VRbanism: assessing Virtual Reality as an urban design tool

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VRbanism: assessing Virtual Reality as an urban design tool

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Design of the Urban Fabric

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Content

Abstract 9
Acronyms 11
Preface 13

Chapter 1: Motivation 15

Chapter 2: Project definition 16
2.1 Problem field & Theoretical Background 16
2.1.1 Virtual reality 16
2.1.2 3D models, LOD & realness 17
2.1.3 Visual aspects of VR 19
2.1.4 Properties of VR in relation to the urban design practice 20
2.2 Problem statement 23
2.3 Research questions 23
2.4 Hypothesis 25
2.5 Thesis outline & time planning 25

Chapter 3: Methodology 26
3.1 Exploratory case study research: Sloterdijk redesign 26
3.1.1 Research by design 26
3.1.2 Design area choice & analysis 26
3.2 Tools 29
3.2.1 VR hardware 29
3.2.2 Software 33

Chapter 4: Research & design 39
4.1 Design problem 39
4.1.1 Approach 39
4.1.2 Sloterdijk background & challenge 39
4.2 Creating the current area model 41
4.2.1 Design questions 41
4.2.2 Creating the model 41
4.2.3 Testing & outcomes 45
4.3 Creating the VR Design System 47
4.3.1 Problem definition 47
4.3.2 Software capacities & limitations 47
4.3.3 Evaluation criteria 49
4.3.4 Creating the system 50
4.3.5 Block & building test 59
4.3.6 Outcomes – Final Design System 60
4.4 Designing Sloterdijk I 61
4.4.1 Design problem 61
4.4.2 Preparation of the design process 62
4.4.3 Variants 63

4.4.4. Spatial analysis of the variants 76
4.4.5 Design process findings 80
4.4.6 Outcomes 84

Chapter 5: Conclusions 87
5.1 Conclusions 87
5.2 Discussion & future research 92

Chapter 6: Reflection 93
6.1 Challenges and observations during the research process 93
6.2 Issues regarding answering the research questions 94
6.3 Relationship between the methodical line of approach of the Design of the Urban Fabric studio and the method chosen in this approach 94
6.4 Relationship between the project and the wider social and scientific context 95
6.5 Relationship between 'Design of the Urban Fabric' and the theme of this graduation project 97
6.6 Relationship between research and design 97

Acknowledgements 98
References 99
List of figures 104

Appendix A: Workflows 106
Appendix B: Design considerations 108
Appendix C: Theory paper 109

Abstract

During the last few years, Virtual Reality (VR) technology has evolved at an impressive pace. The newest VR systems offer a high level of visual realism and accurate interaction with the virtual environment through spatially tracked controllers. This technology is increasingly being applied in many professions, but in architecture and urbanism the use of VR was mostly restricted to visualization purposes. Meanwhile, an increasing amount of (3D) data becomes available which is now mostly visualised with 2D screens, while there exists a plenitude of complex urban problems that could potentially benefit from the use of this data. Also, our cities are still mainly designed with traditional design methods such as sketches on paper and unintuitive CAD software. These methods are viewed on 2D screens, often from bird's eye view, while our cities are in 3D and experienced from eye level perspective. Designing in VR could potentially bring the designer on eye level and connect the design with the world of available 3D data, offering a new, intuitive design method: 3D hand movements.

This project focuses on the application of VR in an urban design process with current state of the art VR hard- and software. A design area was converted into a 3D virtual environment, a VR design tool was created and then used to create multiple design variants in VR. The lessons that were learned during this research form a first step towards new design methods, making use of the possibilities of software and immersion offered by VR.

Acronyms

AR:	Augmented Reality: a layer of digital information put on top of the physical world, for example through a Microsoft HoloLens headset
BIM:	Building Information Modelling
CAD:	Computer Aided Design
HMD:	Head Mounted Display, or VR headset
IVE:	Immersive Virtual Environment
LOD:	Level of Detail
VR:	Virtual Reality
UE4:	Unreal Engine 4

Preface

This report contains the documentation of the graduation project “VRbanism: assessing Virtual Reality as an urban design tool”. This graduation falls under the ‘Design of the Urban Fabric’ research group, part of the master track Urbanism within the MSc Architecture, Urbanism and Building Sciences, TU Delft.

This booklet is divided into a number of chapters that give a detailed account of the realization of this research and design project. Chapter 1 briefly introduces the personal motivation behind this project. In chapter 2, the project is defined. First, a set of key issues and literature concerning VR are introduced: the basis on which this research has been built. This part is followed by the problem statement, the research questions and hypotheses. Chapter 3 describes the research methodology and the tools that were used. The main part of this project, the research and design process, is covered in chapter 4. After this lengthy chapter the conclusions are offered in chapter 5. Finally, the research process is reflected upon in chapter 6.

Chapter 1: Motivation

"Every correct answer is necessarily a secret: something important and unknown, something hard to do but doable."

Peter Thiel (2014)

I have always been fascinated by two things: technology and cities, preferably cities filled with skyscrapers. While my education was focused on the built environment, I have always kept an eye on the constant progress of technology. Combining these two passions never occurred to me as something that would be straightforward. Not until my master Urbanism at least, where I finally discovered the importance of the link between the built environment and technological improvement. Our world is rapidly changing due to these advances, and so is the practice of urban design. Computers are now inherently integrated in some way or another to urban design, especially during the later stages of the design process (Portman et al., 2015). Now, the time seems finally right for another technology that could fundamentally change the way designers operate: immersive Virtual Reality (VR). It is an exciting technology that already has a long history (Bowman & McMahan, 2007), but only recently the technology that was needed to create a truly immersive experience became available at a low cost. Although the current VR systems were chiefly designed for gaming, other professions have grabbed the opportunity to use this technology for the advancement of their fields, like in psychology (Felnhofer et al., 2015). By choosing this subject, I aim to do the same for urbanism.

The world population is growing and the world is urbanizing at an unprecedented rate (United Nations, 2014), causing more and more problems to be concentrated in our cities. Thus, urban design becomes increasingly important. Since cities are extremely complex entities in which everything is connected to everything (Washburn, 2013), new ways to get over and insight into these entities could be useful.

I hope this research might constitute a useful first step into discovering how this technology can be applied in our profession, that many researchers may follow this path in the future and that our profession may benefit – indirectly offering new solutions to problems our cities face.

Chapter 2: Project definition

2.1 Problem field & Theoretical Background

In this paragraph, Virtual Reality (VR) technology is introduced along with other critical aspects considering VR. Multiple disciplines cross each other in this research project, making it both complex and potentially overwhelming. In order to make the underlying theoretical context visible in a structured manner, and to prepare the foundation for the next research steps, the literature that was used for this project has been categorized and will be elaborated in four subparagraphs.

The main goal of this paragraph is to clarify what aspects of VR are important and why, and to give a good view on the various aspects of the technology, before moving on to the problem statement.

2.1.1 Virtual reality

Virtual Reality is a technology that allows the user to be immersed in a virtual environment, for example by wearing a Head Mounted Display (or HMD) (Portman et al., 2015).
At this moment, VR technology has been in development for multiple decades (El Araby, 2002) and has drawn a lot of attention in both the academic world as in the media, often being trumpeted as the 'next big thing' (Bowman & McMahan, 2007). Especially in the 1990s research into VR was popular, even though the VR technology was expensive and archaic compared to modern standards[1]. The increased attention to VR during this period brought insights like the definition of VR by Sherman & Judson (1992): the five i's of VR. El Araby (2002) describes them as follows (p. 457):

- *Illustrative: Virtual Reality offers information in a clear, descriptive and illuminating way.*
- *Immersive: Virtual Reality should deeply involve or absorb the user.*
- *Interactive: In Virtual Reality, the user and the computer act reciprocally via the computer interface*
- *Intuitive: Virtual information should be easily perceived. Virtual tools should be used in a "human" way.*
- *Intensive: In Virtual Reality the user should be concentrating on multiple, vital information, to which the user will respond.*

Even after 25 years, this definition is still usable to evaluate both the technology and the experience it offers.

Since 2012, there has been a renewed interest in VR due to the development of the Oculus Rift[2]. The emergence of this new headset, making use of the advances in computing power

[1] https://www.vrs.org.uk/virtual-reality/history.html Accessed: April 28, 2017
[2] https://www.technologyreview.com/s/526531/oculus-rift/ (Accessed April 28, 2017)

and the widespread availability of high resolution smart phone screens and miniaturized sensors, lead to a renaissance of the technology[3]. Now, five years later, a number of high-end VR systems are commercially available, offering highly realistic VR experiences at relatively affordable prices. As described in the theory paper (Appendix C) that was written during this graduation period, these new systems offer input methods that allow the user to interact with the virtual environment intuitively: so-called ‘Room Scale Tracked VR’. By tracking the motions of the headset and a set of controllers held by the user within a room, the movements made by the user are reflected in the virtual environment, heightening the sense of immersion and offering a way to interact with the virtual environment[4]. The combination of affordable prices, improved visual experience and intuitive interaction allows VR to be used for many new cases, like urbanism.

2.1.2 3D models, LOD & realness

3D models

The dominant way we access the information of computers, which are used throughout the urban planning and design discipline, is visual (Batty et al. 2001). Visual representations of data have gradually made the step to 3D with the steady rise of computer power and increasing amount of available software.
As was discussed in the theory paper (Appendix C), 3D data offers many advantages to designers in the form of enhanced “imagination, comprehension, and evaluation of models or concepts, which are otherwise difficult to capture” (Göttig et al., 2004, p 101). As stated by Batty et al. (2001) and Yin (2010), 3D data helps with the communication of ideas between the designer and the layman. Extrapolating 3D images from 2D maps is a skill that is developed during years of design experience, which laymen normally lack (Shiode, 2001, Silvestri, 2010).

With the breakthrough of modern, high quality and affordable VR, a period of even more intensive use of 3D data might begin. Since 3D data can be shared using visual media such as 3D models, it eases communication with the laymen (Silvestri, 2010), which might be an advantage for public participation processes and thus empowering citizens (Luigi et al., 2015).

[3] http://www.economist.com/news/science-and-technology/21662481-virtual-reality-flopped-1990s-time-its-differentapparently-grand (Accessed April 28, 2017)
[4] https://www.tractica.com/user-interface-technologies/virtual-reality-input-devices-aim-for-immersion/ Accessed: 7 may 2017

Level of Detail

A key term in 3D city modelling related literature that is highly important in this research is Level of Detail (LOD). It communicates the degree in which features of real world objects are translated into a 3D model (Biljecki et al., 2014). Many different classification systems have been used to define LOD's, based on multiple properties such as geometry, texture, semantics and interior, but the classification system described by Biljecki et al. (2014) was used as the main reference in this research.

Realness

For VR, a level of 'realness', or 'level of realism' of the immersive virtual environment (IVE) might be necessary to fully convince the user that he or she is actually *present* in the IVE. Note that this is different from 'immersion': realness is a property of the experience, a factor that can lead to greater immersion. The degree of necessary realness is not yet defined clearly in the context of urban design (Portman et al., 2015). In case of a VR design process, realness likely needs to be a supportive factor of the virtual experience, for example to determine aesthetic considerations (Bowman & McMahan, 2007, Portman et al., 2015). These visual aspects, which are related to perception, visual preference, immersion and spatial insight, will be covered in the next paragraph.

Difference LOD and realness

A distinction needs to be made between realness, which is related to perception, and LOD, the degree in which the 3D object matches its physical equivalence. The perception of realness is influenced by display techniques such as 2D screens versus 3D VR HMDs, resolution and rendering techniques, whereas the LOD is purely defined by the properties of the model, like geometry and texture (Biljecki et al., 2014). In this research it was at times hard to separate the two, because the level of detail has a strong influence on the realness of the object model through its properties.

Achieving realness

How to achieve the necessary level of realness depends not only on properties of the 3D model such as geometry and façade textures (Biljecki et al., 2014), but also on the way the model is rendered by software. Finally, the display technique defines how the model is perceived: a 2D screen does not offer the immersive experience of 3D VR. More about this subject will be discussed in paragraph 2.1.4 under 'immersion', an aspect of VR that is strongly linked to technology (Slater & Wilbur, 1997).

Summarizing, LOD and 'realness' are two different things: LOD is the degree in which the properties of a 3D model match those of the object in reality, while 'realness' could be defined as the degree in which a model, or 3D context, is experienced as physical reality rather than a 'fake' representation of reality.

2.1.3 Visual aspects of VR

Expanding on the previous subject, some visual aspects of VR need to be elaborated upon.

Depth perception

The validity of VR as a tool for spatial interventions could be partly based upon the accurateness of the depth perception it offers. There are several cues that support our capacity of perceiving depth, separated in two main types: binocular cues and monocular cues (Grondin, 2016). Binocular cues are derived from the fact that we have two eyes with distance in between them. The two binocular cues involve binocular convergence and retinal disparity (Grondin, 2016). VR headsets make use of retinal disparity by creating a slightly different image for each eye, which gives the viewer two points of view on the object that is put in front of him or her, which is perceived as 3D (Grondin, 2016).
Grondin (2016) and Prak (1979) also give a useful oversight of the monocular visual cues of depth perception:

- Linear perspective (the fact parallel lines leading away from the observer seem to converge in the distance)
- Texture, which is closely related to linear perspective: in a texture gradient, the further away the texture is, the denser it gets
- Occlusion (objects being hidden by other objects, giving sense of relative distance)
- Relative height (objects of the same height placed in a line away from the viewer seem to get less tall the further they are, giving a sense of their distance)
- Relative brightness (impressions of depth by shading)
- Aerial perspective (relative sharpness of contours)
- Motion parallax (impression of depth caused by the movement of the observer, causing nearby objects to seemingly move faster than far away objects)

All of the monocular cues can be used to give a sense of depth in 3D software on a 2D screen, depending on its sophistication, while many are more or less inevitable in 3D depictions of reality.

Depth perception in VR has been repeatedly researched, for example by Ng et al. (2016), Jones et al. (2008) and Peer & Ponto (2017). The outcome of the Ng et al.'s research suggested that the distance of simple geometric objects above 15 meters, in VR, is generally underestimated by around 40%. If a 3D jet was shown, which offered multiple visual cues, the distance estimation was improved considerably (Ng et al., 2016).
Jones et al. (2008) earlier came to the same conclusions. Peer & Ponto (2017) used modern VR HMD's and room scale 3D tracking to measure distance underestimation and linked the measured underestimation to contemporary displays. The question remains if, and how, depth estimation will improve when VR HMD's get significantly higher screen resolutions, possibly near the maximally perceivable pixel density at some point in the future.

Luigi et al. (2015) researched the validity of VR as an evaluation tool of urban spaces and concluded that the perception of a real environment did not differ much from the perception of a detailed 3D version of the same environment in VR. Kuliga et al. (2015)

more or less came to the same conclusions while researching VR as tool to research how people react on a corresponding real and virtual building. They stated that results from earlier research showed a lack of arousal, which might be attributed to the less convincing graphics and less advanced VR HMD's (Kuliga et al., 2015). Their research showed higher levels of arousal, though.

Visual complexity & preferences

A closely related aspect to LOD and realness, one that is even more subjective, is the issue of visual complexity and visual preferences. This is important because it could help to formulate design scenarios or to substantiate design choices made during the VR design process, which is strongly visually oriented. Prak (1979) wrote in his book 'De visuele waarneming van de gebouwde omgeving' about the human desire for (visual) variety, which he linked to the Gestalt theories. By breaking up flat façades by setbacks and variations in the façade alignment and material, more visual information would be brought into the design, creating visual complexity. On average, higher levels of visual complexity are preferred, although this varies among individuals (Prak, 1979). Much more research has been done on visual preferences, such as the void-to solid ratio in residential façades (Alkhresheh, 2012) or the preference of architecture and engineering students of various house façades (Akalin et al., 2008) which seem to validate the findings of Prak. The degree of variation and visual complexity is an element that could be tested in VR, later on in this project.

Spatial model & spatial insight

One of the possible advantages that VR might bring is a higher amount of spatial insight. As stated before, 3D models help to enhance the comprehension and evaluation of spatial concepts (Göttig et al., 2004, Silvestri et al., 2010), but experiencing a 3D model stereoscopically and immersively might potentially give more insight. Some of these effects might be experienced during this research process.

2.1.4 Properties of VR in relation to the urban design practice

Immersion

One of the key aspects of 3D VR is its 'immersion', as stated by Sherman & Judson (1992). To repeat the definition: immersion is the degree in which the user is absorbed into the virtual environment. Slater & Wilbur (1997) described the concept of immersion as a technology to deliver an illusion of reality to the senses of a human. The goal of immersion would be to achieve 'presence', a sense of actually being *in* the virtual environment[5].
They define immersion using four parameters: Inclusive (shutting out the physical reality), Extensive (the range of senses that are accommodated), Surrounding (how many degrees of the field of view are 'filled' with the virtual experience) and Vivid (resolution and colour

[5] https://medium.com/@choongchingteo/the-concept-of-presence-in-virtual-reality-6d4332dc1a9c Accessed: 22 june 2017

depth) (Slater & Wilbur, 1997). This definition is usable to this day, since it seems many of these parameters have been improved upon with the newest VR hardware. Higher pixel densities, wider fields of view, lighter headsets and introduction of new senses, driven by more advanced HMD technology and increased computer power, could possibly lead to levels of presence that would make a person forget where he or she physically is. Today, VR headsets offer sufficient levels of presence to trick the brain, which can lead to experiences like motion sickness and a fear of heights (Heydarian et al., 2015).

Why is immersion important for urban design? As Slater & Wilbur (1997) state, increased task performance is often stated as a possible advantage. This advantage has not yet been proven, though. By eliminating the experience of the interface between person and virtual environment, the VR user would only be confronted with the user interface and the task at hand. It needs to be researched if the task performance would improve, but the hypothetical advantages would be based on the direct contact between the user and the visual environment, in more intuitive ways – which will be discussed in the next indentation.

Bowman & McMahan (2007) give another reason for the possible importance of immersion. They argue that VR offers an enhanced *spatial understanding*, through the provision of depth cues that other technologies cannot offer, like 3D stereo imagery and head movement tracking (Bowman & McMahan, 2007, p.39).

The third possibly important aspect of immersion is its potential ability to decrease 'information clutter', the excess of symbols, text, windows and other information that has to fit on a single screen (Bowman & McMahan, 2007, p.39). Enhanced immersion through viewing information in a 3D scene could decrease this effect and make the presentation of information more clear.

Intuitive interaction with 3D data

As stated earlier in the theory paper, current CAD and BIM software is complex, has a steep learning curve and puts a high cognitive load on the designer while using it (Bernal et al., 2015). This, plus its preciseness and explicitness, makes it less useful in the conceptual design phase where precision and complexity hinder the creative process (Bradecki & Stangel, 2014). Furthermore, the user interface and the complexity of using it can lead to multiple pitfalls, as described by Bernal et al. (2015):

- circumscribed thinking (limitation of design alternatives to what is possible with the tool)
- premature fixation (resistance of changing the design due to the premature complexity of the model)
- bounded ideation (distraction from creative tasks because of technical and software issues).

These pitfalls have a negative influence on the capability of the designer to use a CAD tool to design in the conceptual stage of design.

For a potential VR design tool, it is important to find out if and how these pitfalls can be avoided. The input method of modern VR systems, like the next chapter will describe, might potentially alleviate these pitfalls. 'Room scale 3D tracked' VR systems let the user interact with the virtual environment in 3D through a set of 3D tracked controllers. The question whether this is actually a big benefit will be researched in chapter 6. More intuitive input methods, combined with 3D visualization in VR, might lead to designers to “explore and express their imagination with greater ease” (Portman et al., 2015). This will be put to the test in this research project.

Design at eye level

Immersion in the virtual environment would make it possible to design as if one were standing at eye level; since we experience the city at eye level and not from bird’s eye view (unless we enter a skyscraper or a helicopter), this might offer a useful new perspective whilst designing. The eye level perspective is essential for VR because this is how we perceive the city. The experience of this perspective through a convincing 3D environment in VR is important, because this experience will be very different from, for example, a picture taken at eye level. Standing in and walking through the design at eye level would not be limited by a frame or a set time: the design could be explored without limits, dynamically.

Use of game engines for design

Modern immersive VR technologies and visualization software offer higher realism than ever (Kuliga et al., 2015). A driving factor has been the positive feedback loop between rising computer power and the applications of this computer power, such as the increasing graphical capabilities of games and scientific simulations (National Research Council, 2010) The video game industry had another positive side effect: the emergence of graphically realistic real-time visualization software that is used to create games, known as game engines (Indraprastha & Shinozaki, 2009). These game engines are now more powerful than ever, many are now free to use and offer VR functionality built-in, allowing everybody to start creating interactive 3D experiences.

There is a lack of ‘best practice’ research using game engines for urban design in academic literature. Most of the documentation that is currently available and that was used for this research consists of tutorials offered by the developers of the Unreal Engine, game designers and enthusiasts. This reflects the current state of the use of game engines for urban design: immature but evolving.

By doing this research, more insights on using game engines in a design process might come to light.

2.2 Problem statement

As mentioned in the conclusion of the research paper and in Chapter 1, there exists a gap of knowledge about designing urban environments using VR. A lot of research has been done on VR for other subjects, as well as on closely related subjects like computer visualization techniques, but the potential advantages and disadvantages of using state of the art 3D VR for urban design, the necessary workflow of using VR in an urban design process and the opportunities and pitfalls of using this technology in practice are still largely unknown.
Considering the immersive aspect of VR and its ability to unlock the potential of software in a more visual way, the use of VR in urban design processes could potentially lead to increased use of 3D data, improved spatial insight in urban situations and design, or lead to more efficient ways of designing. This could be immensely helpful to solve pressing issues in our cities, such as increasing the sustainability of our cities, solving congestion, offering affordable housing or creating more housing in dense urban fabric. The assumptions about the potential advantages of VR have not yet been tested, though.
Therefore, it is necessary to fill this gap of knowledge and answer many questions involving the practical use of this technology, possibly making VR useful to solve urban problems in the future. If 3D VR is to become a mainstream technology in the near future, it is important that the use of this technology for our profession will be thoroughly researched and its use will be academically established. Thus, the main problem statement of this graduation project is as follows:

There exists a gap of knowledge about the benefits, disadvantages and potential of using immersive 3D Virtual Reality as an urban design tool.

2.3 Research questions

The first step in gaining knowledge on this subject was to write the theory paper during the P2 phase of this graduation project, which focused on the state of the art of the technology in relation to the profession of urbanism. This paper can be found in Appendix C. The research question of this paper was as follows:

"What is the state of art of VR concerning urban design?"

Apart from the possibilities, pitfalls and current position of VR in literature, the theory paper described the current practice of urban design in relation to the evolution of computer driven technologies and the advantages of using 3D data. The paper concluded with potential future developments and necessary research to fill the gap in knowledge that has been discussed in the problem definition and thus served as a prelude to this research project.

The process of researching the use of VR for urbanism promised to be an exploration of mostly uncharted domain. A research question was therefore formulated that should offer the flexibility to explore the subject in a free way, while still aiming to fulfil the greatest goal of this research project: filling the gap of knowledge of using VR as an urban design tool. These considerations led to the following main research question:

"What are the advantages, disadvantages and potential of VR as a design tool for urbanism?"

The next sub-research questions have been defined to help answer this research question in order to validate VR as a viable urban design tool.

"What new possibilities does VR offer in an urban design project?"

This question aims to explore the new capabilities designers could be empowered with when using VR for urban design. For instance, the possibility of running simulations using the resulting 3D model of the design in order to gain new insights.

"What limitations does VR currently impose upon designers in an urban design process?"

This question aims to answer what currently can't be done with VR during the urban design process using current technology, or what other intrinsic attributes of the current technology limit the designer in some way.

"How effective is VR as a tool for designing at eye level?"

This question aims to explore the effect of the immersive character of designing in VR and its possible advantages of designing at eye level, like using sight lines, the experience of density and judgment of scale, for instance.

"How effective is VR as a tool for designing at various scales?"

It is not yet clear at which scale VR performs best. It could therefore be necessary to test the effectiveness of designing in VR while switching between various scale levels.

"How effective is VR when used to evaluate the quality of the public space of a design?"

This question touches on the immersion aspect of VR again, by answering how effective the tool is in evaluating various properties of the public space and why it would be so effective.

"What factors of using VR in an urban design project obstruct the design process?"

The act of designing in VR for urbanism could possibly be obstructed by various causes that only come to light by actually performing an urban design process. This question aims to find these issues.

"What factors of using VR in an urban design project speed up or simplify the design process?"

Conversely, VR could also have qualities that have positive influence on the design process. These should be examined as well.

2.4 Hypothesis

As described in the theory paper (Appendix C) and problem statement, potential advantages of using VR include a higher amount of spatial insight in the design situation regarding sightlines, spatial quality, a sense of scale and the experience of public space. These lessons are mainly important as a contribution to the Urban Fabrics research group. Also, increased use of 3D data by using VR is expected, which leads to additional advantages such as more informed design decisions.
The problems that are expected would be mainly software and data related, since there are no integrated CAD solutions for urban designers yet. An experimental approach is taken using potentially unstable software, which might lead to multiple technical challenges. Also, converting the design results to other kinds of software might be troublesome. All these challenges might contribute to understanding how VR can be used at this moment and in the future, what problems should be addressed and how specific technical pitfalls can be avoided.

2.5 Thesis outline & time planning

This thesis project has the following structure. After this chapter containing the project outline, chapter 3 will cover the research methodology followed by chapter 4, covering the main research and design part. Chapter 5 contains the conclusions. The booklet is concluded with the reflection in chapter 6 and appendixes. The image below shows the time planning for this project that was used during this graduation.

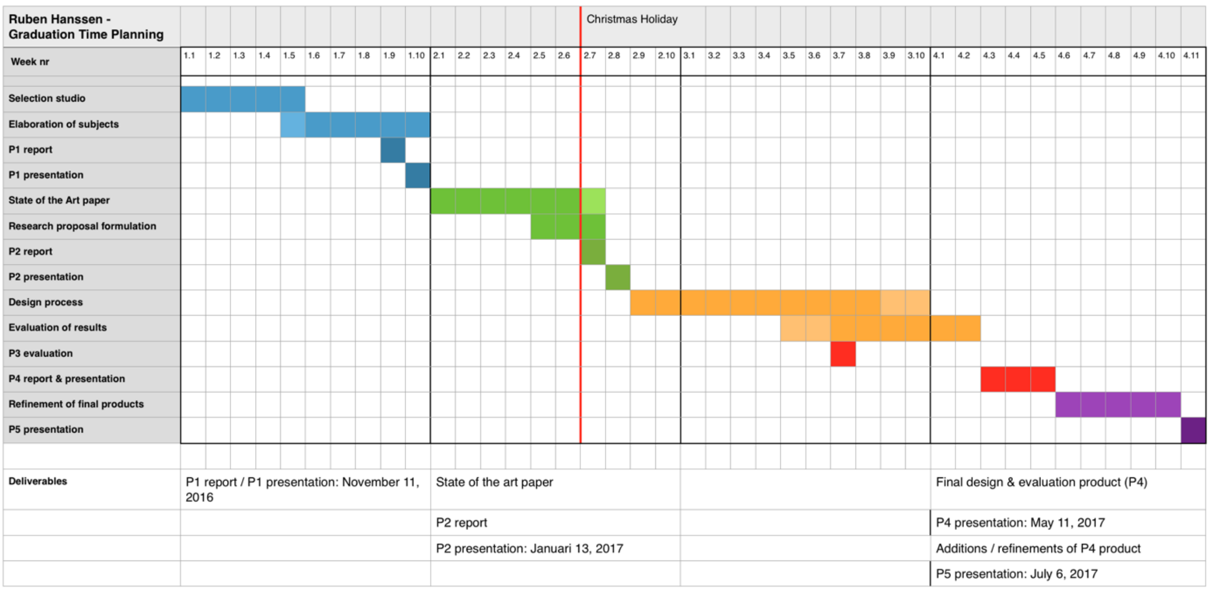

Fig. 1: Time planning. This booklet is handed at the end of week 4.10

Chapter 3: Methodology

3.1 Exploratory case study research: Sloterdijk redesign

The goal of this graduation project is to find the advantages, disadvantages and potential of using VR as a design method for urbanism. As described, there exists a lack of precedent research and literature about how to use VR in urban design. Therefore, the choice was made to perform a case study research involving a design project of an urban environment. The design element, including the design outcome, is a mandatory part of the Design of the Urban Fabric studio. Nevertheless, the design part is mainly used to investigate the method that is used for designing: 3D Virtual Reality.

3.1.1 Research by design

In order to actually answer the main research question and the sub research questions, a design project was used. The design element of this research was the last step of a greater challenge however, since designing for urbanism hasn't been done before with the current state of the art technology. This makes this project special: it is a first in our profession.

In total, three important hurdles had to be overcome, each delivering critical pieces of knowledge that were needed to continue this research:

- Preparing a 3D model of the urban design location in its current form, suitable for designing in VR.
- Creating a designing system that works in and with VR.
- Using the VR design system to solve a specific design problem.

The first phase was necessary because the software and hardware needed to be tested for two reasons:
Firstly, the design would need some form of an urban context. Secondly, the accuracy of the model should be validated in VR. Creating this context and testing it in VR could deliver much knowledge about both the necessary workflow as the ecological validity of VR. The second step was necessary in order to discover a VR design workflow and -system. Finally, the last step was critical in testing the urban design process itself in VR, and to come to necessary design outcomes for analysis.

In chapter 4, the process of following these steps and their analysis are discussed.

3.1.2 Design area choice & analysis

The explorative nature of this research project allowed for more flexibility in choosing a design location, since the VR design method is the study object rather than the design area and the problems of that specific area.

Choice for Amsterdam

A location has been chosen in the city of Amsterdam, because of several reasons. Firstly, the city of Amsterdam is the city I lived in while studying at the University of Amsterdam for around 4 years. My familiarity with the context of the design location would supposedly offer advantages during the research process.
Secondly, Amsterdam is very accessible, which would be helpful in the case of site visits.
Thirdly, I am personally interested in the development of Amsterdam, partly because of the surge in developments caused by the housing shortage in Amsterdam[6] .

In order to find a suitable location within the city of Amsterdam, the municipality of Amsterdam was approached and an appointment was made with Rick Vermeulen, an employee of the planning department of the municipality who explained the Koers 2025 strategy, as well as connecting me to Robert Heit and Bas Koppers, who took an interest into this project.

Koers 2025 is focused on adding housing capacity to the city while still being flexible in case of changing housing demand. Important locations for additional housing are proposed mainly in the 'Ringzone' (Gemeente Amsterdam, 2016), preferably close to key infrastructure nodes.

Location choice & suitability for VR research

Many locations within this framework could have been suitable for this project, but the area that was chosen was an industrial area located near Amsterdam Sloterdijk rail station: Sloterdijk I. This area is currently a low density business and industrial district.

The reason for this specific location is mainly its suitability for this VR research. The area has a simple layout. It almost perfectly oriented on a north-south axis, which helps greatly with the used software. The existing buildings will, according to the plans, all be demolished to offer space for new developments. This allows for a 'tabula rasa' approach: for the recreation of the area in a 3D model, only the surrounding streets would have to be taken into consideration instead of a swath of complex urban fabric.

[6] https://www.bewustnieuwbouw.nl/toenemende-schaarste-aan-woningen-in-grote-steden/ Accessed: 7 Mei, 2017

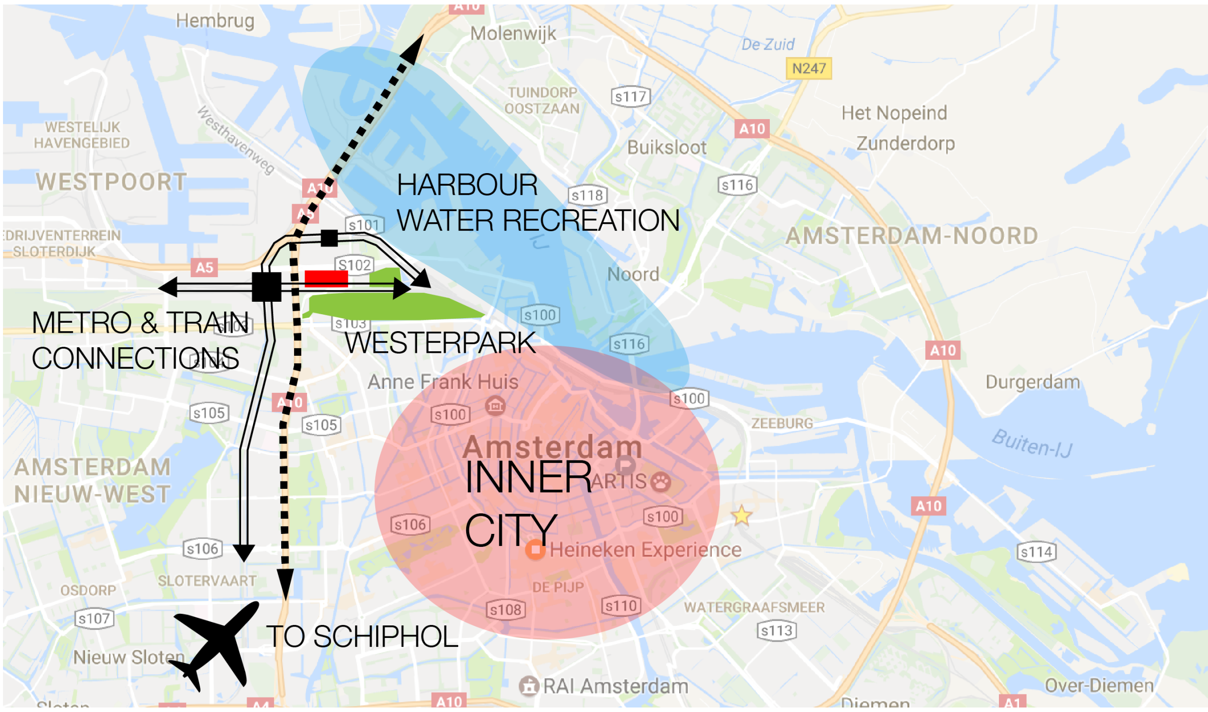

Fig. 2: City scale context of Sloterdijk I. Google Maps, own editing.

The area is located in the wider Havenstad area, which is set to be redeveloped in the near future (Gemeente Amsterdam, 2016). It is located near multiple transport nodes and borders on the far western end of the Westerpark. The area is delineated by a set of transport corridors: the A10 highway on the west, the Amsterdam-Haarlem railway in the south and the Transformatorweg in the north.

Fig. 3: Aerial view of Sloterdijk I from the South-East

Since the area would offer a blank slate, plus the interesting externalities of the location and a high potential for development due to its strategic location, this area was deemed very suitable for this research project.

In the chapter 4, the design problem for this area has been stated.

3.2 Tools

The selection of the VR design tools was potentially the most important choice during this project. In order to research the use of state of the art VR systems in urban design, the most modern VR system at the time of writing was used, plus a software solution that was deemed capable enough for the task.

3.2.1 VR hardware

The VR hardware that was chosen for this research project was the HTC Vive system. The choice for this system was made since it was *the* state of the art VR system, supported by a capable, free software solution and offering room scale tracking of the controllers – a function that was essential to the design task. The system consists of multiple elements: the head mounted display (HMD, or 'VR headset'), a set of tracking stations, a set of 'motion controllers', a link box and the computer system that drives the necessary software. In this paragraph I will concisely elaborate how they work and how they serve the VR system and the immersive experience of VR.

HTC Vive HMD

The headset, made by HTC, is the main interface between the designer and the virtual model. It consists of a headset with two internal screens, one per eye, that project the virtual world through a set of lenses into the wearer's eyes[7]. By using two screens a stereoscopic 3D effect can be created, which supports the immersive experience. The position and orientation of the headset are tracked to mimic the movements of the user in the virtual world, which is another aspect of great importance for an immersive experience[7]. The headset is linked to the computer by means of a long cable. The disadvantage of this cable is that it is a distraction from the experience of immersion; it tends to get in the way, twist around chair and desk legs or around the feet of the user. For this project however, the disadvantage of the cable is not deemed significant.
The field of view (FOV) of the HTC Vive is 110 degrees[8], which is far higher than earlier headsets dating back to the 90's. The higher the FOV, the more immersing the experience will be[9].
Another important aspect is resolution: the amount of pixels per unit of area[10], which defines the 'sharpness' of the screen. The higher the resolution, the sharper the images in VR will appear. Since the screens in the HMD are placed so close to the eye and are magnified through lenses, the gaps between individual pixels are currently still visible, leading to the 'screen door effect'[11] – which is comparable to the effect viewing an image

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[7] https://www.wareable.com/vr/how-does-vr-work-explained Accessed: May 8, 2017
[8] https://www.digitaltrends.com/virtual-reality/oculus-rift-vs-htc-vive/ Accessed: May 4, 2017
[9] https://vr-lens-lab.com/field-of-view-for-virtual-reality-headsets/ Accessed: May 4, 2017
[10] http://www.digitalcitizen.life/what-screen-resolution-or-aspect-ratio-what-do-720p-1080i-1080p-mean Accessed: June 22, 2017
[11] https://www.vrheads.com/what-screen-door-effect-and-why-does-it-happen Accessed: June 23, 2017

through a screen door. This hinders the immersiveness of the experience. Higher resolution screens with less screen door effect will lead to significantly more realistic and immersive experiences.[12, 13]

Fig. 4: The HTC Vive VR system, with Motion Controllers and the 3D Tracking bases stations at the left and right sides. Available through: http://cdn2.pu.nl/media/hardware/vive2.jpg

[12] https://vrscout.com/news/vr-video-look-soft/ Accessed: 26 june 2017

[13] https://www.theverge.com/2017/6/19/15820336/nokia-varjo-virtual-reality-headset-microsoft Accessed: 26 june 2017

HTC Vive Base Stations

The HTC Vive system tracks the translational movements of the headset and controllers with the help of two ‘base stations’. These stations send out horizontal and vertical sweeps of a laser, which are picked up on sensors placed on the headset and controllers, to calculate their position within 3D space (Lang, 2016). The Base Stations are not connected to the computer, but do require a connection to a power outlet. Because the stations use laser rays for the positional and rotational tracking, reflective surfaces can interfere with the correct functioning of the system.

Fig. 5: HTC Vive Base Stations (without cables). These boxes contain spinning lasers to track the HMD and controllers. Available through: https://blog.turbosquid.com/wp-content/uploads/2016/06/1-zGtToYJuc2wPodUW5Wf0ug.jpeg

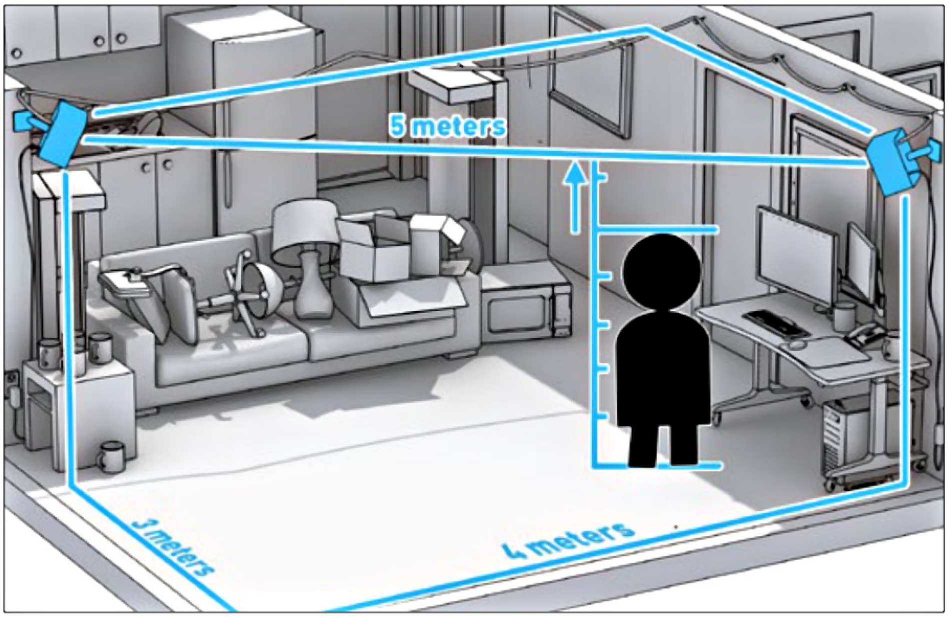

Fig. 6: Room scale tracking system by means of the Lighthouse system, using two Base Stations. Available through: https://i.kinja-img.com/gawker-media/image/upload/t_original/js55zljoa3b6v8nj1bfc.jpg

HTC Vive Motion Controllers

In order to manipulate the virtual world, the system offers a set of 'motion controllers': roughly shaped like a stick with a torus-shaped element on top, each with a trigger button for the index finger, 'squeezing' buttons at the sides of the controller, and lastly two buttons plus a circular touch sensitive 'track pad' for the thumb. These controllers are tracked the same way like the HMD and offer accurate and versatile interaction with the virtual environment.

Fig. 7: A motion controller of the HTC vive. Available through: http://a4.images.reviewed.com/image/fetch/c_limit,w_856,h_570,q_89,f_auto/https://reviewed-production.s3.amazonaws.com/attachment/95645bba928346f9/HTC_Vive_Controller.jpg

Link box

The headset is connected to the computer by means of a cable, which is not directly plugged into the computer but by a 'link box' that serves as an interface between the computer and the HMD. Cables are plugged in at either end of the box.

Fig. 8: HTC Vive Link Box, the interface between the PC and the HTC Vive. Available through: https://c.slashgear.com/wp-content/uploads/2016/04/htc-vive-review-4.jpg

Computer system

The HTC Vive system needs a powerful PC system to be operated at the required frame rate. At the time of writing, Apple computers are not powerful enough to power adequate VR experiences[14]. This may change over time, however. Laptops with regular graphics cards for laptops are not powerful enough as well.
The most important part of the computer system is the graphics card, which calculates the image that needs to be sent to the VR headset. The computer that was used for this project had the following specifications:

Intel i7 processor, 4.0 GHz (8 CPU cores)
NVIDIA Geforce GTX 1070 graphics card
ASRock socket 1151 mother board
500 GB SSD hard drive
16 GB of DDR4-2133 random access memory cards
650 watt power supply

This PC system had a total cost of around 1200 euro, which is just above standard for a high-end gaming PC anno 2016.

3.2.2 Software

Various software was used during this research for different purposes. In this paragraph, the used software will be elaborated on.

Unreal Engine 4

As software solution for designing in VR, Unreal Engine 4 (UE4) was chosen. This choice was based on two considerations. Firstly, UE4 offered a native solution to editing 3D environments in VR through the UE4 VR editor. This editor is a new function of UE4 that was developed for the creation of game levels.
Secondly, UE4 makes use of a more accessible and easy to learn way of programming called Blueprints, which is a visual node-based form of programming.

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[14] https://www.vive.com/uk/support/category_howto/can-i-use-vive-with-mac.html. Accessed: 7 mei, 2017.

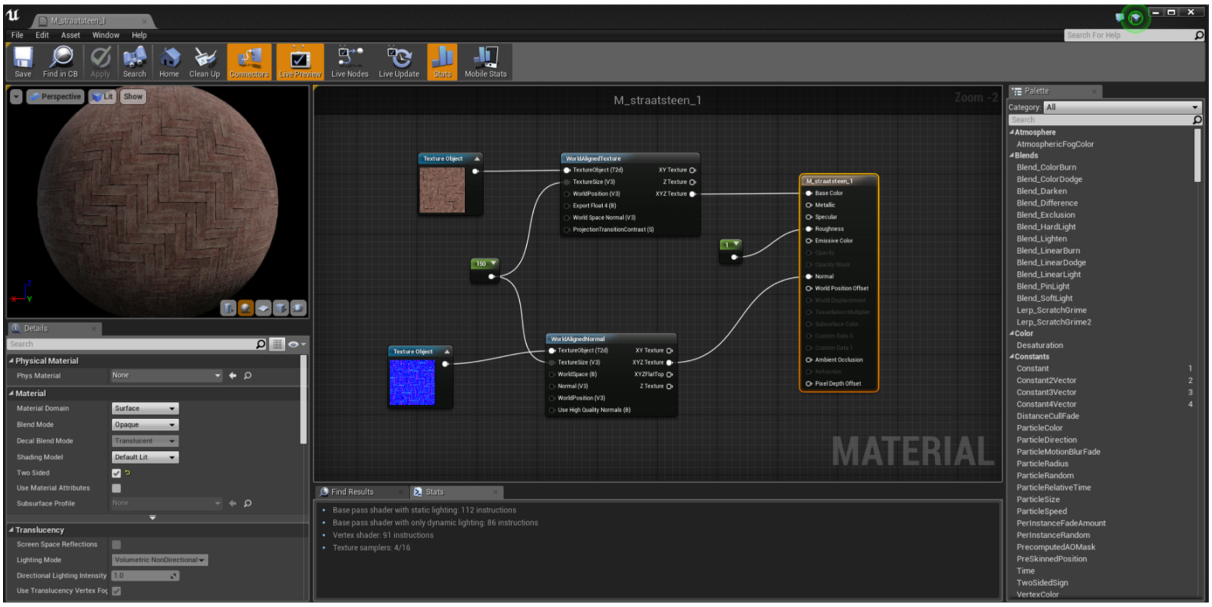

Fig. 9: : The Blueprint system in action, in this case to create a brick street material. Own work

Blueprints could be used for many purposes, unlocking many of the powerful software features without the need to learn advanced C++ programming (the programming language on which UE4 is based). Since I did not master programming in C++ (or any other language), this node based solution was both practical and necessary for the success of this project.

Unreal Engine 4 VR Editor

The Unreal Engine 4 VR Editor was essential to this project. It can be used by game developers to create game levels or experiences in VR and offers most of the functionality that the regular Unreal editor offers two-dimensionally.

The VR version of the editor can be opened within the regular Unreal Engine editor, if the SteamVR software is properly installed and activated, if the headset is properly set up and if the headset is connected to the computer. Within the VR editor, wearing the headset, the user sees the 'level', or design environment, in VR. The motion controllers play a critical role in designing; they are the interface between the designer and the model. These motion controllers are shown in the VR editor, in 3D, with a laser beam coming out at the end. The laser beam is used as a cursor, to aim at objects within VR.

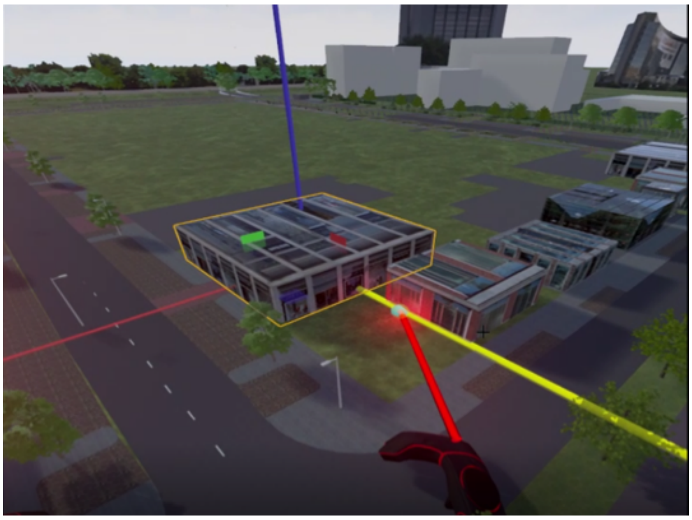

Fig. 10: The Unreal Engine 4 VR Editor in action. Own work

By pulling the trigger with the index finger, the object that is being aimed at is selected. By pulling the trigger and moving the motion controller, the object is moved. Note that the tracking of the motion controller in 6 degrees of freedom becomes essential at this point, since the wide variety of natural arm and hand movements can be used to interact with objects. More accurate translation-, scaling- and rotation actions can be performed by using their particular ‘gizmo’ – a coloured 3D tool that shows the translation/rotation/scaling axes at the ‘origin point’ of the selected object. By selecting the desired axis and moving the motion controller, the object is translated, rotated or scaled only along that axis.

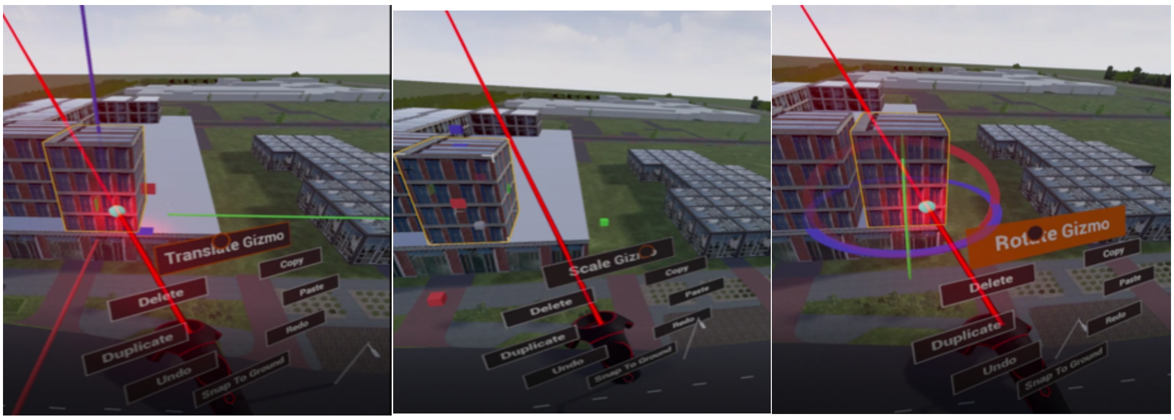

Fig. 11: Translate, scale and rotation gizmo in action. Own work

The VR Editor allows to activate ‘snapping’ along a grid, forcing the objects to only move/rotate/scale at predefined increments. This helps to accurately align objects. The grid size can be changed by aiming one of the controllers at the other, which summons a menu that seems to be floating at the back of the controller that is aimed at.

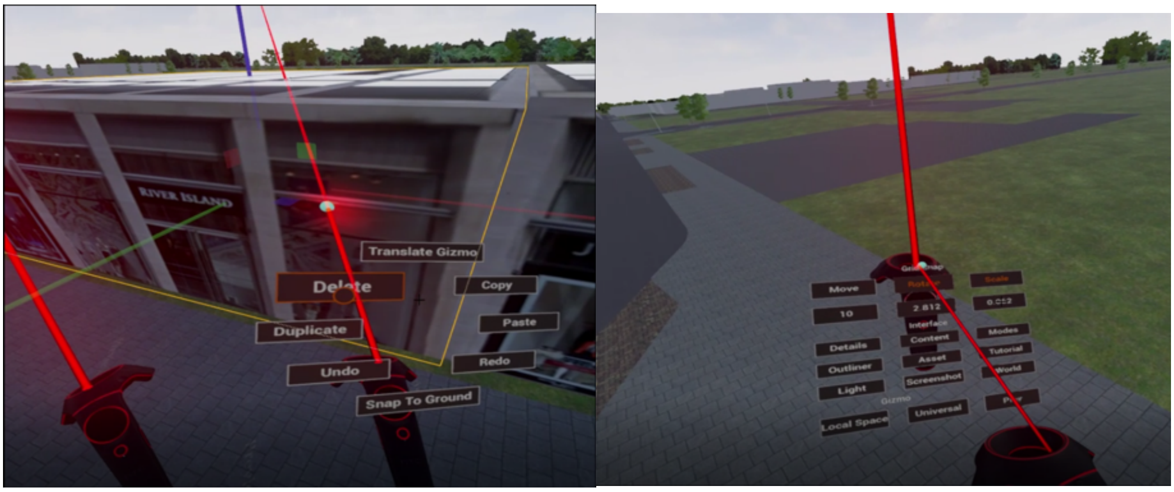

Fig. 12: Thumb trackpad & pointing menus. Own work.

New objects / design parts can be selected and ‘dragged’ from the Content Browser, the main object library in the Unreal Engine that shows all the imported or created assets, into the design environment.

Fig. 13: Selecting and dragging objects into the design using the Content browser. Own work.

The light direction can be changed in Unreal to simulate various lighting situations:

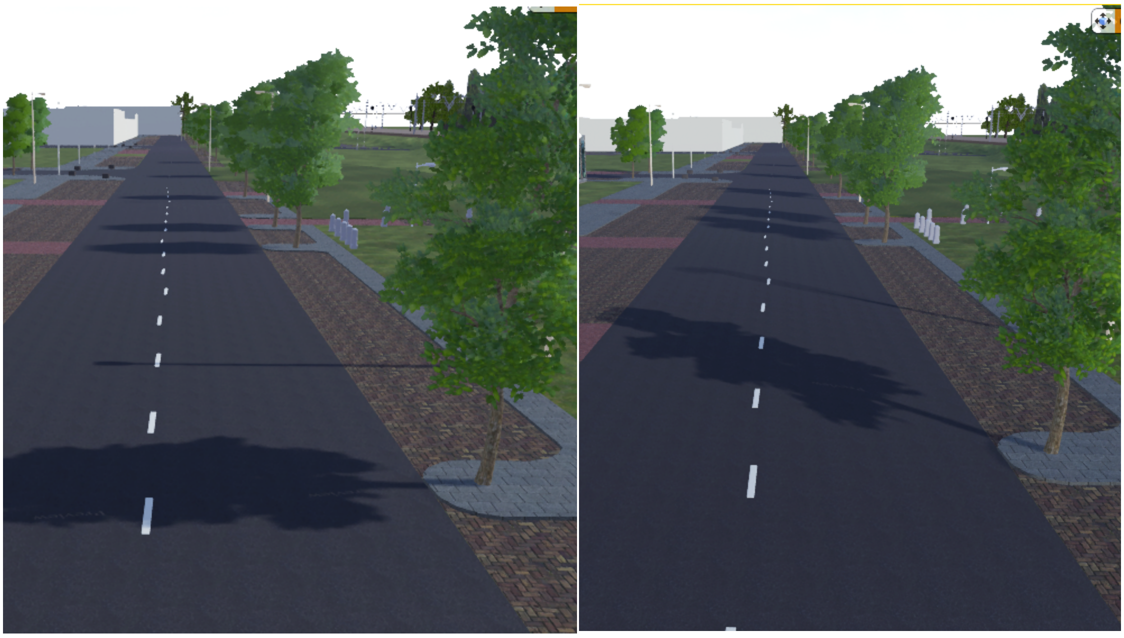

Fig. 14: The angle and intensity of lighting can be changed to create any lighting condition. Own work.

Another option is to add atmospheric fog to a scene. Fog could help as an extra monocular depth cue (Grondin, 2016):

Fig. 15: Fog added to a 3D scene. Own work

Blender

Blender is an open source 3D modelling program that could be used to create 3D assets for use in Unreal Engine 4. It has a different user interface than many other programs that requires time to learn. With relatively little pre-existing knowledge, following several tutorial and using a cheat sheet with keyboard shortcuts, one can produce relatively advanced 3D designs in short amounts of time. It will be used as a 3D modelling tool in this project.

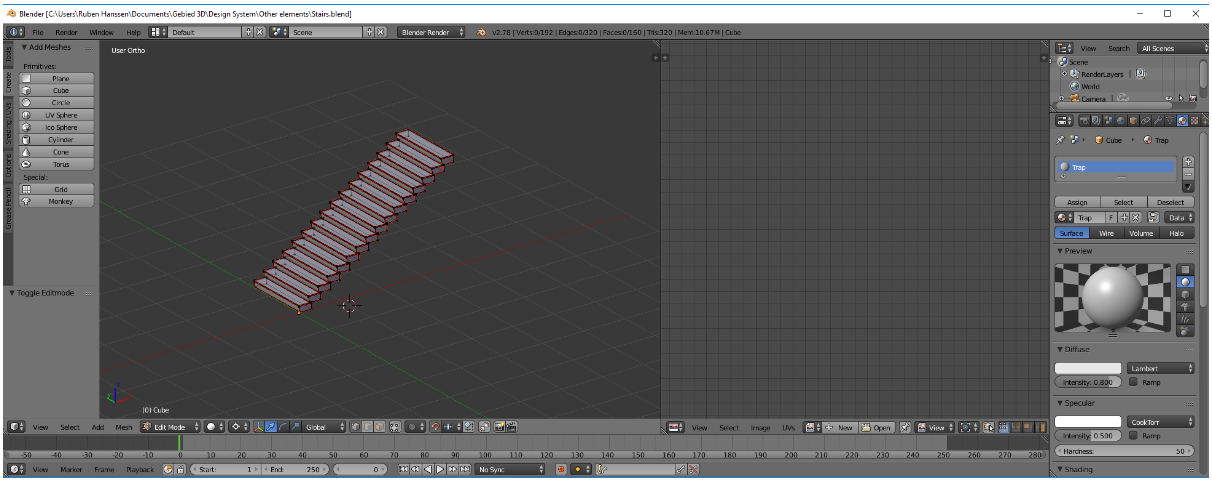

Fig. 11: The user interface of Blender. Own work.

Autodesk Maya

Autodesk Maya is another 3D modelling program that offers more advanced options and is better integrated with software solutions such as Autodesk AutoCAD and related file types, such as .dwg. This program will be used to create a 3D version from 2D maps, as described in chapter 5.2.

Chapter 4: Research & design

4.1 Design problem

4.1.1 Approach

In this chapter, the actual research and design process will be described. Since using state of the art VR technology in an urban design process has not yet been done before, the process of designing was initiated by a long start-up phase to find out if, and how, it could be accomplished. In chapter 3, three phases were identified in that would be used to answer the main research question and its sub questions:

- **PHASE 1: Preparing and testing a 3D model of the urban design location in its current form, suitable for designing in VR.**
- **PHASE 2: Creating and testing a designing system that works in and with VR.**
- **PHASE 3: Using the VR design system to solve a specific design problem.**

This chapter describes the execution of these phases and what was learned during the process. Each phase will be introduced by a short description of the knowledge that would need to be obtained during that step and what information was necessary to continue to the next phase.

4.1.2 Sloterdijk background & challenge

The Area

If VR is to be researched as a tool in urban design, an urban design challenge which can be tackled with VR needs to be selected. As discussed in chapter 4, the chosen area is Sloterdijk 1, an industrial site near Amsterdam Sloterdijk Station, that is likely to be redeveloped within several years.

Sloterdijk 1 was considered suitable for this VR design project because the development of this area would take a tabula rasa approach: most of the existing buildings would be demolished. Also, the north-south orientation of the plots and the relatively simple urban context made it an ideal location to model into 3D and use for this experimental approach. More complexity would have complicated the process unnecessarily.

Design challenge

Currently, the area is an unattractive low density industrial area. The area is part of the Koers 2025 framework that aims to redevelop areas such as this one to solve the housing shortage of Amsterdam, to offer new employment possibilities and to 'add new qualities to the city' (Gemeente Amsterdam, 2016). The area is strategically positioned within the city, being close to a major railway station (Amsterdam Sloterdijk), the A10 highway, the Westerpark and the harbour area.

The municipality set up multiple ambitions for the area, of which the following three are of main importance to this project:

1. Creating an attractive residential area
2. More intensive land use, without suppressing current work functions
3. Urban design with high spatial and functional quality of both buildings and public space

Summarising: the aim was to create a highly mixed, dense working and living neighbourhood.

Preferences of the municipality

The municipality prefers to aim for maximum building heights between 40 and 50 meters, in combination with a mix of other building heights and –types.

Qualitative criteria are views, wind hindrance, sun exposure regulations and inner courtyards.

Connection streets and inner courtyards could get a more intimate character by creating 'thresholds' at the outer ends.

There are multiple options to fit non residential functions in the area:

- Horizontal ownership & function separation (non-residential functions linked to ground floor)
- Vertical ownership & function separation (business complex)
- Mix between vertical and horizontal ownership forms on block level
- Work functions (offices, workplaces) at inner court yards
- Zoning of functions (dependent on location or orientation in plan)

The current layout of plot alignments and streets is kept. More attractive public spaces are created by revitalizing the streets and sidewalks, creating new connection streets, squares and a park at the south end of the area.

Streets will be adjusted to the needs of the work functions at ground level, which means that parking, storage, garbage and bike stalling need to be solved within buildings.

4.2 Creating the current area model

4.2.1 Design questions

During this phase, the goal was to research the following things:

- Testing the viability of the chosen software and hardware to create an accurate depiction of reality
- Validating VR as method to visualize current urban situations / contexts
- Validating the current area model using VR

More importantly, this phase was necessary to create an accurate and effective design context for the upcoming design phase. Also, this phase could learn lessons what factors are important in using VR for urban visualization and to create and test a reproducible workflow for converting urban contexts into virtual environments that can be explored in VR.

4.2.2 Creating the model

The 3D model of the design location was created using three main steps: Editing and grouping the map in Illustrator, creating a 3D environment of the map in Autodesk Maya and finally importing and editing this environment in Unreal Engine 4.

Some difficulties became apparent during the creation of the virtual environment. The first issue was problems caused by double / intersecting lines, which prevented faces from being created in Maya. Secondly, the lack of UV maps and incorrect 'normal' direction of the model in Maya caused lighting and display problems with the .fbx model in Unreal Engine 4. After these issues were fixed, the model could be finished using some custom created 3D models and downloaded trees.
In order to keep this chapter compact, the exact steps taken while creating the 3D model in various software programs have been placed in appendix A.

The next figures show the various steps involved in creating the model, including the final result:

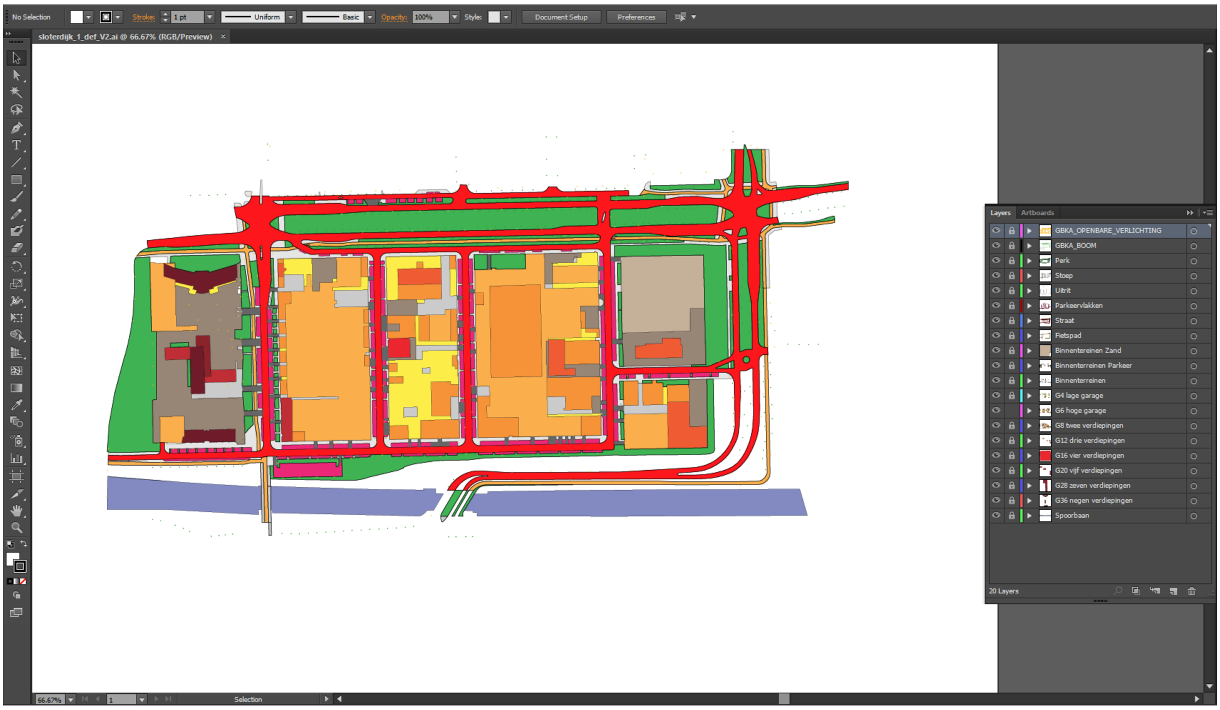

Fig. 16: Area divided in various layers, each with a different colour and function, in Adobe Illustrator CC. Own work

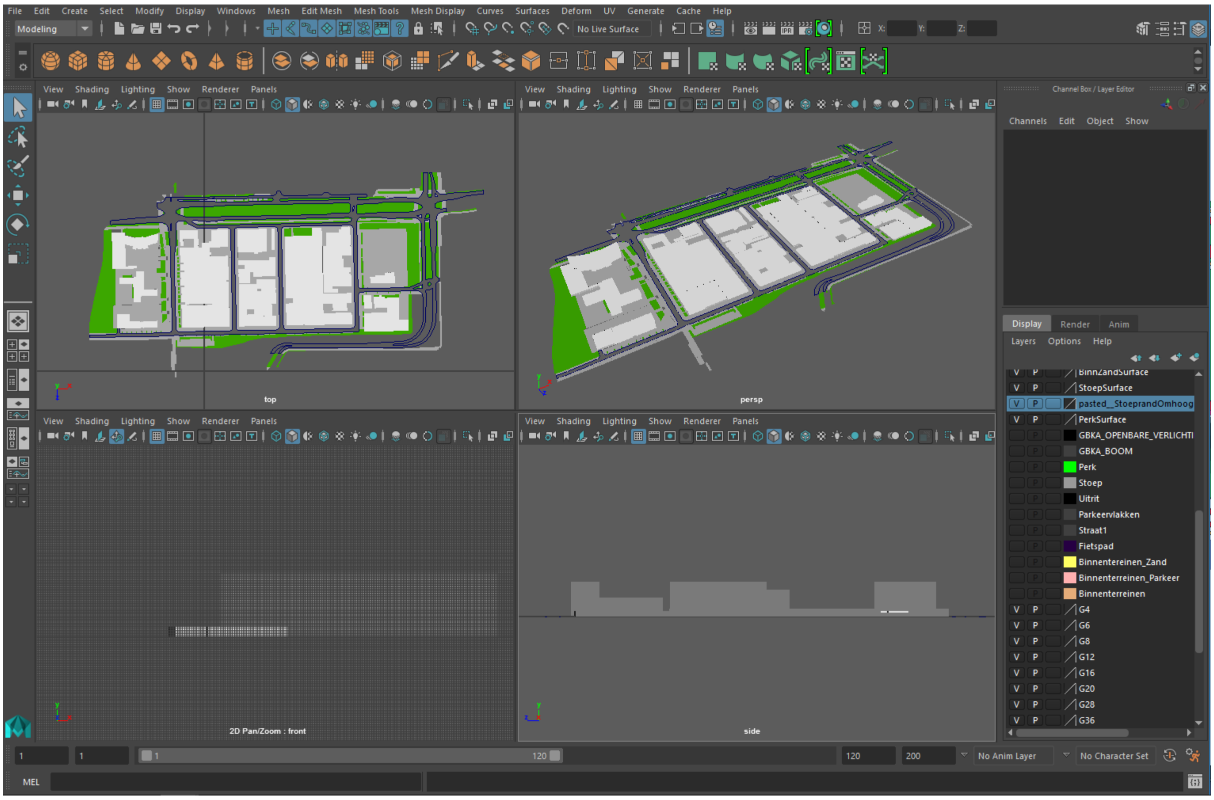

Fig. 17: Area imported in Autodesk Maya, buildings are extruded. Own work

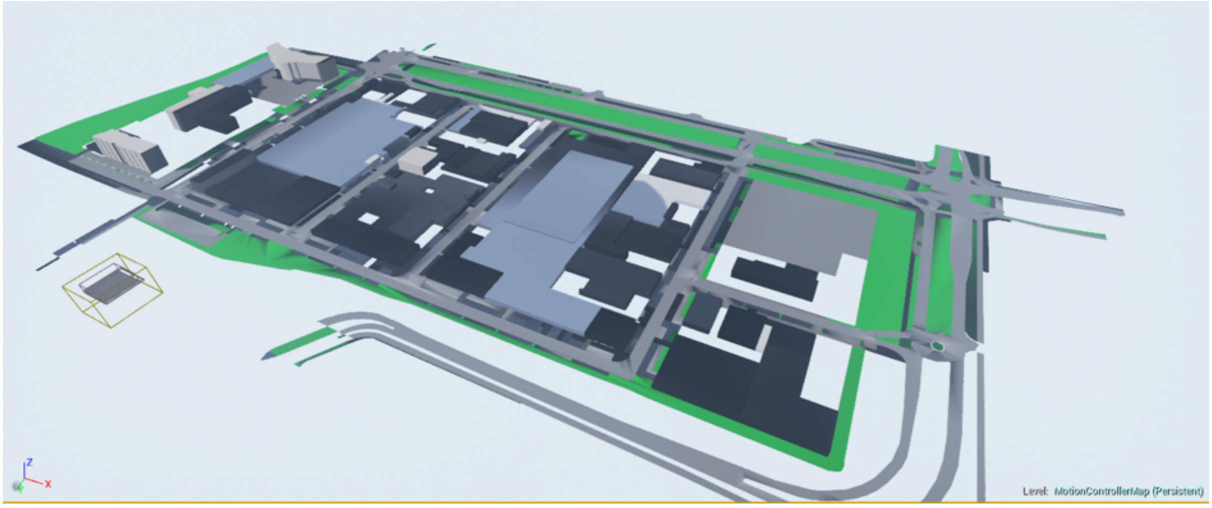

Fig. 18: Lighting errors in UE4: blocks lack UV maps and normals are not calculated. Own work

Fig. 19: Final area in UE4, correct lighting, public space elements are placed. Own work

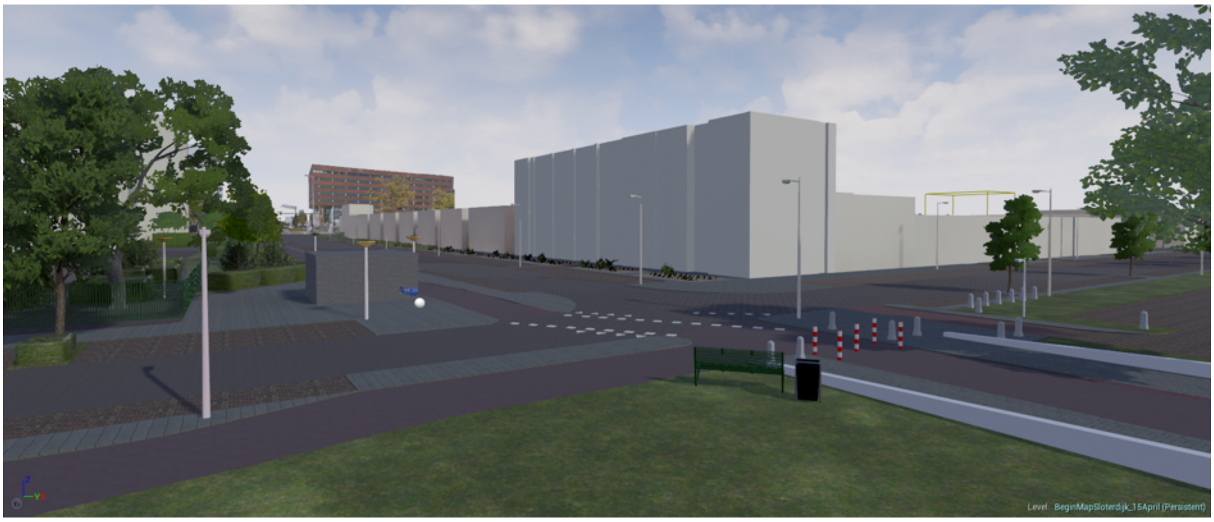

Fig. 20: Detail of the South-West corner of the area in UE4, looking North-East. Own work

Fig. 21: Comparison between the model and the actual area. Own work & Google StreetView

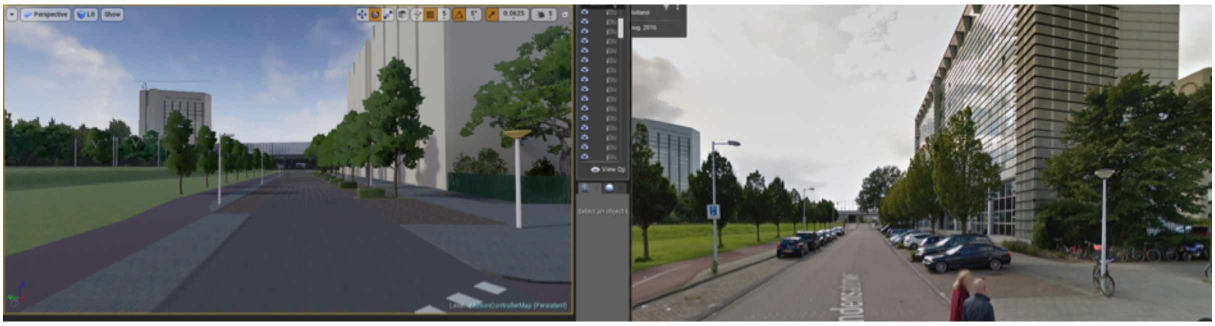
Fig. 22: Comparison between the model and the actual area. Note the lack of cars, lower detail in the grass and the absence of façade detail in the building on the right. Building on the left is placed on a flat plane to give the illusion of the actual context. Own work & Google StreetView

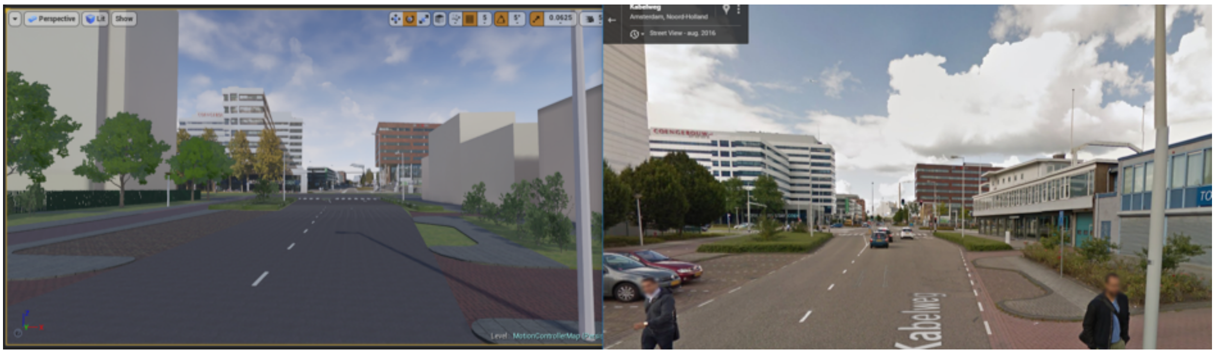

Fig. 23: Comparison between the model and the actual area. Note picture of buildings in the distance, which are placed upon a flat plane in the model. Context delivers higher degree of 'realness' to the scene. Also note the lack of detail in the buildings on the right side of the road: their size is hard to estimate. Own work & Google StreetView.

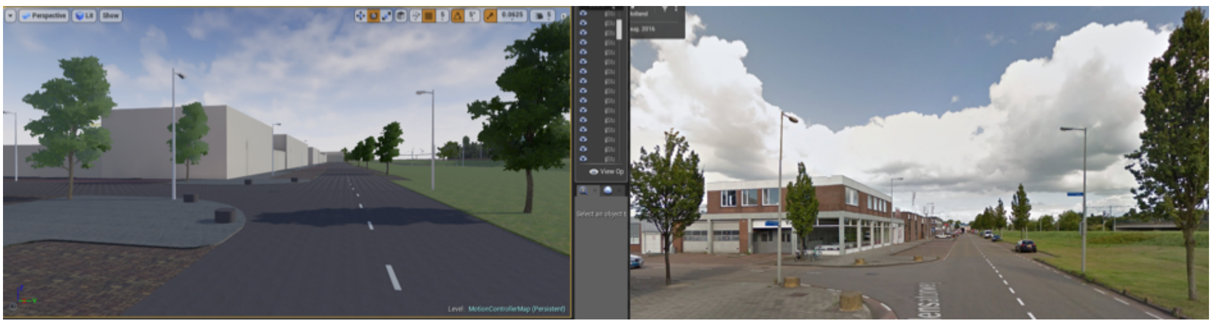
Fig. 24: Comparison between the model and the actual area. Note the way public space elements and trees deliver a sense of scale in the model. Own work & Google StreetView

4.2.3 Testing & outcomes

After the area was created and the public space objects were placed, the area could finally be explored in VR using the HTC Vive. This test was meant to validate the approach taken in this project, and as a validation of VR as a functional tool to visualize the current situation. These tests were a success: the VR visualization worked, it was possible to explore the 3D model of the current situation. This both validated the effectiveness of the software, the hardware and the used approach. It also resulted in a number of important insights, which are important for the next two steps in this project:

Firstly, the detailed lighting and **realistic rendering** of the model in 3D became apparent, powered by UE4. This software delivered real-time renders of the area in high quality, which resulted in a realistic visualization of the area.

Scale turned out to be very important. If elements or buildings were either too big or too small, this diminished the immersion of the VR experience. **Detail** was another important factor. Without accurate reference points to judge the size of both spaces and the observer, it was hard to estimate scale and distance. The extruded volumes of the current buildings did not offer enough information to guess their height. This implicated that detail in buildings is an important factor to estimate scale. The same counts for the public space: without textured materials and public space elements such as fences, trees and lanterns, it was hard to estimate distances. Another advantage of increased detail was the higher degree of realness it provided, increasing the immersiveness of the experience – the sense of 'being there'.
Increasing detail could be accomplished by adding detail in the geometries, adding materials (photo textures combined with normal maps, which provided a sense of three-dimensionality), higher numbers and complexity of public space objects (like fences, lanterns, trees, road markings). The result is illustrated nicely in Fig. 20: the public space objects and materials create a sense of realism.

Context of the design location in the virtual environment turned out to be very important as well. Images of surrounding buildings, taken in Google StreetView, were placed around the design location to give an impression of the actual urban context. This, too, heightened the degree of realness and immersiveness. Example can be seen in Fig. 22 and Fig. 23.

More detail and a more fully developed context would lead to a more immersive experience, potentially until a level at which the hardware rather than the software becomes the bottleneck: pixel density is still relatively low compared with what the retina can observe[15]. The limited amount of pixels blurred the artefacts in the far distance, while giving more accurate and convincing display at short distances. Future HMD's could make experiences far more realistic. This may lead to current graphics looking faker, since low levels of detail and texture resolution might become clearer if the view is sharper.

[15] http://sensics.com/understanding-pixel-density-and-eye-limiting-resolution/. Accessed May 7, 2017

Creating more detail in the 3D model uses more computer resources, and more importantly: more time to create this detail. Using the limited amount of time available for recreating the current situation in an effective way still led to favourable results, however.

As described, creating the 3D model of the current situation and testing it in VR served many useful purposes for this project. It validated VR as an effective visualization tool of current situations, which was already assumed to be true, but necessary to build the next steps upon. Also, it learned us that scale and distance estimation are correlated with detail, offering visual cues, as was stated by Ng et al. (2016). It improved my software skills and showed which pitfalls could turn up.

However, the creation of this 3D model was a complex project that required a lot of trial and error and the operation of 4 different software programs. Also, the .dwg file of the area was obtained through a designer of the municipality, it might not be readily available online. Access to the various programs, data and the required software skills is not self-evident. Thus, the step of converting an existing area into a 3D model fit for VR viewing and editing might be a serious obstacle for other researchers or designers.

4.3 Creating the VR Design System

4.3.1 Problem definition

The next phase towards designing with VR, was to create a VR design methodology using the selected hard- and software. To do this, it was necessary to set up a system that would be both practical and quick to set up, while resulting in a desired design outcome.
The 'cost-benefit ratio' between the workflow of creating the system and its qualities was translated in evaluation criteria, both as a means to guide critical decisions as a way to analyse and validate the tool.

This phase would serve several purposes:

- Testing how to create a system for designing urban environments with VR in practice
- Researching and describing the workflow of the creation of the design system
- Testing various levels of 'realness' and various building solutions
- Exploring software limitations and capacities

These tests were integrated in the creation process of the VR Design System, as described in the next sub paragraphs.

4.3.2 Software capacities & limitations

The VR Design System was designed to work with the UE4 VR editor, which is a function within version 4.14 of the Unreal Engine. Blender was selected as the 3D modelling tool for specific 3D components. It is important to show the software capacities and limitations to understand choices made later on in the process of building the VR Design System.

Capacities

In overall, UE4 is extremely powerful software. One of its core strengths is the ability to create extremely realistic materials with many different qualities: normal maps, roughness maps, translucency and reflectivity, for instance. The control over lighting is very high, as well as its visual quality and realism. Advanced control of the many capabilities of the engine has been made easier by means of 'Blueprints', which is a visual node-based programming system. This allows for non-programmers (such as myself) to still make optimal use of the editor.

The VR Design System relies heavily on the UE4 VR Editor, which offers the functionality that enables the designer to place, remove and edit elements in VR.
3D elements can be intuitively translated, scaled and rotated using the VR editor, using the HTC Vive's motion controllers.
Another exciting possibility offered by the engine, which is mostly enabled by the Blueprint system, could be the ability to create parametric designs. This requires rather

advanced use of the Blueprint system however, but it allows a designer to create parameters that can be translated into various kinds of spatial elements.

Limitations

Unreal Engine is developed as a game engine, which comes with a number of limitations for users that have other preferences than game designers. One of the main limitations is that it is not designed to run relevant simulations for urbanism, such as space syntax, sun exposure, noise and temperature simulations. The 3D elements of a finalised design can be exported as a .fbx file however, which might be opened in other 3D editing programmes and put into simulation software. This is possibly a time consuming workaround. Plugins are becoming available however, such as an OpenStreetMap plugin[16].
Secondly, it is currently not yet possible (at least, not in version 4.14) to perform advanced 3D modelling actions directly in the Unreal Engine, other than scaling a pre existing element. External applications are necessary to create 3D files (.fbx files in this case) that work well in the Unreal Engine. This limits its usefulness in a rather big way, since it limits a significant amount of design freedom. Creating unique geometries for building blocks, for instance, now has to be done outside of the Unreal Editor. This has repercussions for our Design System, as will be discussed.

Approach

The chosen approach was focused on using Unreal Engine 4 mostly as-is, with all its limitations, rather than heavily experimenting and risking instability of the software. The choice to work within Unreal Engine rather than using an iterative process with more software, since Unreal Engine 4 would offer enough options to design multiple design variants. Also, a lot of software that would be used for analysis doesn't work in VR, so using it would be contradictory to the aim of doing a VR design process.

[16] https://github.com/ue4plugins/StreetMap. Accessed: June 10.

4.3.3 Evaluation criteria

The next evaluation criteria aim to operationalize the performance parameters of the system. Together, if followed during the creation of the Design System, these criteria should be able to achieve the main goal and help with the assessment of Design System elements. The next four criteria are identified:

1. Versatility
2. Flexibility
3. Using the immersiveness of VR
4. Limited complexity

These criteria will each be shortly discussed to clarify why they are chosen, what they should ensure and how they are (roughly) measured.

1. Versatility

This criterion has been chosen because the system needs to afford the designer with the necessary tools and freedom to create a design, and to solve spatial problems. Thus, versatility of the system is important for its usability and the value of the design outcome.

The 'Versatility' criterion should ideally ensure that:

- the system offers a limited but essential set of options and tools that can handle multiple design problems
- the system needs little to no reconfiguring
- the system supports the creativity of the designer
- singular, one-of-a-kind building elements are avoided

Versatility can be rated by the availability of a small but essential set of design parts, the degree in which reconfiguring is necessary, the degree in which the system allows for creative expression and out-of-the-box thinking and the restriction on singular, one-of-a-kind building elements.

2. Flexibility

In order for the system to be adapted to new needs, its components and general setup should be as flexible as possible.

The 'Flexibility' criterion should ideally ensure that:

- it is easily adjustable to future needs

Flexibility can be rated by the amount of steps and time that are needed for adjustments.

3. Using of the immersiveness of VR

The VR Design System should make optimal use of the immersive aspect of VR, because that is one of the most important elements that is investigated in this research. A tool that allows more immersive design outcomes might help investigate the effects of this aspect better.

The 'Using the immersiveness of VR' criterion should ensure that:
- The scale of building system elements is correct
- The system offers a level of detail and realism that does immerse the designer, without distracting from the design process
- The system offers enough visual cues to help the viewer / designer estimate distances and sizes

'Using the immersiveness of VR' can be rated by the ability to correctly estimate scale while using the system, and the level of present visual details, visual complexity, realistic façades and building elements.

4. Limited complexity

In short, the design tool should not be too complex. This counts for the design elements themselves, the scope of the system, its creation and its composition. This is important, because the more complex the system is, the more time it will take to create and the harder it will be to use it. Also, powering VR uses a lot of computer resources, so the less complex the parts are, the better.

The 'Limited complexity' criterion should ensure that:
- The design system is clear and functional
- The design options are relatively easy to create and adjust
- The design options do not use a lot of computer resources

'Limited complexity' can be rated by the structure and organization of the parts, the degree in which all elements function properly, the ease of adjustments in both time, steps and limitation of the use of advanced software options, and the amount of computer resources the tool uses (less is better).

4.3.4 Creating the system

After setting up the evaluation criteria, the system had to be actually built according to the evaluation criteria. This turned out to be a learning process; by creating the system a lot of software related issues and best practices came to light. More fundamental questions came to mind too, such as what the 'right amount' of realism was, and how to accomplish this in the most effective way. In this paragraph, the most important choices that had to be made during the creation of the system are discussed.

The design system was tested in a copy of the 3D model of the area, with two plots emptied to create space for scale- and block size- and detail experiments. Another testing zone was created 'south' of the railway, where the blocks were placed in a straight line to inspect them in VR. The results of the tests have been described below.

Fig. 25: Version of the 3D model with empty plots to experiment with building blocks. Own work.

1. **What Level of Detail to design in, and how to accomplish this level without creating too much complexity?**

The question which Level of Detail (LOD) to strive for was a very important design choice which would have repercussions for the rest of the design tool. The definition of 'Level of Detail' used in this research, as described in 2.3 ('Terminology'), focuses mainly on the visual detail. This means that, for instance, with photorealistic textures pasted on a simple cube geometry, a seemingly higher LOD can be achieved. A high LOD of the geometry would be complex to create (time consuming) and not easily adjustable or usable in many contexts, thus not meeting three of the evaluation criteria. Thus, higher LOD's would have to be achieved by using textures instead of complex geometries.

Although a high LOD and the accompanying improved sense of realism would probably 'look nicer', it could have unwanted consequences for both the design process, design outcome, perception in VR or communication to the layman. Summarized, the next potential pitfalls of using a high level of detail were identified:

- Distraction from the design process
- Design bias: the appearance of building elements might steer the design in a certain (unwanted) direction.
- A too specific looking design that might suggest permanence to the layman, while the design is in fact still a proposal.

Potential disadvantages of a low level of detail were also recognized:

- Less realism could lead to a reduced sense of immersion
- Less visual cues for scale & distance estimation (Ng et al., 2016)

Achieving the most effective LOD for designing in VR could be the subject of an entirely new research project. In this a decision had to be made that would mitigate most of the accompanying disadvantages. Since this project is focused more on researching the immersive aspect of VR than on the relation between LOD's and a design process or the layman's perception of design outcomes, I made the choice for a high LOD using photorealistic textures.[17] The next illustration shows various options to test LOD's I considered while creating the tool.

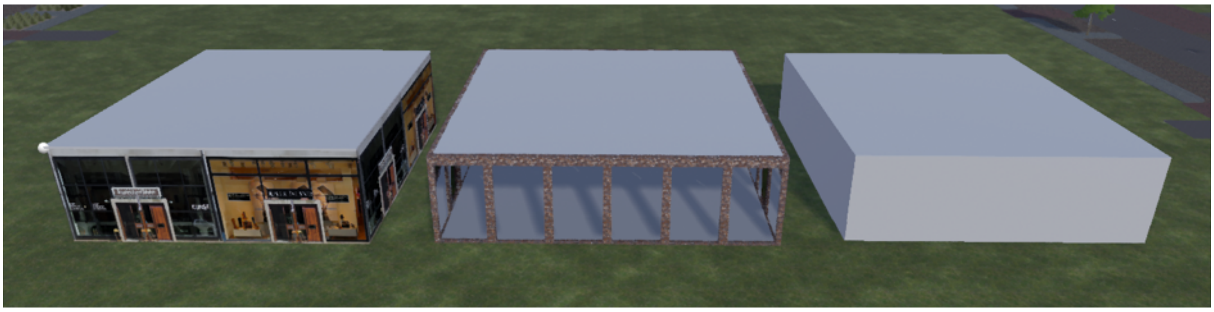

Fig. 26: Three LOD approaches: photorealistic, complex geometry and a simple geometry. Own work.

In the picture above, three approaches are visible. A photorealistic texture, a 'complex' geometry with two materials and a simple, plainly coloured geometry. The first approach looks the most realistic, even though the geometry is flat. The reason it looks as if the geometry itself has more detail might be explained by the visual cues (shadows, perspective) that suggest depth (Ng et al., 2016, Prak, 1979). The 'complex' geometry looks fake, since the interior is empty and it still has a relatively low level of geometric complexity. The scale of the block is harder to estimate, even though the brick material suggests some scale. The form is too generic to estimate what function this building element would serve. The simple geometry offers too little detail to either show scale or function.

During experiments with the photo realistic textures in UE4, a relatively simple way of adding reflectivity to the 'windows' was discovered. If the roughness value of a texture was set to 0 in Blueprints, the material would become reflective, while a value of 1 would be non-reflective. Copying the photo texture, making the windows black (colour value 0) and the rest of the image white in Adobe PhotoShop and feeding the result into the roughness value, the windows could be made glass-like. While considering the necessity of this extra layer of realism, this easy step seemed not to be in conflict with the evaluation criteria. The added complexity was limited, the roughness maps were extremely easy to create and could be removed or adjusted easily.
By figuring out how to combine the photo textures with the building block, it became clear that the used photo texture would dictate the size of the block size, since stretching of the photo textures would lead to inaccurate façade proportions, while keeping the proportions intact and cropping the texture could lead to strange outcomes such as cut off windows or doors. This problem leads us to the next design consideration.

[17] The possibility of first designing with plainly coloured geometries and later applying textures was contemplated and is in theory possible by creating 'adaptable Blueprint classes', which will be discussed later on.

2. How to ‘build’ in VR?

This was an elemental question to solve, because creating the building volumes is key to the design process. In the traditional design process, a designer would put lines on paper or in a computer programme to sketch the outlines of blocks, or the cross sections of buildings. In VR, the volumes themselves could be placed. Due to the limitation of Unreal Engine that would not allow us to design complex geometries in VR but did allow scaling of previously imported blocks, I would have to choose between a modular system of standardized building elements, a semi modular system of blocks that could be scaled as desired, but would only ‘stretch out’ on one or more axes, and custom-designed buildings.

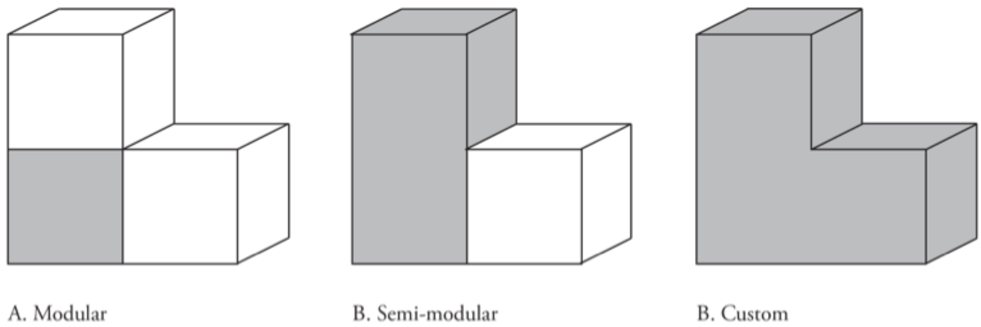

Fig. 27: Three basic building approaches, each with distinctive qualities. Own work.

The custom designed building option was eliminated since it would be too inflexible, and this option could actually be regarded as a traditional design method. Buildings would each have to be designed in 3D modelling software, it would require custom UV maps to make a texture wrap around it correctly and it would not be versatile, since it would most likely only be fit for one specific situation. It would be more complex than a modular or semi modular system. An advantage would be the inclusion of more specific, geometry based details, which might add to the realism of the model, but this advantage was considered trivial compared to the disadvantages. The semi-modular building option was considered until some experiments with façade textures pointed out that stretching blocks, combined with world aligned textures, would not work as desired. In a ‘world aligned’ texture, a texture would be ‘repeated’ rather than stretched out when the geometry was scaled. This would be fundamental to the semi-modular system. The problem with this technique was that the textures could not be made to start at the origin point of the blocks. This led in some cases to the textures being cut off in wrong places, like in the middle of a window.

This would look strange and would be in conflict with the strive for realistic façades in the evaluation criteria. Only the semi modular and modular systems were tested, since the custom building approach was ruled out beforehand. In the next pictures the problem with the world aligned textures is shown:

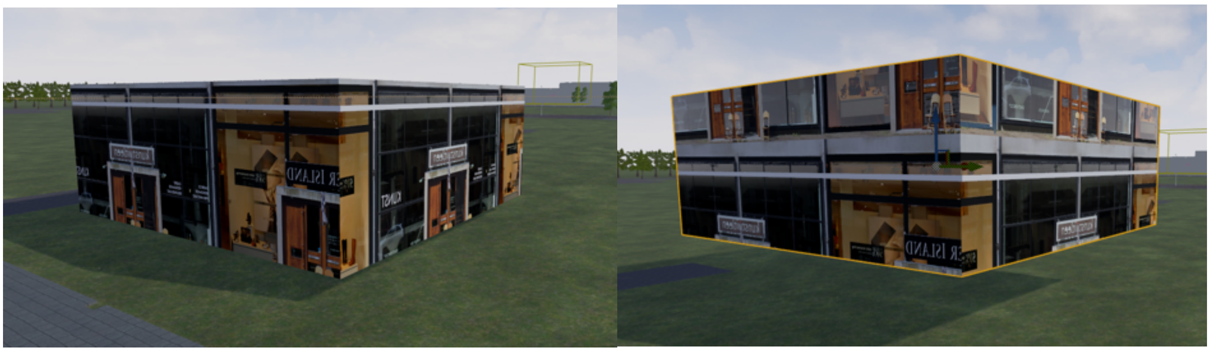

Fig. 28: Problem with 'world aligned' materials: they do not always align properly with the building block object. Own work.

This problem is prevented by using a strictly modular approach:

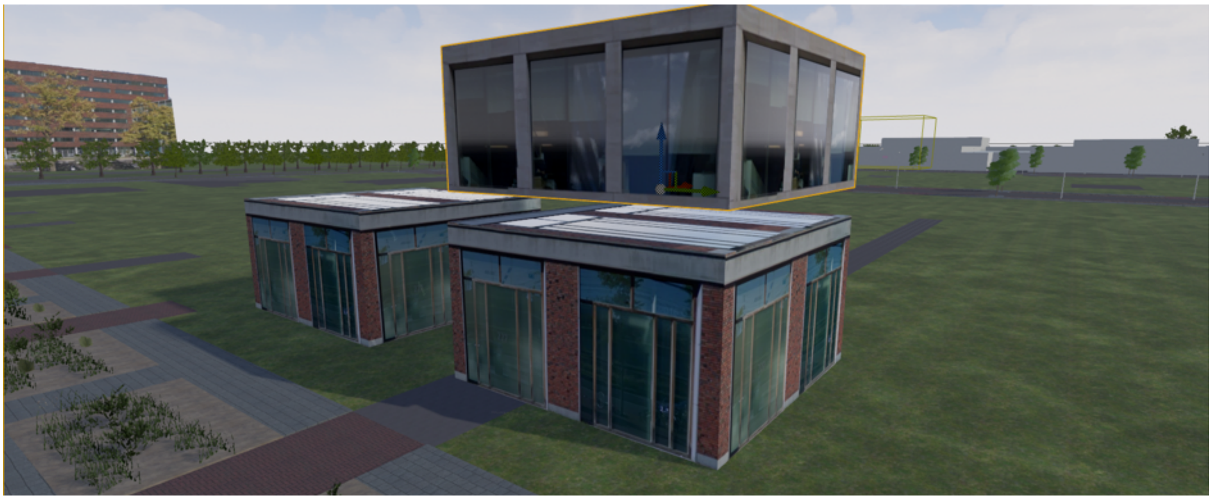

Fig. 29: Modular building approach. Own work.

Also, setting up these world aligned textures was more complex than previously assumed. The advantage of the semi modular system was increased building speed, since buildings could easily be scaled up, but the texture problem proved more important than this one advantage. Cut-off textures would seriously undermine the immersiveness of the result. Moreover, by testing the building speed of the modular system, more insights on the VR design process could be gained.

In the end, the modular system was chosen because it scored the highest according to the evaluation criteria. It turned out to be the most versatile option, more flexible than the other solutions, delivering less problems regarding the immersive aspect and not very complex; it could be set up relatively quickly (when the workflow was established).

A final observation is that by using the modular approach, the tendency to just scale blocks up would be prevented. A semi modular approach could cause the designer to unconsciously choose for longer uninterrupted building blocks, while the modular approach might incite more fine grained design outcomes and façade variation.

3. Façade selection

After choosing for photorealistic textures in combination with 'simple' geometries and a modular design system, the façades themselves needed to be selected. This was an important decision, since the façades would impact the block sizes and appearances and thus the design outcome.

The selection of the façades would need to help to tackle the design problem as described in paragraph 4.1. The façades thus had to reflect a number of things:

- the required architectural quality of the area
- the desired functions in the area
- the required plinth height

The façade selection would have to satisfy the evaluation criteria. In order to meet these criteria, a diverse but limited palette of relatively generic but modern façades was selected.

The selected façades fell into two categories: ground floor plinths and upper floors. The ground floor plinth façades were selected based on their height, since the design objective in the area is to reserve the first floors for non-residential functions that benefit from, or even require high ceilings.

The upper floor façades were mostly based on residential buildings with brick walls.

The façade choice was also an artistic design consideration, since the selection was not random but partly based on aesthetical judgment, which is fundamentally subjective. For inspiration, two books were used: Jan Gehl's 'Cities for People' (Gehl, 2010) and STIPO's 'The city at eye level. Lessons for street plinths' (STIPO, 2012). Based on these works, the aesthetic considerations were openness of the façade, a strongly 'urban' character and preferably a certain amount of visual complexity.

Fig. 30: Façade selection. Note that some of the narrower façades are subdivisions of wider façades. Own work.

Collection of the façade texture samples was performed by taking pictures in Amsterdam Oost, screenshots of buildings taken in Google StreetView and pictures found through Google Images. These were organized into folders, edited in Adobe Photoshop to straighten skewed proportions and saved into a new folder. These images were copied and turned into 'roughness maps', in order to give the windows reflectivity. Next, in UE4 a new material was created that would serve as a template. This material was copied, after which the textures and roughness maps were applied to the copies of the template. The resulting materials were ready for use.

Some of the façade materials were split into two in order to get narrower blocks, others (consisting of two stories) were separated into upper floor- and ground floor materials.

4. Putting together the pieces: creating the building modules

The first approach was to use Blender to create the blocks and later apply materials that would fit perfectly on these blocks. However, this did not work. The imported blocks from Blender stretched out the façade material over all the six sides of the blocks.

The solution to this problem was creating a 'Blueprint Class'[18] for each building module, which contained the primitive mesh of a standard cube. The material was applied to this cube and stretched out over each side individually, instead of over all the sides together. The cube properties could be edited to get the right block scale. The next scheme shows the structure of the building module Blueprint Class:

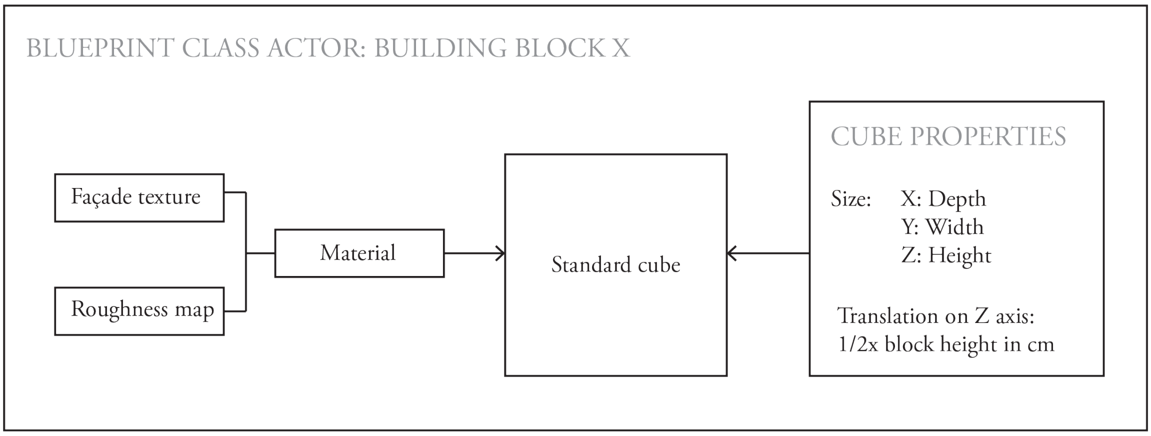

Fig. 31: Building block blueprint class structure. Own work.

One of the advantages of using blueprint classes for the building blocks, was that changing elements within the blueprint class would directly affect the blocks in the model. This could be useful in situations like changing the material, reducing the reflectivity of the windows, adding a normal map or increasing the size of the blocks.

[18] https://docs.unrealengine.com/latest/INT/Engine/Blueprints/UserGuide/Types/ClassBlueprint/ (Accessed: May 4, 2017)

The final design system consisted of 7 different building styles, 4 of which consisting of both a plinth- and upper floor block. Some of the styles offered subdivided blocks for smaller scale design interventions.

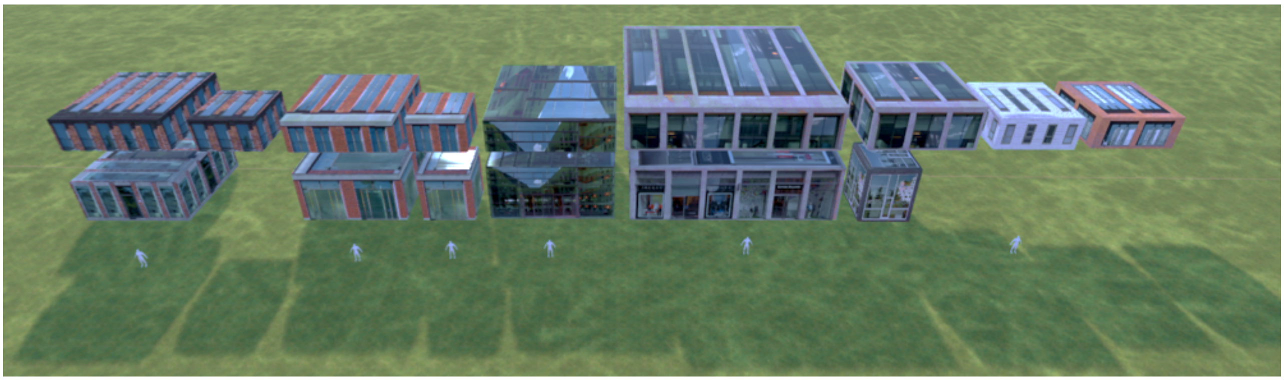

Fig. 32: The selection of 3D building blocks to be used in the design process. Note the various styles and dimensions. Human male figures measuring 1.85m are placed in front of the blocks. Upper floors are shown above, ground floor plinth parts below. Own work.

Placing these objects into the world could be done by dragging them from the content browser into the model. The content browser shows the building blocks by means of pictograms, as is seen in the next figure:

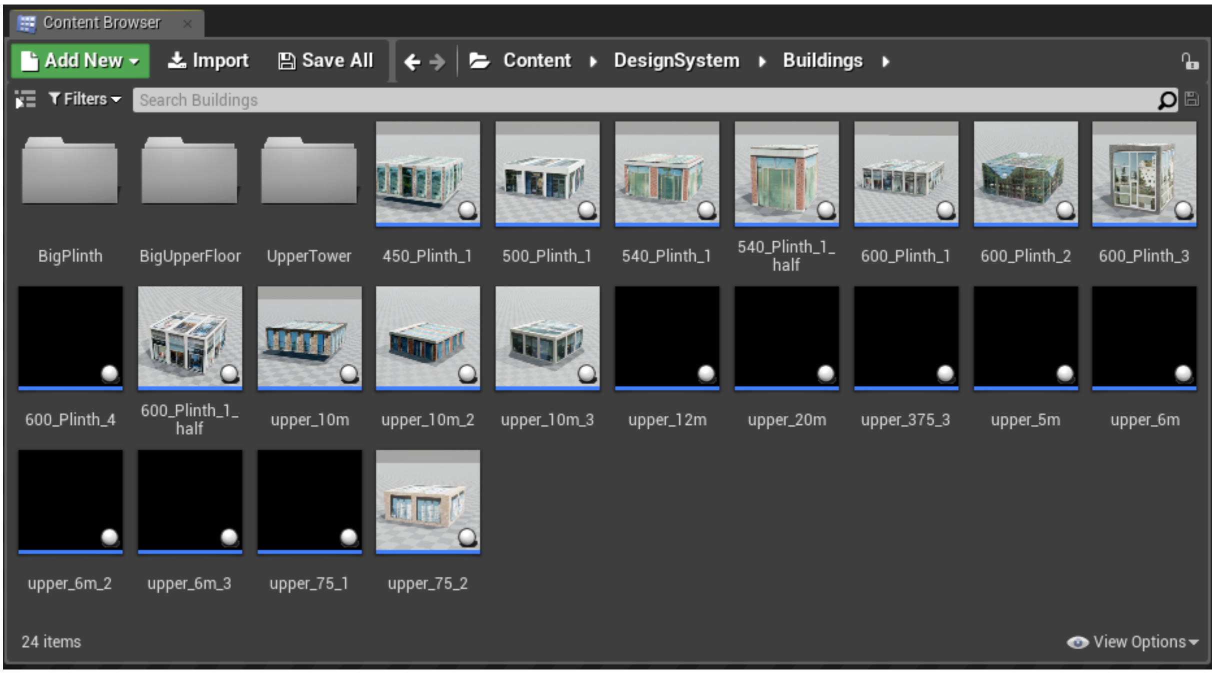

Fig. 33: The building objects in the Content Browser. The black squares of some of the icons are caused by a bug in the software. The three folders in the upper left corner contain the bigger building blocks that were created later during the process. Own work.

5. Other component selection

The system had to offer enough versatility: it had to allow lot of freedom to the designer. Beside building blocks, a set of auxiliary elements were selected that would allow for most of the common design situations to be handled.

The final selection included several basic forms like plateaus that could serve as both a roof or a street surface, a column, a bridge section, a wall section, a glass curtain wall, garage and truck entries, balconies, stairs, two types of benches and a fence. These elements were created in Blender and edited in Unreal.

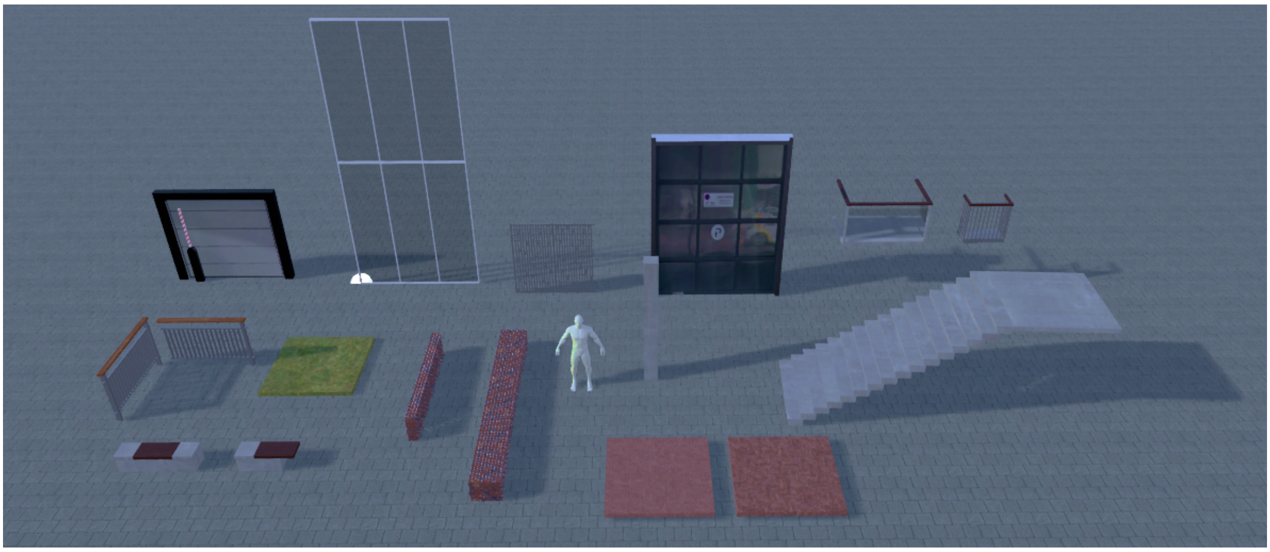

Fig. 34: Auxiliary design elements: public space elements, roof, floor, stairs, railings, garage doors, balconies and a glass curtain wall. Human figure for scale. Own work.

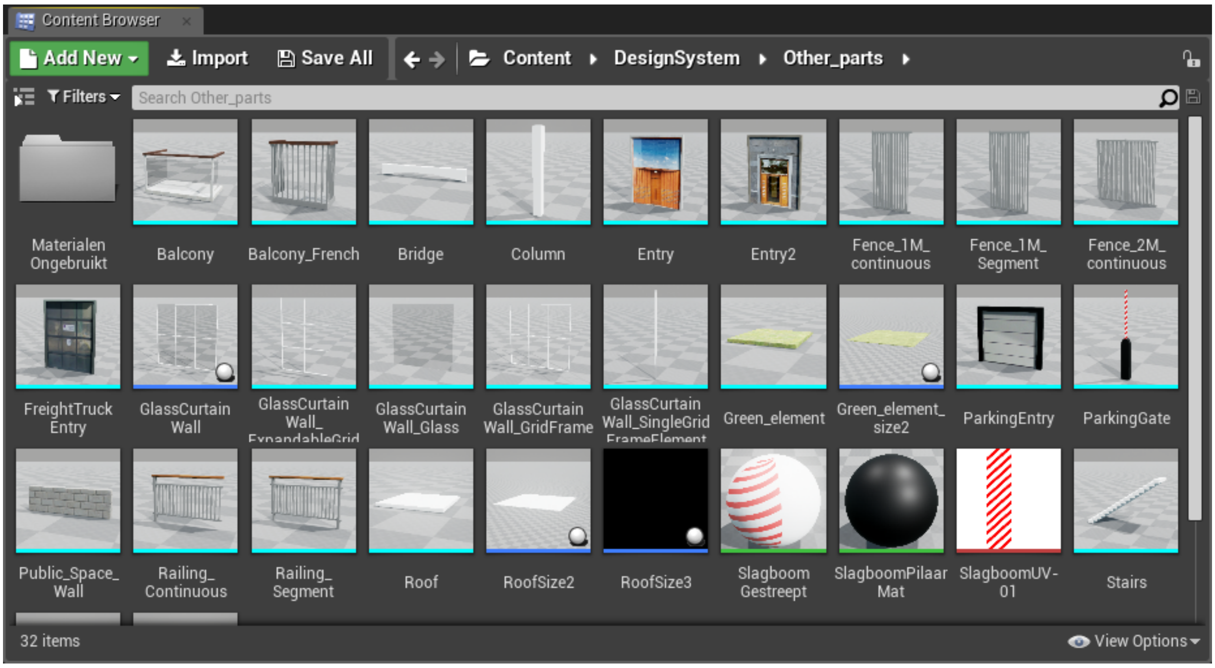

Fig. 35: The auxiliary design objects in the Content Browser. Own work.

Another tool to help estimating the scale of buildings was the custom made 3D Scale Bar, which showed 1 meter increments with a special marking every 10 meters. The second tool to show scale was a white human male figure measuring 1.85m. These elements could be placed next to buildings to show how tall they would be or their relative size compared with humans.

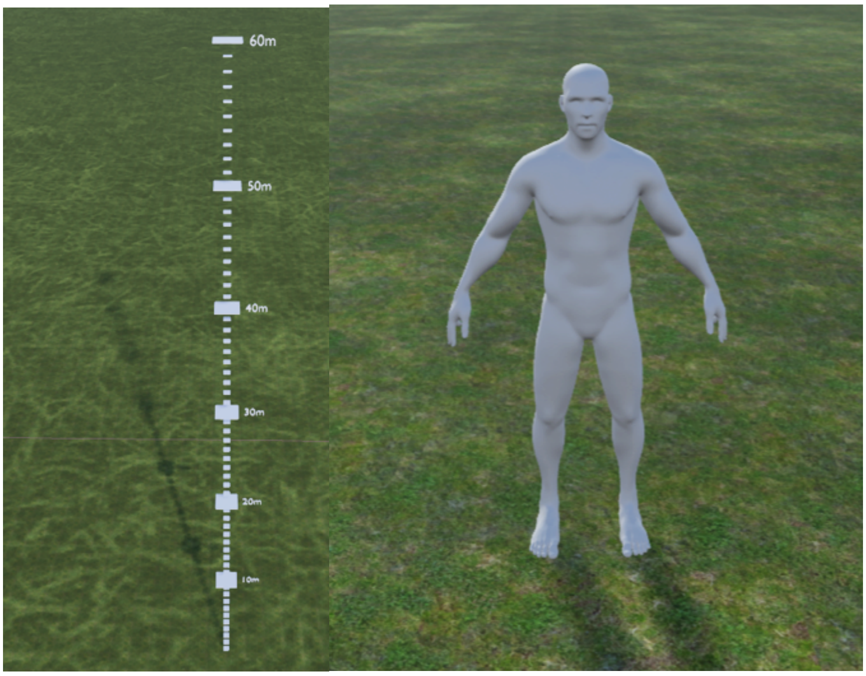

Fig. 36: 3D Scale Bar and human figure to help estimate distances and scale. Own work.

4.3.5 Block & building test

After the creation of the tool, the blocks were placed in the model to view them in VR. The UE4 VR editor was used to do some quick testing of the building system and of the VR editor itself. In the test, a small scale design was created without restriction, using many of the previously built elements.

This test resulted in the insight that the system would at least work as intended, but it did not become clear if it would work at bigger scales. The workflow of accurately placing objects became apparent, as well as the effectiveness of the detailed façade textures in offering visual cues to estimate scale and distance. The effectiveness of switching between eye-level and birds eye view became apparent as well.

Almost everything was set for the next step, including a test to see how new design variants could be created. This could be done by saving the ‘map’ as a new file, which would become new variant. Any changes to the VR Design System would be available in all the versions, since all the versions would be saved within the same project. This made asset management easier.

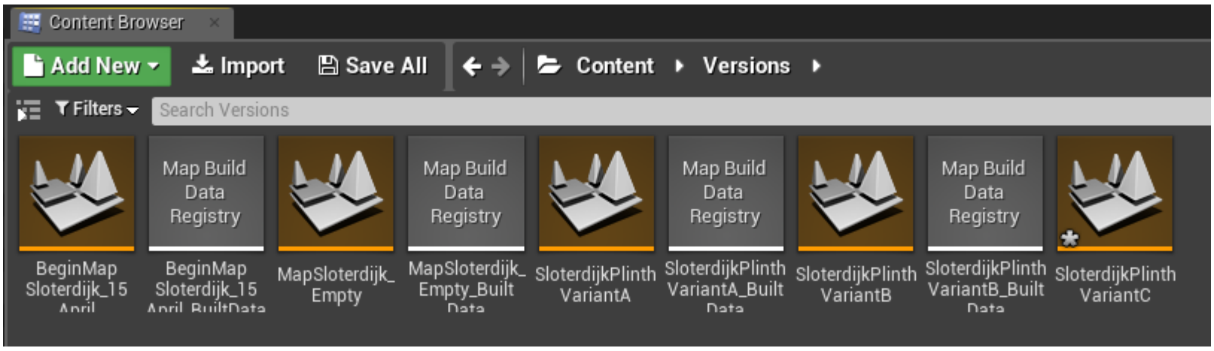

Fig. 37: The 3D model, or 'map', can be copied and edited. They share the same object and material library. Own work.

4.3.6 Outcomes – Final Design System

During this step, multiple important lessons were learned. Firstly, it became apparent that photorealistic textures would be the best option for the façade. Creating blocks by using blueprint classes offered flexibility later on in the process, since they acted like 'containers' of properties.

Ways of measuring scale were found: firstly, by using detailed façades. Secondly, by using a scale bar and a human figure, scale could be estimated more precisely.

Finally, the workflow of how to create and edit new design variants was demonstrated.

The most important limitation of the software that was found, or possibly a limitation to my current proficiency in the software, was the disability to create unique geometries in any shape, that would be automatically applied with the façade material. To deal with this, a system of building blocks was invented as a workaround. Already an example of 'circumscribed thinking' (Bernal et al., 2015) was found: the design alternatives were limited to what was possible with the tool.

It is possible that through Blueprints, or by programming, the desired functionality could still be achieved using UE4. This would need to be proven in a new test, for which there was unfortunately no time.

The software did show great proficiency in showing very realistic graphics however and a great control over materials. Also, the software seems to operate well with assets imported from Blender.

After this step, it was finally possible to start the actual design process and test if this design system would work as intended. The chosen approaches regarding detail and building method would be put to the test in an actual design challenge: designing Sloterdijk I.

4.4 Designing Sloterdijk I

After having created the design system, the final and most important step of the research had to be taken: designing with VR, using the knowledge from the previous two steps. The following elements needed to be tested in this paragraph, which were mainly focused on the design process:

- Testing if the VR Design System actually works
- Testing how VR as design method performs as a workflow
- Testing what new insights are gained while designing in VR, using eye level insights and using intuitive 3D hand gestures
- Seeing what design outcomes a VR design process leads to.

Out of these tests, most of the answers and insights would flow that would help to finally answer the research questions.

4.4.1 Design problem

In Sloterdijk I, the essential problem that would need to be addressed during this project was how to design a neighbourhood with a high degree of non-residential functions in the plinth and a high density, while still offering attractive public spaces. The approach to attack this problem was to experiment with various plinth and high-rise approaches that would allow for a high degree of function mixing and still offer attractive streets and spaces.

The plot sizes of the selected area were so big that connection streets would be necessary, while externalities had to be considered; the area is located adjacent to the periphery of the Westerpark, a railroad and a traffic corridor. The surrounding area consists of mainly industry and business parks, so high-rise would still be an option. The maximum height would be limited to 60m, because of Schiphol Airport air traffic. There were many other considerations that were of influence during the process. In Appendix B, a list of all the design consideration input can be found.

This design problem could possibly help to research VR more effectively because the plinth and high-rise have a great influence on the experience at eye level, through its effects on sunlight and shadow, its material, setbacks and its relation to the street. Immersion through VR could lead to new insights.

Except for design constraints, there were many elements that could be used to experiment with to create various scenarios:

- the alignment of the façade
- alignment of the buildings
- relation between plinth and superstructure
- height of the plinth
- variation of façade types and materialization
- ground level and elevations

- inner courtyards
- views
- access points of housing
- garages and cargo
- residential and non-residential spatial programme
- relation between façade and street
- attractiveness of the streetscape
- openness of the façade
- connection of inner courtyards and the street

These elements would offer a lot of design freedom. The design process and -choices were recorded partly by creating a recording of the screen, partly by summarizing the experiences on paper during the design process.

4.4.2 Preparation of the design process

Before starting the actual design process, some steps were taken to make sure insights could be recorded and the model of the design context was ready for use.

Recording the design process

Parts of the design process would be recorded, by using software that would record the screen while designing in VR. This open-source software (Open Broadcast Software) also offered sound recording, so it could record simultaneous voice feedback on choices that were made.

As a failsafe, the design process would be temporarily paused at convenient times during the design process to save the progress made within the VR Editor, and to write down the various considerations and choices that had been made, struggles with the software, hardware and other aspects.

Preparing the design environment

The design environment was prepared by creating two levels with two plots emptied of unnecessary objects such as the existing buildings. These new levels were called Plinth Variant 1 and Plinth Variant 2.

4.4.3 Variants

After the preparation of the design area, the design process could finally start. In a number of design sessions, multiple design variants were created. In this sub paragraph the variants will each be discussed and snapshots of the result will be shown.

Variant 1

This design variant was designed with little diversity and setbacks and straight alignments of buildings. The result is a design with hard 'gestalts' (Prak, 1979): the buildings seem to be different entities than the plinth blocks, especially the north side of the plot. The plot is divided in two blocks by a single connection street, which has a less intimate character than the streets in Variant 2 and 3.

Fig. 38: Variant 1, birds-eye view from the South East. Own work.

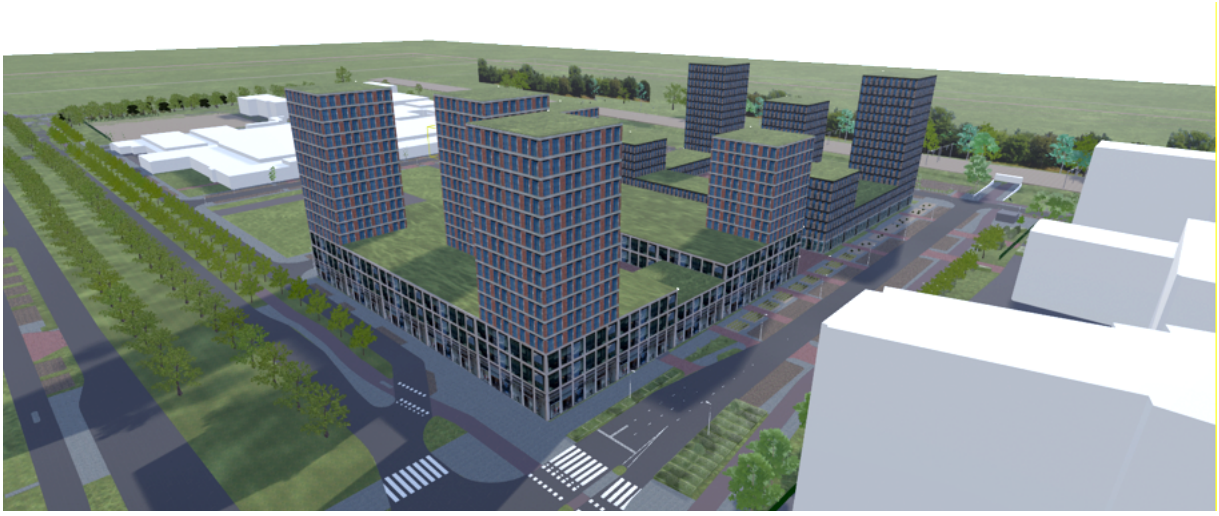

Fig. 39: Variant 1, birds-eye view from the North West. Own work.

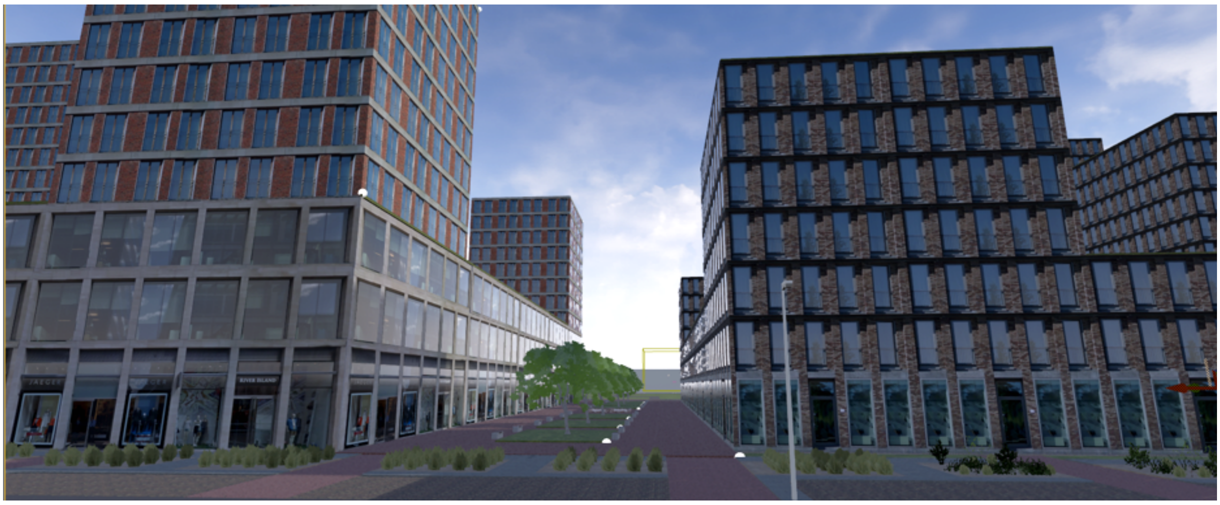

Fig. 40: Variant 1, inner connection street. Own work.

Fig. 41: Variant 1, North-East corner, eye level. Own work.

Fig. 42: Variant 1, South-West corner, eye level. Own work.

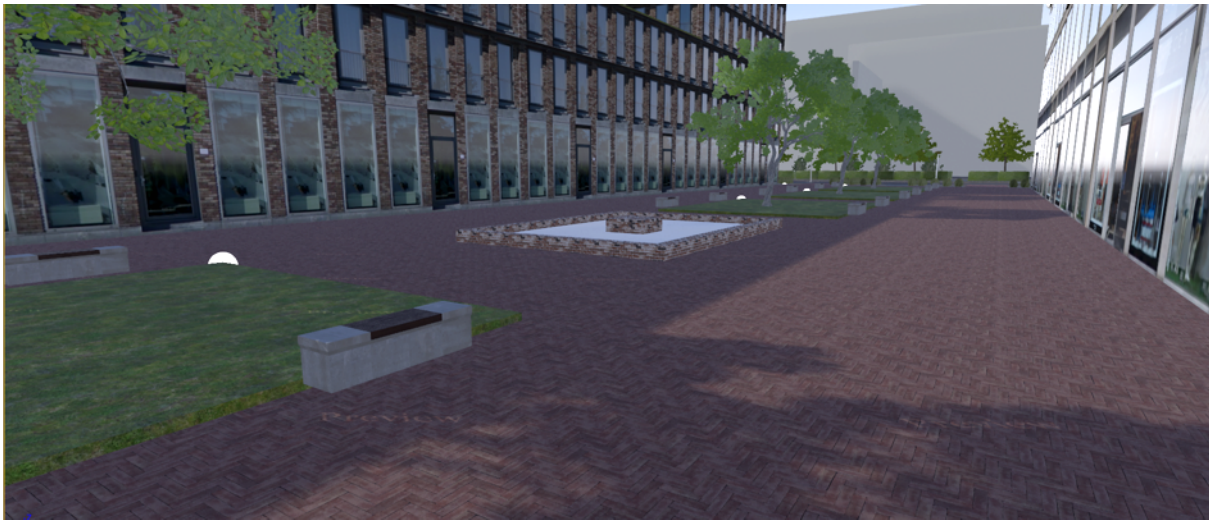

Fig. 43: Variant 1, detail of the public space in theconnection street, eye level. Own work.

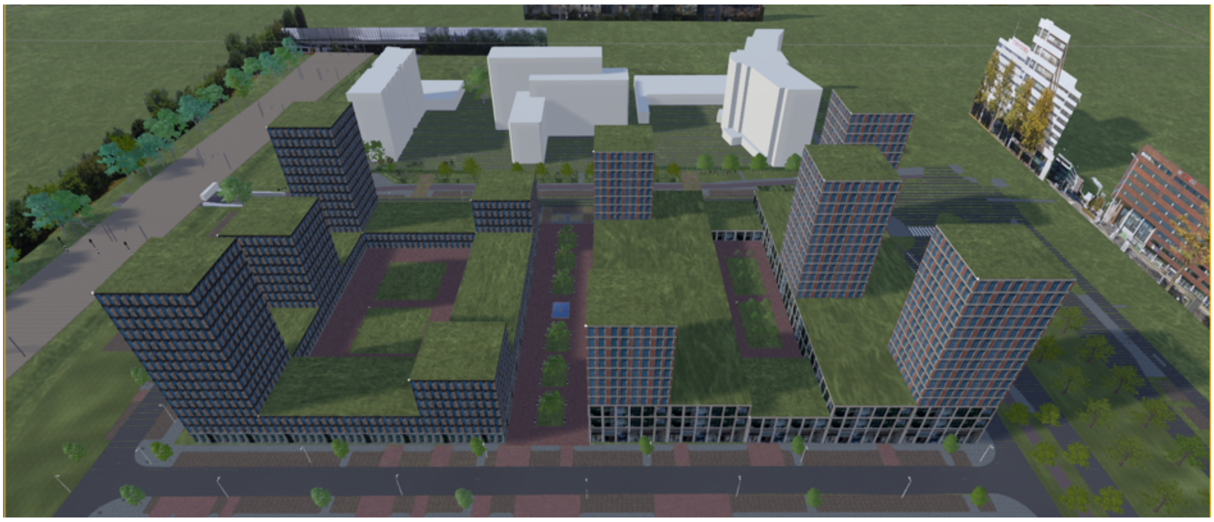

Fig. 44: Variant 1, total overview. Own work.

To see an animation of this design variant, scan the following QR code:

Variant 2

This design variant was designed to achieve diversity of materials, setbacks and variety of building alignment. The goal was to 'soften' the design in order to make the experience from eye level more appealing, as well as to offer increased visual complexity. The plot is divided into three smaller plots, separated by two connection streets. The blocks each offer elevated inner courtyards, one of which is open to the public.

Fig. 45: Variant 2, Bird's eye view from the South-East. Own work.

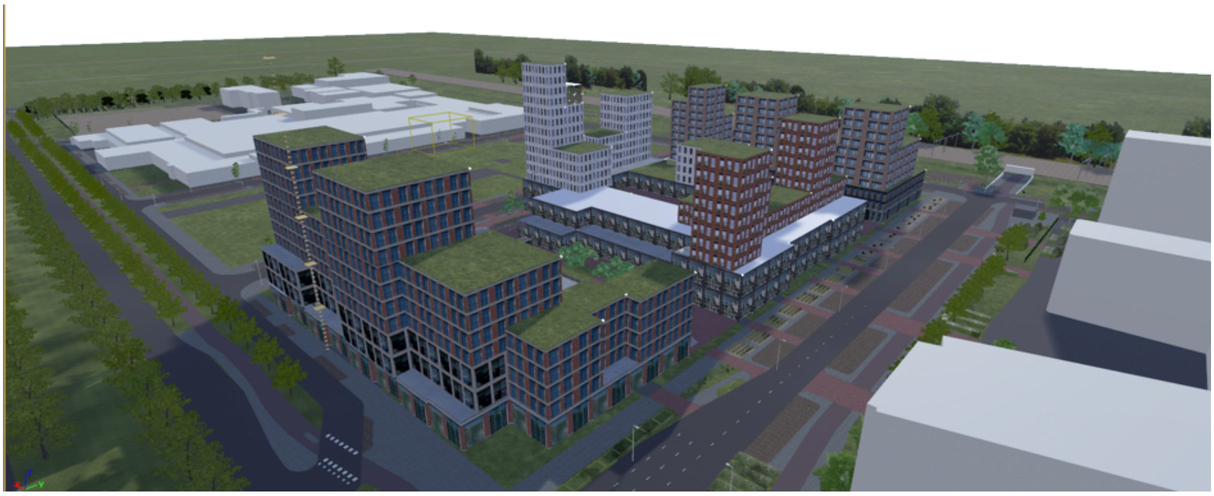

Fig. 46: Variant 2, Bird's eye view from the North-West. Own work.

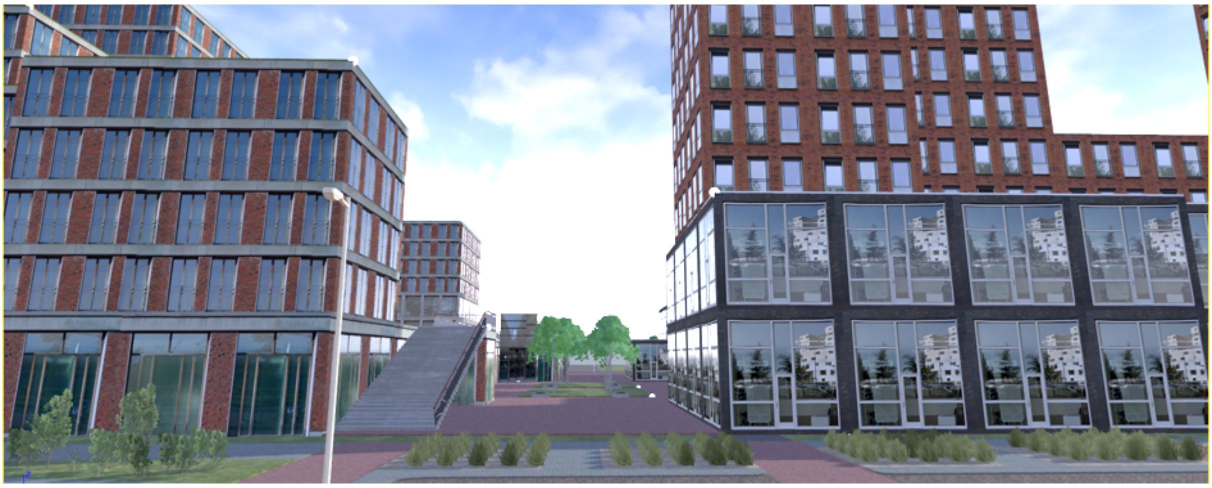

Fig. 47: Variant 2, inner connection street with access to second ground floor level. Own work.

Fig. 48: Variant 2, North-East corner, eye level. Own work.

Fig. 49: Variant 2, South-West corner, eye level. Own work.

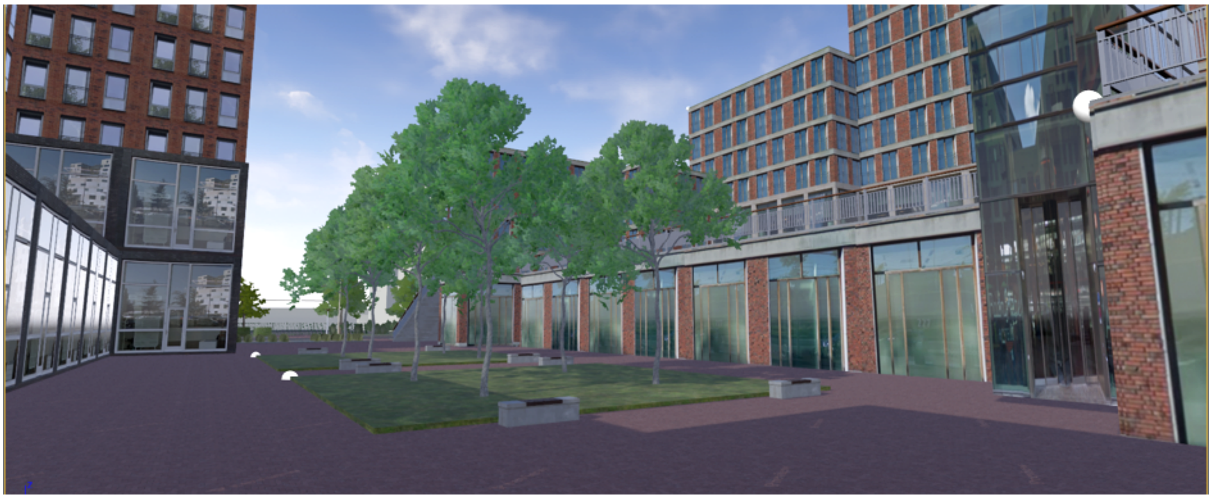

Fig. 50: Variant 2, detail of the intimate connection street, eye level. Own work.

Fig. 51: Variant 2, total overview. Own work.

To see an animation of this design variant, scan the following QR code:

Variant 3A

This variant shows the final state of the volume study for Variant 3. It is made out of plain white blocks, which made it easier and faster to experiment, but lacked information about the number of floors or the size of blocks. The South side of the block is left open, functioning as an extension of the Greater Westerpark. Variant 3A and 3B offer an even finer grained inner street structure than variant 2.

The goal of variant 3 was to make maximum yet realistic use of the 3D insight and immersiveness offered by VR, by trying to find three-dimensional solutions wherever possible and desired.

Fig. 52: Variant 3A, view from the South-East. Own work.

Fig. 53: Variant 3A, view from the North-West. Own work.

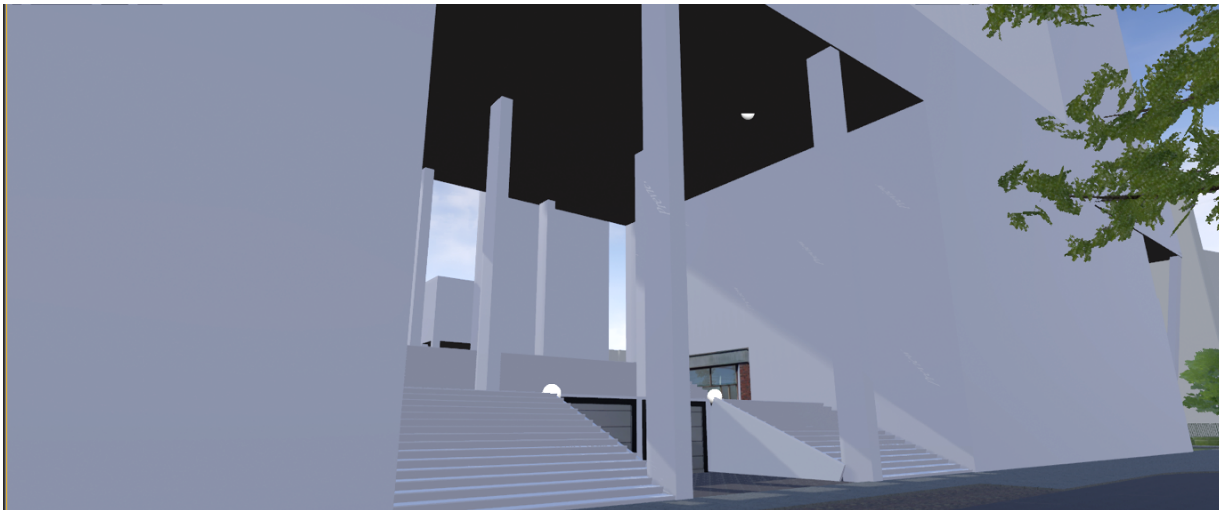
Fig. 54: Variant 3A, North side entry of the second ground floor level. Own work.

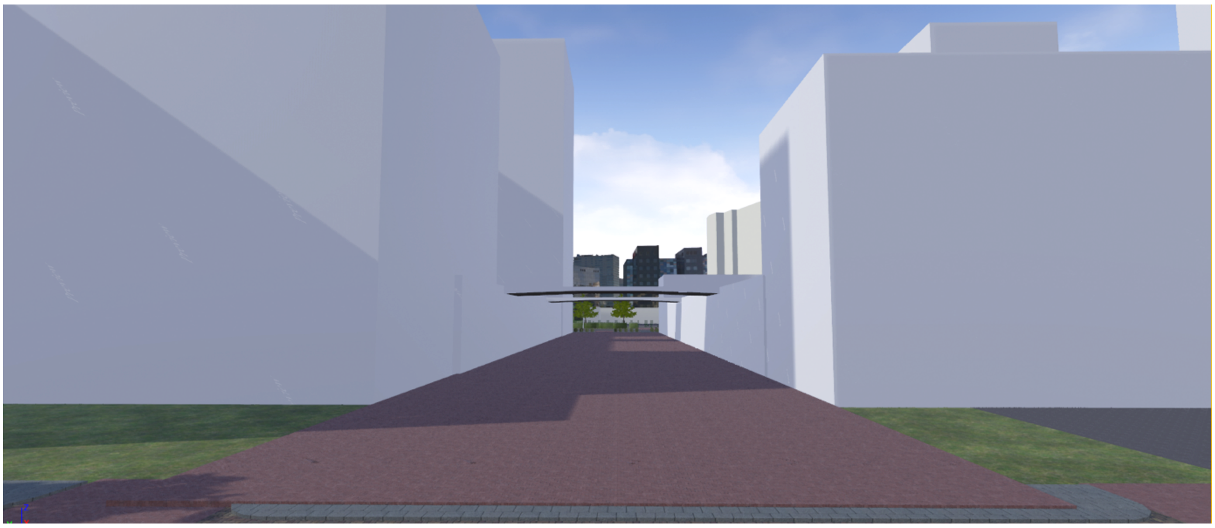
Fig. 55: Variant 3A, Connection street. Own work.

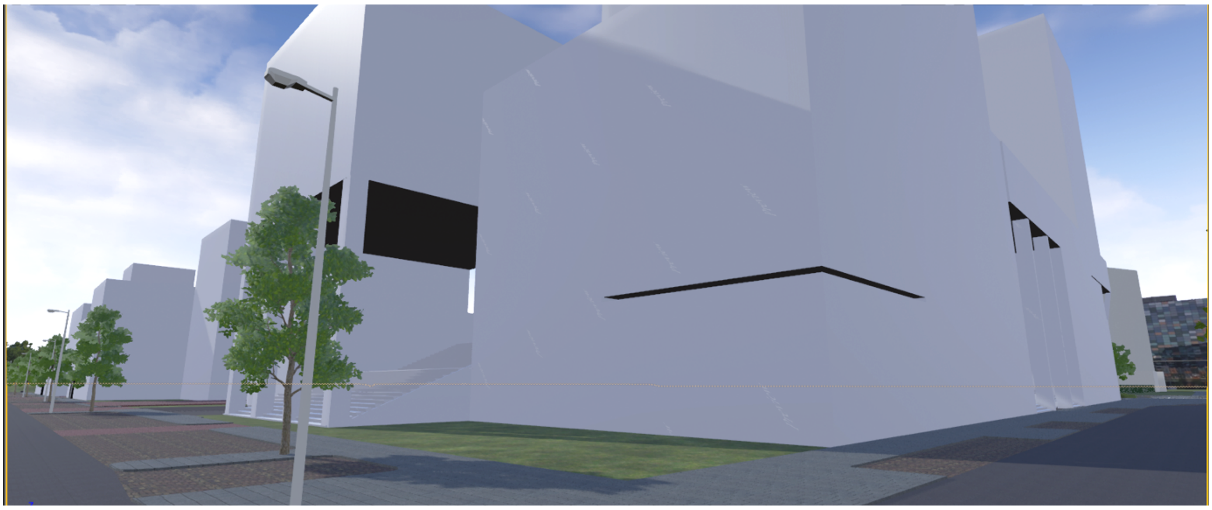
Fig. 56: Variant 3A, North-East corner, eye level. Own work.

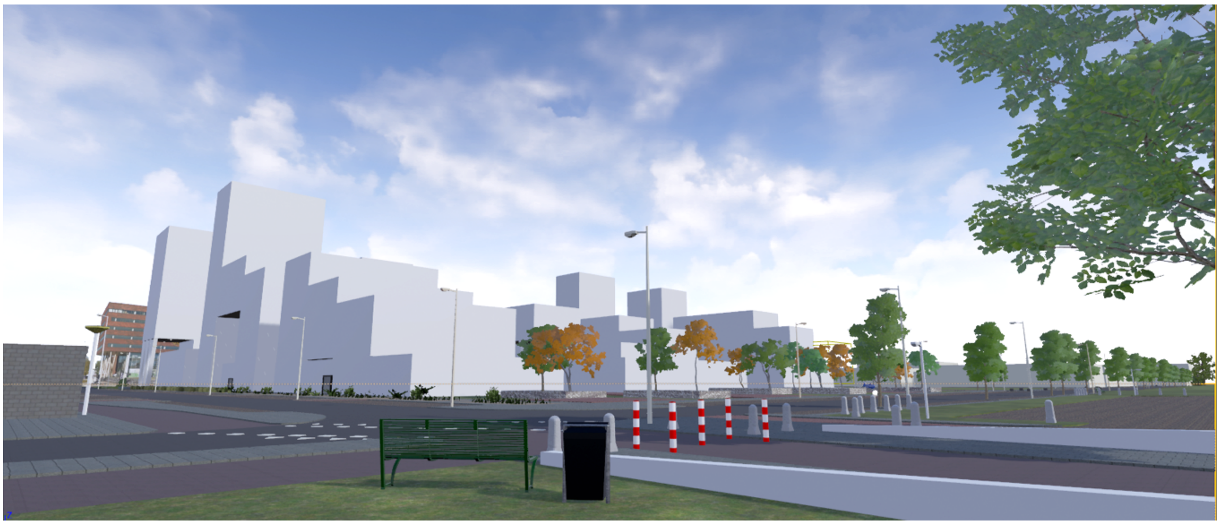
Fig. 57: Variant 3A, South-West corner, eye level. Own work.

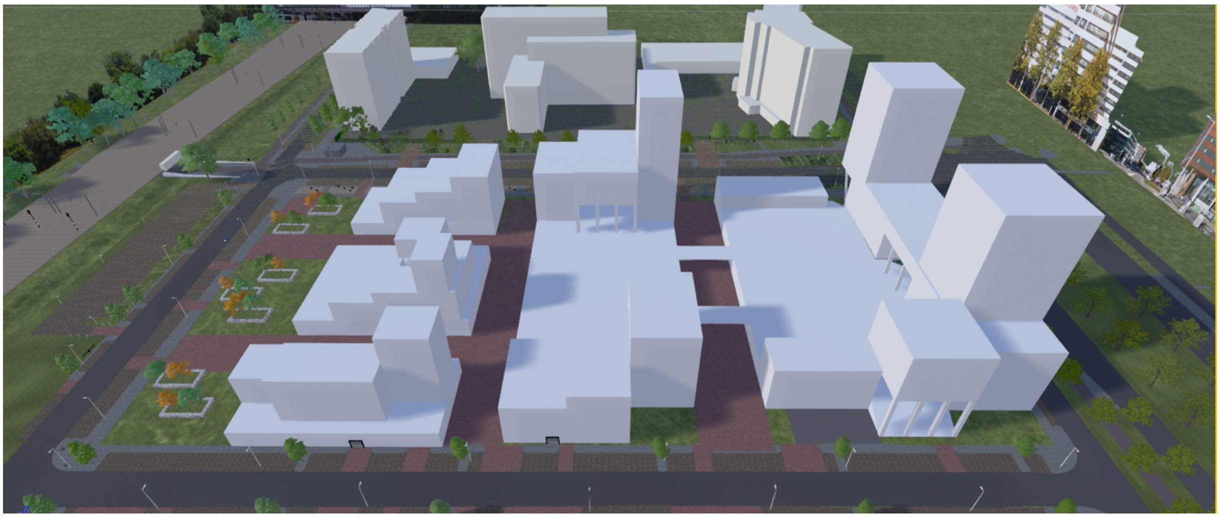
Fig. 58: Variant 3A, total overview. Own work.

Variant 3B

Variant 3B is the result of replacing the plain volumes of Variant 3A by textured building blocks. It immediately shows how the south part of the design is characterized by lower building heights, which was caused by an overestimation of the size of the plain volumes. It also shows how big the influence of the façade detail is on the experience of the design.

The design uses more overhanging parts, gaps in buildings and elevated public spaces compared to Variant 1 and 2, as can be seen in the next images.

Fig. 59: Variant 3B, view from the South-East. Own work.

Fig. 60: Variant 3B, view from the North-West. Own work.

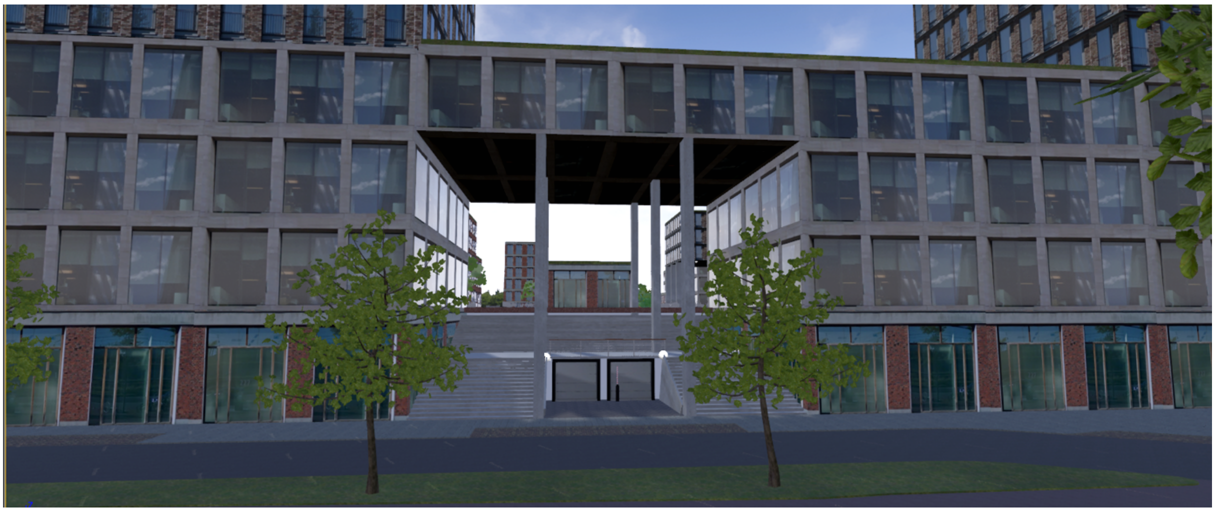

Fig. 61: Variant 3B, North side entry of elevated public space on the parking deck. Own work.

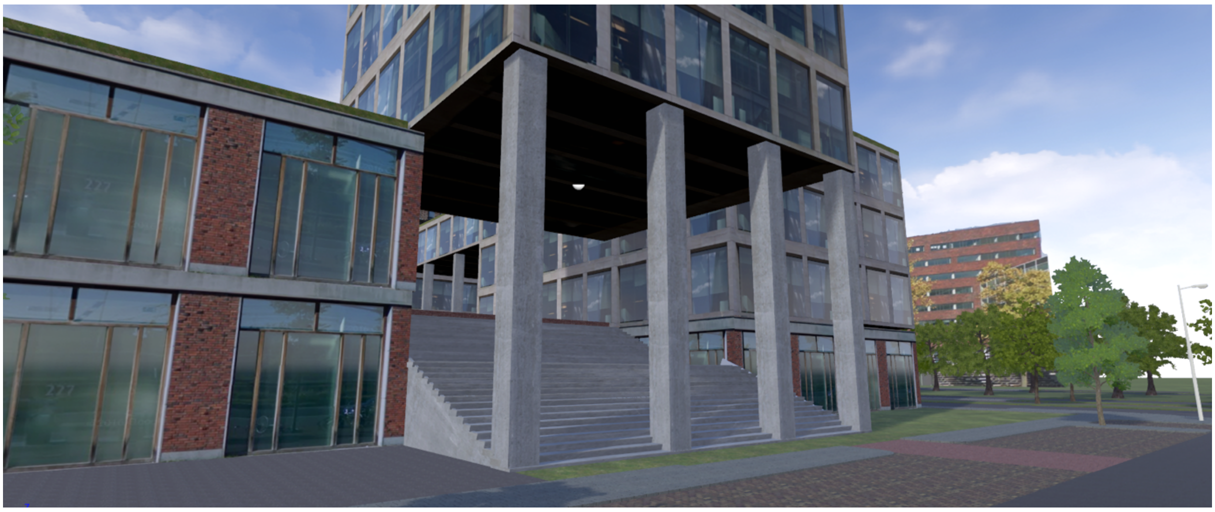

Fig. 62: Variant 3B, East side entry of the second ground floor level. Own work.

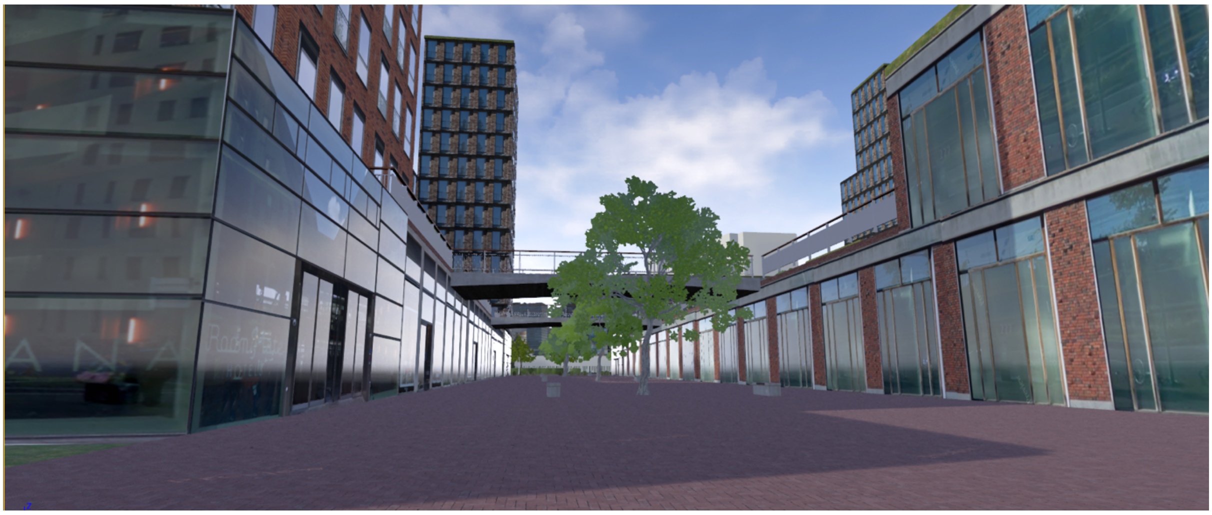

Fig. 63: Variant 3B, Connection street. Own work.

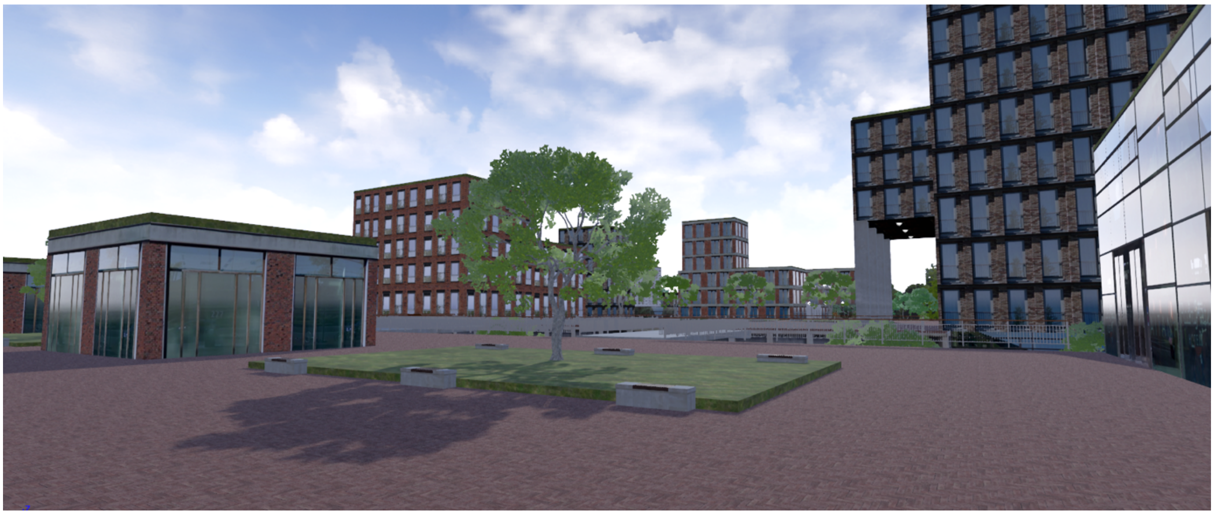

Fig. 64: Variant 3B, detail of the inner courtyard at the second ground level. Own work.

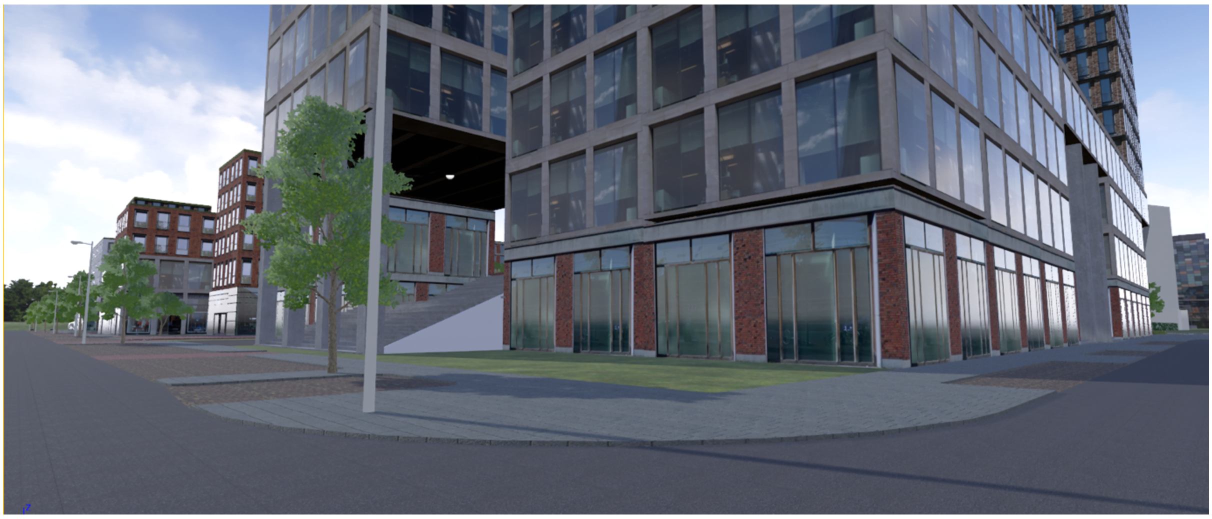

Fig. 65: Variant 3B, North-East corner, eye level. Own work.

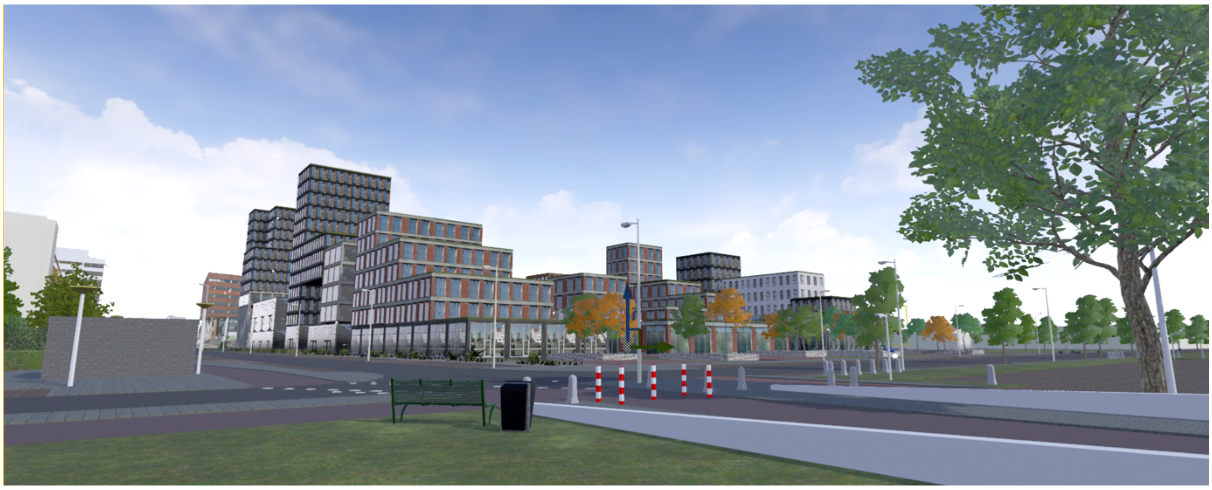

Fig. 66: Variant 3B, South-West corner, eye level. Own work.

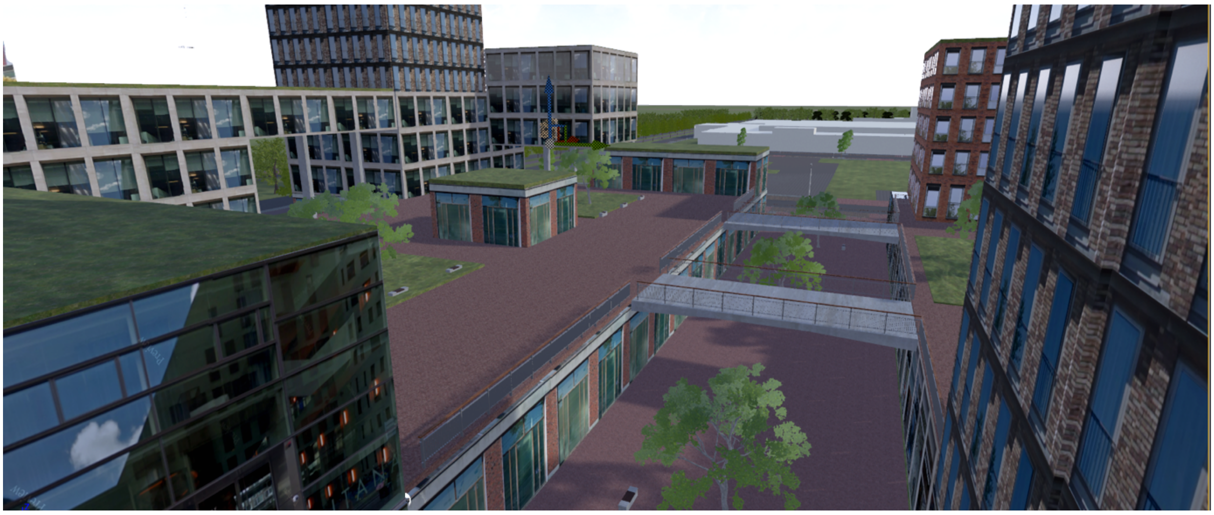

Fig. 67: Variant 3B, the inner area including elevated public space. Own work.

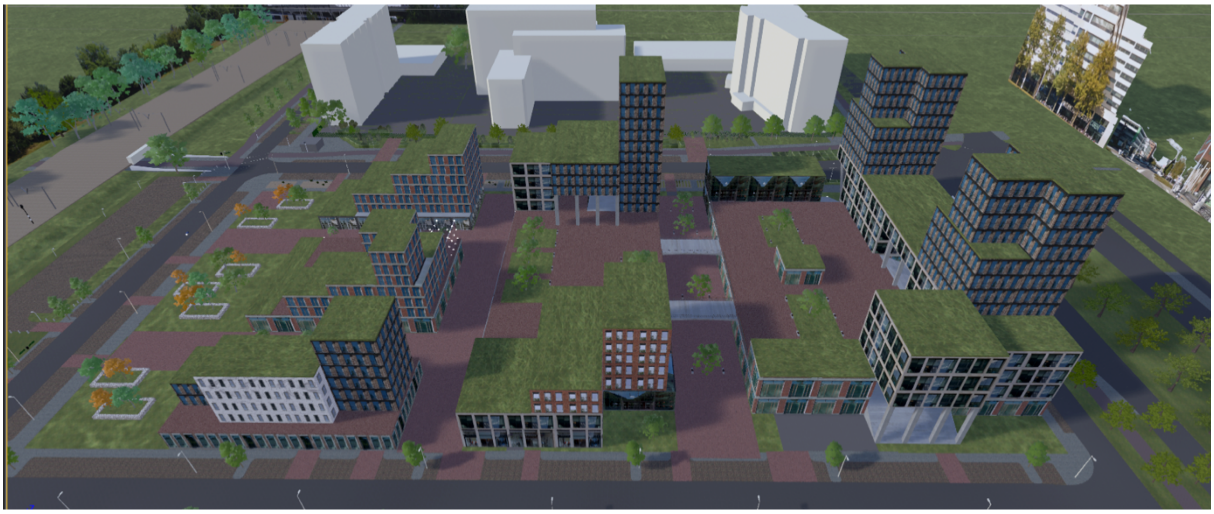

Fig. 68: Variant 3B, total overview. Own work.

To see an animation of this design variant, scan the following QR code:

4.4.4. Spatial analysis of the variants

In this subparagraph, a quick overview will be given on the spatial concepts behind the three design variants using a set of diagrams and maps. As described, the first design variant ("V1") has a less complex shape, less material diversity, a courser grain size of the urban fabric and has a symmetrical layout. Design variants 2 and 3 ("V2" and "V3") are both more complex of shape, have more diversity of materials, are more fine grained and have different spatial layouts, but each in a different way. V3 has been designed in a more three-dimensional way, using overhangs, openings and bridges.

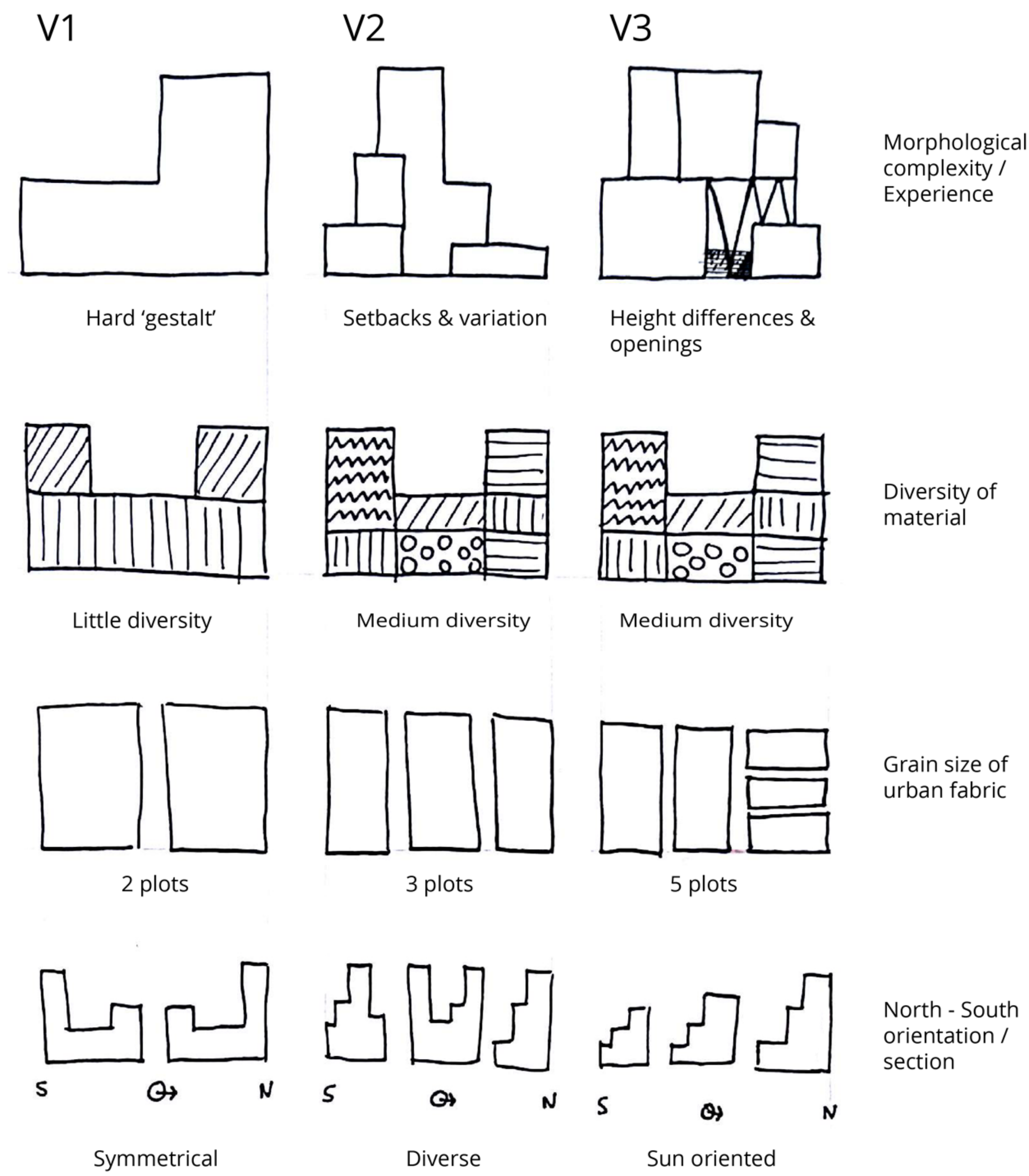

Fig. 69: Analysis of the differences between three variants based on material, grain size, orientation and form. Own work

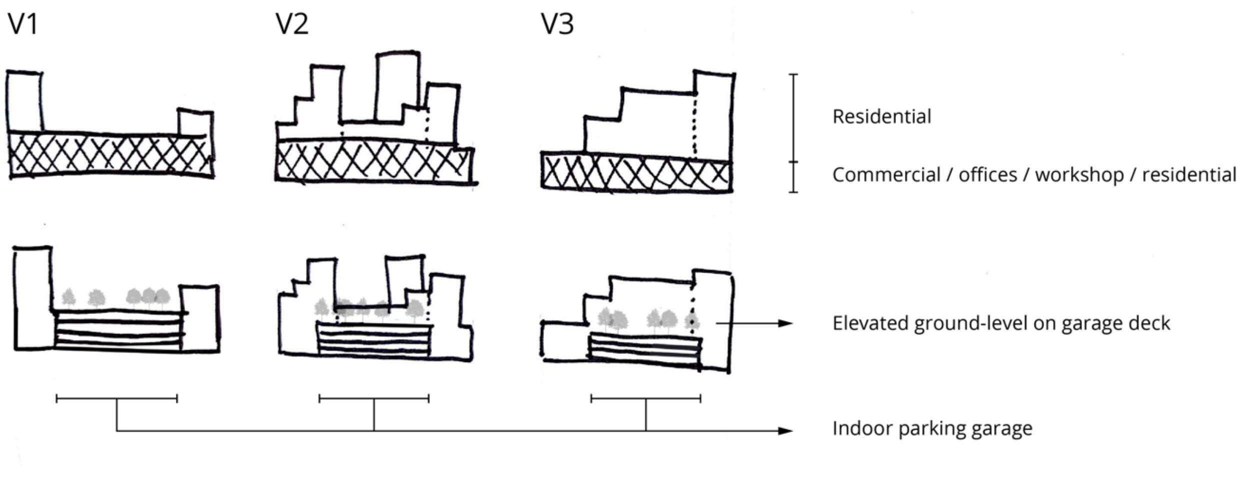

Fig. 70: The design variants share aspects too: they share a setup with a high multifunctional plinth and integrated, indoor parking garages with elevated deck on top offering public, semi-public or private space

The previous images show both the variety of spatial and visual aspects of the design (Fig. 69), as the corresponding aspects of the design (Fig. 70). The shared aspects as in Fig. 70 were defined by the requirements the municipality had set for this area.
The differences between the different variants were partly caused by organic design choices, partly by the goal of researching if the immersiveness of VR would enable a designer to truly experience differences in complexity of shape and material.

In Fig. 71, Fig. 72 and Fig. 73 plans with analyses of the design variants are shown. Fig. 71 shows the layout of the main public, semi public and private spaces in the area. Fig. 72 gives an indication of the distribution of functions in the plinth. The plinth functions were purposefully not planned on specific locations, but the general guideline that was followed during the design was to create three zones: an intimate residential zone at the south end of the plot, a commercially oriented zone at the north end and a flexible mixed plinth programme in between.
Fig. 73 is an analysis of main mobility flows and their relationship with the publicly accessible spaces in the design. The street on the north end side of the area is an important city axis, while smaller mobility flows are expected in the streets at the east and west side of the area. According to the plans of the municipality (Amsterdam, 2016) the southern end of the area will only be accessible to cyclists and pedestrians. A flow of pedestrians is expected through the area towards Amsterdam Sloterdijk station and to the various functions in the plinths.

Fig. 71: Maps of the three variants with public, semi public and private spaces. Own work.

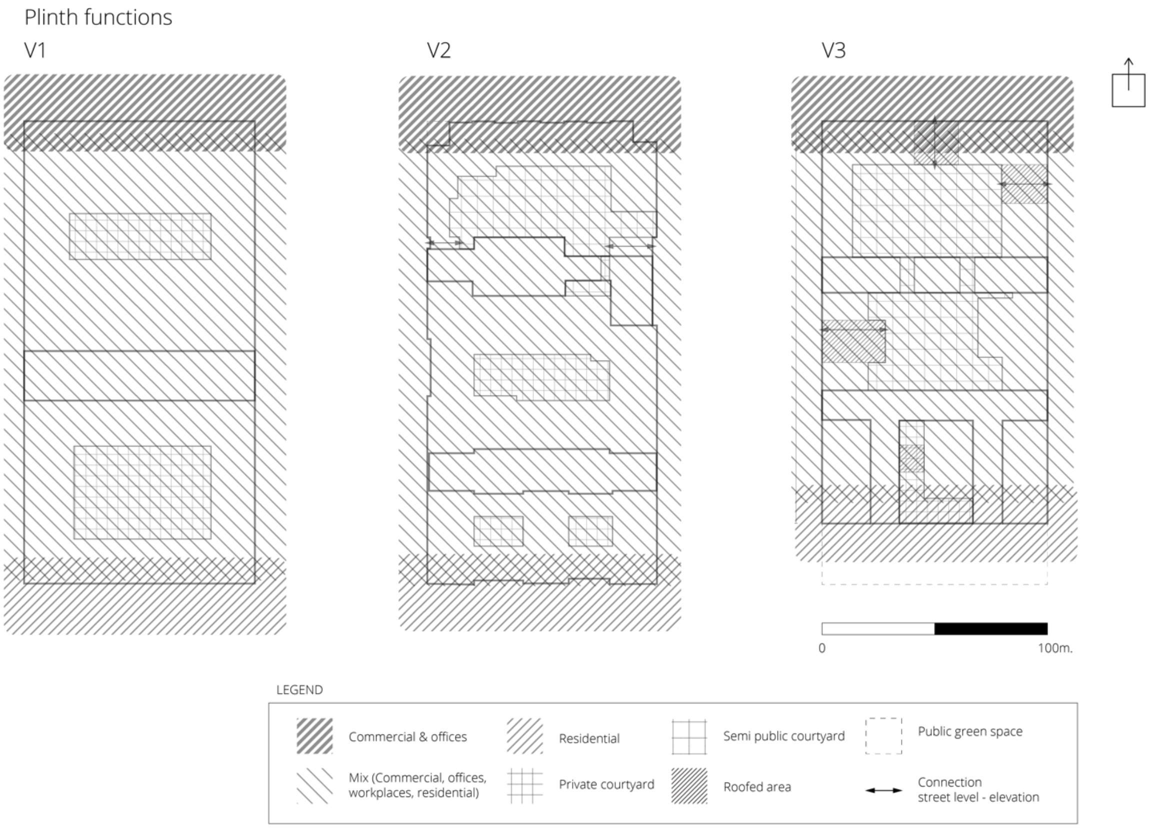

Fig. 72: Broad indication of the plinth function zoning. Residential to the south, commercial in the north, mixed in between. Own work

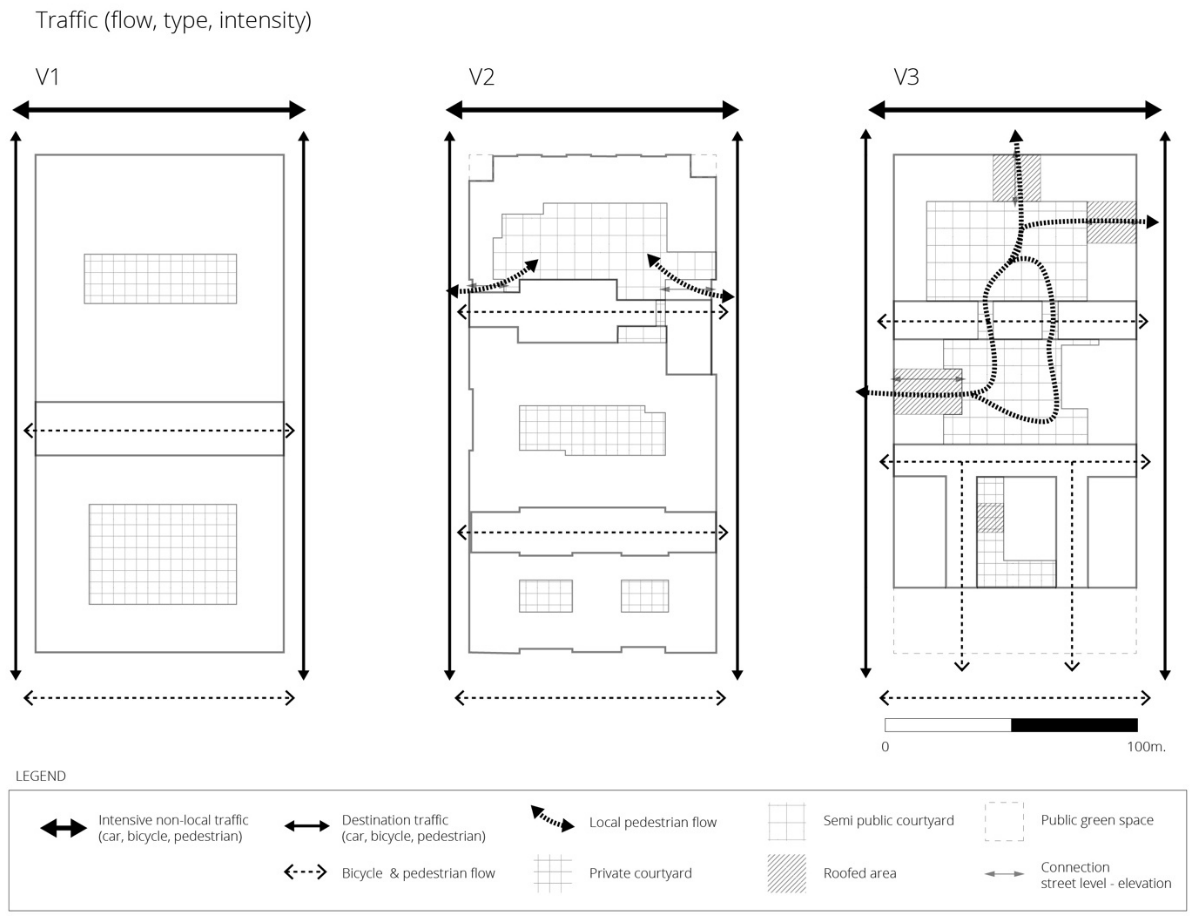

Fig. 73: Maps of the three variants with relation between the (semi)public spaces and the various possible mobility flows in the area. Own work.

Fig. 74 shows an issue with ambiguity of plinth appearance versus plinth function. The choice for generic plinths offered design freedom but also a degree of uncertainty about the actual function of the buildings at street level. The amount of 'vagueness' of the design is a serious issue: when does a design become architecture instead of urban design? How specific does it need to be, how much detail and information should it contain?

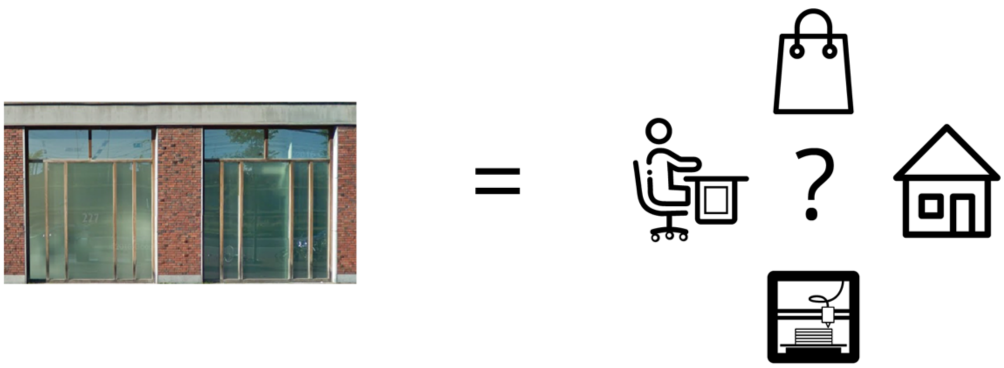

Fig. 74: The choice for generic plinths led to ambiguity about the functions it supported. This was done on purpose, but resulted in ambiguity about the specific location of functions in the design. Own work.

4.4.5 Design process findings

During the creation of the three design variants, many important findings were recorded. These are the factors that were encountered during the design process:

First design steps

After the empty Variant A environment was loaded in UE4 and the headset was connected and put on, the first issue that arose was the question of where to begin with the design. Unlike with a 2D medium, the designer is 'in' the area, floating above the ground, the empty plot in front of him. The bird's eye view in VR gave a strong impression of how big the area was, the scale of the total design. This led to a feeling of lack while designing: the need to apply some first 'broad strokes', to explore options, was felt: placing blocks was the chosen option of designing, which now appeared more limiting than thought before. A lack of analysis tools was strongly felt.

Importance of façade texture choice

The north façade was chosen as a starting point in variant A, the first blocks were placed in the model. This brought the attention to the sizes and types of the blocks: their appearance influenced the experience of the building and the street. This affirmed the importance of the façade choice earlier during the research, but also seemed to validate one of the pitfalls of using CAD programmes for design: their specificity (Bradecki & Stangel, 2014).

Experience of the model in VR

The possibility of switching between scales and levels allowed the designer to check and experience the model at eye level, which is the natural way in which we perceive cities. The height of the buildings, the materials, sunlight and experience of space on the street could intuitively be checked. This allowed the designer to experiment with setbacks and building alignment changes. Especially in Variant A, this process led to designs with many variations in building alignment, both horizontal and vertical. The room scale 3D tracking of the HMD allowed to actually walk around some steps, giving the experience of motion parallax effect (Grondin, 2016). Checking the height and desired setbacks of high-rise from eye level was very intuitive and in many cases helpful.

Exploring toolkit options

Another remark was the desire to explore the toolkit possibilities, by reserving some free space near the design and placing in the model all the building blocks that might be used for the next building or plinth section. By means of trial and error, the Design System elements were explored, resulting in a more fluent interaction with the system.

Building system: placing blocks

Placing the building blocks and other Design System elements proved to be the most important element of the design process. Since every building or building part had to be placed one by one, this caused the process to be slow. The initial building system only offered relatively small blocks (between 6 and 20 meters wide), which slowed down the process even further – especially since the plot size was roughly 200 by 100 meters in size. During the first few design sessions, multiple blocks were selected, copied, pasted and moved – a tedious and annoying process. This was clearly a flaw of the design method using small blocks, without offering a variation of bigger elements.

Choice for bigger blocks

After two design sessions for variant A, new Blueprint Classes were made with bigger building blocks that were made out of multiple smaller blocks. Using Blueprint Classes, any size of building block could be created, potentially entire buildings with roof included. This building system expansion significantly sped up the design process.

Placement mechanism (snapping to grid) issues

Another extremely important aspect of the building process was the placement mechanism using the 'snapping to grid' function. Without snapping, blocks would not line up perfectly, leading to gaps and faulty alignment.
The snapping to grid-system was both helpful and annoying, since the grid would form a surface that blocked the sight of what was underneath, especially at a grid size of 10 cm, which was used most often. This obstructed the placement of objects.
Also, blocks needed to be placed correctly on the X and Y axis in their Blueprint Classes by default, so they would be aligned correctly when placed in the model.

Block alignment issue

Alignment of blocks was another issue: blocks that were supposed to be aligned, needed to be placed very carefully, using the grid snapping system. It was sometimes hard to check whether elements lined up due to the effects of linear perspective. The 'laser' coming out of the motion controller could be used as a measuring device if held still, but mostly close inspection and changing between scale levels would solve this problem.

HMD related issues

Next to software and interface related issues, some HMD related issues came to light. The HMD, which is secured on the head with straps, had the tendency to become warm and sweaty if the wearer moved too much or had been sweating before. Sometimes condensation would form on the lenses. This was a small problem however, most of the time the presence of the headset was not noticed.

Physical design experience

Designing in VR proved to be a very physical process due to the use of 3D tracked motion controllers. Many arm movements were used to interact with the model. Standing while designing was even more intensive; most of the process was performed while sitting down on a chair. Two hours seemed to be a natural limit to take a small brake from wearing the headset and designing. The intensity of designing with VR could potentially be a limiting factor to the use of this technique by very old, weak or handicapped people. It was definitely a very different experience than designing behind a desk.

Graphical representation

The graphical representation of the model, as described before, was very convincing. The choice to use photorealistic façade textures with reflective windows gave an extra sense of realness and immersion in the design.

VR Editor issues

The VR Editor itself worked as it should, except for issues with the translate and scale gizmos. Some of the ‘handles’ used to scale or translate an object would only work in one direction, often the wrong one, or only with great effort. Sometimes, these issues could be solved by changing the left and right motion controller, by changing the scale level or the orientation of the laser pointer relative to the handle. Working around these issues cost a lot of time. It is likely that these problems are caused by a bug in the software. These issues are a good example of the ‘bounded ideation’ pitfall as described by Bernal et al. (2015): distractions from the creative process caused by software malfunctioning.

Faulty selections

Another annoying aspect of the VR editor was the faulty selection of items using the ‘laser pointer’, that occurred in some cases. The pointer had to be pointed exactly on the target in order to select it, which did not always happen smoothly. Small hand movements could lead to a wrong item being selected, which would cost a lot of time, especially when multiple items had to be selected at the same time.

Design freedom

The design freedom that was offered by VR in a design process was great, even though it was limited to using only building blocks. Imagination, skill, time and software related issues would be the only limits to the designer. Since the formulated design problem was to investigate plinth options in a realistic situation, not all of this freedom could be used. Finding a balance between context- and design challenge related constraints and creative freedom is a challenge in any design situation however, but the direct visualization of design interventions helped to more quickly analyse design choices.

Block 'roof' issue

The VR Design System had another issue, related to the configuration of the building blocks in the Blueprint Classes. Since the façade textures of the blocks were applied to every face of the block, both the roof and floor had to be covered to 'hide' this texture for accurate renderings from birds-eye view. The roofs could have been integrated in the Blueprint Classes beforehand, which would have cost more computer power but saved time during designing. Placing all the roofs manually proved to be time consuming and tedious work.

Immersion in the design task

Designing in VR proved to be a very immersive experience. Often, the outer world would be forgotten because of the deep absorption into the virtual environment. The immersion had the effect of increasing the attention to the design process and the interventions.

Design of the public space

Only the inner connection streets, (semi) public courtyards and the southern part of the design location have been designed with street furniture and trees. However, placing public space elements such as benches, trees and green areas effectively increased the realism of the experience at eye level. The possibility to check the design at eye level was exciting: it felt more intuitive to estimate distances while being immersed in the design instead of guessing appropriate distances from a 2D screen. The amount of public space elements in the Design System was limited, additional elements could have been introduced to give a designer more choice.

Final touches

After the big interventions in the area had been made, many final touches had to be performed, which took more time than was anticipated. Most of the work consisted of closing gaps between building blocks, placing roofs on top of buildings, putting railings in place (which were hard to select due to the precise selection mechanism which often pointed to the gaps between the railing's pillars). These final touches were mostly necessary for cosmetic reasons, though – studying urban form alone could be done with approximate block placement.

Third Variant

The initial plan was to design the entire Sloterdijk I area. This turned out to be too ambitious if the design of more variants was to be considered. The next choice was to design only two plots. However, the design process proved to be slower and more cumbersome than expected, which led to the decision of designing a third variant. A amount of design variants might lead to more interesting comparisons between these variants, even opening up the possibility of studying other design approaches. Expanding the same typology to other plots would be more repetitive and probably lead to less interesting insights.

A different design approach was taken for designing variant C: first the volumes would be designed using plain white blocks, which were then replaced by the textured blocks.

This approach seemed to result into a faster design process during the first phases. More form experiments were done, it was easier to do and it led to bigger reconsiderations about many different design choices.

However, when the volumes were replaced by the textured blocks, an interesting issue came to light. It became clear that the size of the plain white volumes had been overestimated.
The result was a design on a much smaller scale, especially the south part, compared to variant A and B.

4.4.6 Outcomes

Choice between more plots / more variants

As stated, a choice had to be made between designing more plots and limiting the amount of variants, or to design more variants but limit to only one plot. Due to the size of the plot and the available time, the choice was made for three variants, each one plot in size, rather than two variants existing of two plots.
The disadvantage of this choice is that interactions between buildings and connection streets, such as visual connections and high-rise options, were not researched. This would have been possible by designing two or more adjacent plots. However, it showed how VR allows a designer to easily create many versions and experiments within each of these variants.

Design related outcomes

There are a number of design related findings for Sloterdijk I that followed from this design process.

Firstly, using the current VR design system, it was hard to find the best locations for certain functional zones within the design area (commercial functions, offices, multifunctional spaces, residential functions) other than appointing various façade types of certain heights that would allow for a flexible layout, possibly affording flexibility for future uses as well. More analytical tools and the possibility to view and influence data layers in real-time are necessary to design the functional aspects of the plan.

Secondly, Sloterdijk I will have to deal with a significant amounts of shadow in case of these high urban densities. Sun exposure had to be guessed from looking at shadows in different lighting situations rather than simulations.

This VR design system seemed to help with designing setbacks and block alignment very well however, which might be an advantage in certain design situations.

Elevated public spaces might be an attractive solution in this area to solve parking issues and to create inner courtyards for public, semi-public and private use. These courtyards should be situated on the south for sun exposure.

The area would need to be safe at night time as well; Variant A would provide a lot of potentially dark corners. This might be experienced as unsafe (Loewen et al., 1993).

Performance of the VR Design System & limitations

The performance of the VR Design System was good for smaller interventions based on visual and spatial considerations, but not suitable for design decisions based on data, and for very large areas. It offered a high amount of detail and freedom, but due to limited block sizes, the block building system and the fact that roofs had to be added manually, it was slow to use.

Designing the public space with VR was one of the strong points of the VR Design System; the immersion in the model and the ability to experience the model at eye level were main advantages for this design issue. Sadly, there was not enough time to design the entire public space around the plot.

The experience of materials and visual details was not as strong in this case as could potentially be achieved, since many of the used textures were of relatively low quality. The illusion of depth created by 'normal maps' was not always visible.

Not all of the VR Design System elements were used: the set of balconies, the truck entry, the wall section, high fence and apartment entry were not used.
The current VR Design System could be expanded and upgraded to make the building process smoother and the choice between objects bigger, but without redefining the building system it would still be slower than desirable.

The main problem with the VR Design System used in this project is its focus on the appearance of buildings and public space, rather than on the functional aspects of the design, which essential to base design choices upon. The function of building parts would have to be guessed by its appearance, and simulations could not be run with the current system.

The lack of simulation options for sun-, wind-, environmental-, sound- and temperature effects, or possibly pedestrian and traffic movements, was missed during the design process. The lack of simulation options was experienced as a limitation, since it caused a lack of critical design information that would be needed for functional, integral designs.
During the process, sunlight was always considered, even though it wasn't a predetermined main design issue.

Thus, the VR Design System functioned well as a tool to study morphological aspects of the designed, but lacked the functionality to function as an integral design tool. This is an important lesson for future design systems: to offer functionality the designer actually needs (Bernal et al., 2015).

Chapter 5: Conclusions

5.1 Conclusions

This thesis aimed to apply 3D Virtual Reality in an urban design process, by preparing a virtual environment suitable for design in VR, creating a VR design tool and using this tool to design multiple design variants for Amsterdam Sloterdijk. It is time to conclude the research part of this project and to find out if the initial research question can be answered:

"What are the advantages, disadvantages and potential of VR as a design tool for urbanism?"

The initial sub research questions were the following:

a. "What new possibilities does VR offer in an urban design project?"
b. "What limitations does VR currently impose upon designers in an urban design process?"
c. "How effective is VR as a tool for designing at eye level?"
d. "How effective is VR as a tool for designing at various scales?"
e. "How effective is VR when used to evaluate the quality of the public space of a design?"
f. "What factors of using VR in an urban design project obstruct the design process?
g. "What factors of using VR in an urban design project speed up or simplify the design process?"

During the research, a number of insights were gained on the application of VR in a design process. One of these insights was that the emphasis of this research and design project was mainly on immersion related aspects of VR which are closely related to visual and spatial aspects of design, rather than data- and function-based aspects. These advancing insights have led to questions about the capability of the chosen method to successfully answer the initial research questions.
Also, due to the extremely rapid development of VR software and hardware, a lot of potentially useful software could not yet be used for this project. One example of these 'missed opportunities' was the software needed to model complex 3D shapes within VR using the HTC Vive. Ironically, this software became available during the course of this design process.
These advancing insights, together with the changing circumstances due to the rapidly developing VR software, meant that this research and design project resulted into a new product that offered different answers, but could not answer the main- and sub research questions as initially stated.
Thus, it was necessary to restate the research questions in order to reflect the knowledge gained in this research and design product. In the last chapter, the focus shift that occurred during this graduation process will be reflected upon.

The restated main research question is as follows:

"How could VR be applied in an urban design process in regard to visual and spatial aspects of urban design?"

This research question will be answered using the following, restated sub research questions:

a. Which visual and spatial aspects are important to apply in virtual environments to effectively use VR in urban design, and why?
b. What advantages does VR bring as a tool to design, visualize and experience urban environments at eye level and bird's eye view?
c. What advantages and disadvantages does a modular VR design system, based on a game engine, have when used in an urban design process?
d. How could a workflow to prepare and execute an urban design process in VR currently look like?
e. What limitations are imposed on taking urban design decisions while using VR for visual and spatial aspects of an urban design process?

The sub research questions will first be individually answered, followed by the answer to the main research question.

a. Which visual and spatial aspects are important to apply in virtual environments to effectively use VR in urban design, and why?

In paragraph 4.2.3, four important visual and spatial aspects were discovered regarding virtual environments. These aspects are all linked to the immersiveness of the VR experience, the importance of which has been emphasized by Slater & Wilbur (1997) and which has been found to be of major importance to this research. Firstly, **level of detail** was recognized as a major aspect for the experience of virtual environments. The level of detail determines the amount of visual information of geometric objects and surfaces (Biljecki et al., 2014). A higher amount of detail serves multiple purposes: adding a sense of realism to the virtual environment and enhancing the estimation of scale and distance of objects in VR. This is important for urban design, because without correct scale and distance estimation, it is hard to make accurate decisions about the urban space (Bowman & McMahan, 2007). Secondly, **coherent and correct scale** of virtual objects and environments is very important for the same reason: if virtual elements are inaccurately sized, spatial choices cannot be correctly made and errors will slip into the final design outcome. The third aspect that should be applied in a virtual environment is a **sense of the urban context**. This can be accomplished using either 3D models of the surrounding spatial elements such as buildings and trees, or using 2D cut-out images displaying the surroundings, placed around the virtual environment. An accurate urban context enhances the feeling of actually being present in the actual urban environment and could make the designer more aware of the surroundings, which has an impact on design choices and outcomes.

These aspects are supported by the **realistic rendering** of the 3D environment and lighting through Unreal Engine 4, without which the experience would have been far less immersive.
Less important factors are the accurate rendering of sky and atmosphere, which add some additional detail but do not have a profound impact on the immersiveness of the experience.

b. What advantages does VR bring as a tool to design, visualize and experience urban environments at eye level and bird's eye view?

As seen in paragraph 4.4.5, the chosen VR design and visualization method offered a set of advantages compared to viewing the same environment on a traditional 2D monitor. These advantages were all linked to the immersive 3D experience offered by VR, the realistic experience offered by the used game engine and the freedom to visualize the environment in real-time from different points of view. Many of these advantages were predicted by Bowman & McMahan (2007, p.39). Especially switching between bird's eye view and eye level proved useful. The next advantages were recognized:

1. An enhanced spatial overview over the design was noticed. Hovering above the design in VR and observing the design in 3D offers a sense of scale and provides a great degree of oversight.
2. A subjective 'experience' of urban space rather than just an observation of a 2D representation of space was identified. This sense of experiencing space could be useful to determine optimal widths of streets, sizes of squares or making otherwise subjective choices.
3. Heights of buildings, setbacks, building alignment and material differences could all be judged from eye level perspective and adjusted according to preference, which helps to make design decisions based on these visual and spatial aspects.
4. Experiencing and designing spaces at eye level, combined with the simulation of sunlight, delivers direct feedback on the amount and effect of sunlight and shadow on street level. By adjusting the sunlight's direction, insight could be gained on sunlight exposure of (parts of) the design.
5. Switching perspective from eye level to bird's eye view and back, which is naturally and intuitively done in VR, seems to give a stronger sense of the scale of the design and its elements, which helps during the design process
6. The experience of public spaces at eye level perspective gives a realistic impression on how the end result would actually look like.

c. What advantages and disadvantages does a modular VR design system, based on a game engine, have when used in an urban design process?

As described in paragraph 4.4.5, the modular VR design system based on a game engine, as used in this research, showed a number of advantages and disadvantages while applying it in an urban design process. The modular approach used for this system offered useful lessons that should be considered by future designers using VR for urban design.
The next advantages were recognized:

- A modular system can be flexible; the appearance, size and composition of elements can be adjusted easily. Extra elements can be added if needed
- It costs relatively little time to set up the system and to start using it
- Placing the building blocks, using hand gestures, is an intuitive experience; it is easy to do

The next disadvantages were recognized:

- The design process resulting from using this system (placing elements one by one) was slow and tedious, possibly having a negative effect on design decision making and creativity
- A modular system could be limited by its perpendicular setup; if no custom corner elements are available, the designer is constrained to 90 degree corners, resulting in straight streets throughout the design. This reduces the design freedom.
- A block-based system containing building blocks that only have volume and appearance, but which do not carry data or are unable to interact with each other, will lead to a design based on only visual and spatial considerations, challenging the usefulness of the design outcome

d. How could a workflow to prepare and execute an urban design process in VR currently look like?

In paragraph 4.2.2 and 4.3.4, a workflow is described to prepare and execute an urban design process in VR. This is not the only or the best workflow to achieve this goal, but the general outline of the workflow could offer lessons for those who want to expand upon this research.
The workflow is divided in a number of steps.
The first step is to prepare the 2D map of the design location. Possible steps include reducing the number of polygons, grouping similar objects and reducing complex geometries.
The second step is to create a rough 3D environment based on the 2D map with accurate building heights and correct UV maps.
The third step is to import the 3D environment into a game engine like UE4. During this step, materials are added, public space elements are placed, a landscape is created and the environment is prepared for viewing in VR. It is important to make the virtual environment match to the actual area, potentially using Google StreetView and photos from site visits.

The fourth step is to use the functionality of the game engine to create a design system, like a modular system with elements imported from a 3D modelling program, or potentially another design approach, depending on available software functionality and skills. Finally, the integrated VR Editor can be used to use the design system in a design process. This design process involves using 3D hand gestures, making use of the Room Scale tracking system, to intuitively put building elements in place. The VR viewing option can be used as a visualization tool to explore the design before, during and after the design process.

e. **What limitations are imposed on taking urban design decisions while using VR for visual and spatial aspects of an urban design process?**

In paragraph 4.4.5, the limitations of using VR for purely visual and spatial aspects of an urban design process are described. Design choices based on visual and spatial aspects affect building size, use of materials, urban composition and street widths. These choices need to be based on analysis, rather than appearance and guesswork. Societal, environmental, economical and demographical data, simulations of dynamic urban processes, legal constraints, zoning regulations and other input are essential for the decision making ability of an urban designer (Washburn, 2013). Using VR for only visual and spatial aspects limits this technology to a visualisation tool or to a tool for morphological studies.

"How could VR be applied in an urban design process in regard to visual and spatial aspects of urban design?"

After answering the sub research questions, it is finally time to give an answer to the main research question. Considering the outcomes from paragraphs 4.2, 4.3, and 4.4, the following answer can be stated:

VR could be applied in an urban design process as a tool to gain **additional spatial overview** and insight at **multiple perspectives**, such as **eye level** perspective or **bird's eye view**, during the design process. During this research it became clear that this degree of overview and insight during the design process can be useful as **direct feedback** on **morphological and appearance based design choices**. The enhanced spatial overview and insight of VR is enabled by its **immersiveness**, but dependent on **correct scale**, a **sufficient level of detail** and a **sense of context** in the virtual environment.
The application of VR in an urban design process is **limited to only visual and spatial aspects** of urban design if the VR design method is not supported by **data, simulations and/or interactive building elements** during the design process. **Data layers** could be added to a VR design tool to give the designer **direct feedback** on design choices by **simulating the effects of design choices on various variables**. This allows for a more **iterative** design process in which the designer **switches from analysis to designing and back –** possibly faster than is possible with traditional design tools.

5.2 Discussion & future research

This research was only able to partly cover many subjects, as it was a rough exploration of a still immature technology. This field of research is still wide open for countless other studies, clarifying topics and finding answers to questions that were only briefly reviewed or not even stated at all. Seeing how this technology advances and seeing what was possible in only a short span of time with limited software skills, I expect a bright future for the use of virtual reality in urban design when more researchers focus on it.

The used method to attain higher levels of detail was mainly through the use of photorealistic textures. While this works well on a distance, nearby virtual buildings its actual flatness becomes clear, and the 3D illusion disappears. This might mean that using another method to create detail is more effective for designs on smaller scale levels. Research could be done on how to easily achieve convincing façades while not having to model every detail.

The chosen method, using a modular approach, is only one out of a multitude of design methods. Many other possibilities to build geometries are possible: drawing lines and planes which could be extruded down-, up- or sideways, chiselling away material from primitive shapes, activating and deactivating voxels, scaling and stretching 3D geometries and (semi)parametric design methods could all be used, possibly together, in one solution. Different designers have different preferences, which should be taken in consideration when developing design tools using VR and intuitive hand gestures for urban design.

A very interesting new research topic could be to compare traditional design methods to a VR design method. Only through a comparative research, the value of VR design processes in relation to traditional design processes can be studied. Another exciting possibility offered by VR is the opportunity to benchmark urban- and architectural ideas and theories. Subjective, immersive experiences of any architectural or urban idea can be tested with many test subjects, potentially making it possible to support or invalidate often vague architectural theories.

Additional research could be done to find the optimal level of realness & detail for designing urban areas. Also, depth perception research using VR needs to be done as long as VR HMD's are improving to check if depth perception becomes more accurate with more advanced screens, or if some fundamental elements of VR HMD's limit accurate depth perception.

As stated before, the pace of technological progress is extremely rapid, while the pressure on our climate and our urban environments is increasing. To face our urban challenges, it is necessary to design smarter and faster, with better spatial insight and from a human perspective. VR could be the intuitive interface between the artistic world of the urban designer and the rational world of urban data. Combining those worlds might lead to answers to pressing urban issues around the world. In order to make that possible, more research on VR in Urbanism is of vital importance.

Chapter 6: Reflection

6.1 Challenges and observations during the research process

Virtual Reality is a rapidly evolving technology. Even during the short time span of this research the technological context changed drastically. New VR plugins became available for modelling software, like Mindesk for Rhino[19] and the Marui plugin for Maya[20]. These plugins made 3D modelling possible *in* VR rather than having to switch to a traditional 2D modelling program. Unreal Engine was upgraded as well[21] and even offered a native 3D modelling option, plus features like 'smart snapping'[22] – a function that would have saved a lot of time during the design process. The fact these solutions were only months away from application in this research is quite ironic, but frustrating as well.
The consequence of the rapidly changing technology is that my project has become outdated, even before the final presentation. The challenge of the rapidly evolving context was addressed after the research and design part was finished, since a change to the methodology during the research process would have distracted the focus on the research. It could not be ignored either, since the rapid change of this technology had important repercussions on the conclusions of this research.

Another challenge was my lack of advanced software skills – a lot of skills had to be learned from scratch, using sources on the internet and experimentation. This was both time consuming and distracting from the research process. With a more advanced set of skills, it might have been possible to use VR for a wider set of applications, like data analysis or the creation of interactive building elements. The potential extra functionality for the design system could have helped to get a better view on the full potential of VR as a design tool.

During this research process, I became gradually aware of the various constraints such as skill level and time. Additionally, I became aware of the true focus of my project, which was based on the immersive quality of Virtual Reality. This 'learning curve' resulted in the realization that the initial research questions did not match with the outcomes of the research – partly because of a focus shift, partly because of the development of the technological context. By carefully examining the actual lessons from this research, it was possible to restate the research questions which could be answered.

[19] http://www.mindeskvr.com/site/ Accessed June 22, 2017
[20] https://www.marui-plugin.com/ Accessed June 22, 2017
[21] https://docs.unrealengine.com/latest/INT/Engine/Editor/VR/GDC2017/ Accessed June 22, 2017
[22] https://www.unrealengine.com/en-US/blog/unreal-engine-4-16-released Accessed June 22, 2017

6.2 Issues regarding answering the research questions

As said, the research questions could not be answered in their initial form. The research was focused on visual and spatial aspects of VR in a design process, while the initial research questions focused on the effectivity of VR as a tool and its functionality. These questions proved to be too ambitious for this research and were not in line with actual focus of this research. The focus shift was partially caused by the definition of the methodology, during which choices were made on which software to use and how to use this software. The choice was made to solve as much as possible within UE4 and not using newly introduced plugins, which prevented a more iterative process. This, together with my lack of advanced Unreal Engine skills and the lack of time, restricted my design approach and the knowledge resulting from the research.

As discussed before, the research questions have been restated to reflect the focus shift of this research. The similarity between the initial and restated research questions is that both are still mainly focused on the application of VR in a design process. Most of the questions have been changed, however. The number of research questions has been reduced, some questions have been integrated into new ones. The emphasis was placed on potential advantages and aspects of VR as used in a design process, mainly of visual and spatial nature. Before, the emphasis had been on VR as a tool itself with research questions that implied benchmarking. While restating the research questions, suggestions of benchmarking, like the measurement of 'effectivity', were avoided.

6.3 Relationship between the methodical line of approach of the Design of the Urban Fabric studio and the method chosen in this approach

In the Design of the Urban Fabric studio, a key method is the use and study of urban patterns in order to find solutions for urban problems. In this research, the design approach was focused on VR as a tool to experiment with spatial and visual aspects of urban space. Concepts such as grain size of the urban fabric, block alignment and setbacks were researched through this VR tool – concepts that are closely related to urban patterns, as I found out in chapter 4. VR could potentially be used to study, even compare, the subjective experience of various urban patterns. With new plugins and software, urban patterns could be tested in various real time simulations like traffic flow, sunlight exposure or wind.

One aspect of the methodical line of approach of Design of the Urban Fabric is the iterative character of design processes. The designer switches back and forth between analysis, literature research and design, gradually expanding knowledge and understanding of the design problem, creating and evaluating design variants using the newly discovered insights. The analyses and evaluations of design variants done during this design process are mostly based on a broad array of urban data, like economical data, flows of traffic, zoning, social aspects and environmental data.

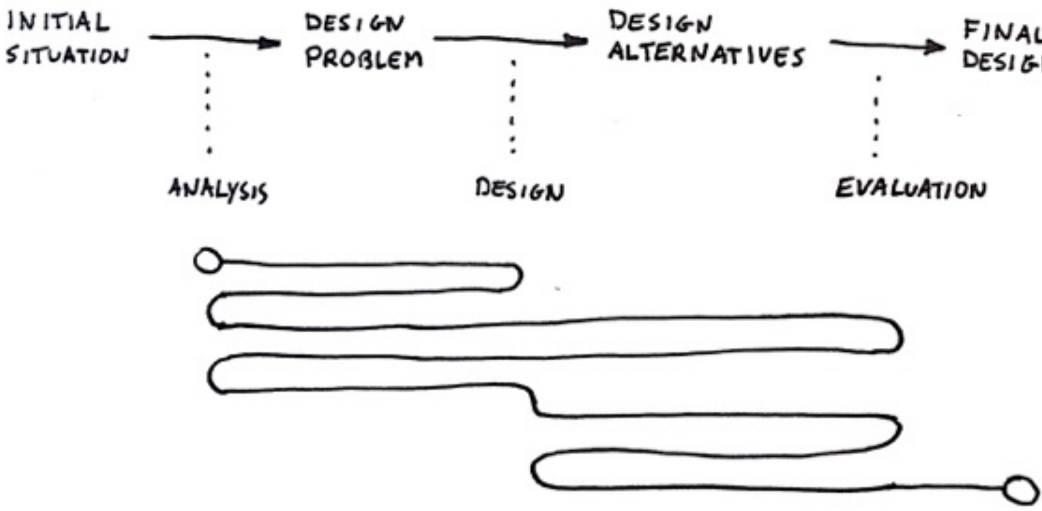

Fig. 75: Conceptual scheme of an iterative design process

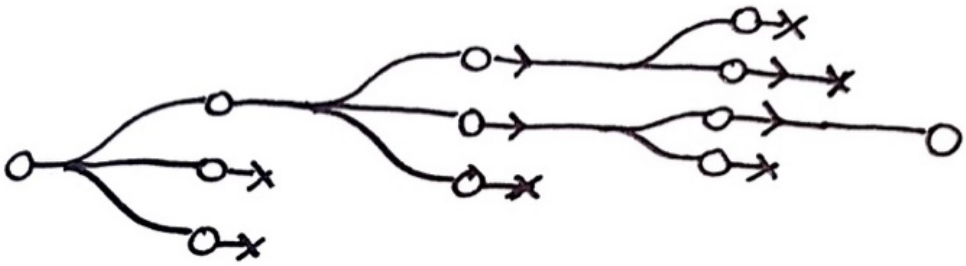

Fig. 76: Conceptual scheme showing creation and selection of design alternatives.

In this project, a set of circumstances restricted the iterative character of the design process.
An absence of 3D modelling plugins or data analysis tools, a lack of programming skill and the limitation of available time led to the rigid adherence to the predetermined methodology, using only one type of software to design and analyse (UE4). This prevented from switching between multiple programmes and possibly analytical tools, which could have made the process more iterative. Without the necessary analysis tools or the skill and time to create these tools right at the start of the project, the iterative character of the design process was limited.

6.4 Relationship between the project and the wider social and scientific context

Surprisingly little research has been done specifically on the use of VR in an urban design process other than as a visualization tool and a tool for public participation processes (Kuliga et al., 2015, Nguyen et al., 2016, Portman et al., 2015). A lot of speculative theory has been written on the potential of VR in its broader sense, like by Bowman & McMahan (2007). Portman et al. (2015) emphasize the lack of research on the use of VR for

architecture, environmental planning and landscape architecture, a lack that is also eminent in the case of urban planning and urban design. A short search on Google Scholar learns that most of the current research on VR is focused on medical and mental health related subjects[23], while the potential benefits of immersion as observed in this research would make it an interesting subject for urban design research.
Apart from research focusing directly on the application of VR in urban design processes, which is nearly inexistent, there are a number of research fields that have been important for this product. Firstly the research on defining levels of detail (Biljecki et al., 2014), secondly research on the use of 3D models (Silvestri, 2010, Yin, 2010), thirdly research on the use of VR for public participation processes (Luigi et al., 2015) and finally research on VR and depth perception (Ng et al., 2016, Peer & Ponto, 2017).

This research fills in the discussed gap in research on the practical application of VR in urban design processes. Although this research was limited to visual and spatial aspects, it is still a unique project that offers a number of important insights on this matter.
This project shows the advantages and disadvantages of a modular VR design system using a game engine, using the latest VR hardware. It has implicated the importance of detail in virtual environments for urban design, of the use of accurate scale and of the need for recognizable context in a virtual environment. It has shown the advantages of immersion related aspects like switching between various perspectives, as well as the outline of a workflow to prepare and execute an urban design process in VR. Finally, this project showed how using VR as only a tool to help with spatial and appearance based choices limits the potential of this technology. It encourages other researchers to continue using VR for urban design and to study if data analysis, zoning and simulation could be integrated into the VR design process.

This project might be an incentive, or inspiration, for future research on the use of VR in urban design processes in our faculty of the Built Environment. This could lead to VR being used more often in design education, increase awareness of this potential application and possibly lead to new design methods in practice as well.
The societal relevance of this project is linked to the possible advantages of Virtual Reality for urban design, as well as the mentioned role of VR in design education. The advantage of VR for actual urban design projects has not been proven in this research, but by offering a first step in the direction of an integrated VR design tool that uses the growing amount of available 3D data (Yin et al., 2010) for a quicker, smarter and more intuitive urban design process, this project might indirectly influence future urban environments.
Another potential aspect of VR that is important for our societal context is its ability to intuitively communicate spatial concepts to the layman, helping in public participation processes (Göttig et al., 2004, Silvestri, 2010).

[23] https://scholar.google.nl/scholar?start=30&q=virtual+reality&hl=nl&as_sdt=0,5&as_ylo=2017 Accessed June 23, 2017

6.5 Relationship between 'Design of the Urban Fabric' and the theme of this graduation project

The design of the urban fabric studio, as described in the MSC3 semester book of 2016/2017, aims to understand how urban design can be strengthened as a scientific discipline, by understanding urban patterns and the development of tools for professional practice.
In this graduation project, a strong emphasis is placed on the use of a possible new design tool (Virtual Reality), related to the spatial aspects of urban design. Although the goal of this project was not focused on gaining a better understanding of urban patterns, the VR design tool *was* used to gain a better spatial insight of urban patterns resulting from the use of this tool, through the immersiveness of VR. Also, experimentation with spatial configurations of modular building blocks was one of the strengths of this tool, resulting into new kinds of urban fabric. These elements characterize the relationship between the Design of the Urban Fabric and the theme of this graduation project.

6.6 Relationship between research and design

In this graduation project, the research and design part were thoroughly interwoven. The main research object was the VR design process itself, instead of the design location or the design outcome. The design process was both research object and research method: in order to study VR as a design tool, it had to be tested as a design method in a design process.

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List of figures

Fig. 1: Time planning. This booklet is handed at the end of week 4.10 ... 25
Fig. 2: City scale context of Sloterdijk I. Google Maps, own editing. ... 28
Fig. 3: Aerial view of Sloterdijk I from the South-East ... 28
Fig. 4: The HTC Vive VR system, with Motion Controllers and the 3D Tracking bases stations at the left and right sides. Available through: http://cdn2.pu.nl/media/hardware/vive2.jpg ... 30
Fig. 5: HTC Vive Base Stations (without cables). These boxes contain spinning lasers to track the HMD and controllers. Available through: https://blog.turbosquid.com/wp-content/uploads/2016/06/1-zGtToYJuc2wPodUW5Wf0ug.jpeg ... 31
Fig. 6: Room scale tracking system by means of the Lighthouse system, using two Base Stations. Available through: https://i.kinja-img.com/gawker-media/image/upload/t_original/js55zljoa3b6v8nj1bfc.jpg ... 31
Fig. 7: A motion controller of the HTC vive. Available through: http://a4.images.reviewed.com/image/fetch/c_limit,w_856,h_570,q_89,f_auto/https://reviewed-production.s3.amazonaws.com/attachment/95645bba928346f9/HTC_Vive_Controller.jpg ... 32
Fig. 8: HTC Vive Link Box, the interface between the PC and the HTC Vive. Available through: https://c.slashgear.com/wp-content/uploads/2016/04/htc-vive-review-4.jpg ... 32
Fig. 9: : The Blueprint system in action, in this case to create a brick street material. Own work ... 34
Fig. 10: The Unreal Engine 4 VR Editor in action. Own work ... 35
Fig. 11: Translate, scale and rotation gizmo in action. Own work ... 35
Fig. 12: Thumb trackpad & pointing menus. Own work. ... 36
Fig. 13: Selecting and dragging objects into the design using the Content browser. Own work. ... 36
Fig. 14: The angle and intensity of lighting can be changed to create any lighting condition. Own work. ... 37
Fig. 15: Fog added to a 3D scene. Own work ... 37
Fig. 16: Area divided in various layers, each with a different colour and function, in Adobe Illustrator CC. Own work. ... 42
Fig. 17: Area imported in Autodesk Maya, buildings are extruded. Own work. ... 42
Fig. 18: Lighting errors in UE4: blocks lack UV maps and normals are not calculated. Own work. ... 43
Fig. 19: Final area in UE4, correct lighting, public space elements are placed. Own work ... 43
Fig. 20: Detail of the South-West corner of the area in UE4, looking North-East. Own work ... 43
Fig. 21: Comparison between the model and the actual area. Own work & Google StreetView. ... 44
Fig. 22: Comparison between the model and the actual area. Note the lack of cars, lower detail in the grass and the absence of façade detail in the building on the right. Building on the left is placed on a flat plane to give the illusion of the actual context. Own work & Google StreetView ... 44
Fig. 23: Comparison between the model and the actual area. Note picture of buildings in the distance, which are placed upon a flat plane in the model. Context delivers higher degree of 'realness' to the scene. Also note the lack of detail in the buildings on the right side of the road: their size is hard to estimate. Own work & Google StreetView. ... 44
Fig. 24: Comparison between the model and the actual area. Note the way public space elements and trees deliver a sense of scale in the model. Own work & Google StreetView ... 44
Fig. 25: Version of the 3D model with empty plots to experiment with building blocks. Own work. ... 51
Fig. 26: Three LOD approaches: photorealistic, complex geometry and a simple geometry. Own work. ... 52
Fig. 27: Three basic building approaches, each with distinctive qualities. Own work. ... 53
Fig. 28: Problem with 'world aligned' materials: they do not always align properly with the building block object. Own work. ... 54
Fig. 29: Modular building approach. Own work. ... 54
Fig. 30: Façade selection. Note that some of the narrower façades are subdivisions of wider façades. Own work. .. 55
Fig. 31: Building block blueprint class structure. Own work. ... 56
Fig. 32: The selection of 3D building blocks to be used in the design process. Note the various styles and dimensions. Human male figures measuring 1.85m are placed in front of the blocks. Upper floors are shown above, ground floor plinth parts below. Own work. ... 57
Fig. 33: The building objects in the Content Browser. The black squares of some of the icons are caused by a bug in the software. The three folders in the upper left corner contain the bigger building blocks that were created later during the process. Own work. ... 57
Fig. 34: Auxiliary design elements: public space elements, roof, floor, stairs, railings, garage doors, balconies and a glass curtain wall. Human figure for scale. Own work. ... 58

Fig. 35: The auxiliary design objects in the Content Browser. Own work. 58
Fig. 36: 3D Scale Bar and human figure to help estimate distances and scale. Own work. 59
Fig. 37: The 3D model, or 'map', can be copied and edited. They share the same object and material library. Own work. 60
Fig. 38: Variant 1, birds-eye view from the South East. Own work. 63
Fig. 39: Variant 1, birds-eye view from the North West. Own work. 63
Fig. 40: Variant 1, inner connection street. Own work. 64
Fig. 41: Variant 1, North-East corner, eye level. Own work. 64
Fig. 42: Variant 1, South-West corner, eye level. Own work. 64
Fig. 43: Variant 1, detail of the public space in theconnection street, eye level. Own work. 65
Fig. 44: Variant 1, total overview. Own work. 65
Fig. 45: Variant 2, Bird's eye view from the South-East. Own work. 66
Fig. 46: Variant 2, Bird's eye view from the North-West. Own work. 66
Fig. 47: Variant 2, inner connection street with access to second ground floor level. Own work. 67
Fig. 48: Variant 2, North-East corner, eye level. Own work. 67
Fig. 49: Variant 2, South-West corner, eye level. Own work. 67
Fig. 50: Variant 2, detail of the intimate connection street, eye level. Own work. 68
Fig. 51: Variant 2, total overview. Own work. 68
Fig. 52: Variant 3A, view from the South-East. Own work. 69
Fig. 53: Variant 3A, view from the North-West. Own work. 69
Fig. 54: Variant 3A, North side entry of the second ground floor level. Own work. 70
Fig. 55: Variant 3A, Connection street. Own work. 70
Fig. 56: Variant 3A, North-East corner, eye level. Own work. 70
Fig. 57: Variant 3A, South-West corner, eye level. Own work. 71
Fig. 58: Variant 3A, total overview. Own work. 71
Fig. 59: Variant 3B, view from the South-East. Own work. 72
Fig. 60: Variant 3B, view from the North-West. Own work. 72
Fig. 61: Variant 3B, North side entry of elevated public space on the parking deck. Own work. 73
Fig. 62: Variant 3B, East side entry of the second ground floor level. Own work. 73
Fig. 63: Variant 3B, Connection street. Own work. 73
Fig. 64: Variant 3B, detail of the inner courtyard at the second ground level. Own work. 74
Fig. 65: Variant 3B, North-East corner, eye level. Own work. 74
Fig. 66: Variant 3B, South-West corner, eye level. Own work. 74
Fig. 67: Variant 3B, the inner area including elevated public space. Own work. 75
Fig. 68: Variant 3B, total overview. Own work. 75
Fig. 69: Analysis of the differences between three variants based on material, grain size, orientation and form. Own work. 76
Fig. 70: The design variants share aspects too: they share a setup with a high multifunctional plinth and integrated, indoor parking garages with elevated deck on top offering public, semi-public or private space 77
Fig. 71: Maps of the three variants with public, semi public and private spaces. Own work. 78
Fig. 72: Broad indication of the plinth function zoning. Residential to the south, commercial in the north, mixed in between. Own work 78
Fig. 73: Maps of the three variants with relation between the (semi)public spaces and the various possible mobility flows in the area. Own work. 79
Fig. 74: The choice for generic plinths led to ambiguity about the functions it supported. This was done on purpose, but resulted in ambiguity about the specific location of functions in the design. Own work. 79
Fig. 75: Conceptual scheme of an iterative design process 95
Fig. 76: Conceptual scheme showing creation and selection of design alternatives. 95

Appendix A: Workflows

.DWG to Unreal Engine 4 map workflow

Starting point: Accurate map of the area in .dwg (in this case, delivered by the municipality of Amsterdam)

- Open illustrator:
  - Import .dwg flight
  - Reduce the number of lines to get lower poly counts
  - Select all the lines, use pathfinder -> divide
  - Place resulting surfaces according to type in separate layers
    - Street, sidewalk, greenery, buildings, inner courtyards,
  - Separate building blocks according to height: 4, 6, 8, 12, 16, 20, 28 and 36 meters
  - Group all objects per layer (necessary for Maya)
  - Export as .dwg
- Import in Autodesk Maya:
  - Import .dwg file
  - Rotate lines -90 degrees on X axis (Maya uses another axis system)
  - Deactivate all layers except for one
  - Create polygon faces from lines of active layer (Surfaces > planar)
    - If unsuccessful, look for faulty lines (overlap, double line objects)
    - Check if the 'normal direction' of the face is correct. If it is black, use Mesh Display -> reverse
  - Extrude planes according to height to get 3D spatial objects
    - Buildings: 4, 6, 8, 12, 16, 20, 28 and 36 meters
    - Urban greenery, sidewalks: 10 cm
  - Create materials for all the newly created mesh objects, apply per layer
  - Object mode: separate all the 3D objects
  - Select individual 3D objects & create automatic UV map in the UV editor
  - Export as .fbx file
- Unreal Engine 4.14:
  - Create new project using the VR template, open the Motion Controller map (which is tailored to the HTC Vive)
  - Delete the default content: blocks & collision volumes
  - Import .fbx file in new folder in the Content Browser
    - Settings: deselect 'combine meshes', select 'compute normals'
  - Group meshes according to layer grouping in the Illustrator file
  - Apply varying materials to varying meshes in order to be able to distinguish them
  - Create a Navmesh & Blocking Volume, in order to allow the VR viewer to navigate the map
  - Create a landscape that is big enough for the model and serve as a horizon
  - Download tree models, import & place in model

    - I purchased two packs of trees optimized for Unreal Engine 4, since they are designed for optimal computer performance and thus require less resources while offering a high amount of detail. Creating simple trees (brown pole with translucent green ball) was another option.
  - Create / download other necessary objects for the public space: poles, concrete blocks, catenaries, lantern posts, benches, waste bins, tunnel walls
    - I created these objects in Blender, free 3D modelling software that is relatively easy to learn with online tutorials. The software offers UV mapping tools and allows for various materials to be applied
  - Place the trees & public space elements in the map
  - Use Google Streetview screenshots of surrounding buildings as 'billboard' at the edges of the design location to offer a sense of context
  - Edit, in Maps & Modes, the current map as default start-up map.
  - Save the map

Using the HTC Vive in 'Play' mode

Walking through the design location with the HTC Vive:

- Connect the HTC Vive, plug in the Vive Base Stations
- Make sure the Motion Controllers are sufficiently charged & turn them on
- Open Unreal Engine 4
- Open the Sloterdijk I-project
- If SteamVR is already installed, it will automatically start up when the Unreal Engine is started
- Press the 'Play in VR' button
- Put on the headset & grab the controllers
- Point to a location to get teleported to that location and pull the trigger

Using the HTC Vive in the Unreal Editor 4 VR Editing mode

- Connect the HTC Vive, plug in the Vive Base Stations
- Make sure the Motion Controllers are sufficiently charged & turn them on
- Open Unreal Engine 4
- Open the Sloterdijk I-project
- Choose the Enable VR Editing in the Editing Preferences mode in the Experimental section
- Press the button in the form of a VR HMD in order to get into the VR editing mode
- Put on the HTC Vive, grab the controllers and start designing

Appendix B: Design considerations

List of design considerations as stated by the ambition document of Sloterdijk I, by the municipality of Amsterdam:

Building volume, building heights, façades
Building alignment, plinth, vertical vs horizontal vs bidirectional accentuation
Plinths (height, layout, façades, entries)
Second ground floor level solution
Dependencies: high-rise, setbacks, shadow, light and sun, wind
Density, fsi
Typology, access, address
Stacking of residential & non residential functions
Flexibility, adjustable buildings, casco building frame
Sound blocking solutions
Inner courtyards, entries of housing
Entries of garages, bike sheds, inner courtyards
Connecting streets east-west
Sightlines, see-through views
Opposing façades
Public space: materialisation, greenery, play & rest facilities
Storage of bikes, cars, garbage

Appendix C: Theory paper

The State of the Art of Virtual Reality in Urban Design

A review of the current possibilities, pitfalls and potential offered by Virtual Reality

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Abstract – Virtual Reality (VR) has seen impressive advances and cost reductions since high quality, consumer grade VR systems have been released. Although it has been regarded as a very promising technology (Bowman & McMahan, 2007), it has not yet found its way to the mainstream practice of urban design. While the use of 3D data and -modelling offers multiple advantages (Yin, 2010), it is often introduced later in the design process than traditional 2D designing methods and data (Schubert et al., 2012). Positional tracking of both the VR Head Mounted Display (HMD) and hands or controllers has enabled intuitive interaction of the user with the virtual world and is commonly known as 'Room Scale VR'. When Room Scale VR becomes available to urban designers, it potentially offers a way to incorporate the use and manipulation of 3D data earlier in the design process. This paper describes the state of the art of VR as a tool for urban design by reviewing the opportunities, pitfalls and potential of this new technology. A reflection on the contemporary practice of urban design and its relation to 3D data is given. Based on the conclusions of this paper, a new set of expectations, prospects and new questions arises that will form the starting point of my design project.

Keywords – vr, virtual reality, urban design, design tool, computer aided design

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1. Introduction

Virtual Reality [1] (VR) is showing potential as an exciting and useful technology for architects, urban designers and many other fields of research (Portman et al., 2015). Former head mounted displays and CAVE (Cave Automatic Virtual Environment) systems were until recently too costly and advanced for use in many applications apart from laboratories and research institutes (Bowman & McMahan, 2007, Orlosky et al., 2015). The current generation of head mounted displays (HMD's) with high levels of reality, immersion and gesture-based input heralds a new era of VR use[2].

This work aims to review the state of the art of VR in the discipline of urban design, with focus on the current possibilities, limitations and near-term potential of VR as a design tool. At the time of

[1] Virtual reality is the term used to describe a three-dimensional, computer generated environment which can be explored and interacted with by a person. That person becomes part of this virtual world or is immersed within this environment and whilst there, is able to manipulate objects or perform a series of actions. http://www.vrs.org.uk/virtual-reality/what-is-virtual-reality.html [Accessed 2 Jan. 2017]

[2] http://www.vrs.org.uk/virtual-reality/history.html [Accessed 22 Nov. 2016]

writing, multiple high quality VR systems have been introduced at prices aimed at consumers, opening it up to many more professions and researchers. The current pace of software development is high, with new programmes, plugins and VR versions of existing software being introduced almost weekly (Bellini et al., 2016). However, as Portman et al.[3] notice, the case for VR as a design tool for urbanism has been sparsely discussed in literature (2015, p. 377). The development of hardware, software, tools and platforms is occurring at such a high rate that most literature, even the most recent, is already outdated. The focus has so far mainly been on the evaluation of designs and existing spatial environments, perception based research or cognitive experiments rather than the application of VR as a tool for designing (Portman et al., 2015). This is unfortunate, because the introduction of positional tracking and 'Room Scale virtual reality' have brought interesting new possibilities for more intuïtive interaction with virtual environments [4] (Orlosky et al., 2015). In this work, the term 'intuitive design tool' will be used multiple times. In order to prevent misconceptions, I will give a definition of this term that is used throughout this paper. Intuitive means, according to the Oxford online dictionary: *"Using or based on what one feels to be true even without conscious reasoning; instinctive"* and, more applicable: *"(chiefly of computer software) easy to use and understand"*[5]. An intuitive design tool is therefore a design tool that can in principle be used instinctively, with little prior training.

This paper focuses on the use of VR in urban design rather than on the cognitive and perceptive aspects of this technology. A lot of research has been done on these cognitive and perceptive aspects, with results showing VR as being emotionally arousing (Felnhofer et al., 2015), featuring ecological validity (Luigi et al., 2015) and, provided that the 3D environment contains sufficient visual cues of its spatiality, little problems with depth perception (Ng et al., 2016). Also, Augmented Reality (AR) and Mixed Reality (MR) will not be covered until the discussions part, in order to reduce the scope of this paper.

The goal of this paper is to describe the state of the art of VR in regard to urban design. By presenting an oversight on the current state of the art of VR technology, this review allows for a suitable starting point for my own research and design project: *VRBANISM, assessing virtual reality as an urban design tool.* In the next chapter, the contemporary practice of urban design will be shortly described, followed by chapters regarding the current possibilities of VR, its the pitfalls and problems and its potential for urban design.

After the conclusions, which bear special importance for my project, the discussions section will offer some relevant topics for further research.

2. Contemporary practice of urban design

In order to see the relevance of the possibilities, limitations and potential of the application of VR in our profession, it is necessary to familiarise ourselves with the current state of affairs in the practice of urban design. This practice has been described by many scholars in as many different ways. Some are focused on the multidisciplinary aspect of urban design (Washburn, 2013), some on the analytical aspect (Leupen[6], 1993), others on the (changing) role

[3] The paper by Portman et al. (2015) is one of the key papers used for this work

[4] http://www.digitaltrends.com/virtual-reality/oculus-rift-vs-htc-vive/ [Accessed 9 Dec. 2016]

[5] https://en.oxforddictionaries.com/definition/intuitive [Accessed 14 Dec. 2016]

[6] Leupen et al.'s *Ontwerp en Analyse* offers a comprehensive and broad view on designing and systematical study of design. Although the first print dates

of the design tools (Scheer, 2014). In this section a short overview is given on some of the influences of technology and the general development of the urban design process.

2.1 The evolving process of urban design

According to Washburn[7], the process of urban design produces "maddeningly complex patterns from the overlap of three not very transparent forces: politics, finance and design" (Washburn, 2013, p.51), while he stresses the importance of fluency and clarity in communicating a design. He argues that the sketch is particularly useful because of its relative convenience, and its ability to show progress in the in-between stages of designing and its ability to clearly communicate the core of design decisions to stakeholders (Washburn, 2013, p.68-69). His views are shared by Bradecki & Stangel (2014), who state the importance of freehand drawing in design education. Scheer (2014) further elaborates how sketching offers structure to the ideas of the architect (designer), and mentions an interaction between form and idea. He sees that hand-drawing is a dying art, while digital forms of design are winning ground (Scheer, 2014). Some examples of these digital methods are AutoCAD, Revit, Adobe Illustrator and Photoshop and SketchUp.

Meanwhile, the amount of digital data is ever increasing and leads to maps with more and more information (Fung et al., 2013). GIS is commonly used in the profession of urban design (Yin, 2010) but also information from the internet such as Google Earth is commonly used (Portman et al., 2015), even though it is not always of high quality.

2.2 Designing with 3D data

Especially in urban design, the focus is still mostly on 2D visual representations, rather than 3D (Yin, 2010) even though researchers have imagined a more widespread use of 3D, even 4D data (time included) for urban purposes for multiple decades (Köninger & Bartel, 1998). The adoption of 3D data such as maps and models has been accelerated by the advances of software and computer processing power (Yin, 2010) but the help of computers in the creative process is still not fully validated, by example due to the high cognitive cost of using computer design aids (Bernal et al., 2015). Some specialist programmes, such as AutoCad or other complex tools, are often difficult to learn and time-consuming (Eastman, 2001, Göttig et al., 2004, Yin, 2010). Others are less complex, but still demand a certain level of training and skill to operate with ease. They all use the same 2D input devices, many of which have not changed during the last decades: keyboard and mouse (Göttig et al., 2004). Note that even for the creation of 3D environments, mostly these 2D input devices are used. In some rare cases pressure sensitive drawing tablets or touchscreens are used. Due to the time consuming and complex nature of many 3D visualization tools, including the use of physical models made of wood or paper, the use of 3D information often happens during later stages of the design process (Göttig et al., 2004, Robertson & Radcliffe, 2009, Schubert et al., 2012).

2.3 Advantages of using 3D data

The added value of using 3D data and immersive visualization is high however, since "it offers the possibility to enhance the imagination, comprehension, and evaluation of models or concepts, which are otherwise difficult to capture" (Göttig et al., 2004, p 101). Furthermore, clear communication of plans and concepts to other professionals and stakeholders is key to effective

from 1993, it has been frequently updated and still offers valuable insights.

[7] An influential contemporary urbanist, former urban design chief of New York City

urban planning and design (Batty et al., 2001, Washburn, 2013, Yin, 2010). Especially stakeholders without a professional background in (urban) design often have difficulty translating the abstract contents of 2D maps, contrary to more naively accessible 3D models (Jobst & Döllner, 2008, Shiode, 2001, Yin, 2010). Intuitive and user friendly 3D modelling software such as SketchUp 3D, which offers a free version, is already popular within urban design education and practice (Khiati, 2010).

2.4 Game engines

Interestingly, a crossover of software use between the gaming industry and urban design is happening as well, as various software companies like Unity 3D and Epic Games are offering free versions of their game engines[8]. These game engines can be used for real time 3D visual simulation of imported 3D models, but also offer a greater degree of interactivity and realism in real-time (Indraprastha & Shinozaki, 2009).

2.5 Summary

In this section, the contemporary practice of urban design has been discussed, showing how the profession has evolved by the introduction of 3D data, CAD programmes and experimental approaches such as game engines. The various aspects of VR that will be discussed next can be considered in context of this current practice.

3. Current possibilities of VR

VR has seen a breakthrough in the last few years with the arrival of several high grade consumer focused HMD's, such as the Oculus Rift and, more recently, the HTC Vive[9].

These two systems, together with the PlayStation VR, OSVR HDK 2, Samsung Gear VR, Google Daydream and Fove 0 form the current state of the art in virtual reality HMD's[10]. All of these HMD's have significant improvements over their predecessors in the late 90's and 00's (Kuliga et al., 2015). These headsets feature far superior degrees of field of view (FOV), resolution, supported frame rate, comfort and a far lower amount of lag between real and mirrored virtual movements [11]. Now that the price has decreased and the quality of the HMD's has drastically improved, the benefits and uses of VR as envisioned in the 90's are finally becoming apparent[12].

3.1 Place of VR in current research

According to Kuliga et al. (2015), virtual reality headsets can currently show highly realistic, complex environments with high visual realism. Some more recent examples of virtual reality research mention the potential of using this newer generation of HMD's, such as the Oculus Rift. Luigi et al. (2015) confirmed the ecological validity of immersive VR in urban contexts, based on valuations of an IVE based on a real environment. Stauskis (2014) showed how VR could help civilians understand spatial and temporal processes of urban designs. In his research he shows the impact of virtual reality on public participation processes, which could be used for promoting more effective public involvement in the design phase of urban environments (Stauskis, 2014).

3.2 Room Scale VR

The greatest improvement that is being offered with

[8] https://create3dgames.wordpress.com/2015/09/07/unity-5-vs-unreal-engine-4/ [Accessed 9 Dec. 2016]
[9] http://www.digitaltrends.com/virtual-reality/oculus-rift-vs-htc-vive/ [Accessed 9 Dec. 2016]
[10] http://www.wareable.com/headgear/ the-best-ar-and-vr-headsets [Accessed 9 Dec. 2016]
[11] http://www.bbc.com/news/technology-23877695 [Accessed 9 Dec. 2016]
[12] http://www.theverge.com/a/virtual-reality/oral_history [Accessed 9 Jan. 2016]

this new generation of VR is 'Room Scale VR', which involves positional tracking of the HMD and tracking of a set of controllers, which will be referenced to as 'motion controllers'. Room Scale VR is a recent term to distinguish VR systems that reflect physical motions of the person wearing the HMD and controllers or hands in the immersive virtual environment (IVE), leading to a great sense of immersion within- and intuitive interaction with the IVE. The person wearing the HMD sees the controllers, represented either by digital replicas of the controllers or virtual hands, reflecting the movements they physically make. By triggering buttons and moving the motion controllers, virtual objects can be intuitively manipulated. Another VR input method is hand tracking, using a sensor like the Leap Motion sensor or similar hand tracking technology that Microsoft and Intel are developing [13, 14]. Since motion tracking and the possibility of interaction with the IVE is so essential for the usefulness and experiential value of VR[15], it could be argued that only Room Scale VR counts as 'true' VR.

The positional tracking is so far only supported by the Oculus Rift, HTC Vive and PlayStation VR, each with their own sets of controllers and sensors [16]. Future headsets might offer 'inside out' positional tracking, using a depth sensing camera system instead of external sensors. Microsoft pursues this technique with upcoming headsets[17].

Room Scale virtual reality offers many new, exciting opportunities. Painting in 3D is good example; multiple programmes for this use have been created like Google TiltBrush, GravitySketch VR and Oculus Medium[18,19,20]. 3D modelling is a logical next step for this technology, but current programmes like VRTX[21], which offers a VR 3D modelling solution, are mostly still experimental. Virtual reality without the Room Scale functionality is limited to less immersive experiences such as viewing 3D models from a more or less fixed position, without the possibility to, for instance, lean in to objects in order to inspect them.

3.3 VR software platforms

The selection of high end VR platforms is currently still limited. Most are mainly focused on gaming, with Oculus VR, Sony PlayStation and Steam having advanced but separate software ecosystems [22]. Microsoft is also working towards a VR ecosystem, which can run on lower powered PC's than the high end HMD's such as Oculus Rift and HTC Vive[23]. Another player is Intel, working on a technology called 'merged reality'[24], using cameras for hand- and positional tracking. Finally there are many of low cost VR systems produced in China[25,26]. Most of

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[13] https://newsroom.intel.com/press-kits/project-alloy/ [Accessed 20 Dec. 2016
[14] http://blogs.microsoft.com/next/2016/06/26/talking-hands-microsoft-researchers-moving-beyond-keyboard-mouse/#sm.00000jsw06pie9dlyzlg7yfucnlgp [Accessed 12 Dec. 2016]
[15] https://medium.com/@arcreality/why-room-scale-matters-627c752e32ac#.9ytz2ixnd [Accessed 4 Jan. 2017]
[16] https://www.cnet.com/news/how-playstation-vr-is-better-and-worse-than-oculus-rift-and-htc-vive/ [Accessed 12 Dec. 2016]
[17] http://www.theverge.com/2016/10/26/13418156/microsoft-windows-10-holographic-virtual-reality-headset-announced-price [Accessed 12 Dec. 2016]
[18] https://www.gravitysketch.com/ [Accessed 12 Dec. 2016]
[19] https://www.oculus.com/medium/ [Accessed 12 Dec. 2016]
[20] https://www.tiltbrush.com/ [Accessed 12 Dec. 2016]
[21] https://steamcommunity.com/app/358720/discussions/1/451852118777984284/ [Accessed 15 Dec. 2016]
[22] http://www.digitaltrends.com/virtual-reality/virtual-reality-and-exclusivity/ [Accessed 12 Dec. 2016]
[23] http://www.theverge.com/2016/10/26/13418156/microsoft-windows-10-holographic-virtual-reality-headset-announced-price [Accessed 12 Dec. 2016]
[24] https://newsroom.intel.com/press-kits/project-alloy/ [Accessed 20 Dec. 2016]
[25] http://vrkommando.com/top-5-chinese-pc-vr-headsets-everything-need-know-hmd/463 [Accessed 20 Dec. 2016]
[26] http://vrkommando.com/hypereal-pano-pc-vr-headset-chinese-frankenstein-headset-controllers-positional-tracking/580 [Accessed 20 Dec. 2016]

these do not offer Room Scale VR, which is a big disadvantage. As a multitude of software platforms is emerging, the question arises which platform becomes the most advanced, affordable and appealing [27]. One of the most well-developed platforms for Room Scale VR is SteamVR, by Valve Software. SteamVR offers mostly games; while Valve is also developing VivePort, which is meant for other types of VR applications[28]. Valve strives to offer many different experiences and tools on SteamVR and VivePort, from 3D sketching to educational tools, virtual meeting / cooperation spaces and 'metaverse' like creation spaces[22]. It is to be expected that in the near future, several big platforms will each offer software in their content stores that can be used for urban design purposes.

3.4 Possibilities for urban design

Regarding the discipline of urban design, there are already some useful applications of virtual reality. For site analysis, the recent introduction of Google Earth VR offers great potential if the location has been fully mapped in 3D. Cities like New York or Florence but also small cities like Delft can be analysed from all possible angles, under any lighting condition, buildings included. The availability of 3D data supplied by Google is a prerequisite for getting the most out of this experience, though. Another option is to import 3D models of a neighbourhood, a plan or design into a game engine like Unity3D or Unreal Engine to be explored, and possibly adapted[29,30,31].

With TiltBrush, GravitySketch VR or Medium, quick 3D sketches can be made and exported to 3D .fbx files[32]. At the time of writing there are limited ways to professionally and intuitively edit 3D models or GIS environments directly in VR, without tweaking existing software or using unstable, experimental programs. This forces designers to use complex CAD programmes for designing, followed by exporting the plan to a game engine for viewing in VR. This iterative process is already criticized for being slow & inefficient (Göttig et al., 2004). The development speed of the VR field is so high however, that this situation might be improved within one or two years. This problematic workflow for urban designers was already encountered by Göttig et al (2004) more than a decade ago. Example of software that might close this gap in the workflow are SketchUp, AutoCAD or Revit, by eventually getting VR versions or plugins. The earlier example of VR modelling software, VRTX, is not yet officially published. Another option is to use the VR editor function of game engines such as Unity 3D or Unreal Engine 4, which let users design levels directly in VR [33, 34] These are not professional CAD programs though, which might lead to problems for urban designers later in the process, when the final design has to be translated into 2D plans. 3D objects can be edited within these game engines, but not as precise as in professional CAD programmes (Indraprastha & Shinozaki, 2009).

3.5 Summary

In this section, a description of the current possibilities has been given, considering the recent advances of the VR hardware and software. Although

[27] http://newatlas.com/daydream-vs-other-vr/43469/ [Accessed 20 Dec. 2016]
[28] http://tech.firstpost.com/news-analysis/htc-viveport-will-be-a-new-destination-for-non-gaming-vr-experiences-on-the-vive-328713.html [Accessed 20 Dec. 2016]
[29] https://docs.unrealengine.com/latest/INT/Engine/Editor/VR/ [Accessed 20 Dec. 2016]
[30] http://www.evermotion.org/tutorials/show/9154/unreal-engine-4-for-archviz-tutorial [Accessed 20 Dec. 2016]
[31] http://www.roadtovr.com/unitys-vr-editor-lets-you-create-vr-content-like-a-god/ [Accessed 20 Dec. 2016]
[32] https://blog.sketchfab.com/tutorial-exporting-tilt-brush/ [Accessed 9 Dec. 2016]
[33] https://docs.unrealengine.com/latest/INT/Engine/Editor/VR/ [Accessed 20 Dec. 2016]
[34] Available at: http://www.roadtovr.com/unitys-vr-editor-lets-you-create-vr-content-like-a-god/ [Accessed 20 Dec. 2016]

the current VR systems allow for many possibilities for urban design, a limited amount of urban design-specific software is currently available. This brings us to the pitfalls, problems and limitations regarding VR for urban design.

4. Pitfalls and problems of using VR for urban design

Although VR has made great strides towards greater immersion and functionality, there are currently a number of pitfalls and problems that have yet to be addressed. In this paper, five categories of these pitfalls have been identified, which will be discussed here.

4.1 User interface of design software

The first type of pitfalls is based on the nature of computer assisted design (CAD) programs. According to Bernal et al. (2015), that what is on the screen of the computer is often different from what is in the mind of the designer. If this is also the case with VR, which offers a more immersive and rich experience, is not thoroughly examined yet. For effective and intuitive designing it is of great importance that the barriers between the designer and design, like the user interface or the complexity of the tool, are minimal (Bernal et al., 2015). A complex user interface can be a strong distraction from the design process, according to Eastman (2001). In their paper, Bernal et al. (2015) describe three pitfalls in designing with computers: circumscribed thinking, premature fixation and bounded ideation. Circumscribed thinking arises when the design alternatives are limited to what the tool, in this case virtual reality, can accomplish. Premature fixation is a resistance to changing a design, because of the "complexity of the structure of the models" (Bernal et al., 2015, p. 164). Bounded ideation is the distraction from the creative designing itself that is caused by "technical and software issues, derived from the abuse of CAD tools" (Bernal et al., 2015, p. 164). An example of why CAD software limits the creativity of the designer, is that most programmes need direct and accurate input of dimensions, in contrast to the loose strokes of a pencil. These three pitfalls all presume that the designer is using traditional CAD tools, however. Just as some designers in product design are using 'digital sculpting' methods to overcome CAD related problems (Martín-Erro, 2016), urbanists might turn to VR. A virtual reality designing tool using Room Scale VR might be less affected by these effects due to its more intuitive input methods (Huang et al., 2010), but this is highly dependent on the used VR software and hardware. The influence of the tool on the designer has not been thoroughly researched yet in the specific field of virtual reality, especially not in with state of the art Room Scale VR. Since VR also involves a software user interface which has to be learned to some degree, some transferability of these effects could reasonably be assumed.

4.2 Lack of 3D data

A second kind of pitfall is the potential lack of high quality, recent 3D data. In order to be able to design with virtual reality, it is essential to have access to a reliable and recent 3D representation of the design area – (Batty et al., 2001, Nebiker et al., 2010), or to be able to generate one within reasonable time (Brenner, 1998). This 3D virtual environment would be the canvas of the designer using virtual reality. Some municipalities in developed countries have good access to 3D models and/or possess reliable (3D) GIS data (Köninger & Bartel, 1998). Traditional modelling of an entire neighbourhood or even city is extremely time consuming and expensive, which makes it in some cases impossible (Chen, 2011). Happily, with advanced software which combines photogrammetry and detailed hight measurement, this process can be partly automated (Brenner, 1998, Chen, 2011, Hammoudi, 2012). Outdated 3D data is a problem too, since many cities see many (re)developments every year (Morton et al., 2012).

4.3 Software ecosystem exclusivity

Thirdly, exclusivity of tools for certain software ecosystems might be another problem. Virtual reality systems are still relatively expensive, which means that buying another system to get access to a specific software tool would be problematic in many cases[35]. This could hurt the adoption of VR as a widely used tool for urban design. This also counts for virtual 3D city models. As Morton et al. (2012) state, the many different file formats that represent 3D city model data possibly pose a threat to the use of these models, as they might not be interoperable. The amount of time and money invested in these models is normally high (Köninger & Bartel, 1998), while this data is highly usable for multiple goals (Morton et al., 2012). Examples hereof are analysis and possibly design in VR.

4.4 Hardware requirements and costs

Fourthly, although VR has seen dramatic cost reductions, it still costs a prohibitive amount of money for widespread use. A typical VR system such as the HTC Vive consists of a high end computer with a powerful graphics card, combined with the VR system itself. An appropriate VR setup, including a computer, costs between €1700,- and €3500,-[36]. As the VR experience gets more realistic, more computer power is needed, increasing the hardware requirements and costs.

4.5 Lack of an integrated software solution

Finally, since there are currently no integrated design tools available for urban design, the designer might run into several problems. Because of the lack of an integrated tool, urban designers are forced to use multiple programmes which increases the risk of data conversion errors (McHenry & Bajcsy, 2008). This can highly frustrate the design process. Using software that was not meant for urban design, like game engines, might also lead to difficulties in the design process, for example when the final design must be converted into 2D plans and sections, or when a necessary function is missing in the software. Working around these inefficiencies costs a lot of time and effort.

4.5 Summary

Due to the complexity of CAD programmes, the potential lack of available high quality 3D data, software ecosystem exclusivity and the lack of integrated VR design software for urban designers, it is probable that VR will only be used for urban design purposes in rare cases the coming few years. However, VR offers great potential when these problems are addressed, as discussed in the next section.

5. Potential of VR for urban design

As mentioned before, the latest VR technologies have only been available since very recently. This technological novelty allows for a lot of innovations in research and practice. In this section, expectations about the potential of using Room Scale VR for urban design purposes are given.

5.1 Potential of VR for research

Since 1990, there has been a lot of research focusing on VR in the field of architecture, GIS and urban

[35] http://www.digitaltrends.com/virtual-reality/virtual-reality-and-exclusivity/ [Accessed 12 Dec. 2016]

[36] http://www.logicalincrements.com/articles/vrguide [Accessed 12 Jan. 2016]

design and planning. None of these researches were executed with the latest generation of HMD's however, while only some involved the use of 3D input devices (Göttig et al., 2004, Portman et al., 2015). Instead, primitive HMD's and CAVE systems were used. Therefore, the full potential of Room Scale VR has not yet been realised in this field of research, rendering many of the literature outdated and/or incomplete. New kinds of research can (and should) be performed.

5.2 Potential of VR for urban design

For urban design, the ability to intuitively interact with IVE's by means of Room Scale VR is a key factor. As mentioned, positional tracking is the technology that drives this interaction. Important to note is that current applications using Room Scale VR like Tilt Brush are highly intuitive, allowing the user to create 3D art with minimum effort to learn the user interface[37]. With this in mind, one could see the possibility that one could at some point edit a virtual model of the city, while viewing simulated 3D data that is adapted real-time (Heydarian et al., 2015, Nguyen et al., 2016). Furthermore, a designer could intuitively and quickly sketch his ideas in 3D, directly into the model of the city. Real-time simulations in VR offer possibilities for studying the broader effects of spatial interventions on the environment, such as the distribution of pollution, influence on the urban heat island effect, the modification of natural walking / cycling routes, wind patterns, etcetera (Morton et al., 2012). As noted in the previous paragraph, an integrated VR design tool for urban environments is not yet available. When such tools are developed, the full benefits of IVE's and 3D data finally become available. Examples are the increased engagement of users in the IVE, enhanced imagination, clearer and easier communication with stakeholders and easier studies of complex urban environments (Göttig et al., 2004, Stauskis, 2014, Yin, 2010). Moreover, by overcoming the limitations and distractions that traditional user interfaces pose on designers, as mentioned by Bernal et al. (2015), virtual reality might be used in the conceptual design phase. This phase, charactarized by ambiguity and vagueness according to Göttig et al. (2004), is currently still dominated by traditional design methods (Bradecki & Stangel, 2014, Köninger & Bartel, 1998). When 3D modelling becomes intuitive instead of complex and time consuming, virtual reality might offer a new medium to express creative ideas effectively and to share these immediately. The consequences could be the emersion of a new paradigm for urban design, in which the link between stakeholder and designer is more direct while communication is more clear and effective (Stauskis, 2014). Portman et al. add that "*[w]hen virtual reality is immersive, designers tend to work interactively and three-dimensionally with their media; every creation is a place experienced directly through movement and interaction parallel to real world familiarity"* (2015, p. 379).

5.3 Summary

In summary, researchers have already showed a lot of potentially useful applications and potential of VR, but none of these has covered state of the art Room Scale VR. Exciting possibilities could emerge when Room Scale positional tracking is combined with integrated, intuitive design software for urban design. This software does not exist yet, but may soon be available. Room Scale VR could offer a more intuitive way of interacting with CAD software, overcoming the limitations generated by complex

[37] https://killscreen.com/articles/vr-will-change-way-create/ [Accessed 10 Jan. 2017]

user interfaces (Robertson & Radcliffe, 2009). Together with the freedom that virtual environments offer, the use of VR might possibly lead to a new paradigm in urban design.

6 Conclusions

In this paper, the possibilities, limitations, possible pitfalls and potential of VR have been discussed, introduced by the contemporary practice of urban design. In this practice, the conceptual design phase was originally dominated by traditional design methods (Scheer, 2014). 3D models and computer aided design are becoming increasingly important but are often introduced later in the design process (Robertson & Radcliffe, 2009). A plenitude of research affirms the value of using 3D data for a clear communication of ideas and spatial concepts (Göttig et al., 2004, Jobst & Döllner, 2008, Stauskis, 2014, Yin, 2010). However, current popular CAD software often has a complex user interface and is still operated with 2D input methods, while the data itself is in 3D (Robertson & Radcliffe, 2009). Instead of traditional CAD programmes, some researchers and designers are using game engines for research and visualization purposes (Indraprastha & Shinozaki, 2009). The possibilities of VR have grown with the introduction of Room Scale VR, which affords an intuitive input method for VR by tracking the HMD and a set of motion controllers[38, 39]. The possibilities of this technology are mainly used for gaming purposes, but a rising amount of professional software is becoming available[40]. An integrated design solution for urban design in VR using Room Scale VR is still missing however, forcing designers to either work with built-in game engine level editors or iterate between designing with complex 3D CAD software and viewing the results in a game engine. Complex CAD software currently distracts from the creative designing process and lead to pitfalls such as circumscribed thinking, premature fixation and bounded ideation (Bernal et al., 2015). Conversion steps between different software can also lead to errors, frustrating the design process (McHenry & Bajcsy, 2008). Lack of accurate, recent, high quality 3D models and data might form another problem, preventing virtual reality from being as a design option (Batty et al., 2001, Nebiker et al., 2010).

If good data is available and the necessary integrated software using Room Scalehas been developed, exciting possibilities could emerge that could redefine the profession of urban design. This means the use of 3D models and data could be introduced at the conceptual phase of the design process, realising the many potential advantages of using 3D data and virtual reality as shown in literature (Jobst & Döllner, 2008, Stauskis, 2014). Virtual reality seems to have reached some form of maturity, since the issues of real-time intuitive interaction and high realism have been accomplished[41]. Future HMD's and tracking systems will offer even more realistic graphics, even more intuitive input and possibly even more possibilities for urban design[42]. It is hard not to be excited about the further cross fertilization between ever cheaper and higher quality consumer focused VR systems and the world of urban design, which in my opinion play a vital role to innovation in design methodology.

7. Discussion

As discussed earlier, Room Scale VR now offers a very intuitive way of interacting with immersive

[38] https://killscreen.com/articles/vr-will-change-way-create/ [Accessed 10 Jan. 2017]
[39] https://www.dezeen.com/2016/05/25/virtual-reality-designing-architects-vrtisan-unreal-engine-htc-vive/ [Accessed 10 Jan. 2017]
[40] http://nicklievendag.com/in-vr-creation-changed-perspective-on-virtual-reality/ [Accessed 10 Jan. 2017]
[41] http://nicklievendag.com/in-vr-creation-changed-perspective-on-virtual-reality/ [Accessed 10 Jan. 2017]
[42] https://www.wareable.com/vr/michael-abrash-what-vr-will-look-like-in-2021 [Accessed 10 Jan. 2017]

virtual environments. Software making use of this technology is available, but research on this subject is barely available. Since this technology offers so much potential for urban design, more research should be done on the use of Room Scale VR in practice and the resultant effects on design outcomes and process. Another possibility of virtual reality that has not yet been researched sufficiently is multi-user VR, in which multiple designers cooperate within the same virtual environment [43]. This could be an interesting field of research for design education.

In this paper, Augmented Reality and Mixed Reality have not been covered, since this would have overly expanded its scope. Augmented Reality is a very promising technology however, possibly offering solutions for viewing and editing a design at location. A merge between VR and AR could be expected at some point[44], when HMD's become able of showing synthetic VR worlds as well as overlaying digital realities over the physical reality (AR). One must keep in mind that at this moment, virtual reality is still mainly an experience focused on one sense: vision. Sound is becoming increasingly important in VR experiences. When other senses like smell, touch and taste are stimulated too, the VR experience will get even more realistic. This is being researched, but at this moment still far from reality.

Another subject that has not been addressed in this paper is the link between software tools and scale. Some tools, such as Google Earth, are very useful on the higher scale levels, while failing at the building/plot level. VR might be difficult on the greater scale levels, such as city- or region scale, since the amount of necessary data would be too immense.

When the lack of CAD software making use of Room Scale VR is finally addressed, a new spur in design innovation is to be expected. Research on resulting new design methods is required, so that urban designers can learn from previous mistakes and possible pitfalls. This gap in research, concerning the use of VR for urban design, will be the main focus of my design project, using a state of the art Room Scale VR system, i.e. the HTC Vive. Many questions will be examined: are current tools useful and/or sufficient for designing in VR? How does one design in VR? What practical limitations does the technology offer, what new possibilities? Can 3D data be effectively used in the conceptual design phase? What specific design elements and challenges are simplified or limited by use of VR? Although my research and design project will not answer all the questions involving this technology, it might lead to more interesting follow-up research subjects.

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[43] https://www.msi.com/blog/no-more-being-alone-multi-user-vr-experience-is-on-the-way [Accessed 22 Dec. 2016]

[44] http://www.zdnet.com/article/ar-and-vr-the-future-of-work-and-play/ [Accessed 10 Jan. 2017]

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