THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Development and Implementations of Virtual Reality for Decision-making in Urban Planning and Building Design

MATTIAS, ROUPÉ

Department of Civil and Environmental Engineering
Division of Construction Management

CHALMERS UNIVERSITY OF TECHNOLOGY

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MATTIAS, ROUPÉ
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Department of Civil and Environmental Engineering
Division of Construction Management
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover:
[The cover shows screenshots from different VR models that has been used by the City Planning Authority in Gothenburg, Sweden]

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ABSTRACT

The use of Virtual Reality (VR) has been seen by many as holding great potential for increasing the effectiveness and improving communication in the decision-making process in urban planning and building design. VR can facilitate processes so that participants can together better understand, identify and analyse problems to improve their decision-making and thereby the future urban environment. However, VR has not had the impact and penetration that was predicted much due to often cited barriers to new technologies in the construction industry, e.g. human and cultural factors, lack of IT skills, lack of knowledge and awareness, and finally the lack of the technology itself including, for example, available tools and methods.

This thesis contributes knowledge that enhances the *usability* and *successful implementation* of VR technology in the *urban planning and building design* process. The approach has been to investigate both the usability and technical aspects of VR. In the context of usability, this thesis deals with whether and how VR can be used in decision-making in the urban planning and building design process. It examines how different stakeholders *experience* and are *affected* by the VR medium in different decision-making situations in the urban planning and building design process. The technical part of this thesis aims to improve the usability and implementation of VR by presenting new tools and methods that suit the existing planning pipeline in the urban planning and building design process. Here it is important to create *cost and time effective* tools and methods for producing virtual worlds.

The results show that VR was *experienced to be useful* by the participants in the investigated parts of the decision-making process. The VR model *imparted a broader understanding* about the *sizes and volumes* of the new buildings and how these *interact with the surrounding urban environment*. The last study showed how the phenomena of reference points and anchoring points could cause *biased judgment effects* in decision-making when the VR medium is used.

This thesis also presents four technical methods that integrate VR efficiently into urban planning and building design by:

1. Enhancing the visual quality of ground material
2. Supporting collaboration and maintenance of 3D city modeling through a sub-version control system.
3. Integrating building proposals with its surrounding ground area into the 3D city model
4. Using the human body as an interactive navigation interface

The methods have been integrated into the MrViz software that has been used at the City Planning Authorities of Göteborg and Kungsbacka.

Keywords: Virtual Reality, 3D city models, Urban planning, Building design, Decision-making, Usability

Preface/Acknowledgements

The work on this thesis has been carried out during 2001 - 2013 at Chalmers University of Technology, Göteborg, Sweden. This project started in 2001 with hands-on experiments at the Visualization Studio, Chalmers Lindholmen. This initial work led to a collaborative research project within the Visualisation Technology research group at Chalmers, Department of Civil and Environmental Engineering.

Thanks are due my colleagues and friends at Chalmers University of Technology for their support, valuable insights, and all the fun times together. Börje Westerdahl and Cleas Wernemyr - it is a pleasure working with you; we have had lots of fun over the years. Special thanks go to Mikael Johansson, my friend and colleague with whom I have had very close collaboration during this project. We have had a number of tough discussions about our research ideas and framework, which have been very valuable and have certainly led to better research implementation and final results. I also wish to thank my main licentiate supervisor; Professor Carl Martin Allwood, Department of Psychology at the University of Göteborg, for all the help during my work on my licentiate thesis (Roupé 2009). Special thanks also goes to my supervisors Mathias Gustafsson and Petra Bosch for helping me navigate the interdisciplinary research approach and for guiding and encouraging me throughout this project. Thanks also to my examiner Professor Christine Räisänen at the Department of Civil and Environmental Engineering, Chalmers for your involvement and the knowledge you have shared with me. Many thanks also to Ilona Heldal who has been my co-author on some of the papers related to this study - it has been a pleasure working with you.

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Mattias Roupé
Göteborg, January 2013

LIST OF PUBLICATIONS

This thesis is based on the work contained in the following papers, referred to by the Roman numerals in the text:

Paper I. "Visual quality of the ground in 3D models: Using color-coded images to blend aerial photos with tiled detail-textures", *ACM Afrigraph 2009, 6th International Conference on Virtual Reality, Computer Graphics, Visualization and Interaction in Africa*, *ACM New York, USA*, 2009. pp. 73-79.
(Co-author: Mikael Johansson)

Paper II. "Supporting 3D city Modeling, Collaboration and Maintenance through an Open-Source Revision Control System", *In Proceedings of CAADRIA 2010 NEW FRONTIERS*, Hong Kong, 2010. pp. 347-356.
(Co-author: Mikael Johansson)

Paper III. "3D city Modeling: A Semi-automatic Framework for Integrating Different Terrain Models", *Advances in Visual Computing, Lecture Notes in Computer Science 2011,* Volume 6939/2011, *Springer Berlin. 2011.* pp. 725-734.
(Co-author: Mikael Johansson)

Paper IV. "Interactive navigation interface for Virtual Reality using the human body", 2013, Submitted to *Computers, Environment and Urban Systems, Elsevier.*
(Co-author: Petra Bosch-Sijtsema, Mikael Johansson)

Paper V. "Biased judgment and decision-making when using Virtual Reality in urban planning", 2013*,* Submitted to *Environment and Planning B: Planning and Design, Pion Ltd.*
(Co-author: Mathias Gustafsson)

Distribution of work:

Paper I: ***Visual quality of the ground in 3D models: Using color-coded images to blend aerial photos with tiled detail-textures.***
Mattias and Mikael wrote the paper together. Mattias presented the work at the Afrigraph 2009 conference. The study was conducted in collaboration; ideas were analysed and discussed until the final implementation of the framework was adopted. Mattias was responsible for the final implementation of the framework and for writing most of the paper.

Paper II: ***Supporting 3D city Modelling, Collaboration and Maintenance through an Open-Source Revision Control System.***
Mattias and Mikael wrote the paper together. Mattias presented the work at the CAADRIA 2010 conference. The study was conducted in collaboration; ideas were analysed and discussed until the final implementation of the framework was adopted. Mattias was responsible for the final implementation of the framework and for writing most of the paper.

Paper III: ***3D-CityModeling: A Semi-automatic Framework for Integrating Different Terrain Models.***
Mattias and Mikael wrote the paper together. Mattias presented the work at the ISVC 2011 conference. The study was conducted in collaboration; ideas were analysed and discussed until the final implementation of the framework was adopted. Mattias was responsible for the final implementation of the framework and for writing most of the paper.

Paper VI: ***Interactive navigation interface for Virtual Reality using the human body.***
The study was conducted in collaboration; ideas were analysed and discussed between the authors, which yielded the final implementation of the framework and result. Mattias did the final implementation of the framework and analysed the result using SPSS, which led to the final result. Mattias wrote most of the paper.
Paper submitted to journal: *Computers, Environment and Urban Systems, Elsevier.*

Paper V: ***Biased judgement and decision-making when using Virtual Reality in urban planning.***
Mattias wrote most of the paper under the supervision of Mathias. Mattias conducted the experiments and analysed the result using SPSS. The study was conducted in collaboration; ideas were analysed and discussed, leading to the final result. Paper submitted to journal: *Environment and Planning B: Planning and Design, Pion Ltd.*

Additional Papers presented in the licentiate thesis (Roupé 2009)

Journal papers

Users' evaluation of a virtual reality architectural model compared with the experience of the completed building.
Börje Westerdahl, Kaj Suneson, Claes Wernemyr, Mattias Roupe´, Mikael Johansson, Carl Martin Allwood. *Automation in Construction Volume 15, Issue 2,* pp. 150-165, 2006.

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From CAD to VR – Implementations for Urban Planning and Building Design.
Mikael Johansson and Mattias Roupé, *eCAADe 2005 Conference*, Technical University of Lisbon, Portugal, 2005.

Efficient Real-Time Rendering of Building Information Models.
Mikael Johansson, *Mattias Roupé*, Proceedings of the 2009 *International Conference on Computer Graphics and Virtual Reality* (CGVR09), pp. 97-103.

Additional publications by the author

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Virtual Reality Supporting Environmental Planning Processes: A Case Study of the City Library in Gothenburg.
Kaj Sunesson, Carl Martin Allwood, Dan Paulin, Ilona Heldal, *Mattias Roupé*, Mikael Johansson. *Knowledge-Based Intelligent Information and Engineering Systems,* Lecture Notes in Computer Science, Springer *Berlin*, 2008, Volume 5179/2008, pp. 481-490.

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Building Information Modelling for Visualisation in AEC Education.
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Mattias Roupé and Mikael Johansson, *Conference on applied virtual reality in engineering and construction III*, 27 - 28 May 2004 Chalmers, Göteborg, Sweden.

Users´ experience of a virtual reality architectural model compared with users´ experience of the completed building.
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Mattias Roupé, Claes Wernemyr, Börje Westerdahl, Kaj Suneson, and Carl Martin Allwood, *Conference on applied virtual reality in engineering and construction*, 4 – 5 October 2001 Chalmers, Göteborg, Sweden.

Technical reports and popular-scientific articles

During my research, my work was published in a number of technical reports and popular-scientific articles:

How can GIS and BIM be integrated? Mikael Johansson, Mattias Roupé, CAADRIA 2010 Conference NEW FRONTIERS.

Development and Implementations of Virtual Reality for Urban Planning and Building Design. Mattias Roupé, Chalmers University of Technology, Göteborg, 2009.

Interaktiv Visualisering för Byggbranschen.
Mikael Johansson, Mattias Roupé, Börje Westerdahl. *FoU Väst Rapport*, 2009.

Interaktiv Visualisering för Byggbranschen.
Mikael Johansson, Mattias Roupé, Cleas Wernemyr. *Boverket Rapport*, 2008.

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Börje Westerdahl, Mattias Roupè, Mikael Johansson, *FoU Väst Rapport 2004.* ISSN 1402-7410.

Is Virtual Reality the Next Generation of GIS?
Mattias Roupé and Per-Åke Roupé, *GEO World – February 2002*, USA.

Table of Contents

1 Introduction

Virtual Reality (VR) is becoming common in urban planning and building design. Virtual Reality refers to the ability to interactively manipulate and move around in a computer-generated environment, (for more details see section 2.1). The main driver for the use of VR is that it is a good communication medium that makes it possible for all interested parties to gain access to a common representation and a better understanding of the planned building object. The overall goal of this thesis is to *investigate* and contribute to *improvements, usability and implementation* of VR technology in the urban planning and building design process. The thesis has a multi-disciplinary approach to both the technological aspects and the human usability aspects of VR. Regarding the technological aspects, this thesis aims to improve the usability and implementation of VR by presenting new tools and methods that fit the existing planning processes in the urban planning and building design process. Regarding the human usability aspects, the thesis examines whether and how VR can be used in decision-making in the urban planning and building design process.

In the following sub-section, the background and motivation for this thesis are explained together with the research aims and objectives. In the subsequent section some important theories, concepts and phenomena of the thesis are presented, e.g., the definition of VR. This is followed by a discussion about decision-making in urban planning as well as a summary of the papers that make up the empirical part of the thesis. The thesis concludes with a general discussion and conclusions.

1.1 Background

Visualization through images has been used since the dawn of mankind. Some examples from history include cave paintings, Egyptian hieroglyphs, Leonardo da Vinci's revolutionary methods of technical drawing for engineering and scientific purposes, and Minard's map (1861) of Napoleon's invasion of Russia. The common purpose has been to communicate both abstract and concrete ideas using visual imagery.

The use of computers for visualization was initially (pre-1990s) constrained by limitations in computer power. In the 1960s flight simulations and computer graphic research started to explore the possibilities of creating VR. Ivan Sutherland (1965) was one of the first researchers to describe VR in his paper “The Ultimate Display”. In 1968, Sutherland created what is widely considered to be the first VR head-mounted display (HMD) system. It was primitive both in terms of user interface and realism. The HMD was worn by the user and was so heavy that it had to be suspended from the ceiling. The graphics comprising the virtual environment were simple wire-frame model rooms.

In the beginning of the 90s, computers for visualization started to be used to create rendered images and film effects. Today the enormous advances in computer science and technology have given us the possibility to use VR in more enhanced and possibly more effective ways.

One way of using VR is to visualize and communicate different types of ideas and information. The purpose of such an application is often to present a more concrete image of something that to varying degrees is abstract or unknown. It is well known that words in a book can be experienced and interpreted differently by readers of different backgrounds and in different contexts. The reader creates his own image of what is narrated. A good example of this is the seemingly simple concept of the square meter. Twelve square meters can easily be expressed mathematically, but how much is twelve square meters actually? Different people with different *backgrounds* will relate or refer to notions in different ways. The same phenomenon also occurs when it comes to *cognitive processes* such as information processing and the spatial perception of visual images that are abstract, as are drawings and maps[1]. According to Kjems (2003), the lower the level of abstraction the easier it is to understand and communicate using the same frame of reference. The above-discussed assumptions are based on an information processing perspective (Atkinson & Shiffrin, 1968; Galbraith, 1974; Lindsay & Norman, 1977), which addresses the limitations of cognitive processes. In this context, VR can help people process the network of information exchanges in urban planning and building design. Urban planning and building design is a technical and political process involving different stakeholders and actors that try to exert control over the use of land and the design of the urban environment. In this context, urban planning and building design concerns development of buildings in existing or future urban environments of varying sizes. These types of design problems are often moving targets that do not have solutions but only have resolutions during the design process, and the context in which these problems exist is characterized by change, conflict, and multiple stakeholders (Arias et al., 1995; Heldal & Roupé, 2012). The most common stakeholders in urban planning are the city planners working for the authorities, the architects/planners working for clients, the clients themselves and finally the general public (Hall and Tewdwr-Jones, 2010). The architect/planner is often the *sender/source* of the information while the authorities, politicians, public/laypeople and other architects are the *receivers/viewers*. Drawings and maps are the most commonly used media for communication in the building and urban planning process, and are often

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[1] ***See section 2.4*** *for more details about cognition and spatial-perception of visual information.*

[2] ***See section 2.2, 2.3 and 2.5*** *for more details about communication and usability of VR in urban*

interpreted and experienced differently by different stakeholders. The different stakeholders, both senders and receivers of the information, often have different *goals* depending on their function (role) in the process, and this can give rise to different representations and interpretations of the information, which in turn may result in inadequate communication and decision-making in the urban planning process. Decision-making in urban planning and building design is a very complex, socially structured process, that involves the decisions of both individuals and groups that are influenced by social, economical, historical, environmental, physical and spatial factors (Maarttola & Saariluoma, 2002). Furthermore, these individuals and groups, which are defined as stakeholders, have their own agendas, interests, expectations and foci (Ambrose, 1994; Faludi, 1996; Friedman, 1996; Hoch, 1996). According to Hall and Tewdwr-Jones (2010) the communication difficulties that routinely exist between planning authorities and designers lead to uncertainties and a lack of consistency in the design process[2]. This may be the main reason why VR is increasingly used in urban planning and building design (Kjems, 2005; Horne et al., 2007; Greenwood et al., 2008). VR has the potential to be an effective communication tool that will allow different stakeholders in the planning process to better understand the project and, hopefully, each other. It could provide the stakeholders with opportunities to identify and analyse problems and to jointly coordinate the project with the aim of improving their decision-making and thereby the urban environment. One of the reasons VR models facilitate decision-making is that it provides stakeholders with the same frame of reference with respect to the new building and the future environment. Furthermore, if the VR model of a building is inserted into a VR model of the city, it can be spatially experienced and analysed in the existing surroundings.

Usability studies of VR applications (e.g., Kjems, 2005; Kodmany, 2002; Patel et al., 2002; Roussou et al., 2005; Westerdahl et al., 2006; Sunesson et al., 2008; Roupé, 2009) have shown that VR helps stakeholders with different backgrounds and knowledge to coordinate their perception and understanding of the project. One conclusion has been that VR fosters a more dynamic decision-making process (Kjems 2005). Moreover, Kjems argues that visualization increases the stakeholders' confidence in that poor decisions will be avoided. However, the virtual space could mislead if the stakeholders involved in the design of the VR model have hidden agendas and an interest in certain outcomes of the decision-making process. The displaying of the VR models and its content could be one way of changing the characteristics and settings for access to the virtual space, and this would have consequences for decision-making on future physical space in the real world. For this reason, it is important to have knowledge of how different characteristics and settings in and around the VR medium influence the experience of the shared visual space that

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[2] ***See section 2.2, 2.3 and 2.5*** *for more details about communication and usability of VR in urban planning and building design.*

the VR medium strives to provide. In this case the decision-making process, perceptions of space, and the cognitive processes of decoding information in the visual space are important. But there are also technical hurdles connected to the VR medium, that have prevented the use of VR in the urban planning and building design process from achieving the importance predicted in literature (Langendorf, 1992; Bengtsson et al., 1997; Orford et al., 1999). Döllner (2008) and Lubanski (2007) discussed this issue and argued that the costly and time consuming hands-on modeling as well as the complicated interactive navigation interface in VR software are major reasons why VR has not been used more in the planning process. The development of effective 3D visualization tools - such as VR - that assist planners and decision makers is important in the strive to improve the quality of building design and sustainable urban planning, as well as for ensuring effective communication with the general public.

1.2 Aims and objectives

The overall aim of this thesis is to investigate and contribute knowledge that improves the *usability* and *successful implementation* of VR technology in the urban planning and building design process.

The research presented in this thesis also aims to *provide tools* and *methods* that can *enhance the use of VR* in the urban planning and building design process. This will facilitate the integration of VR as a tool into the planning working processes and so enable decision makers to obtain better material and information to base their decisions on. It is important to create efficient tools and methods for producing virtual environments. However, it is also important to investigate how different stakeholders *experience* VR in different decision-making contexts in the urban planning and building design process. In addition, it is important to determine how the VR medium can beget bias in communications and judgments. In the urban planning and building design process the architect or planner is frequently the *sender/source* of the information while the authorities, politicians, public/laypeople and other architects are the *receivers/viewers*. The sender in this case often generates a large amount of information that needs to be decoded so that it can be understood by the receiver. The main challenges for the sender are:

- to eliminate ambiguities in the communication process
- to maintain the accuracy of the communicated information
- to understand the receivers' decoding and perception of the message

Figure 1 (page 7.) is a simplified representation of how different hurdles occur in the communication and decision-making process, due to different attributes and contexts surrounding the VR medium. There are both human and technically related issues that produce these hurdles.

The theoretical conceptual framework is based on information processing theory (Atkinson & Shiffrin, 1968; Galbraith, 1974; Lindsay & Norman, 1977) and communication theory (Berlo, 1960; Shannon & Weaver, 1949). First, the human related issues that stakeholders in the process encode/decode and interpret information differently depending on the sender/receiver *background* and *goal*[3]. This aspect is connected to *information processing* and *cognitive processes*[4] *(e.g.,* Galbraith, 1974; Fulk et al., 1987). These aspects will be reviewed in more depth in section 2.3-2.5. Second, there are also *technical aspects* that change the attributes and processes connected to information processing, such as how the VR model is created or displayed. These technical hurdles can change how the VR model is presented to the receiver, which could bias reasoning and judgments[5]. It is therefore important to create tools and methods that are efficient for producing VR models or these will not be suitable for the urban planning process[5]. This issue is also related to how detailed or abstract a VR model should be and how is it going to be used. Furthermore, if the end-user cannot handle the *interactive navigation* in VR this could also act as a big hurdle for the usability and hinder the user's information processing capability[6]. Therefore, it is important to find suitable interaction interfaces. Figure 1 provides an overview of factors that come into play, and a number of these issues are investigated in this thesis and described in detail in section 2. In this thesis the focus is on the integration of VR as a communication and decision-making tool in the urban planning process.

In order to achieve the goal of *providing tools and methods* that can *improve the use of VR* in the urban planning and building design process, the following questions are explored and considered:

1. How can VR be integrated in an efficient way into urban planning and building design?
  - *1.1 How can 3D city modeling support visualization of urban planning and building design?*
  - *1.2 How can we develop a user-friendlier navigation interface that supports a more natural viewer experience?*

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[3] ***See section 2.2 and 2.3*** *for more details about communication and usability of VR in urban planning and building design.*

[4] ***See section 2.4*** *for more details about cognition and spatial-perception of visual information.*

[5] ***See section 2.1*** *for more details about the surrounding attributes around the VR model.*

[6] ***See section 2.2.1*** *for more details about interactive navigation in VR*

Furthermore, in order to contribute *knowledge* that helps improve the *usability and experience of VR in decision-making in urban planning and building design,* the following research question is considered:

2. **How can the VR medium support viewers experience and decision-making in urban planning and building design?**

To assist the reader, these questions are also used as headlines and sub-section headlines in the discussion and conclusion parts of this thesis.

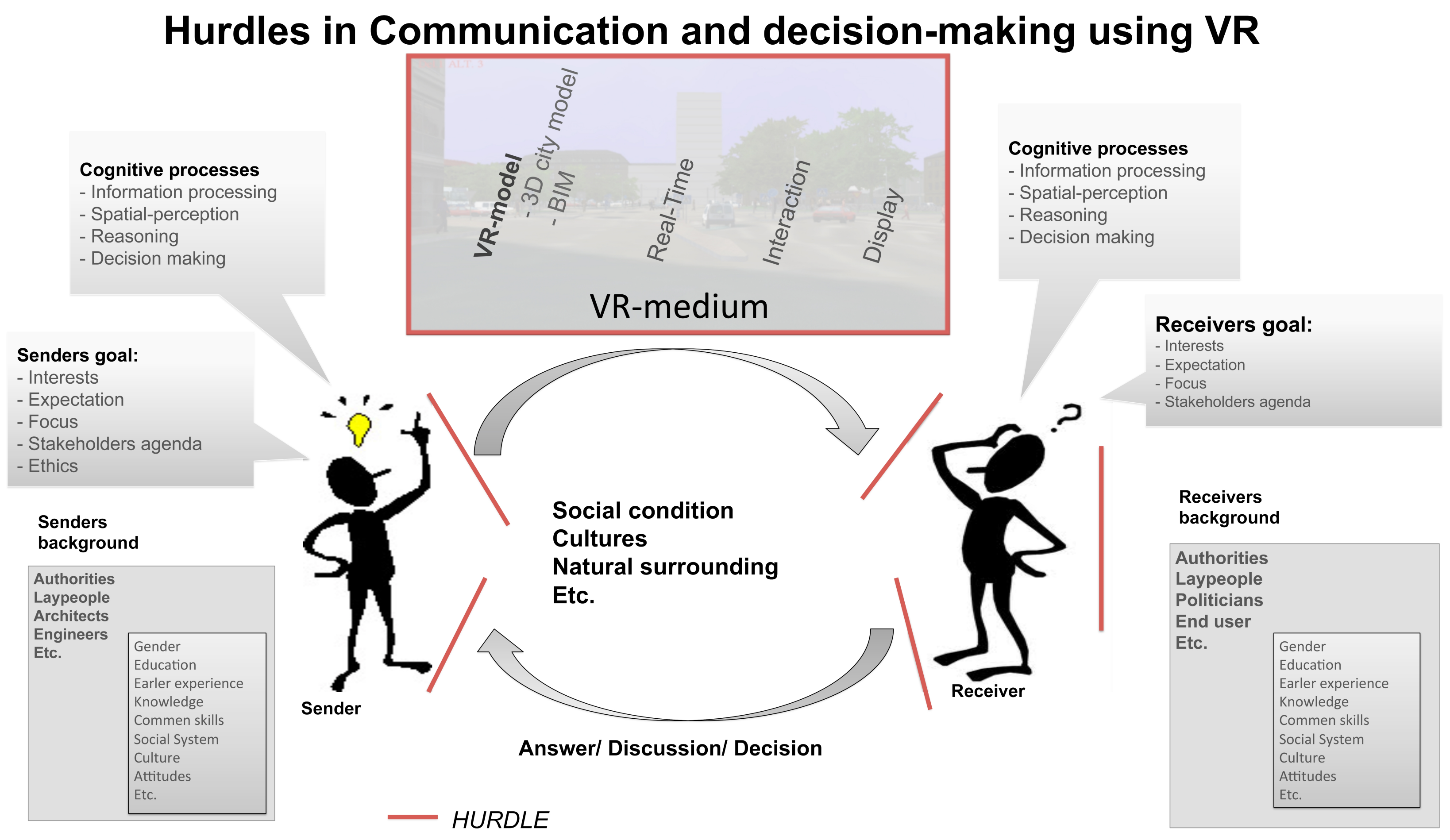

Figure 1. The figure shows the different hurdles that are present when using VR as a communication and decision-making medium. These hurdles influence the communication and decision-making process and thus the outcome.

2 Important concepts in the thesis

This section introduces the main theoretical framework on which this research is based. The section starts with a short background of visualization and a discussion and definitions of a number of terms used throughout this thesis. These terms are *Virtual Reality and Virtual Environment*, *VR models*, *Virtual Building* and *Virtual 3D city model*. This will be followed by theory discussing Virtual Reality as a medium used in communication and decision-making processes in urban planning and building design.

2.1 Virtual Reality and Virtual Environment

Virtual Reality (VR) seems to have no definitive definition, but is a commonly used term and buzzword. The term Virtual Reality in this thesis refers to the ability to interactively manipulate and move around in a world represented by a digital three-dimensional geometric model. Unlike animation or film, the user can interactively move around in this virtual world. VR models should be distinguished from other 3D CAD and digital models because 3D models do not have the same possibilities of presence and interaction. Presence in this case is defined as a sense or a feeling of actually being in the virtual world (Schuemie et al., 2001).

The term Virtual Reality (VR) is often used to describe a wide variety of applications, commonly associated with immersive display systems and environments (Craig, 2009). Immersive VR means that the user is completely surrounded by the virtual world as when Head Mounted Displays (HMD) are used and in CAVE systems (see Roupé, 2009). The most common VR system in use today is desktop VR. In a desktop VR system, the virtual world is displayed on a computer screen or a large cinema screen (shown in Figure 2). In the studies in this thesis I have focused on the type of VR that is commonly called desktop VR. In the studied situations - urban and building planning processes - people communicate about different problems and proposals, and therefore immersive VR using HMDs or a CAVE has its limitations as only a certain number of people can be present during the VR presentation. It is therefore easier to use mobile equipment, for example a laptop and a projector for meetings at new locations and with different stakeholders. The disadvantage of using desktop VR is the lessened experience of presence or feeling of being in the virtual world compared with immersive VR systems (Draper et al., 1998; Sadowski & Stanney, 2002). At the early stages of this research, a large cinema screen was used to display the VR model in stereo (shown in Figure 2).

Figure 2. An example of a Desktop VR system with a large cinema screen. *(Chalmers)*

Virtual Environment is another term with no commonly agreed upon definition, and in order to minimize confusion I have in this thesis chosen to use the term *VR model* (see below) instead of Virtual Environment. Another reason is that I focus on the computer-generated 3D world and digital spatial environments (see Figure 3), and not on displaying of the 3D world.

Figure 3. Illustration of VR models used in urban planning and building design.

A *VR model* is basically a collection of many individual 3D objects containing 3D geometrical forms such as triangles or quadrilaterals (quadrangle). The VR model is often built in special 3D-modelling software designed for creating 3D environments, i.e., 3D Studio MAX, Alias Maya and MultiGen Creator. The software is used widely within the gaming industry to build terrain models for flight simulators. An important feature of VR models is that the frame rate or update rate for such models should preferably be more than 30 frames per second (fps). This as a lower frame rate, such as 16 fps, does not offer the same possibilities of presence and interaction and also increases the risk of motion sickness (also called cyber sickness).

In the urban planning and building design process, the virtual world is built by creating two basic components: the planned new building and the surrounding environment. The surrounding environment (e.g. 3D city model) is important for the experience of how the new building interacts with the surrounding environment as well as the spatial relations between them. 3D models of cities are becoming more and more common (Horne et al., 2007). 3D city models are used in urban planning, building design and virtual tourism, among others. The difficulties lie in the creation and the actual maintenance and management of the city model. Cities are never fully completed products; there is constant development in new and rebuilt urban areas. The creation of 3D city models is usually a very costly and time-consuming process (Jobst & Döllner, 2008; Lubanski, 2007). As mentioned above, in the 90´s the city models were often modelled in special 3D-modelling software. Today, a common solution is to use Geographic Information System (GIS) data and digital maps to create a terrain model covered by aerial photos. Information about existing buildings is often available and buildings can be modelled as volumes with façade textures applied. But currently the use of 3D scanning from helicopters, known as LiDAR, together with photogeometry and existing GIS databases are being used more and more (Döllner, 2009; Leberl et al., 2012; Li & Chapman, 2008; Wang et al., 2008). In our case, we used the base map of the City Planning Authority of Göteborg together with associated aerial photographs to semi-automatically create the 3D city model of Göteborg (Roupé & Johansson, 2004; Johansson & Roupé, 2005), see Figure 4.

Figure 4. A part of the city model of Göteborg.

In this chapter three components that are important for urban planning and building design are described: *The Virtual Building, Virtual Terrain* and *Virtual 3D city models*.

2.1.1 The Virtual Building

The construction industry is in the early stages of a historic shift in the way that the design of buildings process is conducted. The industry is moving from drawing based design to model based design. This means, as noted above, that the 2D layouts, blueprints and text-based descriptions will be integrated into a 3D information model of the building, a Building Information Modelling (BIM). Compared to a general 3D-CAD model, BIM is a different type of representation since it defines not only geometrical data but also information regarding spatial relations and semantics. The BIM model contains information about the different parts and components of the building. For example, a wall has information about its shape, material, cost and structure, among others. From being firmly set in the analog world of drawings and written descriptions, the construction industry has moved into the digital age where digital models can now represent an object from sketch to the facility management stage.

In studies, BIM information has been used to optimize performance of real-time rendering for buildings (Johansson & Roupé, 2009; Johansson & Roupé, 2012). Using the techniques available today, it is not possible to visualize a complex building from a BIM model in real-time. The amount of geometric data in complex BIM model is too much for the computer to process in real-time (30 frames per second). However, in the BIM database there is information about what walls, windows and doors are connected to a room. This means that we can select only those walls, roofs, floors, windows and doors we would actually see in the view to be rendered, so this type of sorting can be used to save computing power. In earlier studies we found that without any manual interaction or expensive pre-processing of the input data, we could often increase the rendering speed more than tenfold in our test scenes compared with the view-frustum culling that is commonly used (Johansson & Roupé, 2009; Johansson & Roupé, 2012). This result supports a better integration of BIM models into the urban planning and building design process. Additionally, in the study presented in Sunesson et al. (2008) (also in Roupé 2009), due to the problems with rendering speed we chose not to include the environment of the building.

2.1.2 The Virtual Terrain

There is conversely no ultimate solution on how to create, edit and render the virtual terrain. The specific purpose of application determines what technical solutions are implemented. There are two major methodologies for representing terrain, using image-based models or geometry based models.

The image-based approach, using height-maps (the term used here), Digital Elevation Maps (DEM) or height fields, is the most common method for the approximation of terrain meshes. Height-maps are raster images that are used to represent 3D data as a regular grid of the terrain surface. The pixels in the height-map represent the displacement of the corresponding mesh coordinate. The height-map only stores the vertical displacement, i.e. the z-coordinate giving the height of the terrain. The x- and y-coordinates of the mesh correspond to longitude and latitude on the image's regular grid of pixels. The main drawback of height-map is its fixed size property which over-represents flat areas and under-represents varied terrains. This mainly because grids cannot adapt to variations of terrain due to their uniform nature. Consequently, this will devote the same amount of data points for a flat land surface as for a mountain. It cannot represent terrain meshes for features such as caves and overhangs, and has difficulties with areas with significant elevation changes such as cliffs with sharp edges. When using height-maps in 3D city models the demands of sharp edges have to be considered or errors will arise when terrain and buildings interact with each other. This problem increases the demand on high-resolution of the height-maps, which consequently gives rise to performance and data size issues. The advantage of the height-map technique is that grid data algorithms are relatively easy to develop since grids have fixed resolutions and can therefore easily be stored in an index table data structure. It is also possible to create interactive editing tools for this type of terrain (Atlan & Garland, 2006; Schneider et al. 2006; de Carpentier & Bidarra, 2009). An advantage with height-map terrain is that it is continuous and modifications to terrain does not give rise to gaps. However, when different height-maps are used in a patch-based system gaps may occur between the different terrain patches.

The geometry-based approach to representing terrain surface is the triangle model also called Triangulated Irregular Networks (TIN). TIN is a triangle mesh based on non-uniform spaced vertices. The advantage with TIN is that regions with little surface height variation can be generated with more widely spaced points whereas in areas of more intense height variation point density can be increased. The TIN represented terrain yield the best approximation of a surface within a predefined triangle budget. TIN can also represent sharp edges and boundaries in the terrain better, and is more flexible in this matter compared to the height-map. However, it is considerably more complicated to implement queries and algorithms on a TIN mesh.

Working with TIN often places high demands on the end-user and it is a very time consuming process to edit such a surface, this because it is based on vertices and triangles that are not continuous in the same manner as the height-map approach is.

2.1.3 Development and management of Virtual 3D city models

As pointed out before, the difficulty in the production process of the 3D city model is the amount of data produced. One of the problems with large 3D city models is that they contain huge amounts of data that has to be stored and processed when it is used. The data is often aerial photos, façade photos, geometry of the terrain and buildings. Data storage and management as well as the maintenance of the models are therefore very important issues (Dokonal et al., 2001). The collaboration and management problem often arises when many people are trying to collaborate and work on the same 3D city model concurrently, and the users may even be at different physical locations around the world. One common solution to this type of collaboration problem is to use external reference and split the model into different parts or files that will later have to be joined together. The external references or files have to be shared between the different users by using email or ftp. This process could be problematic and cause administrative problems such as where is the model stored, what is the latest version, who changed or created that part of the city, have you sent me the latest model? This type of process is very sensitive when people are absent or not able to answer the requests from the others users. The result for many users is unnecessary delays and time wasted. These problems also tend to worsen during the deadline rush of a project as more people are assigned to and work in the project. In software development projects these type of issues are often solved by using a version-control system such as SVN (Collins-Sussman et al., 2007). The absence of an explicit standard makes it difficult to share models created by different actors. The CityGML file format has attempted to be generally accepted as a 3D city model standard for storage, but it is not supported by many software. However, CityGML can be connected to an Oracle database, which makes it possible to have a version-controlled system for management of the 3D city model (Kolbe et al., 2009; Stadler et al., 2009). However, this type of system puts high demands, such as high cost and high level of expertise on the end-user. Drawbacks with CityGML are that it is text based and fairly complex to implement, and as it uses XML schema files grow to be very large (Curtis 2008; Stadler et al., 2009). The processing of data from a 3D city model in a Oracle database is very time consuming and it is therefore not the best solution for when work towards a deadline or even for daily work, especially when many there are many concurrent users.

The use of the 3D city model together with VR is meant to facilitate communication and collaboration in the decision-making process in urban planning. It is therefore important to understand how the VR medium can be used, and how it can give people a better understanding of the design. The next sections will discuss the usability of VR in urban planning and building design.

2.2 Usability of VR in urban planning and building design

The main reason for using VR in urban planning and building design is to provide users the same visual access to space and to give them the possibility for spatial reasoning about the architectural design. This could be achieved if people did not have to use all their cognitive resources in decoding the visual information from the presentation.

In VR models motion presents the viewer with the necessary depth cues needed for a comprehensive perception of depth and consequently for the ability to perceive the virtual urban environment. In contrast, perspective static images only communicate "part of the picture", and objects might be blocked or the particular perspective might distort the size and position of certain objects. Therefore, a sense of space requires the representation of at least two or more perspectives, or the ability to navigate interactively through the model (Buziek, 2000; Lange, 2005). Tress & Tress (2003) used static photomontages during stakeholder workshops on landscape change scenarios in Denmark. One of the conclusions reached was that users favoured the perspective of a moving observer for landscape perception. However, VR has not gained the penetration in urban planning and building design that had been predicted. Sarjakoski (1998) argued that the usefulness of using VR in the urban planning and building design process suffers from a number of institutional issues such as limited willingness on part of the traditional players to open up and allow others to participate through information sharing. For example, there are at least four professional groups and/or stakeholders involved in the city planning process (Hall and Tewdwr-Jones 2010):

- City planners working for the authorities
- Architects/planners working for clients
- The clients themselves
- The general public

Collaboration between different stakeholders when using computer systems is often referred to as *Computer-Supported Cooperative work* (CSCW). CSCW enables collaboration between different stakeholders with different levels of knowledge and with disparate agendas (Fischer, 2000; Arias et al., 2000). This type of collaboration aims at bringing about a shared understanding of the problem among the stakeholders, and can lead to new insights, ideas and knowledge building (Fischer, 2000; Arias et al., 2000). Furthermore, CSCW has been shown to help groups make decisions and to reach consensus. In this context Virtual Reality can be used as a common frame of reference and enhance communication and the understanding of the problem. Al Kodmany (2002) analysed different kinds of visualization tools and methods in community planning and found that each context required the right visualization tool, and that VR and other high-tech methods provide opportunities for analysing data and understanding different problems that are not provided by traditional methods. It is usually the cost and accessibility as well as the audience's level of experience that provide the cues for identifying the correct visualization tool.

Other authors have mentioned various possible reasons for the limited use of VR in the urban planning and building design process. Lubanski (2007) claims that the *time-consuming model generation* and *complicated interaction handling* is the reason why VR models are not used more in the urban planning process. Greenwood et al. (2008) mentioned human and cultural issues in organizations as being the main barriers for implementing new technologies. The main driver for implementing new technologies in the building industries is competition and a need to follow the latest innovations. Dawood and Sikka (2007) argued that the lack of IT-skilled individuals and a lack of awareness in organizations as being the main barriers for implementing new technologies. Based on this research I argue that, mainly due to limited IT skills, the costs related to the VR model, cultural issues and uncertainties about the outcome of the use of the medium, it is difficult for a city planner to make the decision to use VR in urban planning. Prior research shows that we humans are limited in our minds and we have difficulties in realizing that *what we do not know, we do not know*. As mentioned above, Sarjakoski (1998) argued that the cultural issues concerning limited willingness for information sharing is a problem for the usability of VR. I argue that this is due to different groups in the urban planning and building design having their own agendas, interests, expectations and focus (Ambrose, 1994; Faludi, 1996; Friedman, 1996; Hoch, 1996).

Bodum & Kjems (2003) discussed this very issue in a real life context and described how politicians and entrepreneurs were very positive about the possibilities of VR but that the architects would only reluctantly accept it. The researchers believe that this may have been because the architects were not willing to present too many of their ideas in public. Furthermore, in a texture representation study Stahre et al. (2008) found that engineers and architects wanted different texture styles depending on whether they were making a presentation to others or using it for themselves. They wanted more photorealism when using it themselves and a higher degree of abstraction when presenting to others. In addition, if the VR model looked too realistic, it would be very difficult to retract or change the design at a later date. This issue was also discussed by Roussou et al. (2005), who reported that realism in the VR model was found to be good for sensing the scale and perception of the virtual world. However, the politicians and the architects were afraid that some stakeholders might commit too early to a too realistic model. This was mainly due to fears that the public would understand the proposal and that this would remove all modification freedom from the project. But at the same time, the architects used the model during brainstorming sessions to understand and play with spaces, a possibility that had not previously been possible in other media. In the above discussions it is notable that different stakeholders interest, focus, expectation comes into the context of the VR medium.

In a usability-oriented study involving VR applications and architectural competition conducted by Kjems (2005) it was found that the VR presentation was very useful for enabling different jury members with different backgrounds and knowledge to reach the same level of understanding and perception of the project. Furthermore, lay people were not pressured into looking at and understanding drawings and sketches and could instead participate in a more equal and open debate with the experts. Another finding of this study was that VR inspired a more dynamic decision-making process (Kjems 2005). Moreover, visualization can provide stakeholders with a greater certainty of not making poor decisions.

However, an assumption is that a VR model could be misleading if the stakeholders involved in the design of the VR model have hidden agendas and thus an interest in influencing the outcome of the decision-making process. Displaying the VR models and the content could be one way of changing the settings for visual access to the virtual space and therefore the outcome for communication and decision. These issues will be addressed in sections 2.3-2.5 and are important to keep in the mind when using the VR medium as a communication and decision-making tool in urban planning and building design. However, interaction and navigation with the VR model is an important issue when it comes to usability of VR. This issue will be addressed in the next section.

2.2.1 Interaction and navigation with virtual environments

Interaction and navigation in a VR is a problematic issue. It is also very important. Lubanski (2007) mentioned that complicated navigation in VR is one of the main reasons why desktop VR has not gained the penetration that was predicted. This is to some extent confirmed in our study (Sunesson et al., 2008), who states that people within the urban planning processes are very positive about using the VR medium during meetings when an IT facilitator and navigator is there to help, but due to complicated interaction handling do not have any interest in navigating themselves. It is necessary to consider the limited visual working memory of the human mind[7] and

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[7] ***Working memory*** *has been defined as the system which has the capacity to both hold and manipulate visual stimuli/information in the mind such as reasoning and comprehension, and to make it available for further information processing (Becker & Morris 1999).*

not to overload it through navigation tasks. It is important that the navigation interface does not demand too much thought. In the words of Ware and Plumlee (2005), “If the navigation itself takes a long time and consumes significant perceptual and cognitive resources, this will leave fewer resources for decision-making.” Additionally, Conniff et al. (2010) compared active navigation and passive observation in an urban design study and found that the two groups of participants observed different characteristics of the VR model. The observers of walkthroughs tend to be more observant of architectural detail, whilst self-navigators of virtual models tend to notice holistic features such as bigger structural and layout alterations. Speculatively, this could be because the self-navigating participants were not gamers and had not used the keyboard/mouse navigation interface previously and this created more stress and demanded attention that consumed significant perceptual and cognitive resources while exploring the environment. Conniff et al. (2010) argued that passive observation may be better when the purpose of the evaluation is to compare design alternatives in architectural competitions, e.g., the exteriors of public buildings or park/garden layouts. Self-navigation may be best used when judging alternative street layouts/urban connections, and for the interiors of buildings since it presents people with a better feeling for what it would like to be there. However, the researchers did not consider that the navigation interface could have been too demanding for the new users who had not used the keyboard/mouse navigation interface previously. Furthermore, studies have shown that active navigation results in better spatial-perception, spatial-memory and spatial-knowledge as well as higher realism and presence (Brooks et al., 1999; Christou & Bulthoff, 1999; Koh et. al., 1999; Larsson et al., 2001, Peruch & Gaunet, 1998; Wilson & Wildbur, 2004), and if the human body is used for navigating (e.g. physically rotating and moving) it further enhances spatial-perception (Ruddle & Lessels, 2009; Riecke et al., 2010).

As with computer games, navigation and interaction with VR are often performed using keyboard and mouse. Although this type of interactive handling works well for IT-skilled individuals and gamers, it can be a hurdle for interaction for many of the end-users within the urban planning process (Lubanski, 2007; Steinicke et al., 2006). Furthermore, no formal experiment has confirmed this type of first-person-shooter game interaction to be the user-friendly interface (Lapointe et al., 2011). The most common interaction interfaces for desktop VR are mouse, keyboard, joystick and spaceball/3D Mouse8. The implementations of these interaction interfaces diverge a lot depending on the task the user performs, as well as on how the different applications have implemented the interaction interface. There is no ultimate solution to how this implementation should be done. The implementations differ depending on how many degrees-of-freedom have been implemented in the navigation interfaces.

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[8] *Spaceball /3D Mouse is an special computer mouse which supports push, pull, twist and tilt of the mouse for manipulating the view in VR/3D-CAD applications.*

The degrees-of-freedom describe how many movements of the camera are possible. Three of the six degrees-of-freedom involve transformation: forward/back, left/right and up/down. First-person shooter games generally provide five degrees-of-freedom: forwards/backwards, slide left/right, up/down (crouch/lie), yaw (turn left/right), and pitch (look up/down). In virtual walkthroughs the up and down manipulation of the camera is often not supported, which only gives the viewer the opportunity to view the model from a pedestrian point of view from the ground or from a flat plan. In these type of virtual walkthroughs, the number of degrees-of-freedom of movement varies between 2 and 4. It is important to realize that the more degrees-of-freedom that the user-interface has, the more demanding it becomes for inexperienced users to learn to navigate. However, if important degrees-of-freedom are excluded from the navigation the viewer may be restricted in executing a task, such as fully exploring the VR model. Lapointe et al. (2011) investigated four different input devices, mouse, keyboard, joystick and spaceball, and how these affected the participants' performance in a walkthrough in a desktop VR environment. The result indicated that the mouse interface produced the best performance. They argued that the respondents were more familiar with the mouse interface as they probably had used the mouse interface on a daily. In this study the mouse interface was not implemented as in first-person-shooter games. It should however be noted that based on other the literature mentioned earlier (Lubanski, 2007; Steinicke et al, 2006; Sunesson et al., 2008), the mouse interface is perceived as an interaction hurdle by many of the end-users within the urban planning processes that are not IT-skilled individuals or gamers. Applying a different, more active interaction interface like the human body has been found to enhance spatial-perception of the VR model, e.g. through physically rotating and moving the body (Ruddle & Lessels, 2009; Riecke et al., 2010). In this context, the Natural User Interface (NUI) can be seen as an attractive solution to this interactive navigation issue. There is no definitive definition of NUI, but the most promising one is "A natural user interface is a user interface designed to reuse existing skills for interacting directly with content" (Blake, 2010). What this actually means is that NUI enables the user to operate technology through intuitive actions using gestures, voice, touch and that it becomes invisible in so far that the user does not have invest much cognitive effort in the interaction. Furthermore, it is also important that the NUI is easy to learn and that the users quickly transition from novice to skilled users using the system. In this context, the release of the XBOX 360 Kinect sensor system, an NUI supported hardware, have provided an opportunity find a more user-friendly and natural way of controlling navigation in VR.

2.3 Communication in urban planning and building design

Communication and the understanding of information is dependent on the context in which the information is presented and the background, e.g. gender, education, social condition and the natural surroundings, of the senders and receivers (Berlo, 1960).

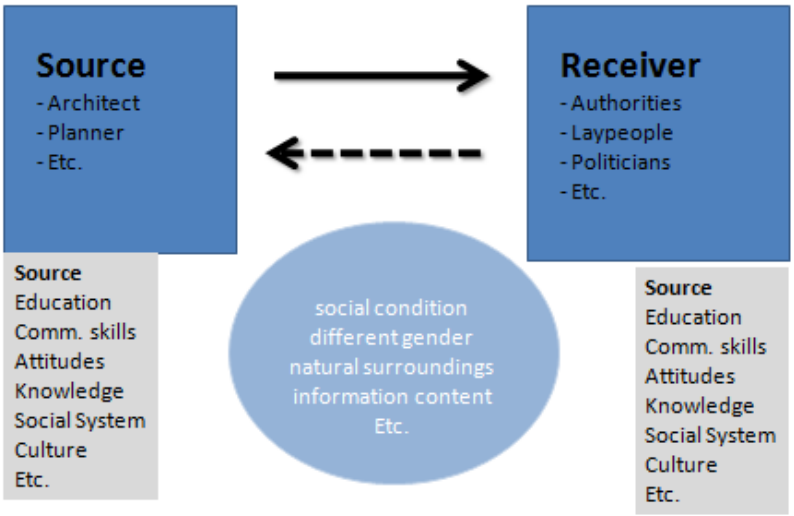

Figure 5. A simplified illustration of how different contexts and settings can influence the communication and discussion between the source and the receiver.

In the design process an architect or planner tries to create a mental 3D image of the space in his/her mind and then tries to convert this mental image into a plan of how the new environment would look like in reality. The next task for the architect is the encoding process of projecting the 3D-dimensional space from mind onto a 2D-dimensional medium such as sketches, technical drawings or perspective drawings (Bilda & Gero, 2005). An assumption is that this can be difficult and can give rise to inaccurate or ambiguous information resulting in mismatches (Logie, 1995). Once the information is created and transmitted to the information receiver, it is up to the receiver to interpret its meaning. How the architect/source encodes the information and how the receivers decode the information influences the intended outcome, see Figure 5. If the receiver decodes and understands the information in the way it was intended an opportunity for discussion and feedback about the design is achieved. In an architectural competition the jury can have difficulties understanding the presentations of the submissions if these are over artistic and vague. In some cases the architect/source can consciously omit parts of schemes that are not fully designed and even hide areas of schemes behind carefully placed trees and other features or use a non-realistic perspective to his/her advantage, (Svensson et al., 2006). The receivers/jury members can decode and create different mental images of the proposal than what the architect may or may not have had in mind. It is therefore important know how this decoding process works.

The next section will give a short background to theories of processes involved in visual cognition, and how these processes can influence the outcome of communication and decision in urban planning and building design.

2.4 Cognition and spatial perception of visual information

To understand how information is decoded and interpreted it is necessary to explain how the human brain processes visual information into mental imagery and spatial perceptions. The visual cognitive processes can be illustrated as in Figure 6.

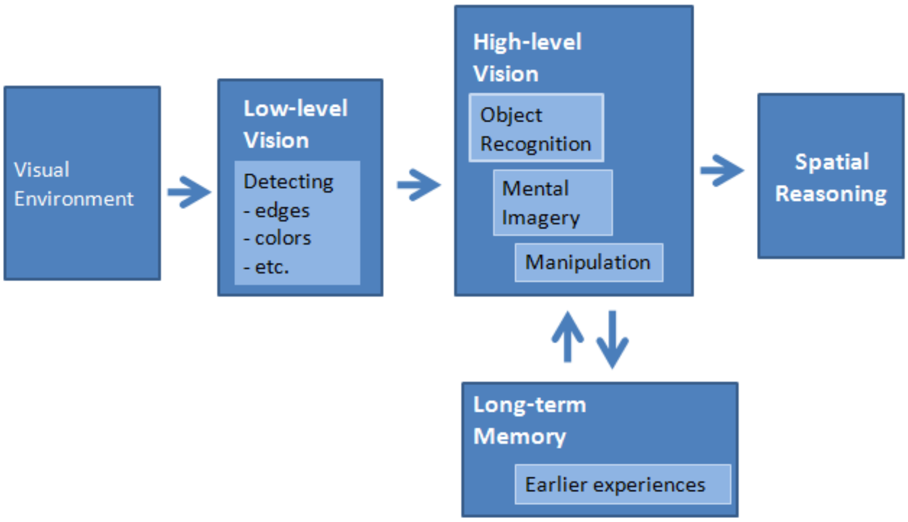

Figure 6. The visual cognitive process in the brain when experiencing a visual environment (Yuille & Ullman,1990).

The visual cognitive process starts with an individual's experience of a visual environment. This could be the impact of an image or a real-world experience of space. The visual cognitive process in the brain works as both low-level and high-level processes, see Figure 6 (Yuille & Ullman, 1990). The low-level vision detects physical properties in the visual environment, such as edges and colours (Kosslyn, 1999). The results of the low-level vision process are then analysed in the high-level vision process by trying to relate them to knowledge stored in the long-term memory. The high-level vision process contains several sub-processes such as object recognition and mental imagery generation and manipulation (Kosslyn, 1999; Biederman, 1990). The object recognition process tries to sort the information into patterns, which are then combined and associated with objects that the user has experienced earlier in life.

For example, the recognition-by-components theory (Biederman & Gerhardstein, 1995) postulates that the human mind uses simple 3D shapes to represent real objects, e.g. a coffee mug is composed of cylinders, houses are composed of walls, windows and doors. One problem with the theory is that people recognize objects slower if the objects are seen from unusual viewpoints. This limitation led to the creation of other theories. The viewer-centred approach proposes that people store a small number of views of 3D objects and that the views help them recognize objects (Dickinson, 1999; Tarr & Vuong, 2002; Vecera, 1998). The mind has to mentally rotate the image of the object until it matches the stored views (Dickinson, 1999; Tarr & Vuong, 2002;

Vecera, 1998). This type of mental rotation requires a lot of time and effort and can cause errors in objects recognition, which in turn can cause interpretation problem that lead to inaccurate communication and decision-making. However, this could be reduced when using VR where the viewer has the capability of choosing a viewpoint freely and will thus diminish the mental rotation process and free up more resources for reasoning. Furthermore, the human mind seems to use this visual cognitive information for spatial reasoning. During this process the mind tries to create an understanding of the visual space within two parallel systems: the self-centred *egocentric* reference frame and an environment-centred *allocentric* reference frame (Burgess, 2006; Klatzky, 1998). Both systems interact during this processing and retrieval of spatial knowledge (Plank et al., 2010). In the egocentric reference frame the viewer compares him/herself with the object in 3D space. During this self-to-object process, the distance and bearing to the object are processed independently of the global environment. As the viewer navigates through the environment, egocentric parameters have to be constantly processed and updated with each view change in 3D space and therefore it is seen as a viewpoint dependent reference frame. By contrast, the allocentric reference frame is built up by comparing object-object or environment-object relationships and is a global reference frame associated with the visual environment. Studies have shown that spatial perception of VR models and of physical reality differ (Kenyon et al., 2008). In fact, there are many features that are processed during spatial reasoning of the 3D space. Naceri et al. (2009) argued that in VR-based depth perception both reality-based and virtual-based unknowns and uncertainties coexist. One of the main reasons for this is that viewers sense a difference between the real environment where the experiment takes place and the virtual one suggested by the displayed images. This difference might result from low rendering fidelity or photorealism (Sinai et al., 1999; Riecke et. al, 2012) as well as visual cues (e.g. known object or textures) and landmarks (Foo et al., 2005; Loomis et al., 1999, Riecke et al., 2002). The display system and its field of view is also an important factor (Mullins 2006; Nikolic, 2007). When it comes to the size and the field of view of the display, Nikolic (2007) found that VR models shown on small screens, such as PC monitors, have to be more detailed and photorealistic in order to provide the same spatial experience as large screens, such as Panoramas. The narrower the field of view the more detailed and photorealistic the model has to be to provide a good spatial experience. Mullins (2006) tested how different display systems for virtual environments provided different spatial perceptions. Comparing these with the real environment they found that CAVE imparted a better spatial perception than Panorama display systems and they argued that this was because the human mind uses the body to examine the size of the surrounding environment. Furthermore, previous studies have also shown that physical-human rotation cues provide clear advantages in spatial tasks (Bakker et al., 1999; Burgess, 2006; Klatzky et al., 1998; Lathrop & Kaiser, 2002; Pausch et al., 1997). In a recent study, Riecke et al. (2010) showed that when VR users are allowed to control simulated rotations with their own body they obtained significant benefits over mere joystick navigation when it came to spatial perception and carrying out tasks. The impact of all factors mentioned above is dependent on how the VR medium is set up as well as the content presented in the VR model.

As mentioned above, the human mind uses the objects stored in it along with different visual cues and patterns of visual space to determine the size of objects. In this process the human mind searches the long-term memory for previous experiences of objects and patterns. This is a very demanding process for the brain, and if the objects and patterns are complex or abstract the outcome of the understanding and the communication of the design as well as decision-making may be influenced (Evans, 2007; Fink, 1989; Kosslyn, 1999). If the architectural proposals are too abstract and complex to analyse, the limited resources of the brain focus on creating mental images rather than spatially reasoning about the architectural design (Chen, 2004; Kavakli & Gero, 2001). It is therefore important to provide the viewer with visual cues in the VR model that contain recognizable objects, as this will enable them the to carry out spatial reasoning.

The results from judging architectural proposals and architectural quality depend on which stakeholders in the planning process are involved in the judging (Volker, 2010). Volker (2010) classified judging architecture into two general categories; the first involves such technical, functional etc. values that are tangible and often quantifiable, and the second involves perceptual, subjective, etc. values that are intangible and thus difficult to measure. The intangible values are soft values and are often connected to emotions and perception. Perceptions and the reasons why some people prefer shapes and architectures is difficult to understand. Reber et al. (2004) presented a processing fluency theory of aesthetic pleasure drawing on the processing fluency theory of Alter & Oppenheimer (2009). The processing fluency theory of aesthetic pleasure is based on the assumption that aesthetic experience is a function of the perceiver's processing dynamics: the more fluently the perceiver can process an object, the more positive is his or her aesthetic response. The features that facilitate fluent processing are related to contrast and symmetry of the objects or figures, as well to also to perception and conceptual priming procedures. These attributes can achieve high fluency that can give the perceiver a more positive experience and make the retrieval of information from memory easier. Is it possible that this phenomenon is a reason behind positive attitudes towards the use of VR?

Furthermore, the visual working memory is limited and can only store about three to four simple objects at the same time (e.g., Luck & Vogel, 1997; Pashler, 1988; Sperling, 1960; Vogel et al., 2001), although this can vary depending on circumstances and between individuals (Becker & Morris, 1999; Buziek, 2000). The information being presented is eradicated after a few seconds if it has not been selected by the mind for future knowledge building in long-term memory. In this context is important to bear in mind that if the viewer has to put lot of effort into the process of interpreting the visual information less resources will be available for visual working memory and spatial reasoning, and this will influence the outcome of the understanding and the communication of the design as well as decision-making. In this context a seminal contribution is Cognitive load theory, which addresses learning and the limited capacity of the human information-processing system and the connecting working memory (Ayres & Gog, 2009; Hollender, et al., 2010; Sweller, et al., 1998). The theory explains how only a restricted amount of cognitive processing can occur in the visual/spatial channel at any given time. Furthermore, the split-attention effect phenomenon indicates that multiple sources of visual information should be presented in an integrated way if all information sources are a prerequisite for understanding. If the sources are displayed in a separate format, the information needs to be integrated mentally, which induces a heavy load on working memory (Ayres & Gog, 2009; Hollender, et al., 2010; Sweller, et al., 1998). This will affect learning, understanding and reasoning, which will influence the judgment and decision-making process.

The next section introduces a decision-making perspective which provides an understanding of how different human cognitive biases and context affect judgments and decisions. These issues, which are linked to cognition and spatial perception of information and how the information is presented to the decision-makers, have so far been under-researched in the context of urban planning related VR.

2.5 Decision-making in urban planning and building design

Decision-making is a concept that is very difficult to define and therefore this thesis will not attempt to present a final definition. The research field is huge. Decision-making is sometimes said to be associated with the regulation of human behavior (Loewenstein & Lerner, 2003). In this section, the intention is to provide background to some decision-making theories and to provide insight into some of the difficulties in decision-making in the context of urban planning and building design.

A seminal contribution to the understanding of decision-making theory is the concept of bounded rationality (Simon, 1957; Gigerenzer & Selten, 2002), which recognizes the human limitations when it comes to analysing, evaluating and choosing between decision alternatives. These limitations can be of cognitive nature but are also be affected by limitations stemming from that decision-making:

- is time-consuming,
- requires a great amount of accurate information,

- requires the availability measurable and rational criteria that need to be agreed upon,
- requires a rational and reasonable process, not often available in a political context with possible hidden agendas,
- requires stable and complete knowledge of all the alternatives, preferences, goals and consequences.

The bounded-rationality approach assumes that the decision makers search for options that are "good enough" or "satisfying" rather than for optimal solutions. The decision maker strives to achieve the best decision, but given the limitations mentioned above will have to settle for a decision that will probably deviate from the optimal.

When judging, many psychological phenomena are in play in which people compare a perceptual input with a certain reference point and notice only changes from that reference point. Helson (1948, 1964) modelled these phenomena using adaptation level theory. Once the "adaptation level" is formed, it is kept throughout the subsequent evaluations, where positive and negative deviations remain in the general vicinity of the original position. In the late seventies, Kahneman & Tversky (1979) proposed prospect theory, which deals with how people make choices in situations where they have to decide between alternatives that involve risk. Prospect theory also highlights the effects of reference points, and how the framing of a decision can lead to different preferences. Most judgments are not made in isolation but relative to something else, as is the case in urban planning and visualization. Judgments are made in their contexts often based on initial information, which can cause framing effects on the judgments and the decision-making process. Tversky & Kahneman (1974) introduced the important concepts of heuristics and biases. These ideas are consistent with the notion of bounded rationality in that humans use simplifying heuristics when making judgments. Kahneman and Tversky also observed that the reliance on these heuristics could give rise to systematic errors of judgment so-called bias. One of the heuristics that Kahneman and Tversky identified is the *Anchoring and adjustment heuristic* (Tversky & Kahneman, 1974, Kahneman, 2002). The anchoring effect is the common human tendency to make judgements towards the initial value or a starting point, (the anchor), and adjusting it from this starting point when additional information is made available. The problem is that people frequently adjust insufficiently (Tversky & Kahneman, 1974; Evans, 2007). This insufficient adjustment means that the initial anchor, regardless of its validity, will have a strong influence on the final judgement. Paper V will address this phenomenon in the context of urban planning and VR.

In a related vein, Weaver (2007) addressed how mass media agendas may change the opinions of the public and of political actors by generating different frames and priming, which can give rise to cognitive bias in decision-making. These framing and priming effects put demands on the decision makers in the urban planning and building design process. This process was seen to have occurred in an applied VR-project concerning a wind farm project. In this project, prior to the VR presentation of the new planned wind farm the public were shown the movie "An Inconvenient Truth" by Al Gore about the global warming and the environmental crisis. The presenter/stakeholder of the wind farm project also mentioned how the Swedish government had environmental goals concerning the development of new wind farms. In this case he tried to prime the public to be positive to the new wind farm. Maarttola & Saariluoma (2002) described decision-making in this type of urban planning process as a very complex, socially structured process, involving both the decisions of the individuals and the groups that are influenced by e.g. social, economic, historical, environmental, physical and spatial factors. These factors are dynamic and interact during the decision-making process (Perraton, 1978). The groups in these kind of situations often include stakeholders from the city planning authorities, architects working for clients, the clients themselves, members of the general public and politicians. Each of these groups have their own agenda with its own background, interests, expectations and focus (Ambrose, 1994; Faludi, 1996; Friedman, 1996; Hoch, 1996). Research on Group Support Systems has shown that the group decision-making environment consists of a combination of *the characteristics of the group* (including group history, member proximity, group size, national culture, leadership behaviour, and group cohesiveness), *the task* (including type of task, level of decision-making, phases of decision-making, level of task structure, difficulty, and time synchronisation), *the group and organizational context* (including corporate culture and behaviour norms, maturity of the organisation, organisational size, time frame of decision-making, management style, and recognition and reward systems), and *the system* (such as CSCW). These influence the group process, and thus ultimately the group outcome (including measures of efficiency, decision quality, group consensus, and satisfaction) (Nunamaker et al., 1991). CSCW approaches are often based on the assumption that complex problems require more knowledge than any single individual possesses and in this context it is necessary for all involved stakeholders to understand, participate, communicate, and collaborate with each other to obtain a higher quality outcome (Arias et al., 2000). In this context, the resolution of the design problem grows out of the shared understanding that emerges as different stakeholders begin to better understand each other's perspectives (Arias et al., 2000). Group decision-making processes have the tendency to use more time and energy discussing information that all members are familiar with and less time and energy discussing information that only some members possess (Postmes et al., 2000; Toma & Butera, 2009). In this context, virtually all group processes can be understood through an analysis of how individual group members process group-relevant information (Schulz-Hardt, 2000). It is therefore important to understand the individuals' information processing and reasoning processes or the discussion and decision-making process will be biased. Hall and Tewdwr-Jones (2010) as well as Maarttola and Saariluoma (2002) highlight the communication difficulties between the different stakeholders in the planning process. Communication difficulties mainly occur as a result of the different planning cultures, and because there is insufficient collaboration and information sharing during the process. The most common problem is that the information is not presented in such a way that people can understand it. It is in this context that the VR medium can be used as a tool to facilitate communicating and understanding the planned new environment.

3 Development of the research area and related questions

My research started at the beginning of 2000 when I, together with my colleagues at the Visualization Studio[9], carried out an R&D project that involved the land development and urban planning of Norra Älvstranden in Göteborg, Sweden. In this project we created and visualized the VR model using commercial software. Our first issue was how to actually build and show the VR model using the fairly limited existing computer hardware. When we completed the VR model, an important question was identified: *How can the VR medium support the viewers' experience and decision-making in urban planning and building design?* Because the VR model was used in an actual urban planning and building design project, we compared the viewers' experience of the VR model with the viewers' experience of the actual building (Westerdahl et al., 2006, e.g. Roupe 2009). A comparison of the results from the SMB[10] questionnaire on the VR model and on the real completed building showed that the VR model was an accurate representation of the real building, in the sense that the viewers' reported experiences of the two objects were very similar. The overall result indicated that the VR model was perceived as a useful aid for understanding and making decisions about their future internal work environment. The study also gave some examples and hints of properties in the VR model that were considered important for the viewer when forming an opinion about room sizes. The properties most often mentioned were furniture, people, objects and perspective. Based on this study, we implemented animation of humans in our software MrViz to provide the experience of social life that had been deemed lacking in the VR model used in the study.

An issue that was not addressed in the paper, but was considered during the project, was the amount of time we had spent building the VR model. We used MultiGen Creator and 3D Studio Max and carried out hands-on modelling. Almost half of the project time had been spent on modelling the existing environment. For the external model we used the city authorities' base map to get the correct height and size in the existing built environment. This part was also done through hands-on modelling, a very time-consuming and costly method. We realized that the costly and time-consuming process of building the VR environment would be a problem if VR were to be integrated into the urban planning process. In this context we identified the next important questions: *How can VR be integrated in an efficient way into urban*

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[9] *The Visualization Studio was a research group located at Chalmers Lindholmen (1999 – 2007). Nowadays its name is Visualisation Technology.*

[10] SMB - from Swedish Semantisk Miljö Beskrivning ("Semantic Environment Description Scale") (Küller, 1991)

planning and building design? In the next study (Johansson & Roupé, 2005; Roupé & Johansson, 2004, also in Roupé 2009), we improved the integration of VR into the existing urban planning and building design process. To do this we focused on trying to create time and costs efficient tools and methods for developing VR models. The results from the study include a framework and a tool to develop 3D city models semi-automatically from the City Planning Authority's base map. The tool uses contour lines to create the terrain surface, and rooflines to create 3d building by extracting them down to the terrain surface. The associated aerial photos of the area are automatically mapped on the terrain and the roofs based on the information contained in their attribute files, see Figure 7. This results in simple volumes representing existing buildings.

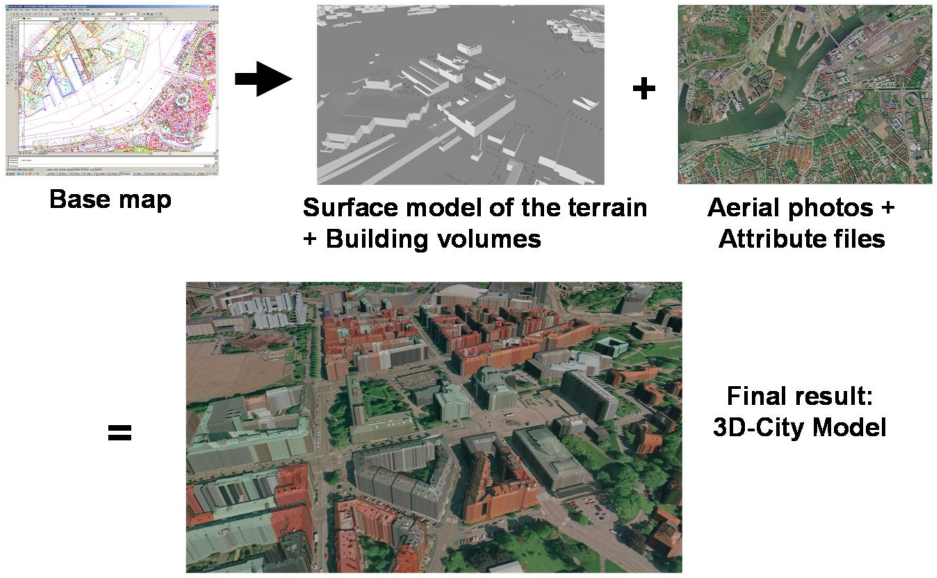

Figure 7. The process of semi-automatically creating the 3D city model using the base map and aerial photos.

This tool is included in the MrViz toolbox and is used by the City Planning Authority of Göteborg when they conduct volume shadow studies and different analyses using a 3D model of the city. Additionally, the semi-automatic framework for creation of 3D city models for VR gave rise to the next important question: *How can 3D city modeling support visualization of urban planning and building design?* Furthermore, in the next study by Johansson & Roupé (2005) (also in Roupé 2009), we developed this approach further and also tried to find a way to edit and work with the representation of the terrain, see figures 8 and 9. This was further researched in Papers I and II in this thesis.

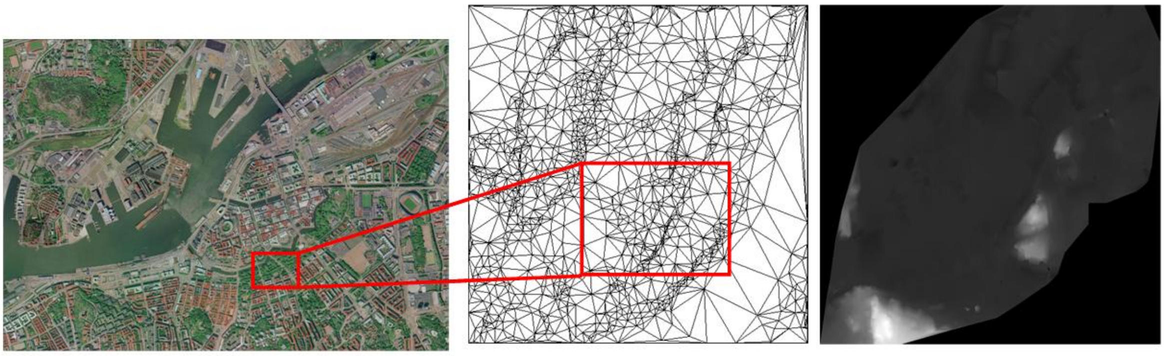

Figure 8. The semi-automatically created 3D city model contains terrain constructed from triangles. The triangles are converted into a height-map, which is a grey-scaled image that describes the height of the terrain. By painting in the height-map, the different grey scales representing the height of the terrain are edited.

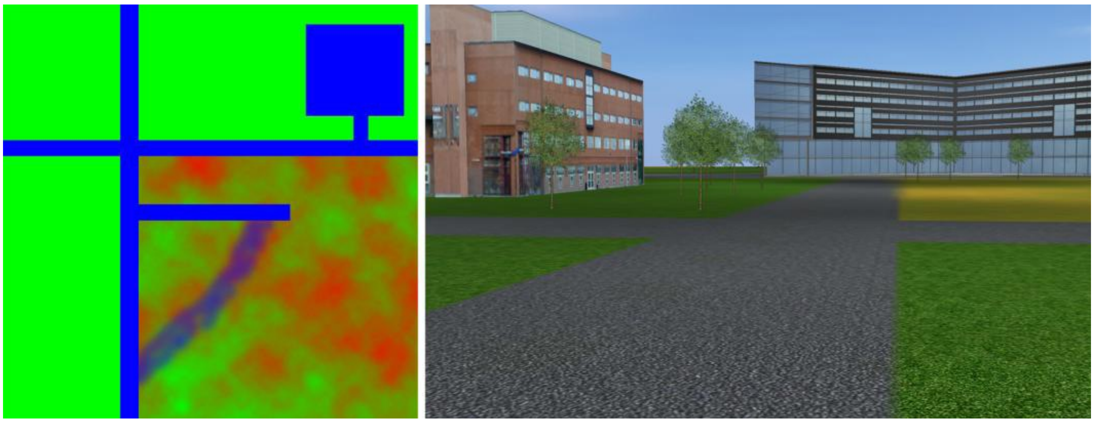

Figure 9. The figure shows the technique of color-coding the different ground material and then replacing these colors with detailed texture of ground material during the rendering phase on the graphic card. The green color-coded part in the left image is replaced with the detailed grass texture in the right image.

After we developed the tools and methods for creating a digital copy of the city, the City Planning Authority of Göteborg began using our software, MrViz. This gave us the opportunity to verify and validate the software in applied R&D projects. This approach gave us feedback loops, which helped in the continuing development of tools and methods that improve the practical use of VR in urban planning and building design. It also gave us a better understanding of the usability of the VR medium in urban planning and building design. To understand more about how to use VR tools, it became important to *understand how viewers experience a VR model in decision-making in the urban planning and design process*. Earlier studies (Sunesson et al., 2008, also in Roupé 2009) examined VR user experience during the architectural competition of how the City Library of Göteborg could be rebuilt (see figure 10).

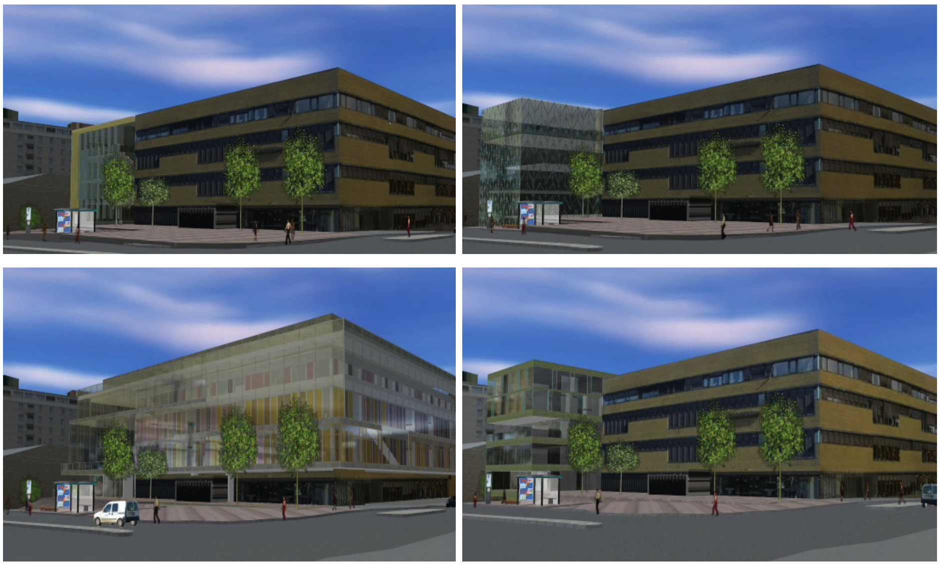

Figure 10. The four different proposals as presented in the VR medium (Sunesson et al. 2008)

This study (Sunesson et al., 2008, e.g. Roupé 2009) showed that the VR model gave a broader understanding about the size and volume of the competition contributions and their interaction with the surroundings. The studies reported that the VR model was used in discussions, clarified the content of the blueprints for persons not familiar with these, and was perceived as a pedagogical method for creating understanding of the different architectural contributions. Being able to understand the interaction with the surroundings and to actually see the volumes was thought to have been beneficial. The studies revealed that the city planner from the City Planning Authority found it important that the quality of the VR-rendering should such that the proposal is clearly illustrated but that it is not so high that the general public would consider the proposal to be complete.

Following on from these earlier studies we began looking into the visualizing of larger areas and became interested in examining possibilities of developing tools and methods of cost and time efficiently creating large - 16 x 16 km - VR models with detailed ground material (paper I, II). In one study the City Planning Authority of Göteborg requested to visualize larger areas for a wind farm project. The City Planning Authority of Göteborg wanted to analyse the visibility of the turbines and requested a detailed 8 km line of sight study and closely detailed ground material. The model was to be viewed both from the ground and from the air. This project examined the possibilities of *how to produce detailed ground representation* (Paper I). This study describes a technique for enhancing the visual quality of the ground by blending aerial photos with tiled detail textures in a level-of-detail integrated system that is controlled by color-coded images. In this study we further developed the technique (presented in Johansson & Roupé 2005) where color-coded images used different colors to describe different ground materials. Furthermore, more detail the depiction of ground material would provide the viewer with better possibilities for spatial reasoning and perception of the VR model.

During the wind farm project, we became aware of issues regarding collaboration and management in situations when different users were working on the same 3D city model. The model contained huge amounts of data that had to be stored and managed during the process. Here we used external references and split the model into different parts or files that would later need to be joined together. This was a demanding approach, and set it high demands on communication between the different users. To come to grips with this issue we adopted a version control system[11], which was then used during our software development. This project led to an *integrated sub-version control system that* supports collaboration and maintenance of a 3D city model (Paper II).

In the courses we taught in 2004 we started using Autodesk Revit. Autodesk Revit is a Building Information System (BIM) which is used for creating digital models of buildings (for more details, see section 2.1.1). Over the years, we had observed that the integration of the BIM models and its surrounding ground into the 3D city model was often a very time consuming process, and it required enormous efforts to stitch together this type of models manually. This issue led to How can BIM models with its surrounding ground be integrated into the 3D city model? (Paper III).

Another issue or hurdle that we encountered was navigation in VR models. The interaction interface has always been a problem in situations where clients or end-users do not have the self-confidence to handle the VR medium themselves. A consequence of the complicated interactive handling has often been that the clients' lack of self-confidence limits them to showing the general public and therefor instead only use rendered images and movies from the VR model. As a result, the full potential of the VR medium, in terms of enhanced communication and understanding regarding future projects, is not fulfilled. When the Microsoft XBOX Kinect sensor[12] was released it provided an opportunity to use this sensor for creating a more user-friendly and natural way of navigating and interacting with VR models. This issue and opportunity led to the following questions: *How can we develop a user-friendlier navigation interface that supports a more natural viewer experience?* (Paper IV).

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[11] *Version Control System – is a system for managing different versions of files, documents, etc. and tracking changes by different users. For more details in section 2.1.3.*

[12] *Microsoft XBOX Kinect sensor - is a motion sensing input device that supports motion tracking of the user's body. It enables users to control and interact with the computer/XBOX360 using gestures and other body movements.*

Observations made during the research and the associated VR project led to the assumption that different stakeholders in the urban planning and building design process have different interests, expectations and focuses concerning what the VR medium can achieve for them. This made us assume that the VR medium could be used as a tool to influence the decision-making process. A review of the decision-making literature revealed different judgement and decision-making phenomena, which we thought were important to explore in the context of VR in urban planning and building design. This led to following question: *How can viewers become biased in their judgement and decision-making when experiencing VR presentations?* (Paper V).

Figure 11 illustrates how the different papers in this thesis are mapped into the context of the usability of the VR medium in communication and decision-making processes in urban planning and building design, and the associated hurdles that might exist. It is important to identify and address these hurdles before the VR medium can be seen as comprehensive decision-making tool.

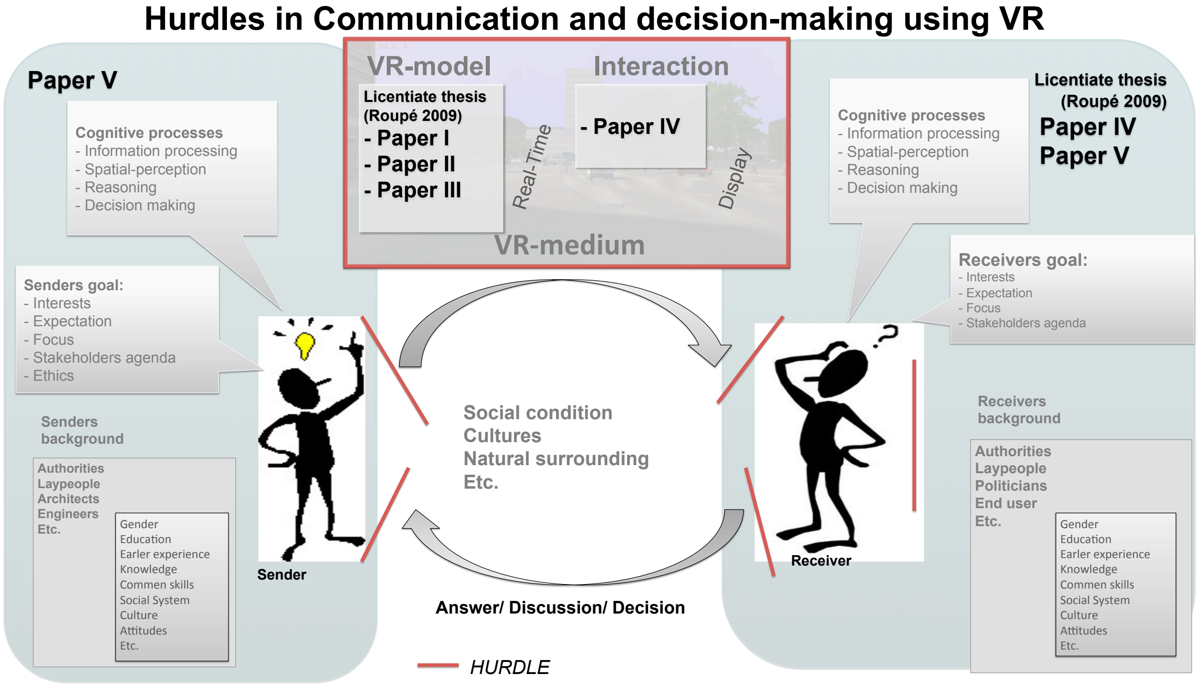


Figure 11. Illustration of how the papers in this thesis are mapped into the context of the VR medium as a tool in the communication and decision-making process in urban planning and building design.

3.1 Research approach

The field of VR spans a variety of different research areas and sciences including computer graphics, visualization, perception, communication and decision-making, social sciences, cognitive science and computer sciences.

When research on VR is applied in real contexts, such as in urban planning and building design processes, things become even more complex. Because of this, I have chosen to explore this field using different, but in some degree overlapping, research approaches. This thesis and the research have been inspired by design science, which contains both technical and human aspects (Hevner et al., 2004). March & Smith (1995 p. 253) stated, *"Whereas natural science tries to understand reality, design science attempts to create things that serve human purpose".* In describing design science March & Smith (1995, pp. 254) state that *"Design science consists of two basic activities, build and evaluate. Building is the process of constructing an artifact for a specific purpose; evaluation is the process of determining how well the artifact performs."* In principle, design science research attempts to successfully design, develop and evaluate technology-oriented design artefacts characterized as novel, innovative and purposeful. Being purposeful implies that these artifacts could potentially provide organizations and humans with recognizable utility since they should address unsolved problems (Hevner et al., 2004), or provide better solutions and thus enhance existing practices (Kuechler & Vaishnavi, 2008). These artifacts aim to provide additional improvements to real-world phenomena. In the context of this thesis the main artifact has been "Virtual Reality as a tool for Communication and Decision-making in Urban Planning and Building Design".

In my research I have tried to solve the technical problems that have been identified hurdles for the use of VR in urban planning and building design. The hurdles have been identified during observations and usage of the VR medium in real applied projects in urban planning and building design. Data was gathered from about 16 R&D projects and about 100 student related projects over a period of 12 years.. Hurdles started to appear during the first study, Paper I, where we found that VR was a usable medium, but that creating VR models was very time consuming and the VR software used had been written for military use or for more general purposes. The human related issues/hurdles connected to the VR medium have been examined to gain a deeper understanding of how certain attributes effect the usability of VR in urban planning and building design. Therefore both constructive research methods as well as qualitative and quantitative methods have been used. The latter methods were used to gather end-user data. Both questionnaires and interviews have been used and in some cases direct observations have been made. The VR software that was developed during the research has been applied in a real-world context in urban planning and building design. The applied projects have provided feedback loops for the continued development of tools and methods that improve the use of VR in the practice of urban planning and building design. The applied projects have also provided a better understanding of how VR is used as well as what usability issues regarding urban planning and building design were encountered. In this process it has been important to remain flexible when researching this complex, changing and broad field of VR, and the complex and dynamic urban planning and building design process.

More specifically, a combination of approaches and methods at different levels was used: literature studies, implementations (constructive research), observations from case studies in a real-life context, individual interviews, scales, statistics, and questionnaire surveys. In individual interviews and questionnaire surveys, respondents frequently reported their experiences, thoughts or behavior, but such reports may not be entirely accurate or true (Kvale, 1996). By combining surveys and interviews with observations made during case studies a deeper understanding was reached. Direct observation entails observing what people actually do or how they behave, or what events take place during the use of the VR medium. This is necessary as interviews and questionnaires do not provide enough accurate information on these subjects. Furthermore, controlled experiments with multiple approaches for data collection were used to test hypotheses and to gain a deeper understanding of the usage of the VR medium. Of course these methods and experiments have their limitations and are thus not entirely reliable. However, they have provided guidelines on how people behave in these situations and supported by findings in the literature they allow more robust conclusions of the usage of the VR medium to be drawn. Table 1 is a summary of the different methods used in this thesis. The methods applied in this research are described in more detail in the appended papers. However, more approaches, methods and data have been used in the additional publications and in my research, which are not presented in this thesis.

Table 1. Summary of the methods used in this thesis.

Studies	Research question	Method	Output
Users' evaluation of a virtual reality architectural model compared with the experience of the completed building. *Licentiate thesis, Roupé 2009* *(e.g. Westerdahl et al., 2006)*	RQ 2.	Literature studies Questionnaire *(99 / 39 respondents)*	Viewers experience of VR-model Usability of VR VR-model vs. Real Building
From CAD to VR – Implementations for Urban Planning and Building Design. *Licentiate thesis, Roupé 2009* *(e.g. Johansson & Roupé, 2005)*	RQ 1. RQ 1.1	Literature studies Implementations Validation (Constructive research)	*Visualization and 3D-city modeling:* Tools and methods for development of VR-models: - 3D-city models - Enhance visual quality of ground
Virtual Reality as a New Tool in the City Planning Process. *Licentiate thesis, Roupé 2009* *(e.g. Sunesson et al., 2008)*	RQ 2.	Literature studies Interviews Observation *(9 respondents from the jury)*	Viewers experience a VR-model Usability of VR in decision making in building design and urban planning
Paper I: ***Visual quality of the ground in 3D models: Using color-coded images to blend aerial photos with tiled detail-textures.***	RQ 1. RQ 1.1	Literature studies Implementations Validation (Constructive research)	*Visualization and 3D-city modeling:* Tools and methods for development of VR-models. - Enhance visual quality of ground
Paper II: ***Supporting 3D City Modeling, Collaboration and Maintenance through an Open-Source Revision Control System.***	RQ 1. RQ 1.1	Literature studies Implementations Validation (Constructive research)	*Visualization and 3D-City Modeling:* Framework for supporting collaboration and maintenance of 3D-city models
Paper III: ***3D-City Modeling: A Semi-automatic Framework for Integrating Different Terrain Models.***	RQ 1. RQ 1.1	Literature studies Implementations Validation (Constructive research)	*Visualization and 3D-City Modeling:* Framework for integrating different terrain models
Paper IV: ***Interactive navigation interface for Virtual Reality using the human body.***	RQ 1. RQ 1.2 RQ 2.	Literature studies Implementations Validation: ***Body navigation vs. Mouse*** • Questionnaire • Observation *(59/22 respondents)*	*Navigation in VR:* Body navigation vs. Mouse User-friendlier navigation interface then using the body
Paper V: ***Biased judgment and decision making when using Virtual Reality in urban planning.***	RQ 2.	Literature studies Questionnaire Observation *(60 respondents)*	Biased judgment and decision making using VR

RQ 1. How can VR be integrated in an efficient way into urban planning and building design?

RQ. 1.1. How can 3D city modeling support visualization of urban planning and building design?

RQ. 1.2. How can we develop a user-friendlier navigation interface that supports a more natural viewer experience?

RQ 2. How can the VR medium support viewers experience and decision-making in urban planning and building design?

3.2 MrViz - VR software for urban planning and building design

MrViz is software used for Real-Time visualization (also called Virtual Reality in urban planning and building design). The software was developed as a research tool in 2001 by Mattias Roupé and Mikael Johansson and has since been continuously improved. The aim has been to implement different methods to speed up the process of creating and visualizing of 3D city models (Roupé & Johansson, 2004; Johansson & Roupé, 2005; Paper I; Johansson & Roupé, 2009; Paper II; Paper III; Johansson & Roupé, 2012).

Many tools and features have been integrated into MrViz, and the perhaps most interesting and innovative ones are presented in this thesis. The implementation of virtual people and a texture-editing tool to eliminate perspective distortion in façade photos could be interesting next development steps. Support for virtual people was implemented with an image-based rendering technique. The main purpose was to populate and to give life to the VR models. This issue had been mentioned by some of the participants in an earlier study (Westerdahl et al., 2008). The technique is illustrated in figure 12. Each character contains 8 vertical faces. On each one of these faces, a sequence of images is displayed that represents a single walk cycle from that direction. The result is essentially giving the impression of a walking character. During rendering, only the face that is most perpendicular to the viewer is displayed. Using this approach it is possible to populate a VR model with a large number of animated characters without stressing the real time performance, see figure 12. It is very easy and fast to populate a scene; by creating a animation path and adding the number of characters that will be randomly populate the path.

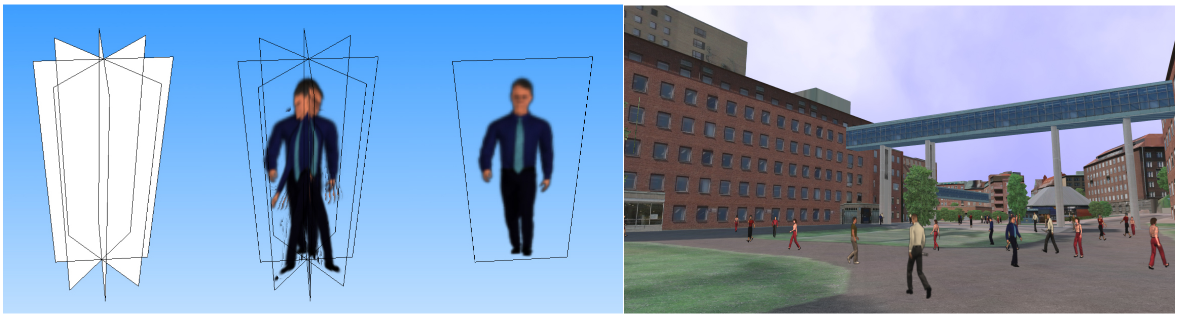
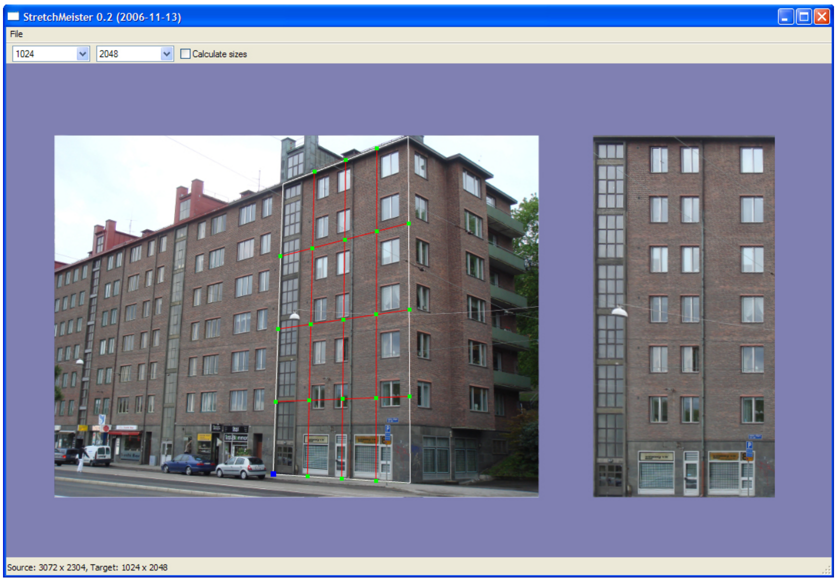


Figure 12. The image-based approach used for rendering of animated people and an example of animated people added to a VR model.

Although 3D models representing the existing environment can be automatically generated in *MrViz*, manual work in still needed to apply façade textures on the buildings. However, as these textures are based on digital photographs of the existing buildings, perspective distortion often has to be eliminated. While this can be done in image-editing software, such as *Adobe Photoshop or Gimp*, the work is generally time consuming. However, our texture-editing tool, *StretchMeister,* was developed in order to simplify this process. In *StretchMeister*, a user imports the digital image that is to be processed and then selects the four corner points of the building façade. By using a discreet implementation of the four-point perspective mapping described by Heckbert (1989), the resulting image, without perspective distortion, is automatically generated, figure 13. This tool has speeded up the process of adding façade photos into the 3D city model.

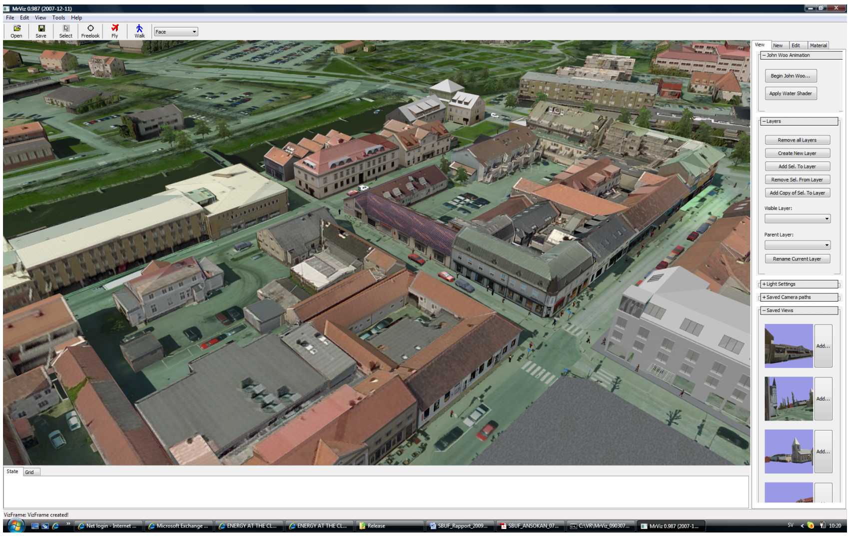


Source: 3072 x 2304, Target: 1024 x 2048

Figure 13. In StretchMeister a user defines the four corner points of a façade in a source image (left) in order to produce a new image without perspective distortion (right).

MrViz is based on the C++ programming code and uses APIs called Openscenegraph and OpenGL. An API, Application Programming Interface, is a toolbox for programmers containing different tools and functions to perform specific tasks. The total number of code lines written in MrViz is about 114 140, that is about 2536 pages of A4 pages of C++ code. The database manager implemented in MrViz makes it possible to handle databases with no limit on size and with very rich details. As most common file formats are supported it is possible to import and export 3D models from and to almost any 3D modelling software.

MrViz has been used by city planning authorities in Göteborg and Kungsbacka, Sweden, for urban planning and building design. It has also been used in the studies Westerdahl et al. 2006 (New office building, Ericsson), Sunesson et al. 2008 (The City Library of Gothenburg), Paper I, II (wind farms) and Paper IV (Volume study of new Building) as well as in several projects in the urban planning process. Figures 14-17 show examples of how of MrViz has been used in different projects.



VizFrame: VizFrame created!

Figure 14. A VR model of Kungsbacka, Sweden, for which laser scanned data and photos taken from a helicopter. The city centre was modified and edited to exhibit more detailed. The façade photos were taken from ground level and applied on the buildings in the model. The photos were edited and added using StretchMeister and MrViz.

Figure 15. Snapshot from a VR model that was used to study proposed new buildings at Danskavägen, Gothenburg, Sweden. This VR model is a good example of how the technology can be used cost efficiently. This model was made in less then one day by using MrViz. This was made in-house by the city planning authorities in Göteborg using drawings from the building permit for the new buildings. The VR model was used by the neighbours and politicians to investigate how the new buildings would affect the views of the city from nearby apartments. The result from this line of sight analysis was that the different stakeholders came to a positive consensus regarding the project.

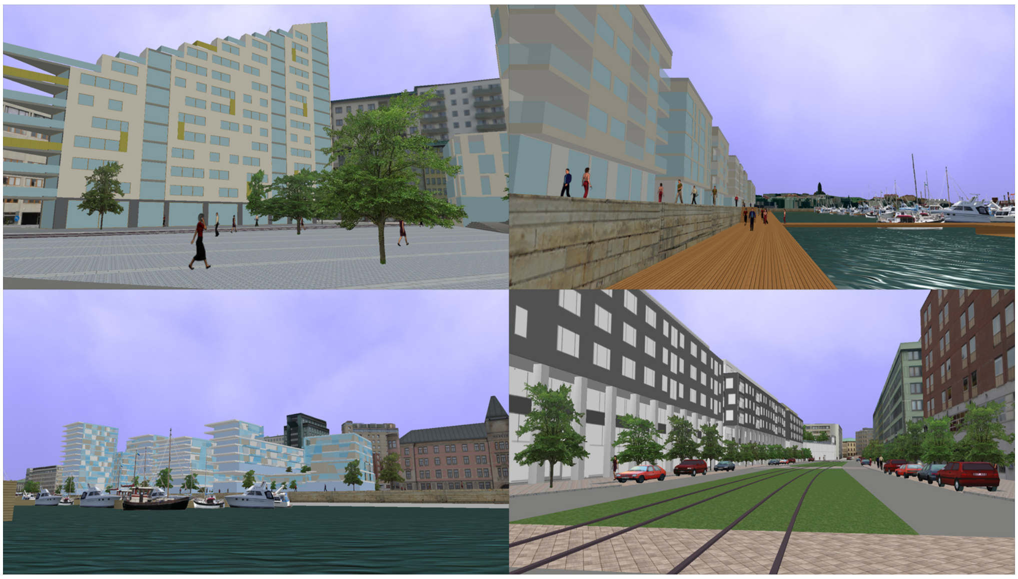


Figure 16. A VR model used by the city planning authority to reach a decision in an architectural competition concerning rebuilding proposals for an urban area in Göteborg, Sweden. The different architects presented their proposals in VR together with posters and physical models. The jury thought that the VR medium provided a better understanding of space and also depicted one of the proposals much more clearly.

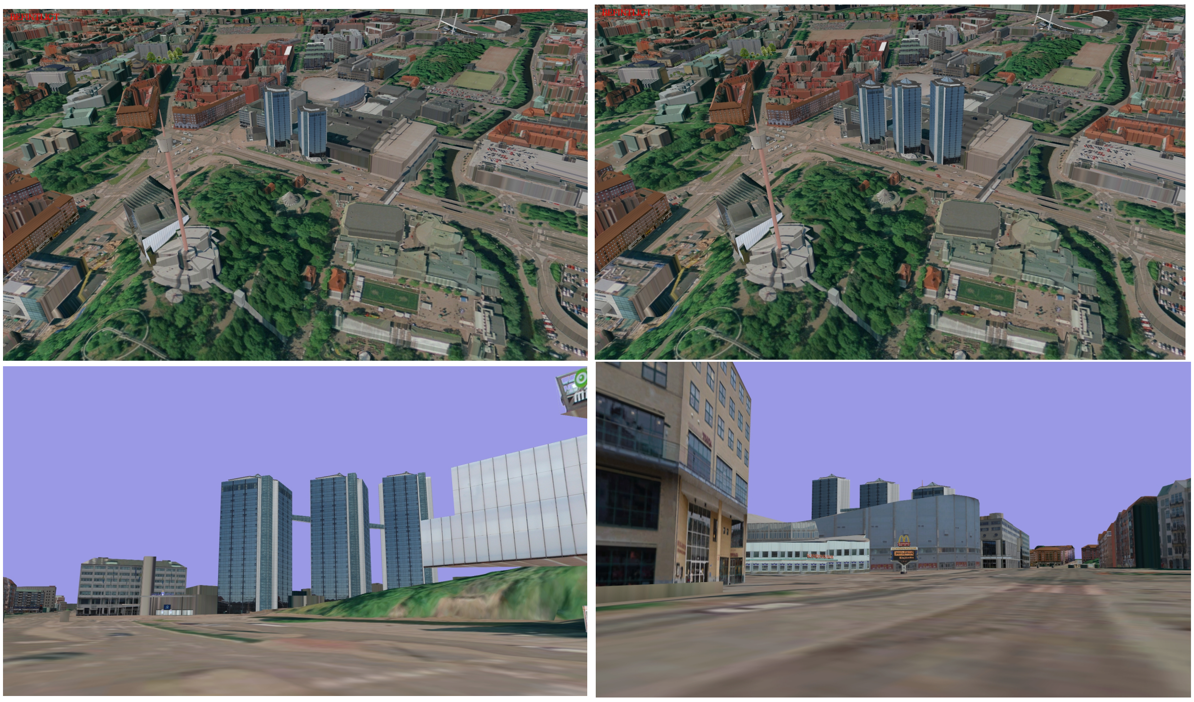
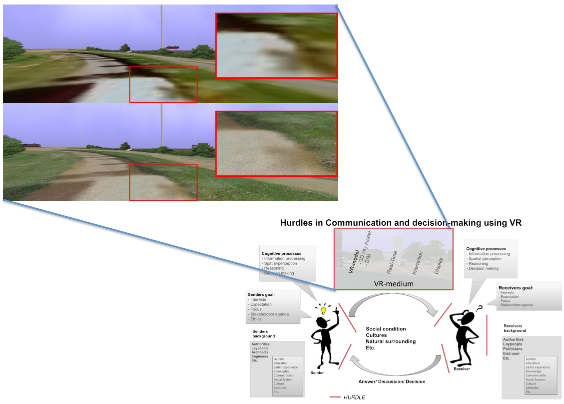


Figure 17. This VR model was used for a volume study of the redevelopment of a hotel in Göteborg, Sweden. The city planners and politicians used the VR model to investigate how the new buildings would affect the urban landscape from different viewpoints in the city. It was possible to switch between the new redevelopment proposed and the existing building. The same model was also used for shadow studies.

4 Summary of Papers

In this section a short summary of the appended papers included in this thesis is presented. Many of the papers in this thesis are related to earlier studies that were presented in a licentiate thesis (Westerdahl et al., 2006, Johansson & Roupé, 2005, Sunesson et al., 2008). The results from these papers will be discussed in the discussion and conclusion section to provided deeper understanding of the development and the implementation of Virtual Reality for urban planning and building design. Furthermore, the summary of the appended papers also provides an account of the preparatory work and realization of the different studies. In the text I use the word *framework*, this implies a basic conceptual structure that addresses complex issues and can be applied and re-used in software systems.

4.1 Paper I: Visual quality of the ground in 3D models: Using color-coded images to blend aerial photos with tiled detail-textures.



Authors: *Mattias Roupé and Mikael Johansson*
Publication:
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4.1.1 Purpose

This study describes a technique to enhance the visual quality of the ground by blending aerial photos with tiled detail textures in a level-of-detail integrated system that is controlled by color-coded images. In this study we further developed the technique that was presented in Johansson & Roupé (2005) and Mittring (2008), where color-coded images were used to identify different ground materials using different colors. These colors were then replaced during the visualization with a detailed representation of texture of the ground material. The paper focused on comparing visual quality when the technique was applied on two data sets: one landscape data set and one urban data set.

The technique was applied and further developed in a project on the visualization of wind turbines in Göteborg. The demands were that the viewer should be able to view the VR model both from a pedestrian point of view and from the sky. The viewer's task was to analyse how the wind turbines looked from different viewing locations. Another demand was that the wind turbines could be viewed from a distance of eight kilometres. The VR application had to handle a huge 16 x 16 km VR model and at the same time be able to portray ground material in great detail when the viewer wished to view the model from the pedestrian perspective. These demands gave us the opportunity to test and develop the technique and apply it in a level-of-detail integrated system[13]. The color-coded image technique suited this type of application well because it is a very cost and time efficient technique for depicting large areas of detailed ground material.

4.1.2 Method

To validate the results of the technique, with respect to visual quality and rendering speed, two data sets were used, one landscape and one urban data set. We chose these particular data sets since they differed in the level of detail and the boundary edges for materials. The urban environment, being mainly constructed by humans, contains many sharp boundary edges of different materials. For the rendering speed, a worst-case scenario was used. This was achieved by applying the color-coded image technique on a quad, and measure time performance on different resolutions on the color-coded image and aerial photo. The worst-case scenario is when the entire screen is filled by pixels from the color-coded image technique. This can only be achieved in a real scene if the viewer is looking directly down on the ground. For more details about the worst-case scenario test, see Paper I.

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[13] *Level-of-detail integrated system - is a system that has different representations of the 3D object depending on where the viewer is located. E.g. the 3D object decreases in complexity as it moves away from the viewer until it can be released or deleted from the local RAM memory.*

4.1.3 Result

The result of this study was that we integrated and further developed the technique described in Johansson & Roupé (2005) and Mittring (2008), to fit the demands mentioned above. This research studied artificial terrains and did not deal with aerial photos and existing terrains in a real-world context where aerial photos are important. In the paper we presented an evaluation concerning the VR model's visual quality by comparing the common technique of only using the aerial photos for ground visualization with the color-coded image technique. The results showed that the color-coded image technique produced images of higher visual quality compared with the technique where only aerial photos were used, see Figure 18. The results further showed that the color-coded image technique enhanced visual quality by replacing the blurred and diffuse aerial photos with more detailed representations of the ground material, see Figure 18. The color-coded image technique was experienced as more detailed because the viewer could actually see such details ground material as small stones on gravel roads.

Figure 18. The figure shows that the color-coded image technique (right) enhanced the visual quality compared with only using aerial photos (left).

We also compared different resolutions on the aerial photos and color-coded images, and found that it is more important to use higher resolutions in the urban data set compared with the landscape data set due to the sharp material boundary edges in the urban environment such as road lines, etc. This is illustrated in Figure 19.

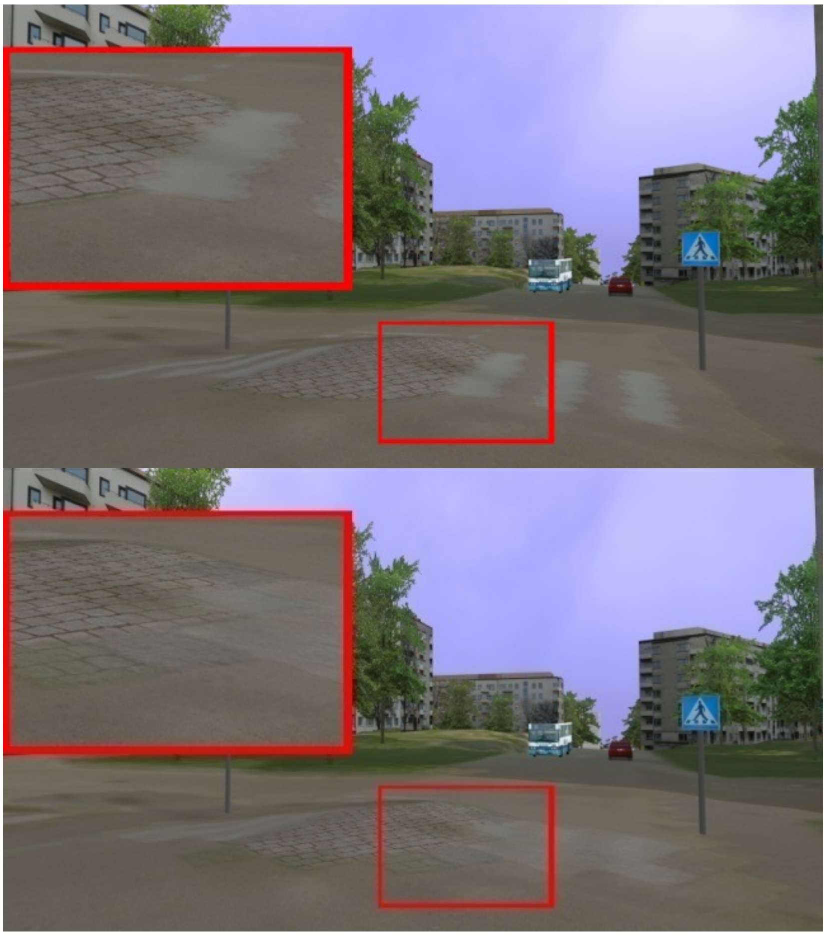


Figure 19. In the images above, pedestrian crossing lines become blurred and lose their boundary edges in the lower image. The upper image has a resolution of 0.2 m/pixel whereas in the lower image the aerial photo is at 0.2 m/pixel and blended color-coded material has a resolution of 0.8 m/pixel.

The advantage with the color-coded image technique is that aerial photos with lower resolutions can be used and the visual quality and rendering speed will still be adequate. A further development of this technique would be to apply it to a web-based VR application. Typically, download speed is a bottleneck of this type of VR application. However, the use of the color-coded image technique could reduce the amount of data that must be sent over the web. As an example, with the color-coded image technique one can reduce the amount of data by 11 times. This is achieved by using a lower resolution on the aerial photos, but the visual quality will still improve, see Figure 20. For more details about the color-coded image technique, see Paper I.

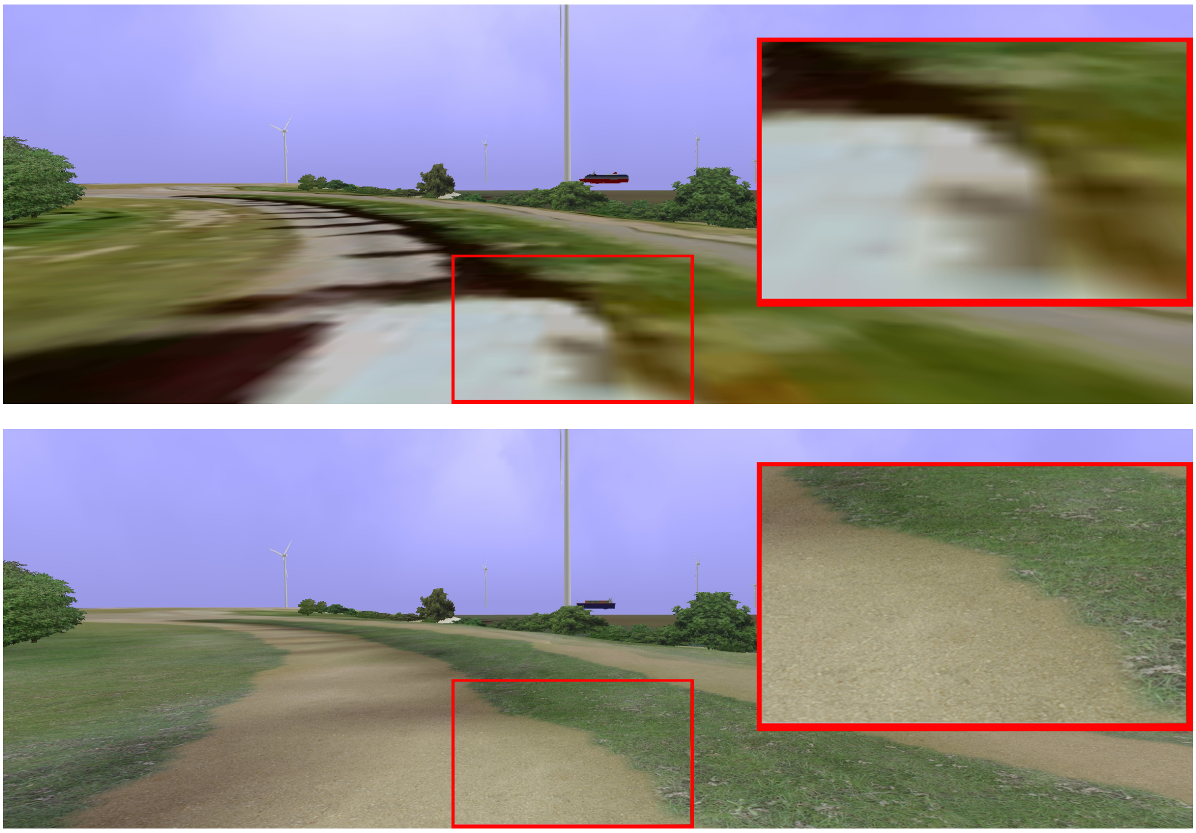
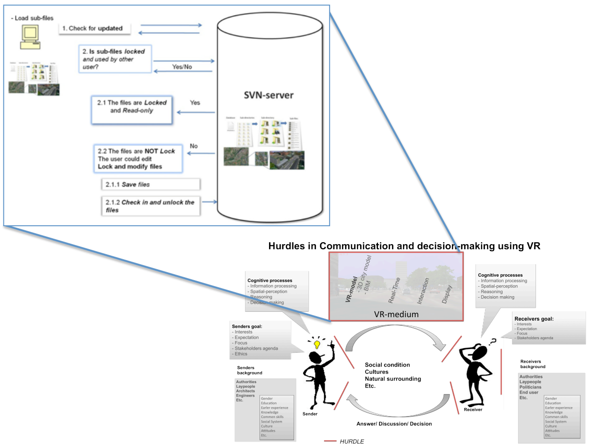


Figure 20. As seen in the images above, the color-coded image technique can reduce the amount of data 11 times and still enhance the visual quality. The first image has a aerial photo with a resolution of 0.2 m/pixel whereas the second image uses the color-coded image technique and has an aerial photo with a resolution of 1.6 m/pixel and the blended color-coded material has a resolution of 0.2 m/pixel.

4.2 Paper II: Supporting 3D city Modeling, Collaboration and Maintenance through an Open-Source Revision Control System.



Authors: *Mattias Roupé and Mikael Johansson*
Publication:
In Proceedings of *CAADRIA 2010 NEW FRONTIERS*, Hong Kong

4.2.1 Purpose

In this study the aim was to investigate the possibility of creating a revision control system, which could handle the creation and maintenance of large 3D city models. The storage and management of the models are a very important issue. The management issue is often that many people concurrently collaborating and working on the 3D city model. This causes administrative problems and results in unnecessary delays and wasted time for different users. During the wind farm project (related to paper I) we developed a paging system for real-time rendering of huge terrains. During the creation process of the model such management and revision control issues (paper I): Is this terrain patch the latest version?, Have you changed or worked with that terrain patch?, etc. were encountered. During the project we spent a lot of time trying to have control over the management and revision control of 3D model. Revision control is a vital component of digital project management, and has been widely used for text files during software development (Collins-Sussman et al., 2007). There have also been efforts to use CityGML[14] with an Oracle database, which would make it possible to get version control into 3D city model management. However, this type of system is costly and demands a high level of expertise in the field from the end-user. Another drawback with CityGML is that it is text based and

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[14] *CityGML – is a file format that are XML-based, for the representation, storage, and exchange of virtual 3D city and landscape models.*

file sizes are very large (Curtis, 2008; Stadler et al., 2009). Additionally, processing data from a 3D city model in a Oracle database extremely time consuming, and it is therefore not the best solution when different users are working towards a deadline nor for daily work. The problem is exacerbated when large 3D city models contain huge amounts of data that has to be stored and processed when it is used. The optimal solution for these type of tasks is to use a binary file format. Our purpose was to try to integrate a revision control system into our application which could handle this type of binary files.

4.2.2 Method

In this paper we tested the possibility of using the same version control system, TortoiseSVN, which we used during the development of our software, but using it here to facilitate managing a 3D city model. However, the 3D city model in this case contained files with binary data. Our system is arranged in a hierarchical structure with multi-resolution of textures and geometries of the terrain. Handling textures of arbitrary size is done by splitting the aerial photo texture into smaller sub-textures, each sub-texture being small enough to be displayable by the graphics hardware. The geometry is cut and simplified against the sub-texture boundary. A paging system is used in combination with a level-of-detail system that makes it possible to render huge terrains or 3D city models that exceed available graphic memory. The editing of the 3D city models has been solved by a user-interface where sub-areas of the model are loaded through an "area-palette". In this user-interface the users choose sub-areas to load and edit. As the database used in our software for 3D city models is essentially a number of external references stored on disk, it is very well suited for use with SVN, see figure 21. To validate the version control system we tested it during the creation and visualization process of three different urban planning projects that used VR and the 3D city model.

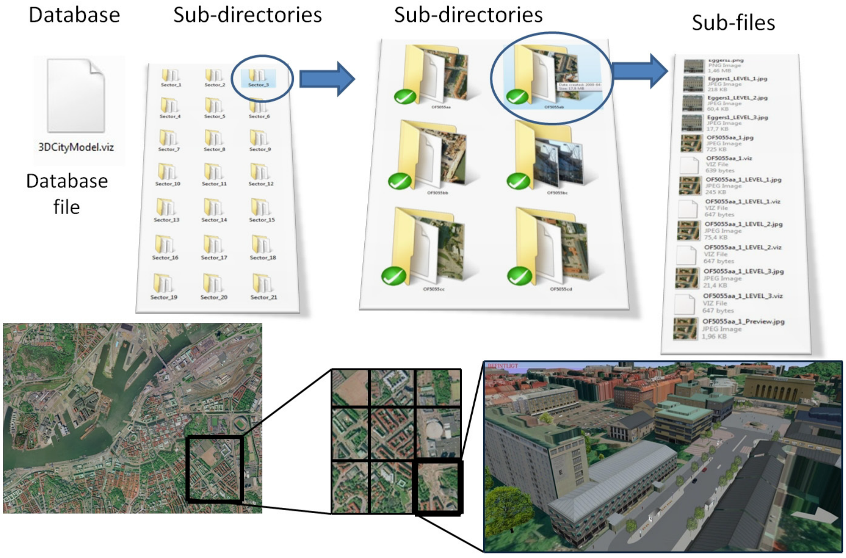


Figure 21. The 3D city model has been divided into sub-areas. The sub-area is stored into sub-directories and sub-files as illustrated in the figure.

4.2.3 Result

A result of the study was that we created a semi-automatic user-friendly interface for the SVN system. The main framework for the version control system of the SVN was implemented in the area-palette. When the user loads a sub-area of the model, the implemented SVN framework looks for updates in the server and if any other user is just then working on that specific sub-area of the model the user receives a message and is granted limited read-only access. If a user gets read/write access then the sub-area and its sub-files are locked by that user and other users can only be granted limited write access, see Figure 22.

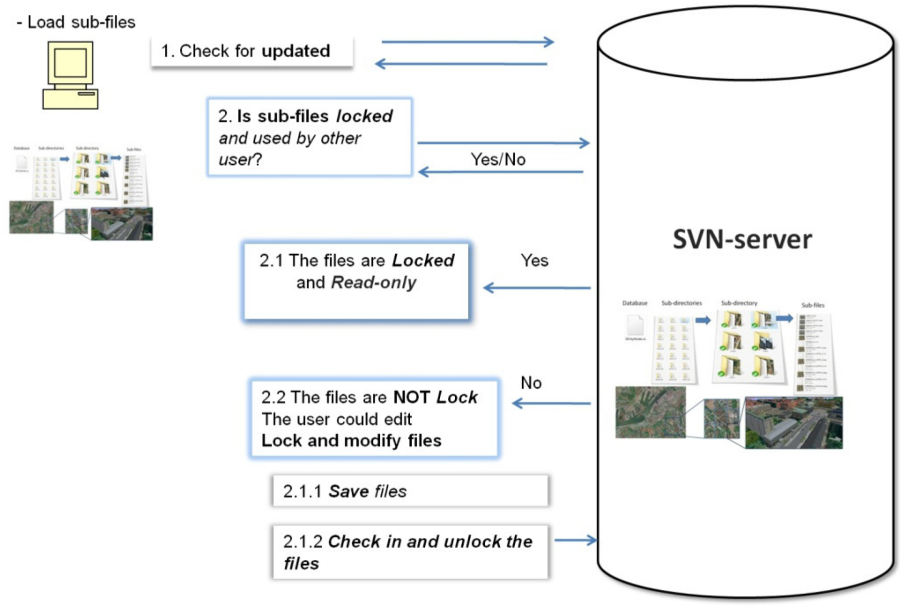
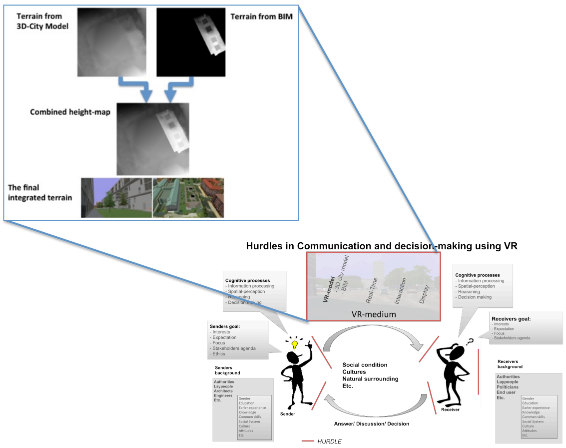


Figure 22. In the "area-palette" in MrViz a semi-automatic interface to the SVN system is implemented. The system checks for updates and whether anyone else is working on the specific sub-area of the model that the user wants to load.

The solution is based on the open-source version control system Subversion (SVN). This system is not as expensive or complex as the Oracle database, nor is it limited to a specific file format. The end-user of the system does not have to invest as much time and money compared with the more complex Oracle database. All the above-mentioned features in the SVN-system are also possible to do outside our interface in Microsoft Windows file manager. The limitation with the system is that it is not possible to trace changes inside binary files, so that trace capabilities are lower than in the Oracle database.

4.3 Paper III: 3D city Modeling: A Semi-automatic Framework for Integrating Different Terrain Models.



Authors: *Mattias Roupé and Mikael Johansson*
Publication:
Advances in Visual Computing, Lecture Notes in Computer Science 2011, Volume 6939/2011, p. 725-734, *Springer Berlin*

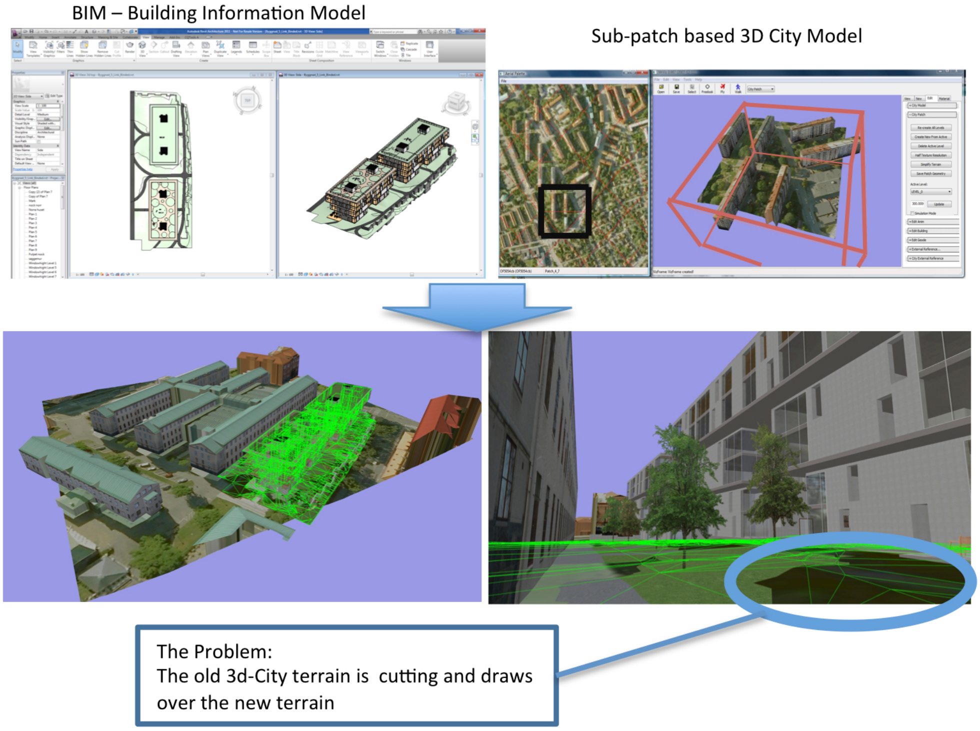
4.3.1 Purpose

In this study we focused on how to integrate the building and it surrounding ground from a Building Information Model (BIM) into the 3D city model in an efficient manner. Recent research in this field has been focused on visualizing large landscapes where GIS and cartographic vector data have been projected into terrain (Bruneton et al., 2008; Vaaraniemi et al., 2011). In this context, the landscape visualization focus has been on macro level, e.g. viewed from a long distance from the objects. Additionally, Vaaraniemi et al. (2011) connected different land features using a multi-layered interface where different cartographic vector data are sequenced after each other and rendered into the height-map. Santos et al. (2008) presented another related height-map approach which used height-maps from different viewpoints to construct 3D geometry. This approach was similar in behaviour to Constructive Solid Geometry in performing Boolean operation with the multi-layered height-maps.

The aim with our approach was to develop a terrain-editing framework that would semi-automatically solve conflicts emerging from interactions between the terrain and other terrain features such as adding new terrains or buildings, see Figure 23. These tools and methods have to suit the existing planning pipeline in the urban planning and building design process. It is therefore important to have a 3D city model into which new planned buildings and environments can be efficiently integrated.

Our objective had been to:

- Find a semi-automatic way of joining different terrain models, such as an existing 3D city model and a 3D model of a planned building together with its surroundings, see Figure 23.
- Combine image-based and geometry-based modeling that can enhance control for the 3D artist.
- Facilitate the export of TIN models to other software



The Problem:
The old 3d-City terrain is cutting and draws over the new terrain

Figure 23. The image illustrates a problem in integrating new buildings (Building Information Models, BIM) into the 3D city model. Old 3D city terrain imagery cuts into or is drawn over the new BIM ground.

4.3.2 Method

There is no definitive solution for how to create, edit and render terrain. Image-based modeling and geometry-based modeling are the two main techniques employed for representing terrain. Both these techniques have their drawbacks, for details see section 2.1.2. The presented terrain-editing framework facilitates the use of both the image based and geometry-based approaches for editing and rendering terrain in a 3D city model. The main objective was to combine the two techniques and their respective benefits.

Our terrain-editing framework is integrated into the MrViz software application. MrViz can visualize and edit 3D city models, and includes a patch or tiled based system that handles the paging of the 3D city model. The system is arranged in a hierarchical structure as described in paper II, see Figure 21.

The validation of the terrain-editing framework was performed on an example model taken from a student project from an urban planning course. The students in the course had to design buildings and the surrounding ground in a BIM-system. Their final task was to integrate the BIM model into the 3D city model and its representation of the existing surrounding environment. Using our terrain-editing framework, we tried to accomplish the same task of integrating the BIM model into a 3D city model, see Figure 23.

4.3.3 Result

The result from this study is a terrain-editing framework that supports the integration of two or more terrain models into one integrated terrain model. It also handles the common problem of integrating new buildings and associated terrain with the terrain of a 3D city model. These types of problems are complex and not easy to solve intuitively when using manual modeling systems. Further, because manual modeling systems are complex and require extensive 3D modeling experience they set high demands on the end-user. Manually stitching together this type of models is often very time consuming and requires enormous amounts of effort.

In our implementation the user starts by selecting the terrain sub-patches that are going to be edited. The next step for the user is to import the 3D model that will be integrated into the 3D city model. Once the imported model has been placed in the right location, the different terrains are converted from a TIN to a height map by utilizing the depth buffer on the GPU, see Figure 24.

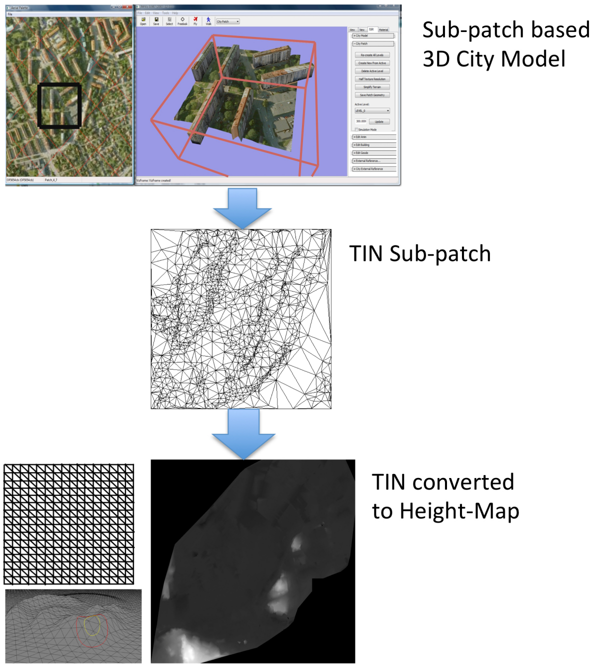


Figure 24. Our approach utilizes the depth buffer on the GPU to convert the TIN sub-patch terrain into a height map.

The joining of the terrains is achieved using a multi-layer approach. The multi-layer approach is done by sequencing the terrain models after each other and uses the GPU to render them into the depth buffer. The result is a height map representing the joint terrain. The process is almost fully automatic, see Figure 25.

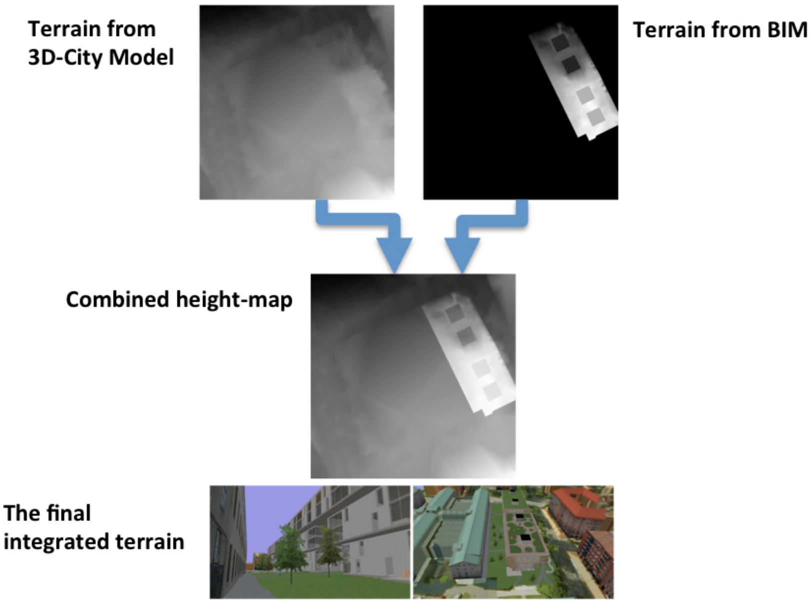


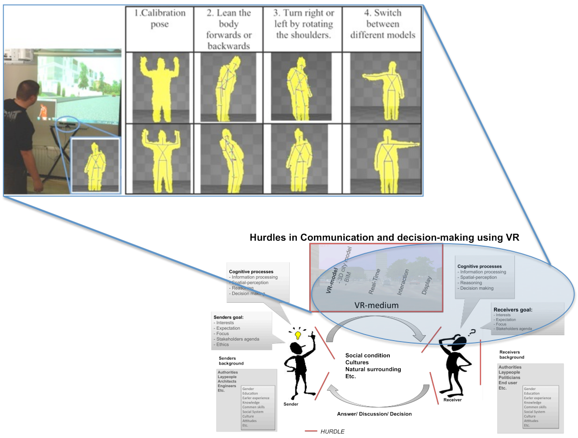
Figure 25. The figure shows how our framework uses the depth buffer to render new ground into the existing height map. The result is terrain merged from the two models.

The developed semi-automatic method was compared with the older method the students used in their projects, and the results showed that the integration of the two terrains took less than a half an hour, while the older method used 6-8 hours (our approach 12-16 times faster). Our framework also supports the use of different temporary geometries that can be sequenced after each other and be rendered into a height map. This approach is similar in behaviour as the Constructive Solid Geometry technique making it possible to perform Boolean operations on the terrain in 2.5D.

The limitation with this approach is that the resolution of the height map sets the resolution of the terrain, which is pixel based, and can give rise to some artifacts. However, this artifact issue can be overcome by cutting up the terrain into sub-patches that can support higher resolutions of the terrain. These modified terrain patches are later finalized into TINs that can present the terrain in a more compacted manner. TINs can also depict sharp edges and boundaries in the terrain better than the height maps.

The benefits of our approach in terms of productivity are that it almost automatically solves conflicts that emerge when different terrain features and terrains are merged together.

4.4 Paper IV: Interactive navigation interface for Virtual Reality using the human body.



Authors: *Mattias Roupé,* Petra Bosch-Sijtsema, Mikael Johansson
Publication:
Submitted Journal Paper to Computers, Environment and Urban Systems, Elsevier.

4.4.1 Purpose

In this study the aim was to find a user-friendlier and more natural way to navigate and interact with the virtual environments in the context of urban planning and building design. Here, the interaction interface has always been a problem in situations where clients or end-users do not have the self-confidence to handle the VR themselves. Because of the complicated interaction handling, the consequence has often been that the end product from a VR has been rendered images and movies, which the clients' self-confidence permits to show to the general public. As a result, the full potential of the VR, in terms of enhanced communication and understanding regarding future projects, is not utilized. Recent research has also suggested that rotation and movement of the human body has a positive influence on the spatial perception of 3D space (Ruddle & Lessels 2009; Riecke et al., 2010). Additionally, the release of the XBOX Kinect sensor gave an opportunity for us to explore and use this device to track the users' body movements and employ it as an interactive interface for navigation in the virtual environment. Recent years several studies have investigated support for hand and arm gestures using XBOX Kinect (D'Souza, et al., 2011; Fiorentino, et al., 2012; Park, et al., 2012; Stannus, et al., 2011). However, the result from these studies has shown that users get slightly fatigued after 8-10 minutes of continual usage because of the continual movement of the arm (D'Souza, et al., 2011). We argue that by using physical-human rotation and movement during the navigation is not only user-friendly but will also enhance understanding of the visual space.

We also wanted to investigate if the human-body interface was perceived as better than mouse/keyboard interaction, and if navigation with the body has any impact on the user's spatial-perception and reasoning of the space. Furthermore, we wanted to investigate if the on-demand switching interface that was used in the study (Sunesson et al., 2008; e.g. Roupé 2009) had any effect on the usability and reasoning process about how the jury used it in judging city library proposals. The result from this study showed that the jury thought it was a pedagogic medium and that it enhanced the understanding of the different proposals. Is it possible that the on-demand switching interface had enhanced the learning, understanding and the reasoning process?

4.4.2 Method

The study was conducted with students and researchers at the Chalmers University of Technology, Sweden. The study was sub-divided into two experiments; *a human body navigation experiment* and *a mouse/keyboard navigation experiment.* The *human body navigation experiment* was conducted with 55 students and 4 researchers. 35 of the respondents were male and 24 were female. The *mouse/keyboard navigation experiment* was conducted with 20 students and 2 researchers. 12 of the respondents were male and 10 were females.

The tasks the respondents had to perform was to examine and explore two different urban environments, see figure 26, using the navigation interface (XBOX Kinect sensor or mouse/keyboard).

Figure 26. a show the first task were participates conducted a volume study of a new building. b-d shows the second task where the participants had to examine and explore a VR model of three different architectural proposals and to decide on which they perceived as the best.

The first task was a volume study of a new building. The respondents had to answer questions related to a building's volume form and size. The second task was to examine and explore a VR model of three different architectural proposals for rebuilding of the city library. This model was used in our study Sunesson et al. (2008) (also in Roupé 2009).

In the *human body navigation experiment* we grouped the participants so that one group were given the ability to do on-demand switching between the different proposals while the other group had to look at the proposals in a sequence with loading time added between the different proposals. The validation of the on-demand switching was done in the last task, which was to identify the proposal they saw in their earlier task, see figure 27.

Figure 27. To validate the switching interface the respondents had to identify which of the alternatives they had seen in their earlier task. (Here alternative 2)

During the trials the respondents together with investigator filled in a web questionnaire that was displayed next to VR model. The questionnaires used seven-step scales for some questions whilst other questions were open-ended. The questions in the questionnaire were related to user experience, i.e. how the users experienced navigation, spatial-perception, the architecture of the 3D models and finally decision-making in the virtual environment.

This study was a part of a larger study that also contained the study concerning judging and decision-making of VR models, and which is presented in paper V VR model.

4.4.3 Result

The paper presented how interaction and navigating in virtual environments with the human body can be achieved (see Figure 28). The main aim with the implementation was to implement a user-friendlier and more natural way to navigate and interact with virtual environments in the context of urban planning and building design. In order to enhance an initial user-friendly experience we wanted as few degrees-of-freedom as possible. We were afraid that too many degrees-of-freedom would complicate the navigation. In this study we therefore chose to use two degrees-of-freedom, forward/back and left/right, together with the on-demand switching interface.

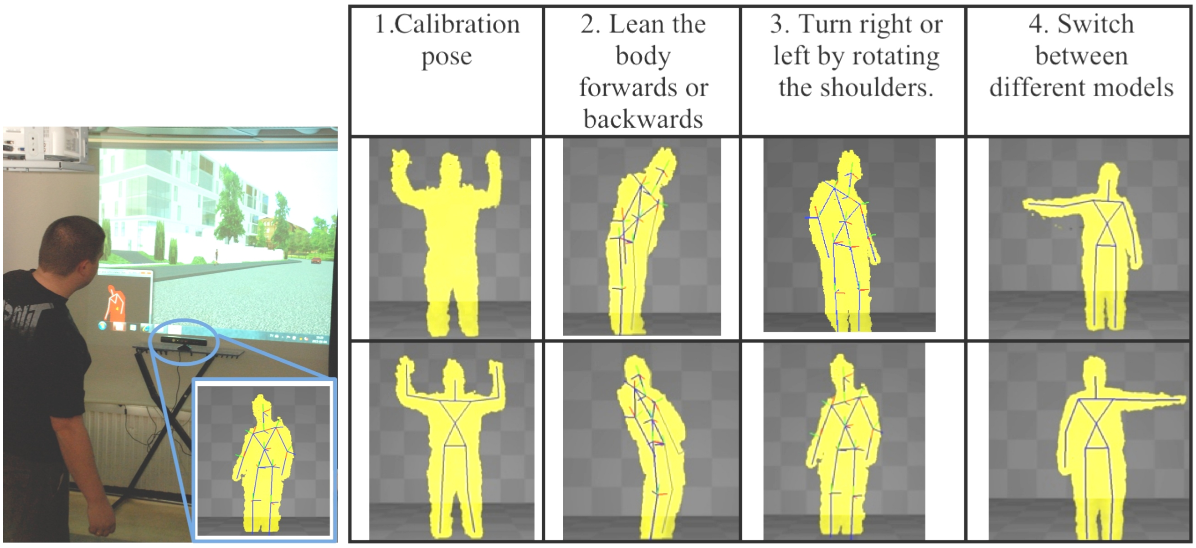


Figure 28. The different human body movements, poses end gestures that trigger interaction and navigation in the VR environment.

The results showed that most of the respondents thought that the interface using the body for navigation was easy and undemanding, and the analysis of the data from the study showed that males perceived the navigation as more strenuous then females.

The result also revealed that switching between different architecture proposals using the on-demand switching interface led to better learning and understanding and reasoning of the proposals. This could be due to the fact that the on-demand switching respondents had the opportunity to be in the same virtual space (i.e., egocentric and *allocentric* reference frames), which decreased the cognitive load associated with creating images representing the other proposals in their minds and that this helped the processes involved in spatial-reasoning and visual working memory.

Furthermore, the participants mentioned that the navigation with the body gave them a better understanding of size proportions in the model. This is in line with the literature on spatial perceptions which has reported that physical human rotation and movement enhance spatial reasoning (Bakker et al. 1999; Burgess 2006; Klatzky et al. 1998; Lathrop & Kaiser 2002; Pausch et al. 1997; Ruddle & Lessels 2009; Riecke et al. 2010).

As the result shows, see figure 29, the human body interface respondents initially perceived the interface as easier and less demanding in relation to the mouse/keyboard interface respondents. Furthermore, no difference was found between gamers and non-gamers when navigating with the body, whereas in the mouse/keyboard experiment differences were found. An observation during the mouse/keyboard experiment was that users who had not previously used the mouse/keyboard interface used often only the W-key (to go forward) together with the mouse while they navigated in the VR model. This limits the degrees-of-freedom to three.

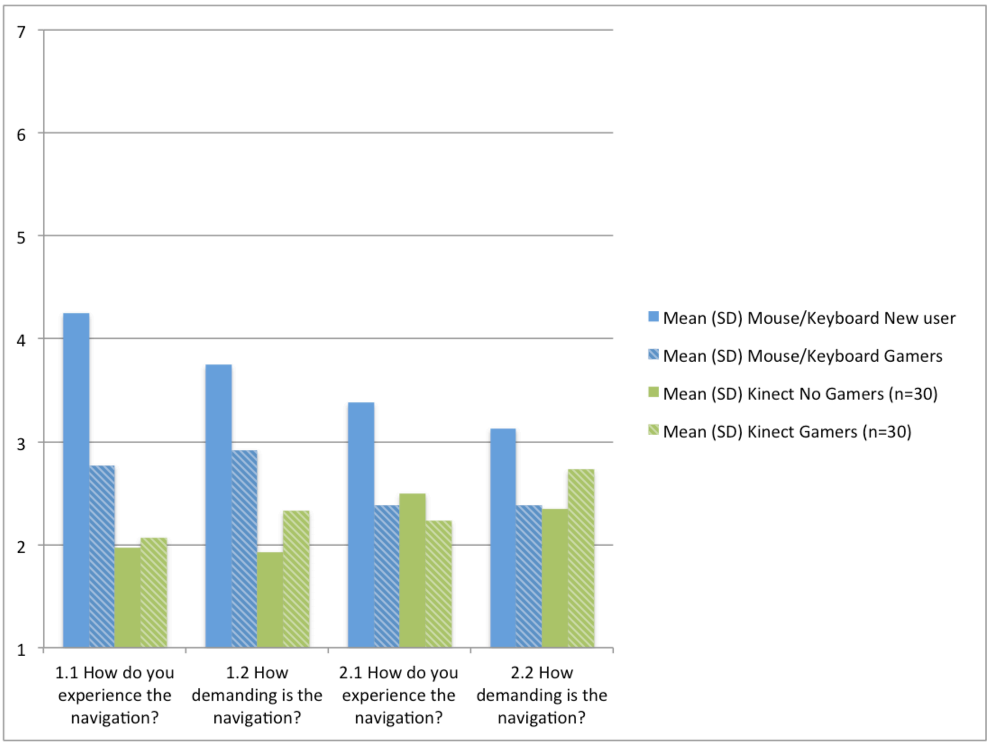
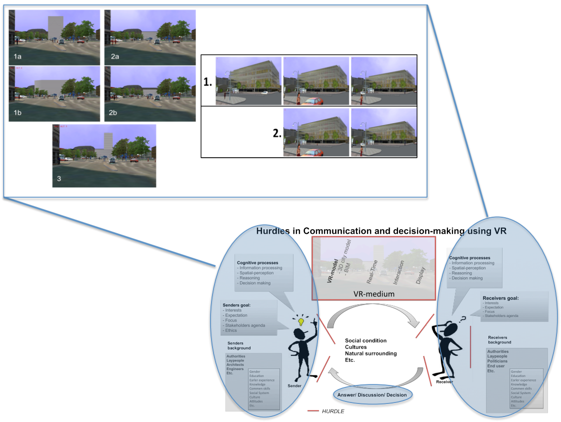


Figure 29. Subjective experience of mouse/keyboard and Xbox Kinect navigation interfaces for new users/no-gamers and old users/gamers.

The result showed that respondents stated that it was harder to navigate using the body to navigate at the end of the experiment, see figure 29. It was observed during the experiment that participants thought comparing the different proposals was difficult during the second task. They put a lot of effort in navigation to gain good views in order to explore the different proposals. Additionally, the participants also gave some comments on what they felt was missing, and what limited their experience of the interface, e.g. slow walking speeds and the need for more degrees-of-freedom in the manipulation of the view. In the future we will try to add the pitch (look up/down) degrees-of-freedom to the interface. This could be achieved by tracking the head, eyes or nose, all of which provide information on what the user is looking at.

4.5 Paper V: Biased judgment and decision-making when using Virtual Reality in urban planning



Authors: *Mattias Roupé* and Mathias Gustafsson
Publication:
Submitted Journal Paper to Environment and Planning B: Planning and Design, Pion Ltd.

4.5.1 Purpose

In this study we investigated how the VR medium can be used to influence or manipulate the decision-making process in urban planning and building design. During the years we have studied VR in urban planning and building design we have come across different stakeholders with different interests in the outcome of the planned project. This observation led me to wonder whether the VR medium could be used to influence or manipulate the outcome of the decision-making process as well as whether, and how, process stakeholders unconsciously do so. Another point of reflection was how contextual factors and circumstances of the VR medium, such as how the VR model is presented, change the spatial reasoning and experience. There are a lot of theories on judgment and decision-making that address these issues (see section 2.3 and 2.5). However, to our knowledge none focus on this type of context. The paper addressed the participants' judging processes and how on-demand switching influence spatial-reasoning.

In this paper we addressed the following questions:

1. What visual information is used during spatial-reasoning of the volumes?
2. How do visual reference points and anchoring points influence, how the visual environment is experienced?
3. To what extent can reference points in the VR-medium, influence the outcome of decisions in the context of urban planning and building design?

4. Does on-demand switching between different proposals in the VR-medium enhance learning, understanding and spatial reasoning and thereby facilitate better decisions?

4.5.2 Method

The study was conducted with students and researchers at the Chalmers University of Technology, Sweden. As previously mentioned, this study together with the study “Using the body as an interactive interface for navigation in VR models” described in paper IV, was part of a larger inquiry. The methods used in both papers are quite similar. However, compared to paper IV this paper highlights the respondents’ judgment of the volume of a new building. The respondents explored and judged two different urban environments using the XBOX Kinect sensor for navigation of the VR models, both of which are taken from real projects. The first sub-experiment is taken from a volume study that was carried out in 2008 by the city authority of Gothenburg, Sweden. In this volume study, the City planners and the local politicians were presented four different volumes that they had to judge and then decide which of volume alternatives would be selected for further architectural design. The second sub-experiment is from the architecture competition regarding the rebuilding of the city library in Gothenburg (also studied in Sunesson et al., 2008; e.g. Roupé 2009). The first task was a volume study of a new building where the respondents had to answer questions related to a building’s volume, form and size. We wanted to investigate if there were any visual framing effects from visualizing the volume study in this manner. To investigate this we chose to use 1a and 1b from the real study together with the volume 3 that is currently being built, see Figure 30. We also created two new smaller volumes that would represent a smaller alternative to the new volume. The task for the respondents was to judge the volume of the building that is being built, see Figure 30 (alternative 3). The participants were sub-divided into three groups; the first group saw building volumes 1a, 1b and 3, second group saw building volumes 2a, 2b and 3, the third group saw only building volume 3, see Figure 30. All of the sub-groups explored and judged their presented volume alternatives. However, it was only the third the alternative that was considered in the questionnaire in this study.

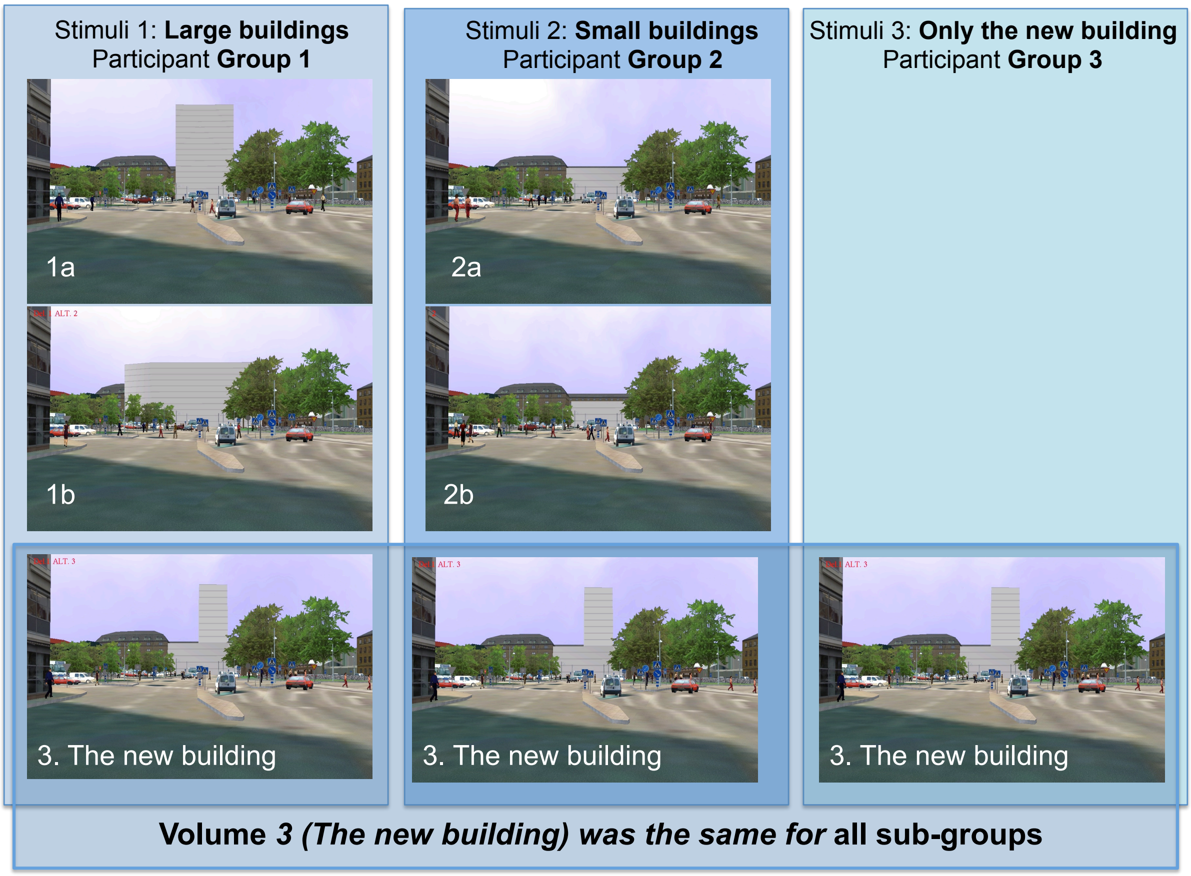


Figure 30. The participants were sub-divided into three groups and had to conduct a volume study of a new building. The first group saw building volumes 1a, 1b and 3, the second group saw building volumes 2a, 2b and 3, and the third group only saw building volume 3.

The second task for the participants was to explore and judge three different architectural proposals of the rebuilding of the city library, also studied in Sunesson et al. 2008, (e.g. Roupé, 2009), see Figure 31.

In this sub-experiment we wanted to investigate if on-demand switching between the different proposals affected the participants judgment of the proposals as well as how it affected the judging process. The participants were sub-divided into two groups, one group had the ability on-demand switch between different proposals while the other group had to look at the proposals in a sequence with loading time added between the different proposals.

Figure 31. The participants had to examine and explore a VR model containing three different architectural proposals and to decide on which they perceived as the best.

In the third sub-experiment we wanted to investigate if on-demand switching between the different proposals affected visual memory, which is related to cognitive load, learning, understanding and reasoning (Ayres & Gog, 2009; Hollender, et al., 2010; Sweller, et al., 1998). This was conducted by test if the respondents actually remembered the first architecture proposal and if there were any effects caused by how the visual alternatives were presented to the respondents. The task of the respondents was to find the first architecture proposal they seen earlier. This was done by presenting the first architecture proposal alongside one or two added modified alternatives, see figure 32.

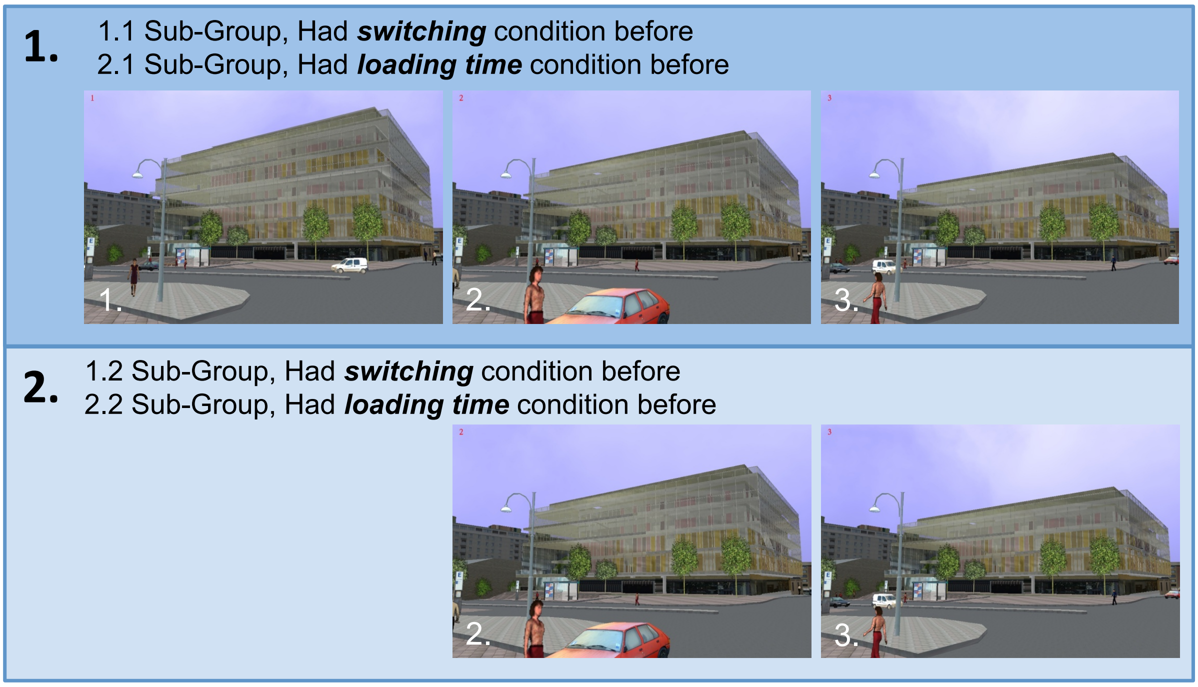


Figure 32. To validate the on-demand switching interface and to test how it affected learning, understanding and reasoning, the respondents had to identify which of the options corresponds to the proposal number 1. Alternative 3 is the correct response.

Added height to the building was the main change that modified the alternatives. The respondents were sub-divided into four sub-groups depending on if they were or were not able to switch between the architecture proposals in sub-experiment 2, and if they had two or three alternatives to choose from, see Figure 32.

4.5.3 Result

Sub-Experiment 1 demonstrated that participants were influenced or affected in their judgments when presented with other building volumes before they judged the size of the new building volume. This can be observed in case 1 when it is compared with cases 2 and 3, see Figure 30. In case 1, the participants were presented two larger volumes before their judgment, which made them perceive the volume as smaller than cases 2 and 3. The larger volume seemed to provide a visual reference point, which in turn affected their judgment. Another interesting observation is that the respondents did not think that the previous volumes affected their judgment of the building volume, though the results clearly showed the opposite. Furthermore the viewer uses the façade textures of the surrounding existing buildings and familiar details such as cars, people/avatars and trees during spatial-reasoning for understanding sizes, which is in the line with research on spatial-perception (Biederman, 1990; Burgess, 2006). It is therefore important to add such visual features in the VR model or it can affect the spatial-perception negatively.

The results from *Sub-Experiment 2* showed that the switching condition and the loading time condition affected how the participants judged the proposals differently. The participants that experienced loading times gave higher scores on the architecture related questions for alternatives 2 and 3. This result shows that the respondents that had seen the other alternatives rank the different alternatives relative to each other. In contrast, respondents in the other group that experienced the loading condition instead judged the first architectural proposal relative to a self-generated heuristic value. Later on, when being presented with the next architecture proposal they adjusted their judgment towards their initial estimate of the first proposal. This phenomenon is in line with adaptation level theory (Helson, 1948; 1964; Frederick & Mochon, 2012). People compare a perceptual input with a certain reference point (e.g. "adaptation level"), which once created is maintained in the subsequent evaluations. However, in this context the result shows that the respondents favoured the same proposals for both conditions and no significant differences were found on the question regarding which proposal they favoured most.

The results from *Sub-Experiment 3* showed that the on-demand switching interface helped respondents to better be able to conduct spatial reasoning as well as to better remember the first proposal. The use of this interface gave respondents the opportunity to remain in the same visual space when engaged in spatial reasoning regarding the different proposals. The sub-group that did not have switching did not perform as well on this task. Furthermore, in absence of relevant information, intuitive judgments of proportions might become more easily activated in the decision-making processes as emotions and aesthetics gain primacy over reasoning (Reber et al., 2004). The result of this reasoning process is that respondents experience less effort when making judgments based on emotional or aesthetically pleasing proportions (Alter & Oppenheimer, 2009; Reber et al., 2004).

In the switching condition the difference observed between seeing two vs. three alternatives can be explained by the fact that the first larger alternative - in the case involving three alternatives - had a significant impact on the decision, even if respondents rejected that alternative early in their reasoning processes. The first initial information, the large alternative, unduly influenced their reasoning about subsequent information. This result shows that the initial visual information has a profound impact on participants' decisions, even though they are aware that the initial visual information has no validity.

5 Discussions and Conclusion

This section discusses the research questions considered in sections 1.2 and contributions to theory based on the results from the five articles. The aim has been to *provide tools* and *methods* that can *improve the use of VR* in practice in the urban planning and building design process. In order to achieve this the VR medium has to be considered in the context of communication and decision-making in urban planning and building design process. Figure 33 presents a simplified representation of how, due to different attributes and contexts, various hurdles arise in the communication and decision-making process in urban development and building design. In the figure hurdles are illustrated as red lines. This figure is based on the research presented in this thesis and discussed in section 2.

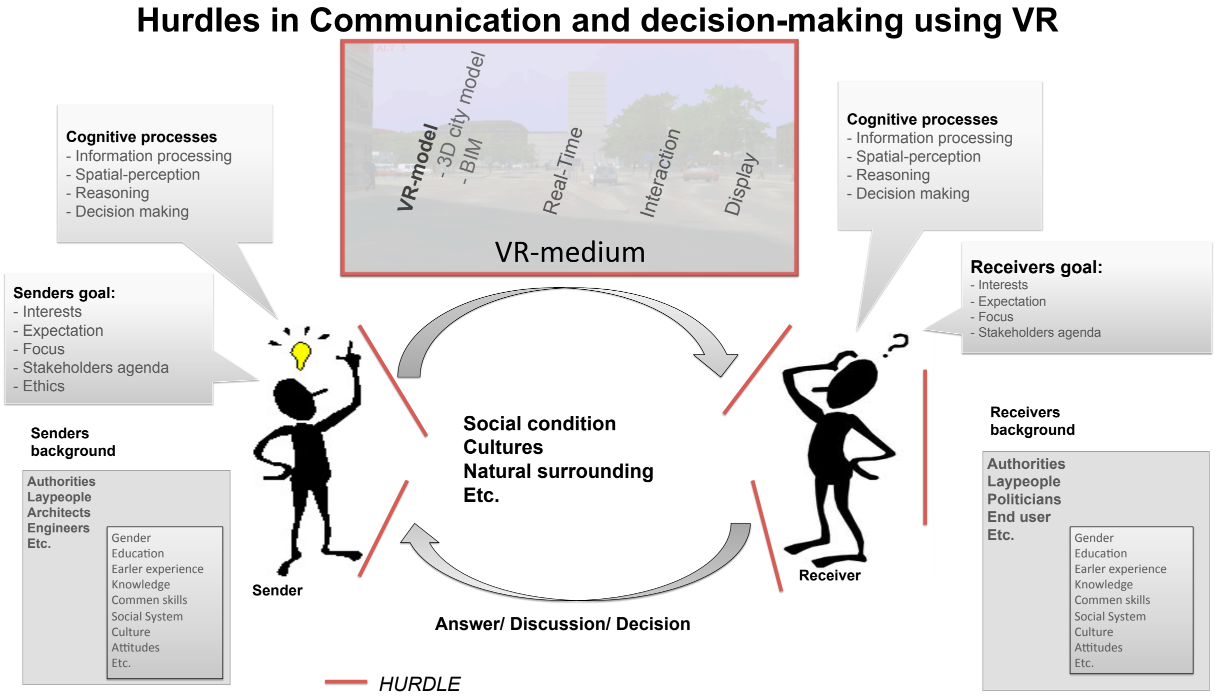


Figure 33. The figure shows the different hurdles often found in the communication and decision-making process when VR is used. These hurdles change the outcome of the process and may give rise to bias. (See also Figure 1 (page 7), for a larger version of this figure).

There are both human and technical issues that cause these hurdles. The human issues are related to information processing and to people with different backgrounds and interests decoding and encoding information differently (cf. Atkinson & Shiffrin, 1968; Galbraith, 1974; Lindsay & Norman, 1977). The underlying cognitive processes are processed differently depending on the surrounding context, and on the backgrounds and interests of the sender and the receiver. There are also technical issues, generally related to the VR medium and how the VR models are presented to the receiver.

In this thesis focus has been on the integration of VR as a communication and decision-making medium into the urban planning process. In this context it is important to create tools and methods that are effective for producing VR models. If the development cost and time for the creation of VR models are too high, VR might not be a suitable medium for the urban planning process. This issue is also related to how detailed or abstract a VR model ought to be and how it should be used. If the 3D artist has to put all his/her effort into the modeling of the existing surrounding environment there will be few resources left for 3D content or features that enhance the end-viewer's perception of the VR model. This will also affect the design process, as more resources will have to be allocated to the visualization part of the project (Heldal & Roupé, 2012). Another big hurdle for the usability of VR and human information processing rises when the end-user cannot handle the interactive navigation interface (Ware & Plumlee, 2005). It is therefore important to find suitable interaction interfaces that are user friendly and support users existing skills.

This discussion and conclusion section is organised by aims and research questions and starts with the technical research related questions, which have provided tools and methods that can improve the use of VR in urban planning and building design. This section will focus on technology related hurdles concerning the construction of a 3D city model and how new buildings can be added and viewed in VR. This will be followed by a discussion about the usability of the VR medium and how it affects the decision-making process. Finally, the findings will be linked to figure 33 and a discussion of how can the VR medium be used in decision-making in urban planning and building design.

5.1 How can VR be integrated in an efficient way into urban planning and building design?

The overall goal with this research question was to find a way to integrate VR into the existing urban planning and building design process. To achieve this goal, the creation of the VR model has to be both time and cost efficient. In the applied project studied in Westerdahl et al. (2006), (e.g. Roupé, 2009), we spent a lot of time with hands-on modeling of the existing built environment by using the base map of the City Planning Authority of Göteborg. The base map was used as reference to ensure correct volume size when creating buildings. In the base map, information about roofs and the ground is represented as 3D lines. In the process of creating the existing built environment, we were interested in finding a more efficient development approach. The existing built environment is a vital part of the process when the VR medium is used in urban planning, because it is used in depicting how the new building will interact with its surroundings and also as it helps the viewers to orientate themselves in the VR model.

5.1.1 How can 3D city modeling support visualization of urban planning and building design?

To address the time consuming hands-on modeling of the existing built environment, we developed a framework that could semi-automatically create a 3D city model using the information contained in City Planning Authority base maps. The framework is based on earlier studies (Roupé & Johansson, 2004; Johansson & Roupé, 2005) and the papers presented in the thesis build further upon this framework. The result from this framework is a tool that creates the city center of Göteborg in only 5 minutes (see Figure 9). Before this tool was created, it took days to create the same amount of area. A similar approach, using GIS data, could be found in literature by (Buchholz et al., 2006; Yao et al., 2004; 2006). Our tool resulted in a time and cost efficient way of creating the 3D model of Göteborg. Because of this, the City Planning Authority of Göteborg is using this tool on a daily basis to perform different analyses such as volume studies, etc.

As mentioned in sub-section 2.1, the use of 3D scanning from helicopters, known as LiDAR, together with photo geometry is in increasingly common use today to create 3D city models and 3D GIS-data (Döllner, 2009; Leberl et al., 2012; Li & Chapman, 2008; Wang et al., 2008). However, it is mainly used for creating *new* GIS-data. In many cases the City Planning Authority has an existing base map in 2.5D that is kept up-to-date using aerial photos as a source. In this context, our tool to create 3D city models can be used for several more years. When discussing 3D city models, there are a number of important issues to consider and these issues are taken up in paper II: how to keep a 3D city model up to date; how can different users collaborate in the model; and how to handle the maintenance and management of a 3D model that contains very large amounts data. In paper I (wind farm project) a large number of collaboration, maintenance and management issues occurred. In Paper II we showed that these issues can to some extent be solved by a version control system used in the software development, TortoiseSVN. Version control systems have been widely deployed for text files in software development, but binary files, that we use in our VR project, have up until now received less attention. One of the problems with large 3D city models is that they contain huge amounts of data that have to be stored and processed when it is used. In the rendering system that was developed this issue is solved by arranging the geometries and textures into a hierarchical structure with multi-resolution of the terrain and the buildings. In our case we used a sub-patched system where the different patches of the 3D city model are external referenced files that are edited via an “area-palette” interface. TortoiseSVN was therefore an attractive solution, because we could implement version control on the external reference files. The version control implementation was added to the area-palette editing interface. The advantage is that the users use the area-palette interface to load and unload sub-patches while working with the 3D city model and this offers natural integration of the version control system. The limitation is that different user cannot concurrently edit the same sub-patch. Unlike other solutions and systems described in the literature (Curtis, 2008; Stadler et al., 2009), our solution is easy to implement and the end-user is not burdened with high demands in the form of high costs and high levels of required expert field knowledge. The support for collaboration in our solutions is extremely valuable during deadline rushes as huge 3D city models can be handled efficiently.

During the wind farm project we also tried to enhance the visual quality of the ground in the 3D city model, (Paper I). We developed a new algorithm to enhance the visual quality of the ground by blending aerial photos with tiled detail textures, see Figure 20. This algorithm was based on previous work done by Johansson & Roupé (2005), Woodard (2005), Mittring (2008). The new algorithm was applied in a wind farm project and was shown to be very time and cost effective as well as providing more enhanced visual quality and visual perception. This technique was also integrated into the above mentioned version control system, see paper II. Another advantage with the color-coded image technique is that it can greatly reduce download sizes when used on the web. A simple case study of an aerial photo showed that the download data amount could be reduced by over 90% with better visual quality when compared to using only aerial photos.

A *limitation* of the color-coded image technique is that it only works on computers that have programmable graphics hardware. Another constraint is that the technique doesn’t provide equally sharp boundary edges as does the surface-applied material and texture technique. Furthermore, the VR model that was used in Paper IV and Paper V (Figure 30) used a combination of 3D geometry and color-coded image techniques. This was done because we wanted to add height and sharp boundary edges to pavements and pedestrian refuges. However, if the user is working on a large terrain, the color-coded image technique is faster to use than the surface-applied material and texture technique. The main reason for this is that the user does not have to cut and manipulate the 3D geometry of the terrain to create the material edges or surfaces. This research area is still an on-going topic (Kooima, et al., 2009; Ferraris et al., 2012; Widmark, 2012). However, these new techniques are currently mainly used with the artificial terrains often found in games.

The use of aerial photos is the fastest way to apply ground material. However, the photos lack detail and look blurred when they are experienced from a pedestrian point of view in the VR model. According to Swedish law it should not be possible to identify people from aerial photos and therefore one cannot use a higher resolution than 0.07 m/pixel on the aerial photos. We have tested a resolution of 0.05 m/pixel but even that was not as satisfying in terms of visual quality as color-coded images. In the future perhaps a combination of aerial photos and the color-coded image technique together with hyperspectral images would prove to be a good solution. Hyperspectral images are images that contain more information than usual images and they could be used to analyse and select different ground material and provide the color-coded images automatically. This could be a very time effective way of automatically creating enhanced visual quality for ground material in 3D city models. It could be argued that this technique could be suitable in applications such as Google Earth, etc., to enhance the visual quality of the terrain. This could maybe be done semi-automatically through image-processing or from a hyperspectral image source.

In many of the projects we have been part of, the architect had the surrounding terrain modelled in a BIM model. However, based on these projects and reviews of the literature (Bruneton et al., 2008; Vaaraniemi et al., 2011) there are no straightforward solutions for combining the proposed building with the 3D city model. The same problem is also faced in infrastructure projects where the road and its neighbouring surroundings have to be stitched together. This is often a very time consuming task. In earlier research (Sunesson et. al., 2008; also in Roupé, 2009) we combined terrains by adding the new proposed ground over the existing terrain. However, this approach had limitations because in some cases the new terrain was lower than the existing 3D city terrain, which consequently meant that some parts of the 3D city terrain were deleted, which in turn caused gaps in the terrain model that hade to be stitched together manually. Based on earlier research (Bruneton et al. 2008; Vaaraniemi et al. 2011), and our findings in the papers I argue that TIN models are better for representing detailed areas in 3D city models because they can represent sharp boundaries better than image-based approaches can. However, the process of creating these types of models requires enormous manual efforts. Integration of both image-based and geometry-based manual editing operations therefore seems to be a very promising and powerful method, combining the best advantages of two worlds. The advantage with the image-based approach, i.e. height-map terrain, is that the terrain continues and do not produce any gaps that have to be modified manually. Another advantage is that grid data lends itself relatively easily for algorithm writing since the grids have fixed resolutions and can therefore be easily be stored in an index table data structure. The presented framework in Paper III also supports the use of different temporary geometries that can be sequenced after each other and be rendered into a height-map. This approach presents behavior similar to the Constructive Solid Geometry technique, which makes it possible to perform Boolean operations on the terrain in 2.5D. This method is an efficient tool when modelling and fixing artifacts that can appear when the two terrains are merged. By combining image-based modelling with geometry-based modelling, it is possible to facilitate more control for the 3D-artist.

5.1.2 How can we develop a user-friendlier navigation interface that supports a more natural viewer experience?

The navigation user-interface has always been a problem when new users are introduced to a VR system. Many clients and end-users do not have the self-confidence or knowledge required to handle a VR model using the complicated navigation interface provided. In an effort to ameliorate this situation, we decided to investigate if it was possible to use the human body as an interactive interface (e.g. Natural User Interface) for navigation. Several studies have investigated different types of navigation interfaces using XBOX Kinect with support for hand and arm gestures (D'Souza, Pathirana, McMeel, & Amor, 2011; Fiorentino, Radkowski, Stritzke, Uva, & Monno, 2012; Park, Park, & Kim, 2012). However, the result from these studies has shown that users get slightly fatigued after 8-10 minutes of continual usage because of the continual movement of the arm (D'Souza et al., 2011). We argue that by using physical-human rotation and movement during the navigation is not only user-friendly but will also enhance understanding of the visual space. To achieve this we implemented support for XBOX Kinect in MrViz. The results from the validation of the navigation interface showed that users found it was easy and not particularly demanding to use. An interesting finding was that male participants' perceived the navigation as more strenuous than females. Other studies related to VR and gender have shown that males perform better in VR in terms of navigation speed, navigation accuracy and pointing accuracy (Czerwinski et al., 2002; Waller et al., 1998; Astur et al., 2004; Lawton & Morrin, 1998). Based on the result of our study, it could be speculated that the participating females, due to their practice of aerobics, may have had better existing skills or control over their body movements, which facilitated the proprioceptive tasks. Furthermore, the respondents thought that the navigation with the body gave them a better feel for sizes and proportions in the model. This is in line with the literature on spatial perception, which has shown that physical human rotation and movement enhance ability to engage in spatial reasoning (Bakker et al., 1999; Burgess, 2006; Klatzky et al., 1998; Lathrop & Kaiser, 2002; Pausch et al., 1997; Riecke et al., 2010). Additionally, Mullins (2006) argued that the human mind uses the body to examine the size of the virtual environment. This assumption is related to the study by Ooi et al. (2001), which shows that eye-height is important when judging distance in 3D space. In comparison to the mouse interface, the human body interface was perceived as less demanding. However, the participants felt it was more demanding to use the interface towards the end of the experiment. They furthermore mentioned that they wanted to have more degrees-of-freedom for the manipulation of the view by combining yaw (turn left/right) and pitch (look up/down) rotation of the camera. In our implementation of the interface we wanted to try to have as few degree-of-freedom as possible since this could make interface use less complicated for new users. This could perhaps be achieved by tracking the head/nose/eye movements of the viewer. By doing this it might be possible to track what the viewer is looking at and move the view towards that direction. The mouse interface used in the experiment was implemented with five degrees-of-freedom. It was observed that the users who were inexperienced in using the mouse/keyboard interface would often only use the W-key to go forward and the mouse to manipulate the rotation of the view (yaw and pitch). This limited the number of degrees-of-freedom to three. We did not log the use of the other keys in this experiment. But participants did rate that the navigation interface was less demanding towards the end of the experiment. This might indicate that an implementation of pitch support in the Xbox Kinect interface could result in a better user interface.

5.2 How can the VR medium support viewers experience and decision-making in urban planning and building design?

The question concerning how the VR medium can support viewers' experience and decision-making was addressed in many of our applied projects (see section 3 for some examples). In earlier studies we addressed viewers' experience of the VR medium in decision-making in the urban planning and building design process (Westerdahl et al. 2006; Sunesson et al. 2008; *also presented in licentiate thesis, Roupé 2009*). These findings are included into the following discussion to present a permit broader coverage of the research question.

In Westerdahl et al. 2006, we studied how employees of a company *experienced* a VR model of a not yet built office building compared with their later perception of the completed real office building. The results from Westerdahl et al. 2006 showed that furniture, people, objects and perspective were the most often mentioned properties when it came to forming an opinion of the size of the room. In the study we did not ask the users about their perception of the room's size nor investigate whether the properties identified are actually important. The answers relating to these properties should, for that reason, be taken as purely indicative. This assumption is in line with literature that was presented in sub-section 2.4 about cognition and spatial perceptual of visual information (Biederman, 1990; Kosslyn, 1999; Yuille & Ullman, 1990). It is therefore important to add such features to the VR model. It could be argued that it is easier to get an impression and a spatial experience of larger rooms or spaces such as urban scenes rather than of small rooms that are common in visualizations of interiors of future apartments. This because the field-of-view of the VR display is more limited than a real-life field-of-view. Nikolic (2007) reported that when VR is shown on a small screen, the VR model has to be more detailed and photorealistic to render the same spatial experience as when the model is shown on a large screen, such as the one we used in the study in Westerdahl et al. (2006). The narrower the field of view, the higher the level of detail and realism of the VR model have to be to provide the same spatial experience.

In Sunesson et al. (2008) we studied how a jury during an architectural competition of the City Library of Göteborg used a VR model when making their decision about which proposal to recommend for future development. The results showed that the jury felt that the VR model gave them better understanding and a common *frame of reference* during discussions and meetings. Furthermore, the VR model enabled the different jury members with different backgrounds and knowledge to reach the same level of perception and understanding. Additionally, our studies show that VR models help the viewers to take in the sizes and volumes of the proposed environment and how the architectural proposals interact with the surrounding built environment, which is also confirmed in Nielsen (2007). In this context it is worth mentioning that though the VR medium was an important medium for the jury the architectural firms had not identified it as such. Both earlier research (Ambrose, 1994; Atkinson & Shiffrin, 1968; Biederman, 1990; Faludi, 1996; Friedman, 1996; Galbraith, 1974; Hoch, 1996; Kosslyn, 1999; Lindsay & Norman, 1977; Maarttola & Saariluoma, 2002; Hall & Tewdwr-Jones, 2010) and our study (Sunnesson et al., 2008) show that different stakeholders in the urban planning process have different backgrounds, interests, agendas, and focuses and consequently different information processing capabilities. Further, if the sender of the information cannot identify the receivers/viewers cognitive information processing capabilities this can influence how the receivers/viewers understand the visual information, see figure 33. Additionally, based on earlier studies and our papers it can be argued that VR models are perceived as helpful tools in decision-making in the urban planning and building design process (Kjems, 2005; Sunnesson et al., 2008; Westerdahl et al, 2006; Roupe, 2009). VR can also be a good tool for communication between different stakeholders in the process. But as mentioned in sub-sections 2.2 and 2.5, the reality of the building design and urban planning process is that it contains different hidden agendas and conflicting interests (Ambrose, 1994; Faludi, 1996; Friedman, 1996; Hoch, 1996; Maarttola & Saariluoma, 2002; Hall & Tewdwr-Jones, 2010). On account of this, it might be suspected that stakeholders in the urban planning and building design process sometimes favour certain presentation media when needing to persuade politicians. For example, the surroundings and context of a VR show can create priming or framing effects which cause positive feelings or experiences. In the wind farm project mentioned in Paper I the public was first shown a movie, “An Inconvenient Truth” by Al Gore, about global warming and the environmental crisis before the VR show about the new planned wind turbines was shown. I do not know if the movie of the environmental crisis had any impact on the final decision, but Weaver (2007) has shown how mass media agendas may change public and the political actors’ opinions. In Figure 33 this is shown by how different interests can change how the VR model is created and presented. An example taken from paper V is the politicians demanding VR to be used in the volume study. The volume of the building was illustrated by using lines to illustrate the different floor heights on the façade in the VR model, see Paper V and figure 30 (1a, 1b). When we showed the model to politicians in the local housing committee, one of them said that he could not decide which volume he wanted to recommend because he could not decode and understand the volume and pointed out that different façade materials gave rise to different experiences. As shown in this example and in previous research (Atkinson & Shiffrin, 1968; Biederman, 1990; Kosslyn, 1999; Lindsay & Norman, 1977; Yuille & Ullman, 1990) different stakeholders with different backgrounds had different information processing capabilities. In this case, the architect had actually chosen a specific façade material, but he did not want to show it. It could be agued that the stakeholders in this case chose to visualize the volume as abstractly as possible because they wanted a positive outcome from the decision-making process. Another observation from this example is that all the presented volumes were large and much bigger than the existing surrounding buildings, see figure 30. Is it possible that the stakeholders in this project had a desire to build as large buildings as possible? In this case they could have tried to arrive at this result by using reference points and anchoring points, which would influence viewers in their judgement and decision-making process (e.g. Tversky & Kahneman, 1974; Kahneman, 2002; Evans, 2007). Many studies have been conducted on the usability of VR in the context of urban planning (Al Kodmany, 2002; Kjems, 2005; Sunnesson et al., 2008; Westerdahl et al, 2006; Roussou et al., 2005). However, to our knowledge, no studies have addressed the issue that when VR is used in urban planning it can bias the judgement and decision-making of the viewers. In this context people are often not aware of these biasing effects. In Paper V we showed how biased judgement occurs. As mentioned before, in some cases in the urban planning process the sender could have hidden agendas. If they are the creators of the VR model and the producers of the VR medium they could use this to their advantage to alter how the receivers experience the VR model thus influencing communication and decisions, see Figure 33. The study in Paper V showed how reference point effects can influence the outcome of the judgment of a volume study of a building. When the participants were shown two larger volumes before their judgment of size, they judged the building as smaller. The larger volume provided a visual reference point, which in turn affected their judgment, a result in line with previous research (e.g. Tversky & Kahneman, 1974; Kahneman, 2002; Evans, 2007). Another important result is that, even though the results clearly showed the opposite, the respondents did not think that the previous volumes had affected their judgment of the building volume. Thus, people are not aware of any bias in their judgments.

Our study Sunesson et al. (2008) showed that the jury thought that VR made a difference in how they understood the four proposals and that got a better understanding of how the proposals interacted with their surroundings. In the study the jury had the opportunity to conduct on-demand switching between the different proposals, which made comparing the different proposals easier. Is it possible that the on-demand switching interface enhanced the understanding and the spatial-reasoning of the different proposals? In the switching condition the different proposals are presented in the same visual space with no loading time added between the spatial-reasoning of the different proposals. The result from Paper V shows that the ability to do on-demand switching between different architecture proposals enhances spatial reasoning and thereby helps the decision makers. This could be due to the fact that when people are given access to on-demand switching, they get the opportunity to remain in the same virtual space, which decreases the cognitive load associated with sustaining images in their memories. The result also showed that respondents that experienced difficulties in correctly identifying the earlier proposal attributed their reasoning to emotional and proportional qualities in cases where relevant information was lacking. Speculatively, this could be due to process fluency. Processing-fluency is the ease with which information is processed in the human mind, and the easier the processing is the more attractive it becomes during judging (Alter & Oppenheimer, 2009; Reber, et al., 2004). Nielsen (2007) compared different presentation media used in urban planning and building design and reported that the VR media gave more imaginative power and attraction than did the other media. However, if this also can be explained by processing fluency then further research is needed before any strong conclusions can be drawn.

5.3 Conclusion and Contribution of the thesis

This thesis has focused on multi-disciplinary research on the development and implementation of Virtual Reality for decision-making in urban planning and building design. It has contributed to knowledge on how VR technology and human information processing capabilities as well as different settings and artifacts affect decision-making in urban planning and building design when the VR medium is used (see figure 33). Stakeholders in the process encode and interpret information differently depending on their *backgrounds* and *goals and interests*. But also different social conditions, cultures and surroundings can affect the outcome. These artifacts together with the VR medium can affect and influence bias in reasoning and judgments. There are also *technical aspects*, such as how the VR model is created or displayed, that can change the attributes and processes connected to human information processing of VR models. These technical hurdles can change how the VR model is presented to the receiver, and this can lead to biased reasoning and judgments. In this context it is important to develop methods that support the process of creating VR models to make it suitable for use in the urban planning process. The following is a short description of how the results and outcome of the presented research have been used and applied in practice in urban planning and building design.

In our research we have constructed methods and tools to semi-automatically generate a 3D model of the city of Göteborg, Sweden (Roupé & Johansson, 2004; Johansson & Roupé, 2005; (also in Roupé, 2009)). This has been done by converting the existing base map containing 3D lines as contours of the roofs and ground to a 3D model. Further, we developed methods and techniques for the creation of detailed terrain and ground material (Paper I). We also developed efficient methods that support collaboration and visualization of large 3D city models containing large amounts of data (Paper I; Paper II). In the building design process, the industry is going from drawing-based design to model-based design, which in practice means that the 2D layouts, blueprints and text-based descriptions that have traditionally been used will be integrated into 3D information models of buildings. This is known as Building Information Modelling (BIM). In our research we constructed methods and tools that support the integration of BIM models into the 3D city models in the context of the VR medium (Paper III; Johansson & Roupé, 2009; 2012). This has resulted in that the City Planning Authorities of Göteborg and Kungsbacka have used our software MrViz, see section 3.2, as a tool in, for example, architectural competitions, volume studies etc. A positive side effect of this research is that the methods used to create cost and time effective VR models for the city of Göteborg, (Roupé & Johansson, 2004; Johansson & Roupé, 2005; Paper I; II; III) have made it possible to export VR models as 3D models and use them in other applications. In addition we can now carry out sophisticated analysis tasks of, for example, the sun, wind, energy efficiency, noise and sound aspects mentioned by Bimber (2010). Additionally, because VR is now being used in real life building projects, it is important to possess knowledge about the usability and the effects the VR medium has in various situations in the planning process (Paper V; Westerdahl et al., 2006; Sunesson et al., 2008; Heldal & Roupé, 2012). When it comes to usability, navigation has been a problem when older city planners have not had the enough self-confidence to handle the VR themselves. A consequence of the complicated interactive handling has often been that the full potential of the VR, in terms of enhanced communication and understanding regarding future projects, has not been utilized. However, support for the XBOX Kinect sensor (e.g. NUI system) and implementation of the user-interface that supports human body navigation in the model have the potential to enhance the usability of the VR medium (Paper IV). The contribution of these studies is efficient methods that support collaboration and visualization of large 3D city models that large amounts of data and could serve as a CSCW-framework during the urban planning and building design process. This could actually be a platform where different stakeholders could share understand, collaborate and reach consensus, which could lead to a better urban planning and building design process. This thesis also contributes to knowledge on how the VR medium can be implemented more efficiently way in decision-making in urban planning and building design where the end goal is an improved future built environment.

5.4 Future work

This thesis has investigated how VR can be implemented in the urban planning and building design process. The possibilities implementing new methods and framework for the use of VR are endless and there are many aspects of this research that can serve as a basis for further research and development. Here I mention some of these:

- To further optimize BIM rendering and to integrate it into 3D city models in a VR application.
- Further develop the XBOX Kinect interface (e.g. Natural User Interfaces) and the interaction with the human body, where I believe we only has scratched the surface of what can be done.
- To use hyperspectral images or image processing to automatically create the color-coded images for the color-coded image technique mentioned in Paper I.
- To conduct more studies connected to using the VR medium in individual and group decision-making.

Finally, research in the field of VR in urban planning and building design is an applied science where the aim is to contribute to the development of the area, both theoretically and in practice. Regarding the human usability aspects, although there is much has been done, there is still much left to do. Examples are how different realism and texture change the visual and spatial experience of the models and how this may change the process and outcome of decision-making. Furthermore, more research is needed to better understand how the VR medium affects bias in judgement and decision-making.

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