Engine. URL `https://www.vrfocus.com/2016/05/unity-ceo-5-5-million-developers-working-with-videogame-dev-engine/`.

[57] Autodesk Inc. Revit. Online, 2019. URL `https://www.autodesk.com/products/revit/overview`. [Accessed 23.01.2019].

[58] Michael J. Muwanguzi. Microfilmmaker Magazine - Software Review: Maya. Online, 2010. URL `http://www.microfilmmaker.com/reviews/Issue56/Maya11_1.html`. [Accessed 22.05.2019].

[59] ECOINVENT. Ecoinvent Database v.3.5. Online, 2018. URL `www.ecoinvent.org`. [Accessed 27.05.2019].

[60] NS-EN 15978:2011. NS-EN 15978:2011: Assessment of environmental performance of buildings - Calculation method. Standard, European Committee for Standardization, Brussels, Belgium, 2012.

[61] Houlihan Wiberg A. Schlanbusch R. Wiik, M. and T. Kristjansdottir. The ZEB Tool Manual-User-Guide, Version 1. ZEN Internal Memo, The Research Centre for Zero Emission Buildings, Trondheim, Norway, 2017.

[62] ZEB. The Research Centre on Zero Emission Buildings. Online, 2019. URL `http://www.zeb.no/index.php/en/`. [Accessed 11.05.2019].

[63] Bernard Marr. How VR Will Revolutionize Big Data Visualizations. Online, 2016. URL `https://www.forbes.com/sites/bernardmarr/2016/05/04/how-vr-will-revolutionize-big-data-visualizations/`. [Accessed 09.05.2019].

[64] Thomas Tullis and William Albert. *Measuring the User Experience: Collecting, Analyzing, and Presenting Usability Metrics: Second Edition.* 01 2008. ISBN 0123735580.

[65] Ciro Donalek, S. G. Djorgovski, Alex Cioc, Anwell Wang, Jerry Zhang, Elizabeth Lawler, Stacy Yeh, Ashish Mahabal, Matthew Graham, and Andrew et al. Drake. Immersive and collaborative data visualization using virtual reality platforms. *2014 IEEE International Conference on Big Data (Big Data)*, 2014. doi: 10.1109/bigdata.2014.7004282. URL https://arxiv.org/abs/1410.7670. [Accessed 09.05.2019].

[66] C. Demiralp, C.D. Jackson, D.B. Karelitz, S. Zhang, and D.H. Laidlaw. CAVE and fishtank virtual-reality displays: a qualitative and quantitative comparison. *IEEE Transactions on Visualization and Computer Graphics*, 12(3):323–330, 2006. doi: 10.1109/tvcg.2006.42. URL https://www.ncbi.nlm.nih.gov/pubmed/16640246. [Accessed 09.05.2019].

[67] Bireswar Laha, Doug A. Bowman, and John J. Socha. Effects of VR System Fidelity on Analyzing Isosurface Visualization of Volume Datasets. *IEEE Transactions on Visualization and Computer Graphics*, 20(4):513–522, 2014. doi: 10.1109/tvcg.2014.20. URL https://www.ncbi.nlm.nih.gov/pubmed/24650978. [Accessed 09.05.2019].

[68] S. Zhang, C. Demiralp, D. F. Keefe, M. DaSilva, D. H. Laidlaw, B. D. Greenberg, P. J. Basser, C. Pierpaoli, E. A. Chiocca, and T. S. Deisboeck. An immersive virtual environment for DT-MRI volume visualization applications: a case study. In *Proceedings Visualization, 2001. VIS '01.*, pages 437–584, Oct 2001. doi: 10.1109/VISUAL.2001.964545. URL https://ieeexplore.ieee.org/abstract/document/964545/citations?tabFilter=papers#citations. [Accessed 09.05.2019].

[69] Eric D. Ragan, Regis Kopper, Philip Schuchardt, and Doug A. Bowman. Studying the effects of stereo, head tracking, and field of regard on a small-scale spatial judgment task. *IEEE Transactions on Visualization and Computer Graphics*, 19 (5):886–896, 2013. doi: 10.1109/tvcg.2012.163. URL https://ieeexplore.ieee.org/document/6261311. [Accessed 09.05.2019].

[70] Jian Chen, Haipeng Cai, Alexander P. Auchus, and David H. Laidlaw. Effects of Stereo and Screen Size on the Legibility of Three-Dimensional Streamtube Visualization. *IEEE Transactions on Visualization and Computer Graphics*, 18(12): 2130–2139, 2012. doi: 10.1109/tvcg.2012.216. URL https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4729196/. [Accessed 09.05.2019].

[71] George Lakoff and Mark Johnson. Metaphors We Live By. *Bibliovault OAI Repository, the University of Chicago Press*, 59, 03 1983. doi: 10.2307/430414. URL https://www.researchgate.net/publication/37688084_Metaphors_We_Live_by/citation/download. [Accessed 10.05.2019].

[72] Dennis C. Neale and John M. Carroll. The Role of Metaphors in User Interface Design. *Handbook of Human-Computer Interaction*, pages 441–462, 1997. doi: 10.1016/b978-044481862-1.50086-8. URL https://www.sciencedirect.com/science/article/pii/B9780444818621500868?via%3Dihub. [Accessed 03.05.2019].

[73] Leap Motion Inc. Leap Motion. Online, 2019. URL https://www.leapmotion.com/. [Accessed 23.04.2019].

[74] Epic Games Inc. Make Something Unreal. Online, 2019. URL https://www.unrealengine.com/en-US/what-is-unreal-engine-4. [Accessed 22.05.2019].

[75] BIMserver.org. Open source BIMserver. Online, 2019. URL http://bimserver.org/. [Accessed 24.04.2019].

[76] Autodesk Inc. Export to Unity Plugin for Autodesk Revit. Online, 2019. URL https://apps.autodesk.com/RVT/en/Detail/Index?id=3759955758891315427&appLang=en&os=Win64. [Accessed 01.05.2019].

[77] Autodesk Inc. 3Ds Max: 3D Modeling, Animation & Rendering Software. Online, 2019. URL https://www.autodesk.com/products/3ds-max/overview. [Accessed 24.04.2019].

[78] Carolina Cruz-Neira, Daniel J. Sandin, Thomas A. DeFanti, Robert V. Kenyon, and John C. Hart. The CAVE: Audio Visual Experience Automatic Virtual Environment. *Commun. ACM*, 35(6):64–72, June 1992. ISSN 0001-0782. doi: 10.1145/129888.129892. URL http://doi.acm.org/10.1145/129888.129892. [Accessed 09.01.2019].

[79] Mike Alger. Mike Alger: About. Online, 2019. URL http://mikealger.com/professional/. [Accessed 30.04.2019].

[80] Alex Chu. VR Design: Transitioning from a 2D to 3D Design Paradigm. Online, 2014. URL http://cargocollective.com/alexchu/Presentation-VR-Design-Transitioning-from-a-2D-to-a-3D-Design-Paradigm. [Accessed 22.05.2019].

[81] 9241-11:2018. ISO 9241-11:2018 Usability: Definitions and concepts. Standard, International Organization for Standardization, Geneva, Switzerland, 2018. URL https://www.iso.org/standard/63500.html. [Accessed on 27.03.2019].

[82] Whitney Quesenbery. *Dimensions of Usability:Defining the Conversation, Driving the Process*. 2003.

[83] J. Nielsen. Iterative user-interface design. *Computer*, 26(11):32–41, 1993. doi: 10.1109/2.241424. URL https://dl.acm.org/citation.cfm?id=619982. [Accessed 29.03.2019].

[84] Ed Huaihsin Chi and John Riedl. An operator interaction framework for visualization systems. In *Proceedings of the 1998 IEEE Symposium on Information Visualization*, INFOVIS '98, pages 63–70, Washington, DC, USA, 1998. IEEE Computer Society. ISBN 0-8186-9093-3. URL http://dl.acm.org/citation.cfm?id=647341.721078. [Accessed 09.05.2019].

[85] Aoife Houlihan Wiberg. ZEN Work Package 1.3. Unpublished, 2018.

[86] Mads Løkeland Slåke and Håvard Auklend. Visual LCA in ZENs: Interactive visualisation framework for materials assocated GHG emissions in preliminary neighbourhood design stages. June 2017. URL https://view.publitas.com/p222-15565/ntnu-masters-thesis-visual-lca-in-zens_havard-auklend-mads-slake/page/1. [Accessed 26.03.2019].

[87] Katrine Peck Sze Lim. ZEB Living Lab Pilot Project. Online, 2019. URL https://www.zeb.no/index.php/en/pilot-projects/158-living-lab-trondheim. [Accessed 10.09.2018].

[88] EnergyPlus. EnergyPlus v.9.1.0. Online, 2019. URL https://energyplus.net/. [Accessed 27.05.2019].

[89] A. Houlihan Wiberg. From net Zero Emission Buildings (ZEBs) to net Zero Emission Neighbourhoods (ZENs) – possibilties and challenges. The Lawrence Berkeley National Laboratory, University of California. Seminar.

[90] Veidekke ASA. Veidekke i norge. Online, 2019. URL http://veidekke.no/. [Accessed 30.05.2019].

[91] Statsbygg. Statsbygg. Online, 2019. URL www.statsbygg.no. [Accessed 28.05.2019].

[92] Dimension 10. Share all your ideas with virtual reality. Online, 2019. URL https://dimension10.com/. [Accessed 02.05.2019].

[93] Peter Hemmersam, Nicole Martin, Even Westvang, Jonny Aspen, and Andrew Morrison. Exploring urban data visualization and public participation in planning. *Journal of Urban Technology*, 22(4):45–64, 2015. doi: 10.1080/10630732.2015.1073898. URL https://doi.org/10.1080/10630732.2015.1073898.

[94] Xiao Li, Wen Yi, Hung-Lin Chi, Xiangyu Wang, and Albert P.C. Chan. A critical review of virtual and augmented reality (vr/ar) applications in construction safety. *Automation in Construction*, 86:150 – 162, 2018. ISSN 0926-5805. doi: https://doi.org/10.1016/j.autcon.2017.11.003. URL http://www.sciencedirect.com/science/article/pii/S0926580517309962.

[95] Jack Steven Goulding, Farzad Pour Rahimian, and Xiangyu Wang. Virtual reality-based cloud bim platform for integrated aec projects. *Journal of Information Technology in Construction*, 19:308–325, September 2014. URL https://strathprints.strath.ac.uk/58018/.

[96] Sami Abbas, Anderson Augusto Simiscuka, and Gabriel-Miro Muntean. A platform agnostic solution for inter-communication between virtual reality devices. 04 2019.

[97] Herbert A. Simon. *The sciences of the artificial (3rd ed.)*. MIT Press, 1996. ISBN 9780585360102.

[98] Barney G. Glaser and Anselm Leonard Strauss. *The Discovery Of Grounded Theory: Strategies For Qualitative Research*, volume 3. 01 1967. doi: 10.1097/00006199-196807000-00014.

[99] C.B. Seaman. Qualitative methods in empirical studies of software engineering. *IEEE Transactions on Software Engineering*, 25(4):557–572, 1999. doi: 10.1109/32.799955. URL https://ieeexplore.ieee.org/document/799955. [Accessed 09.04.2019].

[100] EU GDPR. Gdpr. Online, 2019. URL https://eugdpr.org/. [Accessed 29.05.2019].

[101] Encyclopedia Britannica. Rensis Likert. Online. URL https://www.britannica.com/biography/Rensis-Likert.

[102] John S. Uebersax. Likert scales: Dispelling the confusion. Online, 2006. URL https://john-uebersax.com/stat/likert.htm. [Accessed 08.04.2019].

[103] Colm O'Muircheartaigh, George Gaskell, and Daniel B. Wright. Weighting anchors: Verbal and numeric labels for response scales. *Weighting anchors: Verbal and numeric labels for response scales*, 11(3):295–307, 1995. URL http://www.websm.org/db/12/16557/Web%20Survey%20Bibliography/Weighting_anchors_Verbal_and_numeric_labels_for_response_scales/. [Accessed 24.04.2019].

[104] I.E. Allen and C.A. Seaman. Likert scales and data analyses. *Quality Progress*, 40: 64–65, 07 2007. URL https://www.researchgate.net/publication/279898134_Likert_scales_and_data_analyses. [Accessed 04.05.2019].

[105] Susan Jamieson. Likert scales: how to (ab)use them. *Medical Education*, 38(12):1217–1218, 2004. doi: 10.1111/j.1365-2929.2004.02012.x. URL https://onlinelibrary.wiley.com/doi/full/10.1111/j.1365-2929.2004.02012.x. [Accessed 24.04.2019].

[106] Fred Decker. How to average likert scales. Online, 2019. URL https://sciencing.com/average-likert-scales-6181662.html. [Accessed 12.05.2019].

[107] Jeff Sauro. Can you take the mean of ordinal data? Online, 2016. URL https://measuringu.com/mean-ordinal/. [Accessed 22.05.2019].

[108] Achilleas Kostoulas. On likert scales, ordinal data and mean values. Online, 2013. URL https://achilleaskostoulas.com/2013/02/13/on-likert-scales-ordinal-data-and-mean-values/. [Accessed 13.05.2019].

[109] Roy S. Kalawsky. VRUSE—a computerised diagnostic tool: for usability evaluation of virtual/synthetic environment systems. *Applied Ergonomics*, 30(1):11–25, 1999. doi: 10.1016/s0003-6870(98)00047-7. URL https://www.sciencedirect.com/science/article/pii/S0003687098000477. [Accessed 29.03.2019].

[110] PTC Inc. Vuforia Library for Unity. Online, 2019. URL https://library.vuforia.com/articles/Training/getting-started-with-vuforia-in-unity.html. [Accessed 22.05.2019].

[111] OGC. CityGML. Online, 2019. URL https://www.opengeospatial.org/standards/citygml. [Accessed 27.05.2019].

[112] OpenStreetMap Foundation. OpenStreetMap. Online, 2019. URL https://www.openstreetmap.org. [Accessed 17.01.2019].

[113] Google Inc. Quickstart for Google VR. Online, 2019. URL https://developers.google.com/vr/develop/unity/get-started-android. [Accessed 04.12.2018].

[114] Valve Corp. Steamvr plugin. Online, 2019. URL https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647. [Accessed 22.05.2019].

[115] Robert C Martin. Design principles and design patterns. *Object Mentor*, 1(34):597, 2000. URL http://staff.cs.utu.fi/staff/jouni.smed/doos_06/material/DesignPrinciplesAndPatterns.pdf. [Accessed 09.05.2019].

[116] Samuel Oloruntoba. SOLID: The First 5 Principles of Object Oriented Design. Online, 2015. URL https://scotch.io/bar-talk/s-o-l-i-d-the-first-five-principles-of-object-oriented-design. [Accessed 09.05.2019].

[117] Dhurim Kelmendi. SOLID principles made easy, Nov 2017. URL https://medium.com/@dhkelmendi/solid-principles-made-easy-67b1246bcdf. [Accessed 09.05.2019].

[118] Unknown. OSM2World. Online, 2015. URL http://osm2world.org/. [Accessed 17.01.2019].

[119] HTC Corp. About the VIVE controller. Online, 2019. URL https://www.vive.com/us/support/vive/category_howto/about-the-controllers.html. [Accessed 22.05.2019].

[120] Jon Olaussen and Are Oust. Energy performance certificates- informing the informed or the indifferent? *Energy Policy*, 111:246–254, 12 2017. doi: 10.1016/j.enpol.2017.09.029. URL https://www.researchgate.net/publication/320373715_Energy_performance_certificates-_Informing_the_informed_or_the_indifferent. [Accessed 13.05.2019].

[121] Mel Slater. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 364:3549–57, 12 2009. doi: 10.1098/rstb.2009.0138. URL https://www.researchgate.net/publication/38062247_Place_Illusion_and_Plausibility_Can_Lead_to_Realistic_Behaviour_in_Immersive_Virtual_Environments. [Accessed 13.05.2019].

[122] J. T. Reason and J.J. Brand. Motion sickness. *The American Journal of Psychology*, 90, 03 1977. doi: 10.2307/1421659. URL https://www.researchgate.net/publication/232565177_Motion_Sickness. [Accessed 13.05.2019].

[123] Louis Hébert. Elements of semiotics. Online, Unknown. URL http://www.signosemio.com/elements-of-semiotics.asp#bibliography. [Accessed 13.05.2019].

[124] Anton Nikolov. Design principle: Consistency. Online, 2017. URL https://uxdesign.cc/design-principle-consistency-6b0cf7e7339f. [Accessed 14.03.2019].

[125] Jeff Thompson. Is nonverbal communication a numbers game? Online, Sep 2011. URL https://www.psychologytoday.com/us/blog/beyond-words/201109/is-nonverbal-communication-numbers-game. [Accessed 14.05.2019].

[126] Philip Yaffe. The 7% rule. *Ubiquity*, 2011(October):1–5, 2011. doi: 10.1145/2043155.2043156. URL https://ubiquity.acm.org/article.cfm?id=2043156. [Accessed 14.05.2019].

[127] Valve Corp. Steam. Online, 2019. URL https://store.steampowered.com/. [Accessed 25.04.2019].

[128] Microsoft Inc. Kinect for Windows. Online, 2019. URL https://developer.microsoft.com/en-us/windows/kinect. [Accessed 24.04.2019].

Appendix A

This is the risk analysis conducted prior to this project.

Increases Risk

1. **3D Modelling**
   If we have available 3D models, work would include to put correct materials on these, and linking the materials with the database. Should we have to also make the 3D models, scope would have to be reduced since this can take up a great amount of time.

2. **Creating an "experience"**
   When making a VR application, we are not only putting glasses on the user, but building an experience. This means that for the user to feel present in a virtual environment things need to have a certain degree of realism.

   (a) Stringent requirements for ease of use:
   For the user to be able to explore information in the application there will have to be some sort of interaction. This may be difficult when using only VR Glasses and no controller since interaction is entirely based on gaze.

   (b) Navigation in application:
   Navigation in this sense is actually moving the user in the application. We would have to find an intuitive way to do so without actually walking in the real world.

   (c) Sound:
   For the user to have an immersive experience we might have to implement some sound and experiment with headphones.

   (d) Realistic models:
   We will have to explore the possibility that for the experience to be immersive the 3D models will have to be realistic. However, we have seen VR experiences with low levels of detail that are still immersive, so this is something we will

have to research.

(e) Hardware:
For the experience to be as good as possible, the hardware used will have to keep up with the software. For our proof of concept this was no problem with the newest iPhones, but if the application should be distributed we might have to consider optimization of the application.

3. **Access to data**
To actually visualize data we will have to access it somehow. We have already made a prototype utilizing a MySQL database which ZEN can update with the newest data from building sites. However, if we do not have access to data, we have nothing to visualize other than dummy data, which might have the opposite effect of what we wish for.

4. **Mathematical formulas for calculating emissions**
For the end user to understand the data presented, there should be some kind of comparison to for example other greenhouse gas emissions or energy consumption. We will also need to calculate a "score" of the different materials so we can compare them to other buildings. For this we will need some formulas.

5. **Visualization of data**
Our main goal is to actually visualize the KPIs. This is a challenge since we will have to do user test iterations to find out which visualization is most understandable to the user and how the data can be presented.

Decreases Risk

- **Functioning proof of concept**
We have already made prototypes for VR, AR and desktop versions of the application. This means that we know this solution is possible to achieve and we already have functionality to further develop and the basis for a new application.

- **Functioning connection to MySQL database with actual data**
With help from Eirik Resch we have a database connection that we also have connected to materials in our prototype application. This means we have access to "up-to-date"-data and that ZEN can update results in the application in real time.

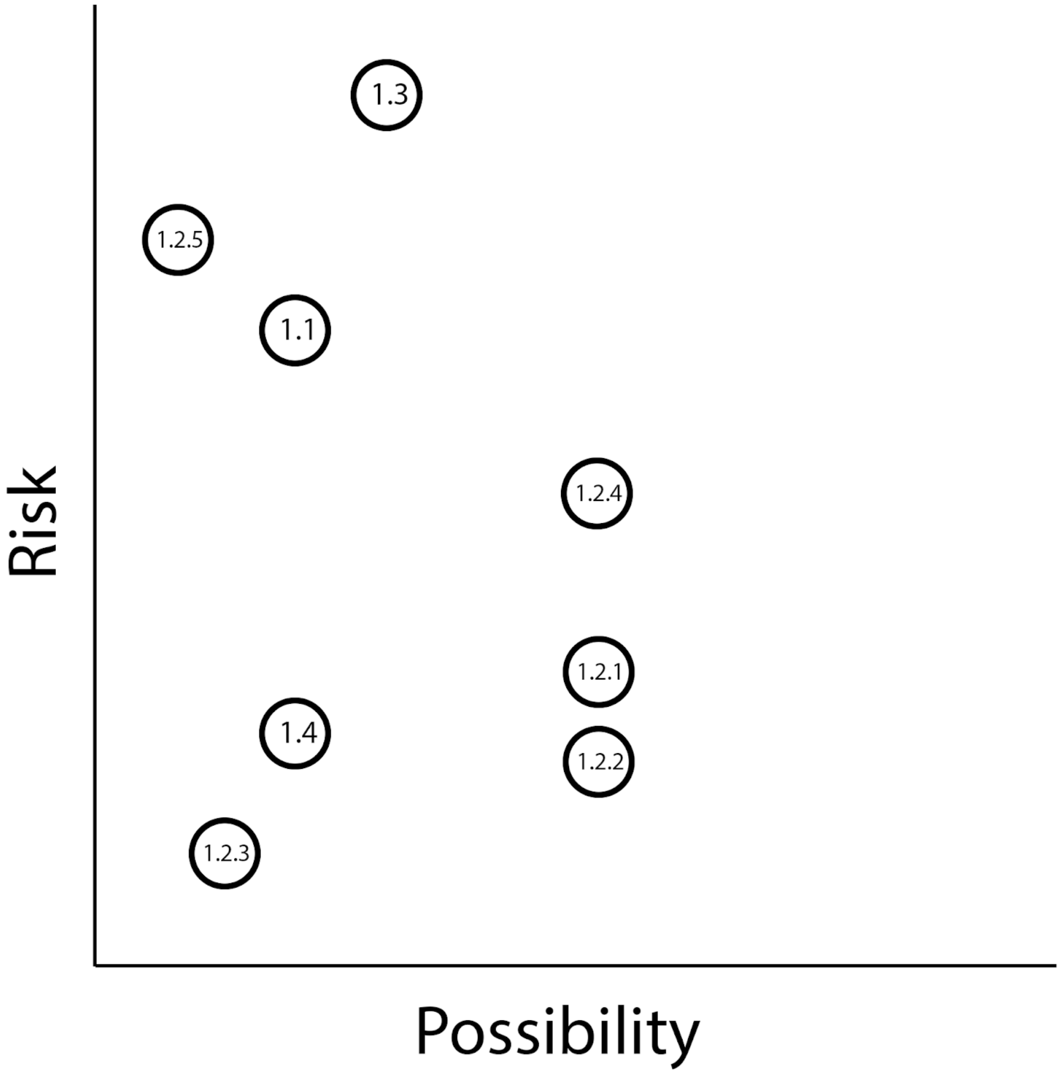
- **Tested the technology**
By creating a prototype we have also tested that the technology works on both software- and hardware level.

- **Using well known software with good documentation and community**
  Unity is a very popular development tool which make access to great documentation and debugging very easy. If we run into problems, there is a big possibility that we are not the first.

- **Using Vuforia as third party library with Unity**
  Vuforia is also very popular with the VR/AR community and is a library with great support for a number of different VR solution. It also comes with finished methods for implementing VR on iPhone and Android and makes it very easy to get started.

- **Available 3D models of ZEB**
  With available 3D models of actual buildings that we have data for from the database, we save a lot of time modelling buildings. This also makes the application much more credible since it uses buildings linked to the real world.

- **Experience with Unity**
  Sondre has worked with Unity before, which makes getting started and debugging easier. Unity also offers a great deal of very good tutorials for beginners, making it easy for Mikael also to join in.


1.3
1.2.5
1.1
1.2.4
1.2.1
1.4
1.2.2
1.2.3
Risk
Possibility

Appendix B

This is the comparison of different solutions conducted during the initial phase of this project.

Technology	Pros	Cons
Desktop application	• Low entry price, just install program and start. • Possibilities for collaboration. • Ability to also be used as a tool. • Visualization of KPIs limited to 2D. • Could be made into a web application for easy access.	• Limited to few stakeholders. • Difficult to make general population download a large application for inspecting buildings. • Not as good in terms of visualizing compared to the XR-platform. • Depending on size; can be hard to distribute
AR application	• Great tool for collaboration since everyone involved can see the screen. • Intuitive interaction where the user "clicks and drags" to navigate. • Easy to distribute • Multiple platforms ranging from smartphones to tablets and "smart tables"	• Collaboration mostly limited to showcasing since it is difficult to double up as a tool.
VR application	• Great for showcasing since it delivers an experience to the user. • Intuitive since you are in the application, and looking at things brings up information. • Easy to distribute • More immersive than any other technology.	• Difficult to interact with the application. • Needs VR glasses to function. • Users may not like VR and can become dizzy.

Appendix C

This is an overview describing the interview subjects and their experience with the technology and knowledge regarding ZEN.

Subject	Field	Title	VR Experience	Knowledge of ZEN	Knowledge of KPIs
A	Architecture	Research Assistant of Architecutre and Technology	Tested mobile VR before, but never high-end equipent	Working for ZEN	Worked with KPIs in education
B	Virtual Reality and Data Visualization	Professor at the Institute of Datatechnology and Informatics	Worked with both XR and MR through student projects and eesponsible for the VR LAB at NTNU Gløshaugen.	No knowledge of ZEN	No knowledge of KPIs
C	Urban Planning	Project-developer and -leader at Trondheim Municipality	Never tried VR	Familiar with ZEN	Familiar with KPIs
D	Stakeholder Engagement	Professor at Institute of Architecture and Technology	Never tried VR	Working for ZEN	Working with KPIs
E	Stakeholder Engagement	Geologist and Scientist at SINTEF Byggforsk	Little experience with VR	Working with ZEN	Working with KPIs

Appendix D

Request for participation in research project

"Visualising KPIs in sustainable neighbourhoods"

This form is a request for you to participate in our research project where the purpose is to use Virtual Reality to visualise key performance indicators in sustainable neighbourhoods. This form will provide you with information on what participation means.

Purpose and background

The purpose of this research project is to investigate how we can utilize immersive technologies, namely Virtual Reality, to visualise emission-data from materials used in buildings within sustainable neighbourhoods.. The VR Application uses different types of visualisation methods to put emission data into context for the user, and we would like to see what methods are most useful for understanding the data. In addition, we want to test the usability of the application. To achieve this we invite experts from fields relevant to the project to perform a defined set of tasks in the application, followed by an in-depth interview. This research project is the master thesis of Sondre Løvhaug and Mikael Mathisen at the Informatics study at NTNU. It is also a collaboration with FME-ZEN (forskningssenter for miljøvennlig energi, Zero Emission Neighbourhoods). The main supervisor of the project is John Krogstie. Co-supervisors are Aoife Houlihan Wiberg, Ekaterina Prasolova-Førland and Eirik Resch.

What does participation mean?

Participation involves a short explanation of the project and mapping of the participants background. Then there will be a demo of the application with predefined tasks to perform. The participant will be informed on how to use the application prior to the testing, to ensure that all participants has an equal starting ground. Following the application testing will be an in-depth interview which will be, with consent, recorded for later transcribing.

Your privacy

We will only use the information about you for the purposes we have told about in this document. We treat the information confidentially and in accordance with the privacy policy. Only the writers of this thesis and, if necessary, the supervisors will have access to the data. The data is stored securely in our password protected cloud storage with limited access only to Sondre Løvhaug and Mikael Mathisen.

Voluntary participation

Participation in the project is voluntary. If you choose to participate, you may at any time withdraw your consent without giving any reason. All information about you will then be anonymized. It will have no negative consequences for you if you do not want to participate or later choose to withdraw. Should you choose to withdraw your participation, we ask you to contact Sondre Løvhaug by either mail: [REMOVED] or by phone: [REMOVED].

This study has been reported to NSD - Norwegian Centre for Research Data.

Statement of consent

I have received and understood information about the project Visualising KPIs in Sustainable Neighbourhoods, and have had the chance to ask questions about my participation. I hereby consent to:

- Participate in this interview - Have the interview recorded for transcribing - Work title and relevant experience published in the thesis - Having information about me stored until the end of the research project (01.06.2019)

Signature:

____(Signed by participant, date)

Appendix E

[In Norwegian]

Oppsett av intervju

- Informasjon og en uformell prat (5 - 10 min)
  - Bakgrunn for samtalen
  - Forklar hva intervjuet skal brukes til
    - Spør om det er greit at samtalen blir tatt opp
  - Forklar anonymitet
  - Spør om noe er uklart og om objektet har noen spørsmål
  - Be om underskrift til forespørsel om deltakelse
- Erfaring (15 min)
  - Kartlegge erfaring med temaet
    - Erfaring med teknologien
    - Erfaring innen feltet
  - Praktisk oppgave
    - Følg samme oppgaveliste for alle objekter
- Nøkkelspørsmål (30 - 60 min)
  - Oppfølgingsspørsmål
- Oppsummering (15 min)
  - Oppsummere
  - Har informanten blitt riktig forstått
  - Spørre om det er noe å legge til

Intervjuguide

Bakgrunn for samtalen

Fortell om hva oppgaven vår er.

Vi ønsker å samle inn data til vår masteroppgave gjennom ekspertintervjuer.

Intervjuet vil bli tatt opp for at vi skal kunne transkribere det i etterkant. Det vil ikke bli brukt til noe annet enn transkribering og vil bli slettet etter fullført transkribering.

Er dette greit?

I oppgaven vil vi oppgi tittel og relevant erfaring til vår oppgave og hvorfor vi ønsket å intervjue personen. Oppgaven vil bli utgitt gjennom vanlige kanaler på NTNU, men kan også bli liggende tilgjengelig på ZENs nettsider.

Er det noe som er uklart?

Erfaring

Kartlegg intervjuobjektets bakgrunn:
- Hva jobber du med daglig?
- Vet du hva ZEN er og hva de holder på med?
- Har du noe erfaring med Key Performance Indicators og hva de betyr?

Hvilken erfaring har du med denne teknologien?
- Har du prøvd VR før?
- Hva vet du om VR?

Nøkkelspørsmål

RQ1: "In what way can immersive technologies be used and adapted to visualize ZEN KPIs in order to engage and improve participation from different stakeholders?"

RQ2: What form of visualization are most beneficial for making an impact on stakeholders?

Hvor enkelt var det å forstå hvordan man benyttet seg av applikasjonen?
- Hvor enkelt var det å bevege seg rundt i systemet?
- Hva tenker du om interaksjon med objekter (Hus, bygninger etc)

Hva tenker du om VR som visualiseringsverktøy for dette formålet?
- Kan du tenke deg andre teknologier som kan fungere bedre? (AR / Desktop)
- Hvordan vil du sammenligne VR med andre teknologier du har prøvd før?
- Følte du deg oppslukt (immersed) i programmet?

Hva tenker du om visualisering-metodene som ble brukt? Typ: Kolonner og Farger?
- Hvilken form for visualisering gjorde det enklest å forstå utslippet til bygningene?

- Var det lett å forstå hva de forskjellige verdiene betydde?
- Klarte du å sette tallene i kontekst?
- Føler du at noen av visualiseringene gjorde ett inntrykk på deg?
- Har du noen ideer om andre måter å visualisere verdiene på?

Hva tenker du er potensialet til en slik applikasjon?
- Kan du tenke deg flere bruksområder enn å visualisere utslipp?
- Tror du en slik applikasjon vil kunne promotere bygging av nabolag med lavere klimafotavtrykk?
- Hva tenker du om å promotere grønnere nabolag ved å sammenligne de med eldre "vanlige" nabolag

Tenker du en slik applikasjon vil kunne engasjere flere parter i et byggeprosjekt?
- Ser du et potensiale til å inkludere flere parter i byggeprosjekt?
- Hva tenker du om å bruke denne type applikasjon som samarbeidsverktøy?

Appendix F

Tasks for user tests

1. Finn utslippet til skolebygningen i Sluppen-området
   (a) Finn de ulike visualiseringsmetodene for utslipp i nabolags-viewet.
   (b) Bytt til visualisering av elektrisitetsforbruk
2. Gå ned til bygningsnivå for skolebygget og finn utslipp og materialforbruk for yttervegg.
   (a) Finn hvilket material som har størst Kg CO2 pr Kg material
   (b) Slå av yttervegg og gå opp i 3. Etg. for skolebygget
   (c) Finn utslipp for innervegg
3. Gå til ZEB Living Lab og finn materialforbruket for taket

Appendix G

[This is the questionnaire sent to informants after conducting user tests.]

Gender

Male
Female
Prefer not to say

2. Age

---

3. Do you have any experience with VR?

Yes
No

3.1. If yes, please elaborate

---

4. Do you have any experience with visualization of emission data?

Yes
No

4.1. If yes, please elaborate

Application usability

These questions focus on the general usability of the system

5. I think this system could be used frequently for promoting sustainable neighbourhoods

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

6. I found the system unnecessarily complex

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

7. I thought the system was easy to use

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

8. I think that I would need the support of a technical person to be able to use this system

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

9. I found the possible actions I could perform in the system were well though out

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

10. I thought there was too much inconsistency in this system

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

11. I would imagine that most people would learn to use this system very quickly

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

12. I found the system very cumbersome to use

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

13. I felt very confident using the system

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

14. I needed to learn a lot of things before I could get going with this system

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

15. I found the interaction mechanism with the application was intuitive

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

16. I found that the objects behaved as expected

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

17. It was easy to understand which objects were possible to interact with

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

18. I found my potential actions to be restricted

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

19. The nature of the system encouraged me to explore

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

20. I felt discomfort when using the system

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

20.1. If so, what did you experience:

---

21. When interacting with objects I received sufficient feedback from the system

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

22. My head movement were naturally rendered in the virtual environment

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

23. I found navigating in the application difficult

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

24. I often got lost when navigating the virtual environment

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

25. It was obvious how to navigate between the different levels

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

26. Using haptic feedback(vibration) and color indication made it easy to understand the different types of interaction

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

27. The application provided support for understanding the virtual environment

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

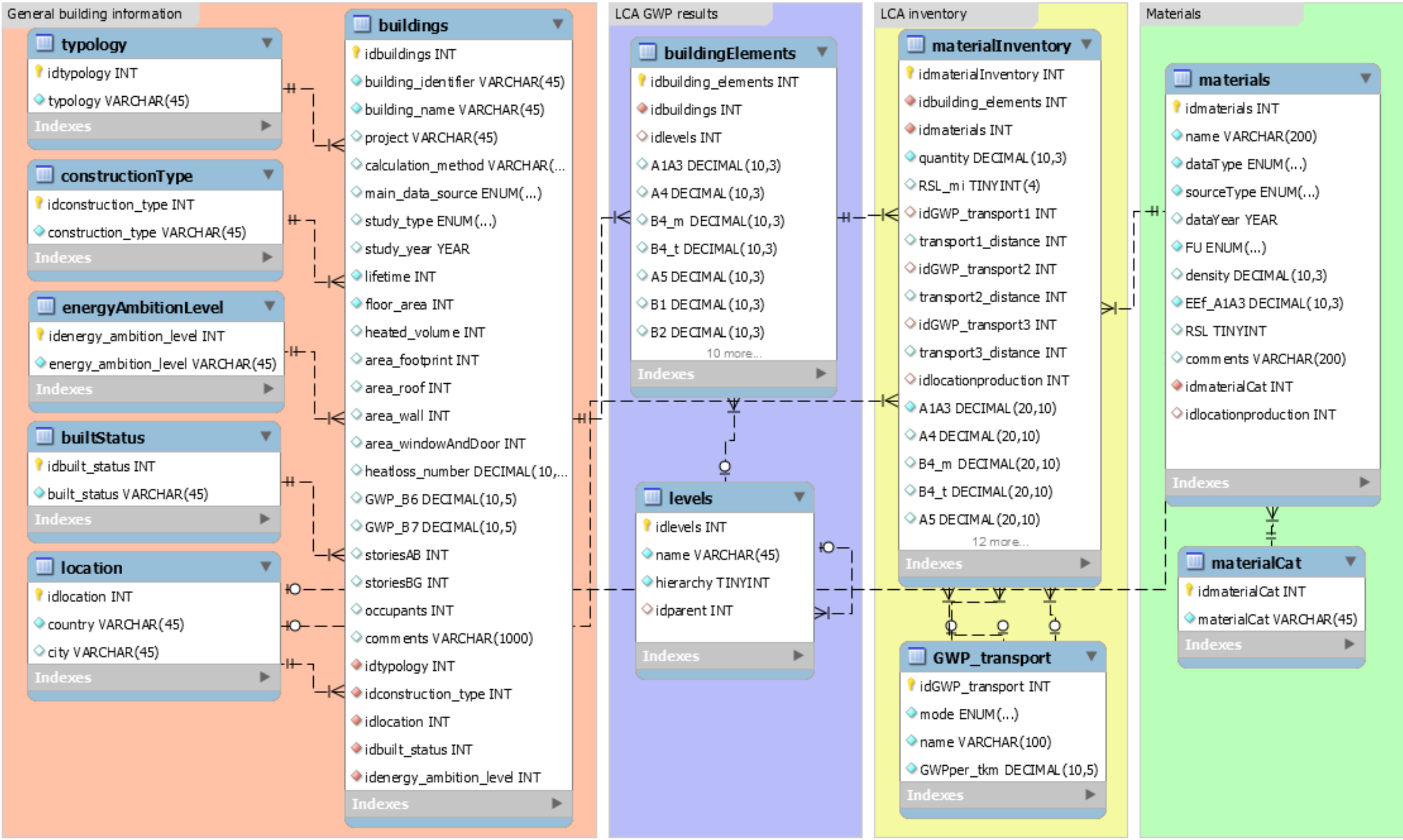
28. My physical movement felt naturally mirrored in the virtual environment

Strongly disagree | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Strongly agree

29. General feedback

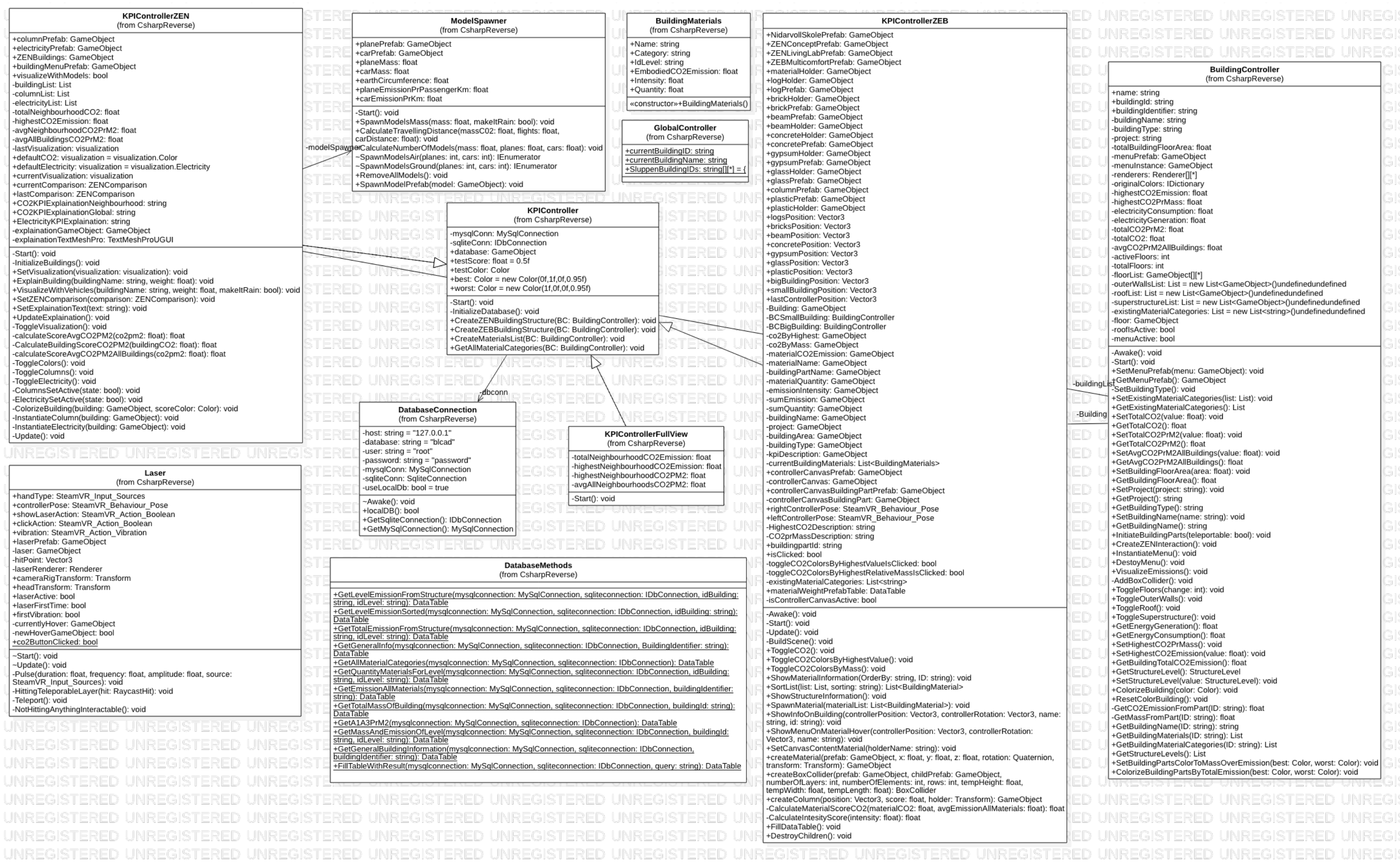
Appendix H

ERD of the bLCAd-tool


General building information
typology
idtypology INT
typology VARCHAR(45)
Indexes
constructionType
idconstruction_type INT
construction_type VARCHAR(45)
Indexes
energyAmbitionLevel
idenergy_ambition_level INT
energy_ambition_level VARCHAR(45)
Indexes
builtStatus
idbuilt_status INT
built_status VARCHAR(45)
Indexes
location
idlocation INT
country VARCHAR(45)
city VARCHAR(45)
Indexes
buildings
idbuildings INT
building_identifier VARCHAR(45)
building_name VARCHAR(45)
project VARCHAR(45)
calculation_method VARCHAR(...
main_data_source ENUM(...)
study_type ENUM(...)
study_year YEAR
lifetime INT
floor_area INT
heated_volume INT
area_footprint INT
area_roof INT
area_wall INT
area_windowAndDoor INT
heatloss_number DECIMAL(10,...
GWP_B6 DECIMAL(10,5)
GWP_B7 DECIMAL(10,5)
storiesAB INT
storiesBG INT
occupants INT
comments VARCHAR(1000)
idtypology INT
idconstruction_type INT
idlocation INT
idbuilt_status INT
idenergy_ambition_level INT
Indexes
LCA GWP results
buildingElements
idbuilding_elements INT
idbuildings INT
idlevels INT
A1A3 DECIMAL(10,3)
A4 DECIMAL(10,3)
B4_m DECIMAL(10,3)
B4_t DECIMAL(10,3)
A5 DECIMAL(10,3)
B1 DECIMAL(10,3)
B2 DECIMAL(10,3)
10 more...
Indexes
levels
idlevels INT
name VARCHAR(45)
hierarchy TINYINT
idparent INT
Indexes
LCA inventory
materialInventory
idmaterialInventory INT
idbuilding_elements INT
idmaterials INT
quantity DECIMAL(10,3)
RSL_mi TINYINT(4)
idGWP_transport1 INT
transport1_distance INT
idGWP_transport2 INT
transport2_distance INT
idGWP_transport3 INT
transport3_distance INT
idlocationproduction INT
A1A3 DECIMAL(20,10)
A4 DECIMAL(20,10)
B4_m DECIMAL(20,10)
B4_t DECIMAL(20,10)
A5 DECIMAL(20,10)
12 more...
Indexes
GWP_transport
idGWP_transport INT
mode ENUM(...)
name VARCHAR(100)
GWPper_tkm DECIMAL(10,5)
Indexes
Materials
materials
idmaterials INT
name VARCHAR(200)
dataType ENUM(...)
sourceType ENUM(...)
dataYear YEAR
FU ENUM(...)
density DECIMAL(10,3)
EEf_A1A3 DECIMAL(10,3)
RSL TINYINT
comments VARCHAR(200)
idmaterialCat INT
idlocationproduction INT
Indexes
materialCat
idmaterialCat INT
materialCat VARCHAR(45)
Indexes

Appendix I

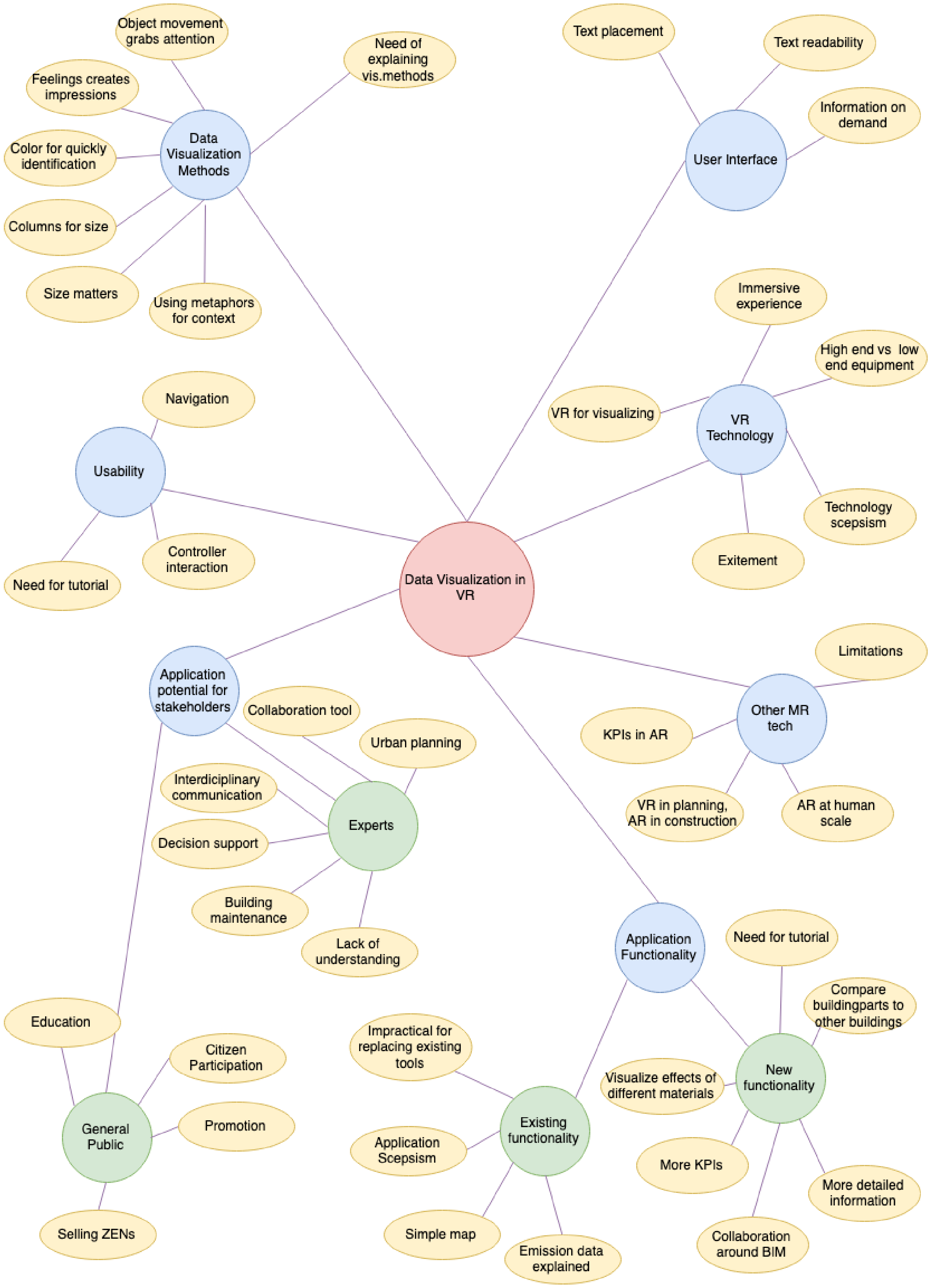
UML diagram of ZENVR


KPIControllerZEN
(from CsharpReverse)
+columnPrefab: GameObject
+electricityPrefab: GameObject
+ZENBuildings: GameObject
+buildingMenuPrefab: GameObject
+visualizeWithModels: bool
-buildingList: List
-columnList: List
-electricityList: List
-totalNeighbourhoodCO2: float
-highestCO2Emission: float
-avgNeighbourhoodCO2PrM2: float
-avgAllBuildingsCO2PrM2: float
-lastVisualization: visualization
+defaultCO2: visualization = visualization.Color
+defaultElectricity: visualization = visualization.Electricity
+currentVisualization: visualization
+currentComparison: ZENComparison
+lastComparison: ZENComparison
+CO2KPIExplainationNeighbourhood: string
+CO2KPIExplainationGlobal: string
+ElectricityKPIExplaination: string
-explainationGameObject: GameObject
-explainationTextMeshPro: TextMeshProUGUI
-Start(): void
-InitializeBuildings(): void
+SetVisualization(visualization: visualization): void
+ExplainBuilding(buildingName: string, weight: float): void
+VisualizeWithVehicles(buildingName: string, weight: float, makeItRain: bool): void
+SetZENComparison(comparison: ZENComparison): void
+SetExplainationText(text: string): void
+UpdateExplaination(): void
-ToggleVisualization(): void
-calculateScoreAvgCO2PM2(co2pm2: float): float
-CalculateBuildingScoreCO2PM2(buildingCO2: float): float
-calculateScoreAvgCO2PM2AllBuildings(co2pm2: float): float
-ToggleColors(): void
-ToggleColumns(): void
-ToggleElectricity(): void
-ColumnsSetActive(state: bool): void
-ElectricitySetActive(state: bool): void
-ColorizeBuilding(building: GameObject, scoreColor: Color): void
-InstantiateColumn(building: GameObject): void
-InstantiateElectricity(building: GameObject): void
-Update(): void
-modelSpawner
ModelSpawner
(from CsharpReverse)
+planePrefab: GameObject
+carPrefab: GameObject
+planeMass: float
+carMass: float
+earthCircumference: float
+planeEmissionPrPassengerKm: float
+carEmissionPrKm: float
-Start(): void
+SpawnModelsMass(mass: float, makeItRain: bool): void
+CalculateTravellingDistance(massCO2: float, flights: float, carDistance: float): void
+CalculateNumberOfModels(mass: float, planes: float, cars: float): void
~SpawnModelsAir(planes: int, cars: int): IEnumerator
~SpawnModelsGround(planes: int, cars: int): IEnumerator
+RemoveAllModels(): void
+SpawnModelPrefab(model: GameObject): void
BuildingMaterials
(from CsharpReverse)
+Name: string
+Category: string
+IdLevel: string
+EmbodiedCO2Emission: float
+Intensity: float
+Quantity: float
«constructor»+BuildingMaterials()
GlobalController
(from CsharpReverse)
+currentBuildingID: string
+currentBuildingName: string
+SluppenBuildingIDs: string[][*] = {
KPIController
(from CsharpReverse)
-mysqlConn: MySqlConnection
-sqliteConn: IDbConnection
+database: GameObject
+testScore: float = 0.5f
+testColor: Color
+best: Color = new Color(0f,1f,0f,0.95f)
+worst: Color = new Color(1f,0f,0f,0.95f)
-Start(): void
-InitializeDatabase(): void
+CreateZENBuildingStructure(BC: BuildingController): void
+CreateZEBBuildingStructure(BC: BuildingController): void
+CreateMaterialsList(BC: BuildingController): void
+GetAllMaterialCategories(BC: BuildingController): void
-dbconn
DatabaseConnection
(from CsharpReverse)
-host: string = "127.0.0.1"
-database: string = "blcad"
-user: string = "root"
-password: string = "password"
-mysqlConn: MySqlConnection
-sqliteConn: SqliteConnection
-useLocalDb: bool = true
~Awake(): void
+localDB(): bool
+GetSqliteConnection(): IDbConnection
+GetMySqlConnection(): MySqlConnection
KPIControllerFullView
(from CsharpReverse)
-totalNeighbourhoodCO2Emission: float
-highestNeighbourhoodCO2Emission: float
-highestNeighbourhoodCO2PM2: float
-avgAllNeighbourhoodsCO2PM2: float
-Start(): void
Laser
(from CsharpReverse)
+handType: SteamVR_Input_Sources
+controllerPose: SteamVR_Behaviour_Pose
+showLaserAction: SteamVR_Action_Boolean
+clickAction: SteamVR_Action_Boolean
+vibration: SteamVR_Action_Vibration
+laserPrefab: GameObject
-laser: GameObject
-hitPoint: Vector3
-laserRenderer: Renderer
+cameraRigTransform: Transform
+headTransform: Transform
+laserActive: bool
+laserFirstTime: bool
+firstVibration: bool
-currentlyHover: GameObject
-newHoverGameObject: bool
+co2ButtonClicked: bool
~Start(): void
~Update(): void
-Pulse(duration: float, frequency: float, amplitude: float, source: SteamVR_Input_Sources): void
-HittingTeleporableLayer(hit: RaycastHit): void
-Teleport(): void
-NotHittingAnythingInteractable(): void
DatabaseMethods
(from CsharpReverse)
+GetLevelEmissionFromStructure(mysqlconnection: MySqlConnection, sqliteconnection: IDbConnection, idBuilding: string, idLevel: string): DataTable
+GetLevelEmissionSorted(mysqlconnection: MySqlConnection, sqliteconnection: IDbConnection, idBuilding: string): DataTable
+GetTotalEmissionFromStructure(mysqlconnection: MySqlConnection, sqliteconnection: IDbConnection, idBuilding: string, idLevel: string): DataTable
+GetGeneralInfo(mysqlconnection: MySqlConnection, sqliteconnection: IDbConnection, BuildingIdentifier: string): DataTable
+GetAllMaterialCategories(mysqlconnection: MySqlConnection, sqliteconnection: IDbConnection): DataTable
+GetQuantityMaterialsForLevel(mysqlconnection: MySqlConnection, sqliteconnection: IDbConnection, idBuilding: string, idLevel: string): DataTable
+GetEmissionAllMaterials(mysqlconnection: MySqlConnection, sqliteconnection: IDbConnection, buildingIdentifier: string): DataTable
+GetTotalMassOfBuilding(mysqlconnection: MySqlConnection, sqliteconnection: IDbConnection, buildingId: string): DataTable
+GetA1A3PrM2(mysqlconnection: MySqlConnection, sqliteconnection: IDbConnection): DataTable
+GetMassAndEmissionOfLevel(mysqlconnection: MySqlConnection, sqliteconnection: IDbConnection, buildingId: string, idLevel: string): DataTable
+GetGeneralBuildingInformation(mysqlconnection: MySqlConnection, sqliteconnection: IDbConnection, buildingIdentifier: string): DataTable
+FillTableWithResult(mysqlconnection: MySqlConnection, sqliteconnection: IDbConnection, query: string): DataTable
KPIControllerZEB
+NidarvollSkolePrefab: GameObject
+ZENConceptPrefab: GameObject
+ZENLivingLabPrefab: GameObject
+ZEBMulticomfortPrefab: GameObject
+materialHolder: GameObject
+logHolder: GameObject
+logPrefab: GameObject
+brickHolder: GameObject
+brickPrefab: GameObject
+beamPrefab: GameObject
+beamHolder: GameObject
+concreteHolder: GameObject
+concretePrefab: GameObject
+gypsumHolder: GameObject
+gypsumPrefab: GameObject
+glassHolder: GameObject
+glassPrefab: GameObject
+columnPrefab: GameObject
+plasticPrefab: GameObject
+plasticHolder: GameObject
+logsPosition: Vector3
+bricksPosition: Vector3
+beamPosition: Vector3
+concretePosition: Vector3
+gypsumPosition: Vector3
+glassPosition: Vector3
+plasticPosition: Vector3
+bigBuildingPosition: Vector3
+smallBuildingPosition: Vector3
+lastControllerPosition: Vector3
-Building: GameObject
-BCSmallBuilding: BuildingController
-BCBigBuilding: BuildingController
-co2ByHighest: GameObject
-co2ByMass: GameObject
-materialCO2Emission: GameObject
-materialName: GameObject
-buildingPartName: GameObject
-materialQuantity: GameObject
-emissionIntensity: GameObject
-sumEmission: GameObject
-sumQuantity: GameObject
-buildingName: GameObject
-project: GameObject
-buildingArea: GameObject
-buildingType: GameObject
-kpiDescription: GameObject
-currentBuildingMaterials: List<BuildingMaterials>
+controllerCanvasPrefab: GameObject
-controllerCanvas: GameObject
+controllerCanvasBuildingPartPrefab: GameObject
-controllerCanvasBuildingPart: GameObject
+rightControllerPose: SteamVR_Behaviour_Pose
+leftControllerPose: SteamVR_Behaviour_Pose
-HighestCO2Description: string
-CO2prMassDescription: string
+buildingpartId: string
+isClicked: bool
-toggleCO2ColorsByHighestValueIsClicked: bool
-toggleCO2ColorsByHighestRelativeMassIsClicked: bool
-existingMaterialCategories: List<string>
+materialWeightPrefabTable: DataTable
-isControllerCanvasActive: bool
-Awake(): void
-Start(): void
-Update(): void
-BuildScene(): void
+ToggleCO2(): void
+ToggleCO2ColorsByHighestValue(): void
+ToggleCO2ColorsByMass(): void
+ShowMaterialInformation(OrderBy: string, ID: string): void
+SortList(list: List, sorting: string): List<BuildingMaterial>
+ShowStructureInformation(): void
+SpawnMaterial(materialList: List<BuildingMaterial>): void
+ShowInfoOnBuilding(controllerPosition: Vector3, controllerRotation: Vector3, name: string, id: string): void
+ShowMenuOnMaterialHover(controllerPosition: Vector3, controllerRotation: Vector3, name: string): void
+SetCanvasContentMaterial(holderName: string): void
+createMaterial(prefab: GameObject, x: float, y: float, z: float, rotation: Quaternion, transform: Transform): GameObject
+createBoxCollider(prefab: GameObject, childPrefab: GameObject, numberOfLayers: int, numberOfElements: int, rows: int, tempHeight: float, tempWidth: float, tempLength: float): BoxCollider
+createColumn(position: Vector3, score: float, holder: Transform): GameObject
-CalculateMaterialScoreCO2(materialCO2: float, avgEmissionAllMaterials: float): float
-CalculateIntesityScore(intensity: float): float
+FillDataTable(): void
+DestroyChildren(): void
-buildingList
-Building
BuildingController
(from CsharpReverse)
+name: string
+buildingId: string
+buildingIdentifier: string
-buildingName: string
-buildingType: string
-project: string
-totalBuildingFloorArea: float
-menuPrefab: GameObject
-menuInstance: GameObject
-renderers: Renderer[][*]
-originalColors: IDictionary
-highestCO2Emission: float
-highestCO2PrMass: float
-electricityConsumption: float
-electricityGeneration: float
-totalCO2PrM2: float
-totalCO2: float
-avgCO2PrM2AllBuildings: float
-activeFloors: int
-totalFloors: int
-floorList: GameObject[][*]
-outerWallsList: List = new List<GameObject>()undefinedundefined
-roofList: List = new List<GameObject>()undefinedundefined
-superstructureList: List = new List<GameObject>()undefinedundefined
-existingMaterialCategories: List = new List<string>()undefinedundefined
-floor: GameObject
-roofIsActive: bool
-menuActive: bool
-Awake(): void
-Start(): void
+SetMenuPrefab(menu: GameObject): void
+GetMenuPrefab(): GameObject
-SetBuildingType(): void
+SetExistingMaterialCategories(list: List): void
+GetExistingMaterialCategories(): List
+SetTotalCO2(value: float): void
+GetTotalCO2(): float
+SetTotalCO2PrM2(value: float): void
+GetTotalCO2PrM2(): float
+SetAvgCO2PrM2AllBuildings(value: float): void
+GetAvgCO2PrM2AllBuildings(): float
+SetBuildingFloorArea(area: float): void
+GetBuildingFloorArea(): float
+SetProject(project: string): void
+GetProject(): string
+GetBuildingType(): string
+SetBuildingName(name: string): void
+GetBuildingName(): string
+InitiateBuildingParts(teleportable: bool): void
+CreateZENInteraction(): void
+InstantiateMenu(): void
+DestoyMenu(): void
+VisualizeEmissions(): void
-AddBoxCollider(): void
+ToggleFloors(change: int): void
+ToggleOuterWalls(): void
+ToggleRoof(): void
+ToggleSuperstructure(): void
+GetEnergyGeneration(): float
+GetEnergyConsumption(): float
+SetHighestCO2PrMass(): void
+SetHighestCO2Emission(value: float): void
+GetBuildingTotalCO2Emission(): float
+GetStructureLevel(): StructureLevel
+SetStructureLevel(value: StructureLevel): void
+ColorizeBuilding(color: Color): void
+ResetColorBuilding(): void
-GetCO2EmissionFromPart(ID: string): float
-GetMassFromPart(ID: string): float
+GetBuildingName(ID: string): string
+GetBuildingMaterials(ID: string): List
+GetBuildingMaterialCategories(ID: string): List
+GetStructureLevels(): List
+SetBuildingPartsColorToMassOverEmission(best: Color, worst: Color): void
+ColorizeBuildingPartsByTotalEmission(best: Color, worst: Color): void

Appendix J

Categories overview

Categories retrieved from coding-process



Appendix K

Database Connection

Querying the database

```
/**
* Method for retrieving level emission form building
* @Param mysqlconnection: connection to the MYSQL database
* @Param sqliteconnection: connection to the SQLite database
* @Param idBuilding: the ID of the building in the database
* @Param idLevel: level of the building structure
* @Return: Data Table with results
**/
public static DataTable GetLevelEmissionFromStructure(MySqlConnection
    mysqlconnection, IDbConnection sqliteconnection, string idBuilding,
    string idLevel) {
    //Building the query
    string query = string.Format(
        "SELECT buildingElements.idbuildings, buildingElements.idLevels,
            (buildingElements.A1A3/1000) as A1A3, levels.name,
            levels.idparent " +
        "FROM buildingElements LEFT JOIN levels ON buildingElements.idLevels
            = levels.idlevels WHERE idbuildings = '{0}' AND idparent = '{1}';"
        , idBuilding, idLevel);

    //Sending query to method for execution
    return FillTableWithResult(mysqlconnection, sqliteconnection, query);
}

private static DataTable FillTableWithResult(MySqlConnection
    mysqlconnection, IDbConnection sqliteconnection, string query)
{
    //Checks to see if the local db connection is used.
    if (sqliteconnection != null) {
        IDbCommand command = sqliteconnection.CreateCommand();
        command.CommandText = query;

        IDataReader reader = command.ExecuteReader();

        DataTable table = new DataTable();
        table.Load(reader);

        return table;
    //Using the online database
    } else {
        var command = new MySqlCommand(query, mysqlconnection);
        MySqlDataAdapter adapter = new MySqlDataAdapter(command);

        DataTable result = new DataTable();

        adapter.Fill(result);
        return result;
    }
}
```

Mikael Mathisen Sondre Løvhaug

Visualizing Key Performance Indicators in Sustainable Neighbourhoods

NTNU
Norwegian University of Science and Technology