2007:49

DOCTORAL THESIS

Virtual Reality in Construction

Tools, Methods and Processes

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Division of Structural Engineering

2007:49 | ISSN: 1402-1544 | ISRN: LTU-DT -- 07/49 -- SE

LULEÅ UNIVERSITY OF TECHNOLOGY

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Preface

This thesis has been produced in two stages, both at NCC Teknik, NCC Construction Sverige AB in Göteborg. Work on the first stage was done between June 2000 and November 2002 at the Department of Structural Mechanics, Chalmers University of Technology, while the second and final stage took place between September 2004 and November 2007 at the Division of Structural Engineering, Department of Civil and Environmental Engineering, Luleå University of Technology.

Over the last few years, I have been surrounded by helpful people to whom I am very grateful. First of all, I would like to express my deepest gratitude to my supervisor Professor Thomas Olofsson for always being involved and supportive. Your expertise and patience is truly appreciated. There is no question that your advice helped keep me focused and heading in the right direction. Thanks also to my colleagues and friends at NCC, Luleå University of Technology and Chalmers University of Technology for support, valuable discussions and all the fun times together. Special thanks go to Christian Lindfors and Rogier Jongeling. It is a pleasure working with all of you.

I would also like to express my appreciation to the staff working with the Centralhuset project and MK3 project for contributing to my research. Special thanks go to Per Lundström, Jaakko Pöyry AB, Håkan Melander, NCC, Anders Lundgren, LKAB, and Peter Vesterlund, CADDesign, without whose help the research work would have been far less rich in information.

I have had the opportunity to conduct part of this research at the Centre for Construction Innovation Research, School of Science and Technology, University of Teesside. Special thanks to Professor Nash Dawood for making my stay pleasant and inspiring.

The financial support of NCC Construction Sverige AB, the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas), the Swedish Construction Development Fund (SBUF), the IT Construction & Real Estate 2002, Chalmers University of Technology and Luleå University of Technology is gratefully acknowledged.

Last, but certainly not least, I would like to thank my family for their unwavering support and, of course, the lights of my life, my wife-to-be Anna for her endurance and for putting up with me during this work, and Daniel, our son, for the joy he gives me. You are truly the most important part of my life.

Luleå, November 2007

Stefan Woksepp

Abstract

Present-day construction projects are characterized by short-term partnerships between multidisciplinary teams with varying levels of process maturity and information handling capability. They involve the planning, design and erection of structures of all types. Compared with other industries, the construction sector has relatively poor profit margins and low efficiency levels. The product development process in construction is still structured as a sequential chain of activities in which each activity is separated in time and space and where design information is communicated using traditional documents, such as 2D drawings and written specifications. This process is slow and error prone and reflects the functional orientation of the construction project. However, lessons learned from the manufacturing industry have shown that new design processes using modern information and communication technology (ICT), tools such as concurrent engineering and virtual reality (VR) can increase efficiency and reduce lead times. So far, VR has been used sporadically in the construction industry, often from the perspective of visualizing the product design for the client.

The objective of my research has been to investigate how VR (and thereby 3D) can be used during the planning, design and realization phase of a construction project with the emphasis on complex building products. What are the main benefits and how should the construction project be organized in order to make use of the potential benefits the technology offers? The main hypothesis during my research has been that the use of digital prototypes visualized using VR technology makes it easier to identify, analyze, coordinate and communicate the product design in order to improve the decision-making and thereby the final product.

The research work is based on the theoretical framework of virtual prototyping and communication models of information systems, in combination with quantitative and qualitative investigations of two large case studies of construction projects in which VR has been used in the different phases of a project.

The main result of the research work contributes to theory and industrial practice in the following way:

- Insight into the way AEC professionals experience and assess VR models in their everyday work. VR is considered in the context of being a carrier of design information in the design and planning phase.

- Guidelines for and examples of the way VR can be utilized in complex building projects during planning, design and realization in order to be beneficial to the project. What are the main benefits and how should the construction project be organized in order to make use of the potential benefits the technology offers?

- A newly developed model for evaluating the benefits and cost to the construction project associated with the introduction of new ICT tools. The model is intended to provide a structure and a work routine to be used by a multidisciplinary working team throughout the process of assessing, planning and managing the implementation, utilization and follow-up of an ICT investment in a project organization.

It is my conclusion that the sensible, well-planned use of modern ICT tools, such as VR, can contribute substantially to increasing the efficiency of the design and planning processes and thus contribute to the quality of the product and the financial result of the project. However, the introduction of a new ICT tool must be supported by methods, suitable processes and project organizations that can make full use of the benefits the tool is able to offer.

Key words: Concurrent Engineering, Construction Project, Virtual Prototyping, Virtual Reality

Abbreviations

2D CAD	Two-dimensional Computer Aided Design
3D CAD	Three-dimensional Computer Aided Design
4D CAD	3D CAD integrated with schedule data (time)
ABR	Active Benefit Realization
AEC	Architecture, Engineering and Construction
BIM	Building Information Model
CAD	Computer Aided Design
CAVE	A Cave Automatic Virtual Environment
CBA	Cost Benefit Analysis
CD	Compact Disc
CE marking	A mandatory conformity mark on many products placed on the single market in the European Economic Area (EEA).
CIFE	Center for Integrated facility Engineering
CPM	Critical Path Method
DCF	Discounted Cash Flow

DWG	Drawing file developed and used by Autodesk Inc.
EC	The European Commission
EU	The European Union
Formas	The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning
FTP	File Transfer Protocol
GDP	Gross Domestic Product
HMD	Head Mounted Display
HVAC	Heating Ventilation Air-Conditioning
ICT	Information and Communication Technology
IE	Information Economics
IRR	Internal Rate of Return
ISSM	Information System Success Model
IST	Information Society Technology
IT	Information Technology
KPI	Key Performance Indicators
LAN	Local Area Network
LCD	Liquid Crystal Display
LMV	National Land Survey of Sweden
NPV	Net Present Value
PC	Personal Computer
R&D	Research and Development

ROI	Return On Investment
ROM	Return On Management
SBUF	Swedish construction industry's organisation for research and development
S.D.	Standard Deviation
SME	Small and Medium-sized Enterprises
VDC	Virtual Design and Construction
VE	Virtual Environment
VR	Virtual Reality
VRML	Virtual Reality Mark up Language

Table of Contents

1 INTRODUCTION

In this chapter, the background to and motivation for this thesis are explained. The research objective, aim, hypothesis research questions and scope are then stated and, finally, a guide to the thesis is presented to provide the reader with clarity and direction.

1.1 Background and motivation

The European construction industry represents around 7-10% of a country's GDP (Voordijk et al. 2000) and is one of the largest sectors in the European Union, employing some 12 million people. The industry is project centered, complex and highly fragmented and covers a wide range of companies from SMEs to multinational corporations. A typical construction project is characterized by short-term partnerships between multidisciplinary teams with varying levels of process maturity and information handling capability. It usually involves the planning, design and erection of structures of all types, involving a number of players such as clients, designers, material and component suppliers and contractors. Compared with other manufacturing industries, construction companies are accused of having low efficiency levels, relatively poor profit margins and problems with quality (SOU 2000) and many reports have been written about the shortcomings of the construction industry (e.g. SOU 2002, Koskela 1992).

The product development process in construction is still structured as a sequential chain of activities in which each activity is separated in time and space in a "relay race" where design information is communicated using traditional documents, such as 2D drawings and written specifications. This process is slow and error prone and reflects the functional orientation of the construction project. According to Kunz and Fischer (2005), Koskela et al.

(2003), Laitinen (1998) and Egan (1998), this type of organization does not provide a solid foundation for an effective construction process.

One of the main consequences of the traditional way of working is the large number of construction errors that are often detected in the production phase. In this case, construction errors refer to deviations from product requirements in contractual documents (such as descriptions and drawings), standards, regulations, material qualities or general practice. Augustsson et al. (1989) estimated the cost of construction errors at approximately 6% of the production cost. According to Josephson (1990), this figure is underestimated. Hammarlund and Josephson added an additional 4% of the production cost for correcting mistakes originating from the design and planning phase (Hammarlund and Josephson 1991). This means that the overall sum of construction errors (detected and hidden) will exceed 10% of the total project cost (Josephson 1994).

The early stages of the design process are of particular importance for the quality of the final results. Most of the building life-cycle characteristics and costs are already committed at this stage and the opportunity to influence the final design decreases rapidly as the cost of making the changes, or correcting design errors, increases dramatically, see Figure 1-1.

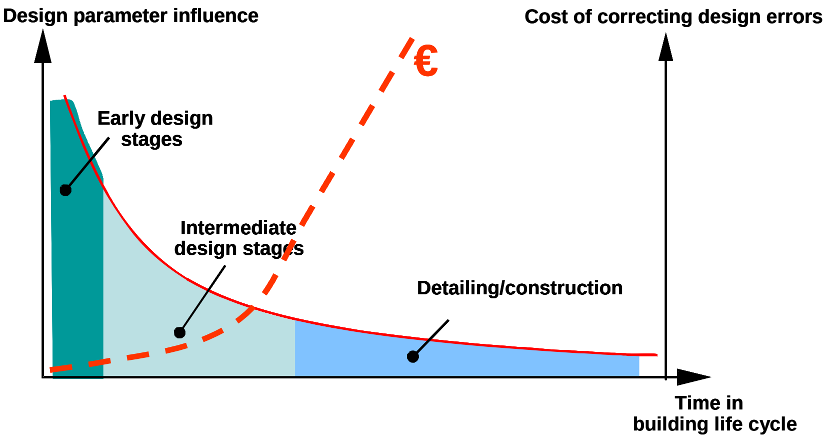

Figure 1-1. Committed design and cost of design changes versus time.

Even if the introduction of computers in the construction sector has changed the “way we work”, their full potential has yet to be realised. In 1997, the

Construct IT Centre of Excellence identified improved information handling in construction projects in order to make the construction process more effective as one of the main future challenges for the construction industry (Luck et al. 1997). In 2007, this still applies. The report entitled “Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry” (NIST GCR 04-867 2004) by the National Institute of Standards and Technology (NIST) estimated that the annual cost of inadequate interoperability in U.S. capital facilities was as much as $15.8 billion in the USA. This report contributes to the awareness of information handling-related issues, not only for owners and operators in the capital facility industries but also for the construction sector as a whole.

Several European Information Society Technology (IST) projects have accepted the challenge of introducing new ICT tools and model-based working methods in the construction industry; they include InPro, Manubuild, I3CON, OSMOS, eConstruct, Divercity, ISTforCE, eLegal, GLOBEMEM et cetera. For example, the result of the ESPRIT CICC EC project (1999) indicates that an efficiency increase of 30% is possible by exploiting the potential of different ICT tools, while the e-Business w@tch EC report (2005) concludes that ICT has significant potential for productivity improvement. However, the results of the ICCI project (ICCI 2004), where one of the objectives was to improve the coordination between European-funded IST projects, concluded that there is a need to overcome business, social and technical barriers before model-based working methods can be introduced.

In spite of these successful programs and the abundance of documented ICT-related research (Ugwu and Kumaraswamy 2007); several studies indicate that the ICT utilization ratio is still relatively low. For example, a comprehensive study within the InPro EU project, which investigated the use of ICT tools in the European construction industry (InPro 2007), revealed a lack of use of ICT tools in construction projects, especially in the early stages, despite several good alternatives being available.

Clearly, many companies are still hesitant about increasing the use of ICT and re-engineering the way they work. It is suggested that some of the causes of this are deficient understanding and a lack of knowledge about the potential of ICT, unsuccessful implementation in project organizations and limitations of software functionality (InPro 2007). The e-Business w@tch EC report (2007) suggests that there is a limited perception of the full impact and importance of ICT. As a result, construction companies often find it difficult to justify ICT investments in an industry that suffers from low profit margins (Alshawi et al.

2003) and instead view an ICT investment as a process of consumption rather than capital expenditure (Irani and Love 2002). Ugwu and Kumaraswamy (2007) point out the deficiency of research that focuses on issues and factors related to the uptake of ICT in construction, including stakeholders' perceived benefits, costs and risks of ICT systems in practice. Another reason is most likely that the importance of evaluating the ICT investment is not understood (Willcocks and Lester 1997) and that traditional approaches to evaluating investments have been shown to be inadequate (e.g. Peacock and Tanniru 2005, Love and Irani 2001, Andresen et al. 2000, Irani et al. 1999, Shank and Gowindarajan 1992).

Another main reason for the low use of ICT is likely that many players within the construction sector experience a large gap between the R&D results and the current needs for ICT in the sector. I believe that this gap implies that there is a lack of applied R&D activities where the use and impact of new tools, methods and processes are empirically evaluated and tested in real construction projects.

1.2 Objective and aim

The objective of my research has been to investigate how VR (and thereby 3D) can be used during the planning, design and realization phase of a construction project with the emphasis on complex building products. What are the main benefits and how should the construction project be organized in order to make use of the potential benefits the technology offers?

The main aim of my research is to provide guidelines for and practical examples of how VR can be practically applied in construction projects of different types.

1.3 Hypothesis and research questions

The main hypothesis during my research has been that the use of digital mock-ups of the product design visualized using VR technology enhances the opportunity to identify, analyze, coordinate and communicate the product design in order to improve the decision-making and thereby the final product.

Five research questions are defined from this hypothesis and they form the core of the research presented in this thesis. The answers to each of these research questions are derived from the appended publications and summarized in the "Discussion and conclusion" section in the thesis. The five research questions are as follows,

Research question 1

How is VR perceived?

This question aims to provide an insight into the way AEC professionals experience and assess using VR models in their everyday work. VR is considered in the context of being a carrier of design information in the design and planning phase. The first research question is dealt with in Paper V.

Research question 2

How can VR be used for decision-making?

Decision-making is a term that is very difficult to define[1] (and this thesis does not attempt to do so either), but the decision-making process is nevertheless a fundamental event in the design process. In this context, the main intention is to provide an understanding of the reason for using VR in the design process. This second research question is dealt with in Papers I, II, III and V.

Research question 3

How can VR be implemented in the design process – what are the prerequisites?

The implementation of VR in the design process requires a holistic approach. Implementing VR in the design process is not primarily a technical challenge but rather a comprehensive process which requires clearly defined aims and all-embracing efforts. The third research question aims to provide an insight into the prerequisites for achieving the best possible implementation of VR in

[1] Wikipedia defines decision-making as: “the cognitive process leading to the selection of a course of action among variations”. (Source: http://en.wikipedia.org)

the design process. This third research question is mainly dealt with in Papers III, IV and V with some additional input in Chapter 2 of this thesis.

Research question 4

How can we assess the value of VR in design and construction?

The most fundamental reason for using VR relates to economic reality. Any ICT investment should be preceded by a careful evaluation of its benefits and values in projects (directly or indirectly). The fourth research question is dealt with in Paper IV.

Research question 5

In which type of construction projects is VR most useful?

The last research question attempts to identify the types of construction project in which VR would be most useful. This fifth research question is an integration of previous research questions, as they are strongly interrelated. It aims to collate the knowledge acquired from dealing with previous research questions.

1.4 Scope

The scope of my research comes from the recognition that any successful implementation of new tools (such as VR) will affect the methods used, the working processes and the structure of the organization and will thereby challenge the business culture and vice versa, see Figure 1-2. This means that change management must address all these levels in the implementation of new processes, methods and tools.

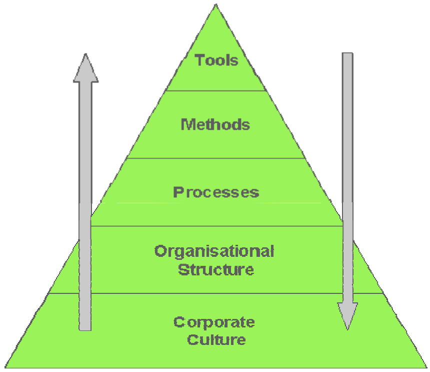

Figure 1-2. Change management in implementation projects involving new tools, methods and processes (courtesy of P3 – Digital service GmbH).

This research is based on quantitative and qualitative research methods of two large case studies of construction projects in which VR was used in the different phases of a project. The outcome of these studies has been compared with results reported in the literature, primarily from manufacturing industries.

Tools – in this case, the research deals with the use and apprehension, use and benefits of VR technology for the AEC professionals involved in the case study projects.

Methods – the main hypothesis in this research is that digital mock-ups visualized using VR technology make it easier to identify, analyze, coordinate and communicate the product design in order to improve the decision-making and thereby the final product. In this case, digital mock-ups are multidisciplinary VR models (and to some extent – 4D models) of the product (typically a building or a plant), assembled from the different design teams' 3D CAD models (mostly sharing geometrical data), investigated in the MK3 project. Digital mock-ups are used to coordinate design and to communicate design intentions to stakeholders.

Processes – a suitable process supporting VR and the creation of digital mock-ups is concurrent engineering, challenging the traditional sequential construction process. An approach to using VR prototypes in a multidisciplinary concurrent engineering process is illustrated in Paper III.

Some aspects of the **organizational structure** and **corporate culture** are investigated in this thesis, even though these subjects are outside the scope of the research work. In particular, the contractual form will affect the opportunity to create an open and collaborative environment that encourages sharing of information, risks and benefits between the players in the project.

1.5 Thesis guide

1.5.1 Target audience

This thesis is written as an academic assignment with the aim of obtaining a doctoral degree. Research in the field of VR in construction is an applied science where the aim is to contribute to the development of the area, both theoretically and in practice. This thesis has therefore been written for both practitioners and researchers.

Practitioners refer primarily to construction company personnel, such as management, project managers, IT managers, project coordinators, design coordinator, designers and planners.

Any reader who would like to obtain an overall view of the conducted research is recommended to read Chapters 1-5, while readers who wish to study the work in more detail should also read the appended papers at the end of the thesis.

1.5.2 Outline

The thesis is divided into the following five chapters.

In *Chapter 1*, the background to and motivation for this thesis are explained and an attempt is made to put the work into perspective. The objective and scope are then presented, the research questions are stated and, finally, a guide to this thesis is presented to provide the reader with clarity and direction.

Chapter 2 presents the theoretical framework and technologies on which the research presented in this thesis is based. It also evaluates processes, methods and tools suitable for the construction industry.

Chapter 3 briefly outlines the nature of science and scientific methods and the building blocks of research. It also presents some of the research methods that are available and reliability and validity aspects of research. It then explains the research design and methodology that were used.

Chapter 4 presents summaries of each appended paper with the aim of providing an insight into the research work and its results. The summaries include the title of the paper, authors, research questions studied, keywords, introduction, purpose, methods, a summary of the main contents and results and contributions.

Chapter 5 discusses and concludes my research work. The research questions are addressed and the scientific and practical contributions of my research are presented. Furthermore, the trustworthiness, generalizations and limitation, relevance to industry and possible barriers to industry uptake of my research findings are discussed. Finally, some suggestions for future research are presented.

The research work presented in this thesis is based on the results of the five appended papers and the combined analysis of these results. The appended papers are listed below in chronological order and this section gives a brief summary of the content.

Paper I

Woksepp, S., Jongeling, R. and Olofsson, T. (2005). Applying Virtual Reality and 4D CAD in the scheduling process of large construction projects. Proceedings of 5th International Conference on Construction Applications of Virtual Reality, 12-13 September, Durham, UK, pp. 352-360.

This paper is a report on a case study of using VR and 4D models to facilitate work-site planning in a large-scale construction project. The research work was performed and evaluated in agreement with the actual work on a building site, including the research group, planners and site managers. My main contribution to this paper was describing and analyzing the application of VR models in the scheduling process. Rogier Jongeling described and analyzed the location-based 4D modeling approach and Thomas Olofsson supervised and reviewed the work. I was the main author.

Paper II

Woksepp, S., Olofsson, T. and Jongeling, R. (2005). Design reviews and decision-making using collaborative Virtual Reality prototypes: a case study of the large scale MK3 project. Proceedings of the 13th annual conference of the

International Group for Lean Construction – IGLC 13, 18-21 July, Sydney, Australia, pp. 145-152.

Paper II presents a report from a case study of using VR models to facilitate decision-making, coordination and the communication of client requirements in the design review process. This paper was written with Thomas Olofsson and Rogier Jongeling, who provided empirical input and reviewed the work.

Paper III

Woksepp, S. and Olofsson, T. (2006). Using Virtual Reality in a large-scale industry project. ITcon Vol. 11, pp. 627-639.

Following up the two previous papers, Paper III seeks to explore and document in greater detail the practical work and experience obtained from using VR in the design and planning process in a large-scale construction project. This paper was written with Thomas Olofsson, who reviewed the work and assisted in drawing conclusions.

Paper IV

Woksepp, S. and Olofsson, T. (2007). An evaluation model for ICT investments in construction projects. Accepted for publication in ITcon, Special Issue on Case studies of BIM use (October 2007).

This paper presents a newly developed evaluation model. The purpose is to provide a structure and a work routine to be used by multidisciplinary project teams to evaluate the implications of realizing ICT investments in a construction project organization. To support a development towards practical applicability, the application of the model is illustrated using a case study. The co-author was Thomas Olofsson, who assisted in developing the evaluation model and reviewed the work.

Paper V

Woksepp, S. and Olofsson, T. (2007). Credibility and applicability of Virtual Reality models in design and construction. Submitted to Advanced Engineering Informatics (October 2007).

The findings from an extensive case study of the use of VR models in large construction projects are presented in Paper V. The paper was written with Thomas Olofsson, who supervised and reviewed the work. The study has two parts. The first part presents a quantitative questionnaire designed to investigate how VR models are experienced and assessed by the workforce at a building site. The second part includes a qualitative field survey of how VR models can be applied and accepted by professionals in the design and planning process of a large-scale construction project.

2 FROM THEORY TO APPLICATION

This chapter presents the theoretical framework and technologies on which the research presented in this thesis is based. It also evaluates processes, methods and tools suitable for the construction industry.

2.1 Introduction

The manufacturing industry, which has a product development process similar to the construction process, has changed dramatically over the past decades. The introduction of new tools such as CAD software during the 1980s improved the design and documentation work to some extent. Instead, the major paradigm shift took place in the 1990s, when the simultaneous product development process was introduced. The development process went from being a sequential chain of activities to having design activities that were carried out in parallel to each other, so-called *concurrent engineering*[2]. In a benchmarking study of the major automotive manufacturers in Japan, Europe and the USA, this technique not only proved to be faster, it also appeared to require fewer engineering hours and to create products that were better adapted

[2] In management literature, concurrent engineering is sometimes referred to as simultaneous product development.

to the production process (Womack et al. 1990). The change in the product development process from a sequential chain of activities to more concurrent design reduced the time to market for new models.

According to Womack et al. (1990), three essential elements are needed to create what they called “a lean development process”: *Leadership*, *Teamwork* and *Communication*. The leadership must be able to gather cross-functional teams from the functionally oriented organization in order to bring multidimensional knowledge from marketing, engineering disciplines and production into the product development process. Effective communication between teams and team members is essential, since different design activities are conducted in parallel. Compared with the traditional sequential development process, concurrent engineering offers a number of advantages, such as shorter lead times; the product is better adapted to market and production demands and this in turn results in a more attractive product with higher quality. The number of engineering hours is reduced, as design errors detected in a sequential process often lead to long chains of design iterations. The staff involved in the early design stages have often left the project to work on something else when errors are detected downstream in the activities involved in a sequential development process.

In the current manufacturing industry, a product can be designed, tested and validated before the first physical prototype is built. The use of virtual prototyping enables multiple design solutions to be evaluated digitally, which leads to a faster design process and more optimized end products. The first industrial use of VR was introduced when virtual prototypes started to be used in the design process.

The majority of today’s construction projects are structured according to a sequential product development process in which each activity is separated in time and space. This process is often slow and reflects functionally oriented organizations, leading to deficient communication and conflicts between the different functional teams in the design and production relay race (Jongeling 2006). As a result, many construction companies are now moving towards the adoption of new processes supported by ICT in order to improve the construction process.

In the following pages, the process (concurrent engineering), the method (virtual prototyping) and the technology (VR) and their potential use and benefits in construction projects will be investigated.

2.2 Concurrent engineering

The inspiration comes primarily from manufacturing industry, where product development with concurrent, parallel activities has been a huge success. This process is known as concurrent engineering and it originates from the product development process Toyota created during the 1980s. Concurrent engineering means that a large number of sequential activities are coordinated and performed at the same time by interdisciplinary teams which bring multidimensional knowledge to the project. One of the success factors for concurrent engineering in the manufacturing industry was that the transformation took place at the same time as the modeling methods became increasingly sophisticated (Olofsson et al. 2007), see Figure 2-1. The interaction between virtual prototyping with digital mock-ups and concurrent engineering demonstrates a symbiotic effect. The concurrent engineering processes are boosted by the use of digital mock-ups improving the information sharing and coordination of the different design teams.

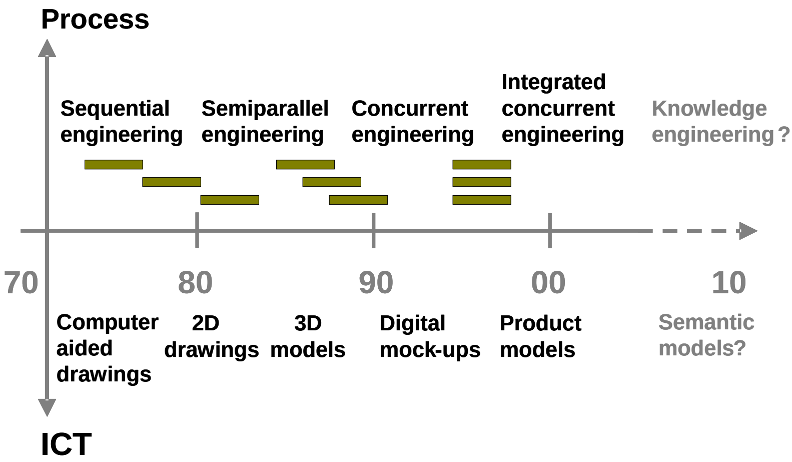

Figure 2-1. Schematic representation of the evolution of the product development process and modeling methods (Olofsson et al. 2007).

Concurrent engineering in a construction setting is largely a question of interaction between clients, design specialties and contractors using integrated project groups. Different disciplines contribute their knowledge collectively in order to implement the design process effectively and thereby obtain the best possible end result. The players work together to make informed and agreed decisions relating to the building process and cost and quality issues of the end product. Individual ideas are replaced by the group’s combined interpretation, based on the integrated teams multidisciplinary experience. Individual objectives are replaced by common project goals.

Essentially, concurrent engineering brings together multidisciplinary teams, in which product developers from different functions work together and in parallel from the start of a project with the objective to get things right as quickly as possible and as early as possible. Compared with a traditional sequential construction process, it produces a raft of benefits, such as the reduction of construction time and construction costs, the improvement of product quality, faster reactions to customer requirements, fewer design errors and less rework.

As concurrent engineering slowly gains acceptance among construction companies, the demands that are imposed on implementation are rigorous. If it is to be performed effectively, concurrent design calls for information sharing, tight coordination of the different disciplines and support for communication of the design. Collaboration is essential. This is supported by the rapid development of ICT, which has resulted in the creation of a range of new tools. The development of CAD systems has, for example, evolved from being a tool for individual designer (2D CAD) to systems supporting and coordinating the construction process in a more overarching manner (object oriented 3D CAD, BIM). Multiple design solutions can be evaluated quickly using virtual prototypes of the to be product. Design alternatives can be designed, tested and validated before the first physical prototype is built, which leads to a more optimized end product. The next step according to many scientists is “knowledge engineering design” supported by semantic models, i.e. model objects that include meaning and knowledge of their own performance (Olofsson et al. 2007).

2.3 Virtual prototyping

Traditional prototyping involves creating and using physical mock-ups to test and evaluate design concepts, but in most cases they are only used to present the final product. Physical mock-ups are expensive, difficult and time consuming to create and modify.

A virtual prototype, or a digital mock-up[3], is a computer simulation model of a physical product that can be used to present, analyze and test from life-cycle aspects such as design/engineering, manufacturing, service and recycling, as if a real physical model were being used. The construction and testing of a digital mock-up is called virtual prototyping (Wang 2002). Compared with traditional prototyping, virtual prototyping is more easily integrated in the design process and reduces the time span between design creation and the use of prototypes. The cost of product development is reduced and the ability to respond to client requirements and involve the client in the design is improved. Moreover, if the traditional prototyping is understood to focus on an understanding of the final result, virtual prototyping has a greater scope, as it addresses all the life-cycle aspects of the construction. These features imply that virtual prototyping, which promotes and is promoted by a collaborative design situation, represents a key technology for a concurrent engineering process.

2.4 Virtual Reality

VR developed from flight simulation research during World War II and early computer graphics research in the 1960s. Ivan Sutherland, (Sutherland 1965), was one of the first scientist to describe VR in his paper “The Ultimate Display”. Until the mid-1990s, VR was an unexplored area for the construction sector. Today, the rapid development of processors, graphics card and displays has led to the ability to visualize large VR models with the aid of common PCs or laptops. Designing in 3D CAD has become widespread and the VR systems have evolved from expensive customized hardware and software to readily available, fairly inexpensive off-the-shelf products. Not only have the 3D and VR technologies developed but also the user attitude towards them. In the

[3] In this thesis, the concepts of “virtual prototype” and “digital mock-up” have the same meaning, i.e. they both (in engineering) involve either a scale or a full-scale model of a structure or a product used for visualization and evaluation.

1980s and 1990s, interest focused on the level of immersion and interaction. Today, attention centers on functionality, compatibility and user friendliness.

VR is a technology which enables the visualization of large amounts of complex information. Users can navigate freely in real time and interact with virtual objects in a three-dimensional environment – a Virtual Environment (VE). Navigation includes the ability to move around and explore features in the VE, while interaction implies the ability to control the VE, such as manipulating virtual objects (Thabet et al. 2002). At the present time, it’s primarily use is to visualize and navigate in VE. The VE can be experienced with varying degrees of immersion, from desktop immersive (computer monitor or LCD screen) to semi-immersive (e.g. stereo projector on a screen) or fully immersive (e.g. CAVE), or through special stereoscopic displays, such as HMDs (Head Mounted Displays). In the domain of VR visualization, large-screen stereoscopic systems of different types have been used for architectural visualization. An overview of VR technology utilization in the UK- and USA-based construction industry is presented by Whyte (2003). The VR demonstrations can also include additional sensory information, such as sound or tactile feedback. Users can interact with the virtual environment by using either standard input devices, such as a keyboard and mouse, or more advanced devices, such as a wired glove or space mouse. It is possible to work individually or to collaborate within a group.

The use of VR in design applications, (VR prototyping) require that the 3D models from the different disciplines can be imported by the VR system in order to create the VE to be explored. The VR systems are often based on technology from the computer games industry and work accordingly, with similar types of navigation modes and representations of the environment. Therefore, the VR environments are often easy to explore and allow non-CAD users to access and interact with 3D models. The use of these tools significantly increases the number of potential users and uses of 3D models (Jongeling et al. 2007).

CAD and VR could be regarded as complementary technologies in design visualization. However, the 3D systems have limitations when it comes to conveying an understanding of complex VE, since these systems are made for a different purpose. The distinction is that a 3D CAD system is developed for a design specialist to create precise three-dimensional representations of real objects, while VR is developed to allow users to display and interact with these objects in a VE. A 3D CAD object is represented as an object with features, such as volume, weight, et cetera; the same object is modeled with surfaces in the VE in order to minimize the required computing power. Also, the VE includes additional definitions for surfaces and spaces for the purpose of photorealistic representation. These differences in the definition and representation of objects currently limit the direct transfer of 3D design models into VR systems (Jongeling et al. 2007). However, the distinction between creating and visualization of models is not so clear. Although each has adopted some of the capabilities of the other, i.e. some VR software have the ability to create models and some CAD systems includes visualization features, neither is meant to replicate all the functions of the other. Ideally, CAD systems should be used to create the models and VR software should be used to display them. In this way, the strengths of both systems can be utilized to improve the information creation done by the different design specialists and the coordination and communication of the design to a wider audience.

In this thesis, the VR applications are restricted to real time, interactive, three dimensional and desktop immersive using projectors or computer monitors. The VR systems that are used are low-cost approaches that consist of commercial software, PC computers, servers and projectors. Walkinside™ and Division MockUp™, which were selected as VR platforms in the case study projects, can import most of the leading CAD formats.

2.5 Virtual prototyping in construction

VR is a spatial and communicative medium, well suited to facilitate collaboration and understanding of the construction design and the processes needed to erect it (Woksepp et al. 2005). Already during its introduction in the construction industry in the 1990s, VR was considered to have great potential in construction industry, providing new opportunities for improving the construction processes (e.g. Issa 1999, Retik 1997 and Cochrane 1997). However, it is only recently that VR has started to be adopted as an enabling technology in construction projects.

Even though VR today is primarily used for visualizing the final product (Woksepp and Olofsson 2006), the potential as a universal interface application is high (Aouad et al. 1997). For example, VR can be used to explore design options, simulate construction activities, support design reviews, communication of the design intent, clash detection and much more. The benefits of VR are often listed as cost reduction, risk minimization, more efficient communication between stakeholders and earlier error detection. Westerdahl et al. (2006), however, argue that the proper use of VR models in the different phases of a construction project is still not clear. This may have a natural explanation, considering the trend towards model-based information processing (3D or BIM) and concurrent processes, inspired by the product development processes in manufacturing industry. The benefits of using virtual prototyping increase when it is used in a concurrent engineering environment and when specialty designs are made directly in 3D CAD. In addition, VE that directly originate from 3D CAD design models are regarded as more credible than those reconstructed from 2D CAD drawings (Woksepp and Olofsson 2007).

An approach to using VR prototypes in a multidisciplinary concurrent engineering process is presented in Paper III. Figure 2-2 illustrates some examples of different areas of application of virtual prototyping in construction.

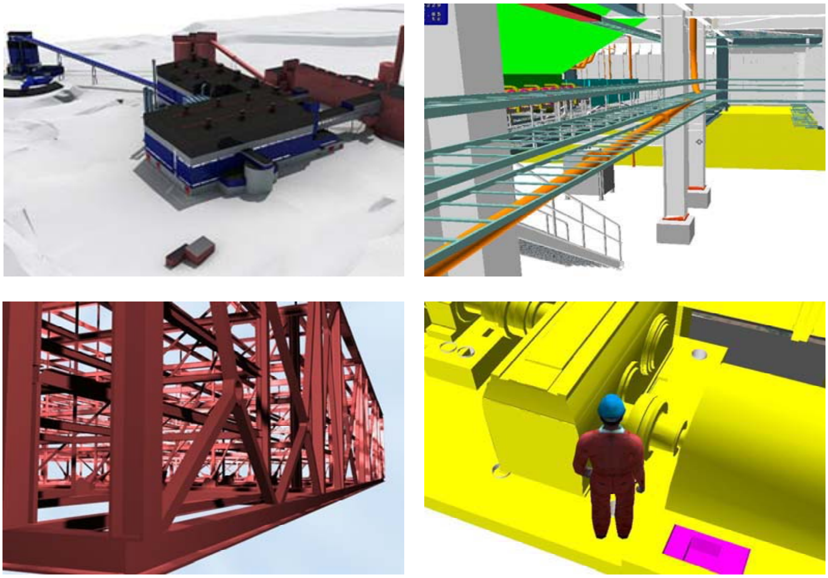

Figure 2-2. Different areas of application of virtual prototyping in construction. (Top left) Layout. (Top right) Design reviewing. (Bottom left) Communication of design intent. (Bottom right) Maintenance.

Applications of virtual prototyping have clearly been an area of increasing research and development activities in architecture and construction (Kähkonen

2003). Research efforts have compiled detailed studies that assess the benefits and limitations of VR and its application at different stages of the construction process (e.g. Messner et al. 2006, Woksepp and Olofsson 2006, Bouchlaghem et al. 2005, Whyte 2003, Savioja et al. 2003, Christiansson 2001 and Kim et al. 2001). Other research projects have been focused on developing VEs or databases (e.g. Wilson and D´Cruz 2006, Dawood et al. 2005, Ganah et al. 2005, Waly and Thabet 2002). Some studies investigate the barriers that affect the adoption of VR (e.g. Fernandes et al. 2006) and the way VR models are experienced and assessed by project participants (Woksepp and Olofsson 2007 and Westerdahl et al. 2006). Dawood et al. (2006) put forward a VR roadmap vision for 2030.

Another virtual prototyping technology is 4D modeling. 4D modeling is a process method in which schedule data and spatial data are combined (Jongeling 2006). The method visualizes 3D CAD models in a time-space environment, facilitating the analysis of different production strategies before work on site is initiated (McKinney and Fischer 1998). A 4D model of a project allows the project participants to review the planned or actual status of a project in the context of a 3D CAD model for any day, week, or month of the project (Fischer and Kunz 2004). The project participants can effectively visualize and analyze problems relating to sequential, spatial, process conflicts and temporal aspects of construction schedules, prior to actual construction operations on site (Dawood et al. 2002). 4D models are typically created by linking building components from 3D CAD models with activities from activity-based scheduling methods, such as the Critical Path Method (CPM). Building components that are related to an ongoing activity are highlighted, providing users with a spatial insight into the construction processes (Jongeling and Olofsson 2007).

At the present time, 4D models are mainly used to communicate a master schedule to different stakeholders in a project (Jongeling 2006). However, several studies have highlighted the more wide-ranging application of 4D as a visualization and planning review tool to give the stakeholders in the project a deeper understanding of the construction schedule (e.g. Jongeling 2006, Chau et al. 2005, Yerrapathruni et al. 2003, Songer et al. 2001). Koo and Fischer (2000) identify 4D modeling as a tool to convey planning information, enhance collaboration among project participants and support users to conduct additional analyses. Although planning supported by visual analyses of 4D models is considered more useful and more effective than traditional planning (Heesom and Mahdjoubi 2004), it does not take advantage of the quantitative data contained in 4D models. Recent research efforts in 4D modeling reveal an increasing interest in providing an integrated 4D environment to support a variety of quantitative analyses of work spaces, work flows and use of resources, for example (Dawood et al. 2005, Akbas 2004, Akinci et al. 2002, Li et al. 2003). Some good examples of 4D model applications can also be found in Fischer and Kunz (2004). These studies clearly demonstrate the potential of 4D.

Figure 2-3 shows an example of work space planning by linking building components and work spaces in a 4D model (Jongeling 2006).

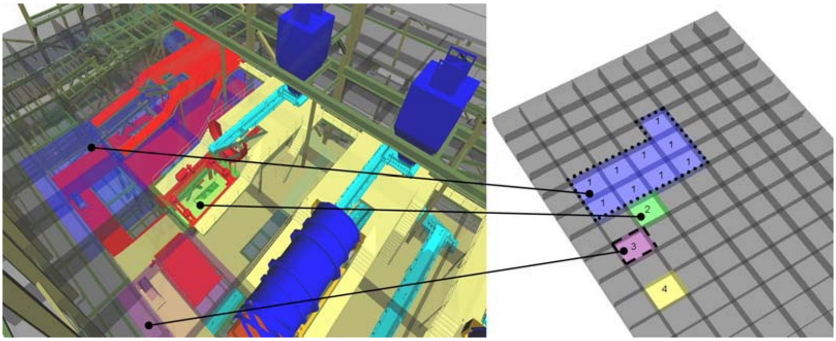

Figure 2-3. (Left) A snapshot from a 4D model including building components and work spaces. (Right) The same 4D model limited to visualizing work spaces (1-4) used by different teams of workmen (Jongeling 2006).

VR is a virtual prototyping technology that offers a natural medium for users, providing a three-dimensional view that can be manipulated in real time and used collaboratively to explore design options and simulations of the construction process (Bouchlaghem et al. 2005). These features certainly bring to mind many potential benefits in numerous applications within the construction process, an area of increased interest in research and development in recent years, of which some applications have been practiced by early adopters in the construction industry (Kähkönen 2003).The research and applications have demonstrated that VR can bring significant value improvement and cost reductions to the construction process. However, very few attempts have been made to quantify the impact on the project (Khanzode et al. 2007).

2.6 Assessment of benefits

A project-oriented evaluation model has been developed in Paper IV to provide a structure and a work routine for the evaluation of the implications of realizing ICT investments in construction projects. Even though it is primarily designed to establish future benefits and costs, the model could very well be used for follow-ups. This chapter describes the theoretical basis that is used in the evaluation model to assess the benefits of an ICT investment and outline the proposed model. The full model and guidelines for using it are presented in Paper IV.

The predefined benefit category structure and variable list is an extension of DeLone's and McLean's theoretical framework Information System Success Model (ISSM) from 1992 (Lindfors 2003, DeLone and McLean 1992), see Figure 2-4.

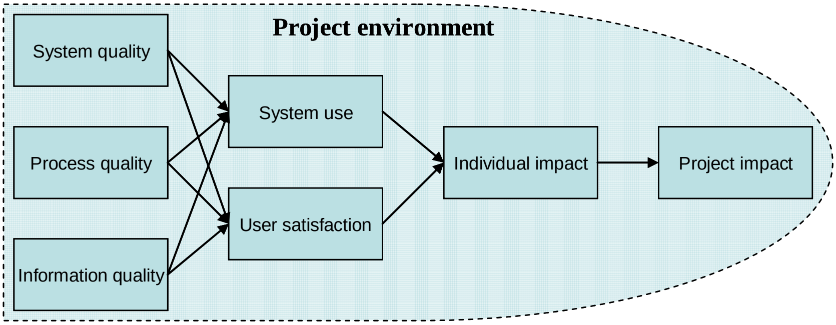

Figure 2-4. The extended ISS model in a project environment (Lindfors 2003).

The DeLone and McLean ISS model from 1992 derives from Shannon's (1948) and Shannon and Weaver's (1949) initiative relating to the theory of communication and Mason's (1978) work on information influence theory (Lindfors 2003). It is basically a mathematical approach to the theory of communication where an information system acts as the information source that is sending information through a system to a recipient. It is divided into three basic levels; first, a technical level that represents the accuracy and efficiency of the system; second, a semantic level that addresses the success in conveying the message and, third, an effectiveness level which measures the effect the information has on the recipient, see Table 2-1. Mason (1978) adopted this theory and revised it according to a product-oriented approach. Instead of effectiveness or influence, Mason presented the categories of receipt of information, influence on receipt and influence on system, also renaming the technical level and semantic level the product and production level (Lindfors 2003).

Table 2-1. Categories of Information System Success (Lindfors 2003, DeLone et al. 1992).

<table>
<tr><th>Source</th><th colspan="8">Categories</th></tr>
<tr><td>Shannon and Weaver (1949)</td><td colspan="2">Technical level</td><td colspan="2">Semantic level</td><td colspan="4">Effectiveness or influence</td></tr>
<tr><td>Mason (1978)</td><td colspan="2">Production</td><td colspan="2">Product</td><td>Receipt</td><td colspan="2">Influence on recipient</td><td>Influence on system</td></tr>
<tr><td>DeLone and McLean (1992)</td><td colspan="2">System quality</td><td colspan="2">Information quality</td><td>System use</td><td>User satisfaction</td><td>Individual impact</td><td>Project/organizational impact</td></tr>
<tr><td>Lindfors (2003)</td><td>System quality</td><td colspan="2">Process quality</td><td>Informati on quality</td><td>System use</td><td>User satisfaction</td><td>Individual impact</td><td>Project/organizational impact</td></tr>
</table>

Following the basic approach of assessing the value of a system, numerous researchers have created different models from various viewpoints. DeLone and McLean reviewed these previous studies and developed their taxonomy using six major dimensions of categories of information system success: System quality; Information quality; System use; User satisfaction; Individual impact and Project/organizational impact (DeLone and McLean 1992). Based on both process and causal considerations, it is proposed that these six dimensions of success are interrelated rather than independent (DeLone and McLean 2003). Lindfors (2003) extended this model to include measures for the perceived quality of the information management process (in Table 2-1). Each of the categories in Table 2-1 consists of a number of variables that recognize the effects according to (DeLone and McLean 1992).

System quality – effect on the information system itself which produces the information
Information quality – accuracy, meaningfulness and timeliness of the information produced
System use – use of the information system
User satisfaction – interaction of the information system with its recipients: users and project owner
Individual impact – influence on management decisions
Project/organizational impact – effect on organizational performance
Process quality – effect on information management process quality (Lindfors 2003).

Lindfors (2003) argues that it is essential to adopt a more project- and process-oriented evaluation approach because of the nature of construction projects. By being able to link the impact of a future information system to a structure of predefined quality variables, Table 2-2, a deeper level of understanding can be brought to the evaluation process.

Table 2-2. ISS categories with associated benefit variables (Lindfors 2003, DeLone and McLean 1992).

System quality variables	Process quality variables	Information quality variables	System use variables
Database content Ease of use Ease of learning Convenience of access Usefulness of system features and functions System flexibility System reliability Integration of systems System efficiency Response time	Information development Information acquisition Information identification Information preservation Information utilization Information dissemination	Relevance of information Usefulness Usableness Understandability Clarity Format Content Accuracy Sufficiency Completeness Reliability Timeliness	Frequency of report request Appropriate use Purpose of use Number of reports generated Regulatory of use Amount of connect time Frequency of access
User satisfaction variables	**Individual impact variables**	**Project impact variables**	
Software satisfaction Decision-making satisfaction Satisfaction with specifics Information satisfaction Overall satisfaction	Information understanding Learning Information awareness Decision effectiveness Decision quality Improved decision analysis Correctness of decision Time to make decision Confidence of decision Improved individual. productivity Change in decision Task performance Personal valuation of IS Information management	Operating cost reduction Staff reductions Overall productivity gains Increased work volume Product quality Contribution to achieving goals Service effectiveness Time effectiveness Improved information management Increased profits	

The proposed evaluation procedure and risk handling are inspired by the PENG model (Dahlgren et al. 1997). The PENG model has become a popular method in Sweden for evaluating IT investments in companies and organizations. The main difference is that the model proposed in this paper is project oriented and ICT investment “specific”. In addition, in the PENG model, the benefit and cost variables and category structure are established by the evaluation group, which means that every evaluation is unique in its disposition, whereas the proposed model provides a predefined structure. I believe that the combination of a pragmatic evaluation procedure and a predefined category structure and variable list makes it easier for users to identify, evaluate and secure not only the tangible benefits and costs but also the intangible and hidden effects of realizing the investment proposal. I also believe that this combination facilitates the implementation process, follow-ups, the re-use of knowledge and the information process as a whole.

The evaluation presents a gross result. Benefit and cost variables are categorized, quantified in monetary terms and classified, depending on the likelihood of their happening. The proposed model assumes that all benefits and costs – tangible as well as intangible – can be identified, categorized and measured in monetary terms and that all costs are incurred within the project and all returns (read: benefits) are received by the project.

3 SCIENTIFIC APPROACH AND METHODS

This chapter briefly outlines the nature of science and the building blocks of scientific research and discusses reliability and validity of research. It then explains the scientific method and research methods that have been used.

3.1 The nature of science and scientific methods

The *Oxford Advanced Learner's Dictionary* (2005) defines research as 'a careful study of a subject, especially in order to discover new facts or information about it'. Research is always based on assumptions that are philosophically grounded and relate to a researcher's view or perception of 'reality'. The purpose of research is to contribute to the existing body of knowledge, to facilitate the learning process and to construct reality. It is an organized, data-based, critical investigation of a specific problem (Sekaran 2000).

Henle (1969) identified five formally distinct, refined ways of knowing or organizing knowledge: scientific, humanistic, philosophical mathematical and theological. The research presented in this thesis was undertaken within the scientific realm of knowledge development.

According to Ackoff (1999), science exhibits the following properties.

- Science is a process of inquiry to answer questions, solve problems and develop effective procedures for answering questions and solving problems.

- The products of scientific inquiry are a body of knowledge and information that allows the improvement of the environment and a body of processes and procedures which generates the body of knowledge and information.

- Science can be a qualitative or a quantitative inquiry.

- Not all inquiry is scientific. As a result, the common sense inquiries are excluded from science. The difference between common sense and science lies in the fact that science is approached using a controlled process, in the sense that it is effectively directed toward the attainment of desired objectives.

- The scientific method is not preferable in all cases. Even if the scientific method can provide a better solution than some common sense inquiry, there are situations in which the application of the scientific method is not justified. Examples include an emergency, where a good answer in time is preferable to a better answer too late.

- Control is necessary, but it is not sufficient to determine the scientific grade. Science is also concerned with self-perpetuation and self-improvement. Scientific endeavours must therefore continuously provide feedback on ways of improving the conducting of research itself.

The scientific method refers to the procedure of selecting the appropriate techniques for a research project; in other words, evaluating alternative courses of scientific action (Ackoff et al. 1962). The scientific method is the “instrument” that scientists use to find the answers to questions. It is the process of thinking through the possible solutions to a problem and testing each possibility to find the best solution.

Inductive and deductive reasoning are two different scientific methods, which are referred to by the generic name of the scientific method.

In inductive reasoning, the researcher begins with specific observations and measures, continues by detecting patterns and regularities, formulates some tentative hypotheses that can be explored and, finally, ends up developing some general conclusions or theories (Figure 3-1).

Deductive reasoning works the other way. The researcher may begin by developing a theory about a specific topic of interest and then narrow it down into more specific hypotheses that can be tested, collect observations to address the hypotheses and, finally, test the hypotheses using specific data, i.e. a confirmation of the original theory (Figure 3-1).

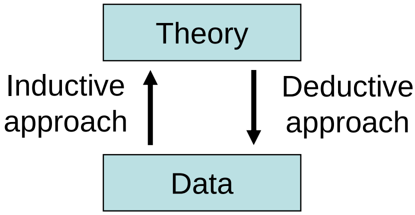

Figure 3-1. Basic difference between inductive and deductive reasoning (Hilmola 2003).

3.2 The building blocks of research

Grix (2004) describes the interrelationships between the building blocks of research, see Figure 3-2.

Ontology, epistemology and hypothesis

Ontology and epistemology are the foundation of research and theory-making (Grix 2004, Love 2000). Ontology is the exploration of the fundamental kinds of things that exist in the world, while epistemology is the theory of knowledge and a critical examination of assumptions about what is valid and what is the scope of that validity (Easterby-Smith et al. 2002). Ontology and epistemology link together assumptions and hypotheses that can be supported or rejected on the basis of the available evidence. A hypothesis is a specific assumption (or prediction) that can be tested.

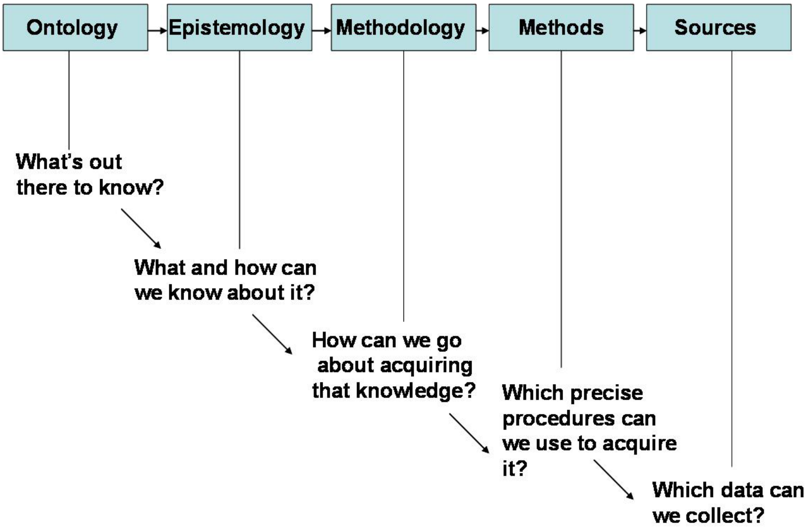

Figure 3-2. The interrelationships between the building blocks of research (Grix 2004).

Methodology

One prerequisite for performing research is methodology. Methodology is the evaluation of investigative techniques within a discipline. The objectives of methodology are to improve the procedures and approaches employed in the conduct of scientific research (Ackoff 1962). When undertaking research, it is important to choose the correct methodology and ensure that the research objectives can be met and the findings can be validated.

Grix (2004) defines methodology as a conceptual approach to a topic, the methods to be used and the data sources. Basically, methodology is driven by certain ontological and epistemological assumptions and consists of a choice of methods and research questions. However, defining hypotheses (ontological and/or epistemological assumptions) does not automatically lead to a given research methodology and research questions. The choice of methods depends on the judgement of which method or techniques will best obtain the information needed in order to achieve the objectives of the research (Naoum 1998). Gharajedaghi (1999) argues that a methodology must define what is to be accomplished and, secondly, how it is to be accomplished. The answer to the first question at issue, “What is to be accomplished”, is providing answers to the research questions. The second question “How to accomplish this” will be answered by describing the choice of methods and how they were applied in the research work.

Methods

For all types of research, the methods of collecting data will impact upon the analysis which may then be executed and therefore the conclusions and validity of the study (Fellows and Liu 2003). This data can be classified as either quantitative or qualitative.

Qualitative methods seek to identify individual beliefs by asking how and why? The advantage of a qualitative method, according to Backman (1998), is that it results in a deep understanding of the situation and contributes to the development of new theories. The disadvantage is that it is time consuming and it can be difficult to analyze and understand the data that have been collected (Easterby-Smith et al. 2002).

Commonly used methods for collecting qualitative data in construction research include the following.

- *Individual interviews* – an interview is a verbal interchange, often face to face, in which an interviewer tries to elicit information, beliefs or opinions from another person (Burns 2000). Its strengths include the opportunity to explore the meaning of the question, the immediate clarification of misunderstandings and the immediateness of the response. Its weaknesses include possible errors in interpretation, an opportunity for bias and the fact that the success is strongly influenced by the skills of the interviewer (Brenner et al. 1985).

- *Ethnographic research* – ethnography is a form of research focusing on applying insight from social and cultural anthropology to the direct observations of socio-cultural phenomena. During the study, the researcher ‘goes native’ by becoming part of the community under study to observe behavior and statements in order to obtain an insight into what, how and why the patterns occur. Ethnographic research is well suited to providing researchers with rich insights into the beliefs and values of human, social and organizational aspects of a socio-cultural phenomenon (Harvey and Meyers 1995). The result of the method is, however, difficult to evaluate due to the uncertainty of the influence caused by the presence of the researcher and existence of the research project (Fellows and Liu 2003).

- *Direct observation* – direct observation refers to observing and studying the people participating in a research study. It is normally used when data collected by other means may be of limited value or are difficult to validate (Hancock 1998).

- *Action research* – this generally involves active participation by the researcher in the process under study, in order to identify, promote and evaluate problems and potential solutions (Fellows and Liu 2003). Argyris and Schön (1989) argue that action research "builds descriptions and theories within the practice context itself, and tests them there through intervention experiments – that is, through experiments that bear the double burden of testing hypothesis and effecting some (putatively) desirable change in the situation". Fellows and Liu (2003) state that, as action research is highly context dependent and reliant on the project and the knowledge and subjectivity/perceptions of persons involved, it is neither standardized nor permanent. The observer is involved and has the main role of creating a field for discussion and an interpretation of the process and products. As change/innovation is the subject of the research, coordination and evaluation mechanisms which involve both the researcher and the participants are necessary.

- *Case studies* – the case study approach is used to obtain an in-depth understanding of the subject, focusing on process rather than outcome, on discovery rather than confirmation (Burns 2000). Yin (1994) defines a case study as "an empirical inquiry that investigates a contemporary occurrence within real life context, especially when the boundaries between phenomenon and context are not clearly evident". The objective is thus to immerse oneself in the situation and obtain an holistic understanding of a phenomenon in its natural setting (a person, a group of people and organization or a particular project). There are three kinds of case study (Merriam 1988).

    1. Descriptive case study: aims to describe phenomena or situations. The result is a detailed report which contributes to the understanding of the phenomenon or situation.

2 . Interpretive case study: aims to describe the study phenomenon and the descriptive information is used to highlight, support or question theoretical assumptions. The case study aims to collect as much information as possible in order to create an interpretation or extended theory about the phenomena being studied.

3 . Evaluative case study: includes descriptions and explanations in order to make evaluations and judgements about the area that is being studied. Since the case study provides holistic information based on the real case, the strategy is well suited for this purpose.

In contrast to qualitative methods, quantitative methods are more formalized and structured. Examples of quantitative methods include experiments, tests and questionnaires and they often result in numerical calculations (Backman 1998). Quantitative approaches compare factual data with theory – how many and how much (Walker 1997). The advantage, according to Easterby-Smith et al. (2002), is that they are economical and not so time consuming. The disadvantage is that they are inflexible and do not contribute to the processes or significations that people put on actions.

Some of the most commonly used methods for collecting quantitative data in construction research are as follows.

- *Experimental research* – experimental research is the only method that can claim true 'cause and effect' and is associated with the traditional 'scientific method' (Ackoff et al. 1962). An experiment intentionally distinguishes a phenomenon from its context, so that attention can be focused on only a few variables. Typically, the context is 'controlled' in a laboratory environment (Yin 1994). In experimental research, the researcher deliberately manipulates an independent variable (cause) to see whether it creates a change in the dependent variable (effect). Experiments are best suited to bound problems or issues in which the variables involved are known or at least hypothesized with some confidence (Fellows and Liu 1999).

- *Surveys* – survey research is a method of collecting information from individuals, about themselves or about their social units, using cross-sectional and longitudinal studies, such as highly structured questionnaires or unstructured interviews (Forza 2002).

The most commonly used research methods in construction research, according to Fellows and Liu (2003), are surveys, case studies, ethnographic research, experiments and action research.

3.3 Reliability and validity of research

Reliability and validity are essential for the effectiveness of any data gathering (Best and Kahn 1993). McMillan and Schumacher (1993) maintain that reliability and validity issues are handled within the actual study to obtain consistency of research strategies. The choice of research methods and the way they are implemented affect the reliability and validity of findings. McMillan and Schumacher (1993) suggested that a combination of strategies should be used to enhance the reliability and validity of the research findings.

Qualitative research findings

In qualitative studies, the researcher is seen as the key instrument, i.e. much depends on the way that person perceives a particular situation and much rests on that person's powers of observation and listening (Hoberg 1999). Reliability and validity in qualitative methods therefore hinge to a great extent on the skill, competence and rigor of the person carrying out the research work (Patton 1990). The preferred research role, according to McMillan and Schumacher (1993), is that of a person who is unknown at the site or to the participants. A researcher who is a participant or already has a status within the work force that is being observed limits reliability. However, there are other researchers who do not agree with this and believe that a person who is known to the participants can still produce credible results. It is therefore important that the qualitative researcher should have the necessary skills to carry out the research in a professional manner.

Quantitative research findings

Kirk and Miller (1986) identified three types of reliability referred to in quantitative research which relate to: (1) the degree to which a measurement (data), given repeatedly, remains the same, (2) the stability of a measurement over time and (3) the similarity of measurements within a given time period. A high degree of stability indicates a high degree of reliability.

The validity in quantitative research is described by Wainer and Braun (1988) as "construct validity", i.e. the construct is the initial concept, notion, question or hypothesis that determines which data are to be gathered and how they are to be gathered. They also assert that "quantitative researchers actively cause or affect the interplay between construct and data in order to validate their investigation, usually by the application of a test or other process."

Triangulation

Triangulation is a form of comparative analysis (Patton 1990) and can be defined as the use of two or more methods of data collection in the study of some aspect of human behavior (Burns 2000). Triangulation means comparing and cross-checking the consistency of information derived at different times and by different means within qualitative methods (Patton 1990). The triangulation approach can definitely strengthen the reliability and validity of data (Best and Kahn 1993). There are four different types of triangulation that can be carried out in order to increase the trustworthiness of the research project (Denzin 1978).

1. Data triangulation - the use of a variety of data sources
2. Investigator triangulation - the use of several different researchers
3. Theory triangulation - the use of multiple theoretical perspectives
4. Methodological triangulation - the use of several data collection methods

3.4 Adopted research methodology

3.4.1 Adopted scientific method

Science is fundamentally a rational process. In its simplest form, the rational model consists of five steps: (1) formulating an assumption, which is then translated into testable hypotheses and research questions, (2) selecting the appropriate research method and designing and carrying out the study, (3) analyzing and interpreting the results, (4) using the results to confirm, reject or modify the assumption or hypotheses/research questions and (5) reporting the findings (adapted from Alcock et al. 1998).

Figure 3-3 presents the five main steps of the deductive scientific method employed.

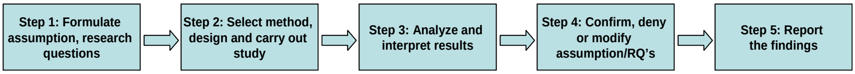

Figure 3-3. Main steps of the scientific method employed.

The basic philosophy of the research that is conducted, in terms of 'ontology' and 'epistemology', is based on a single assumption: *VR can improve the construction process*. Five research questions are identified in order to support this single assumption. (1) How is VR perceived, (2) how can VR be used for decision-making, (3) how can VR be implemented in the design process, (4) how can we estimate the value of VR in design and construction and (5) in what type of construction projects is VR most useful? For each research question, specific work tasks were carried out using various methods.

3.4.2 Research methods used in this research

The primary aim of research, as stated earlier, is to contribute to the development of VR in construction. The objectives that were defined to meet this primary aim provided a clearer perspective on how the research would be approached. Flexibility was a necessary factor due to the broad and changing nature of the research area. The overall methodology was to split the research into two main stages. Each stage was then subdivided into main objectives. One or more work tasks were defined to provide enough input to realize each objective. Continuous literature studies[4] provided knowledge and in-depth understanding. Early in the project, it became clear that it would be necessary to have a portfolio of research methods that could be used, depending on the contextual requirements at the time.

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[4] Although the general opinion is that literature studies in themselves are not a research method, they are nevertheless termed as such in this thesis.

Extensive interdisciplinary literature studies using academic and industrial literature were carried out throughout the research project to achieve the following.

- Establish and define problems, research questions and solutions
- Provide knowledge (construction process, ICT, VR, et cetera)
- Identify gaps in existing knowledge and research
- Review previous and ongoing research
- Chose methodologies and tools

This study applies a mixed method approach; a combination of qualitative and quantitative research methods. Modern construction research benefits from the merits of both qualitative and quantitative approaches (Seymour and Rooke 1995, Wing et al. 1998). The first stage conducted in 2000-2002 dealt with main objectives 1-3 and used a combination of literature study, individual interviews, action research, descriptive case study and questionnaire survey. The second stage conducted in 2004-2007 dealt with main objectives 3-5 and used a combination of literature study, individual interviews, action research, descriptive and evaluative case study and questionnaire survey. Table 3-1 shows the “research map” which identifies the objectives and work tasks against the output and research question concerned. It should be noted that the table is not chronologically organized and several of the work tasks occurred concurrently. Moreover, since the research that was conducted took place within an industrial context, the methodology has had to evolve throughout the research to align itself with the evolving environment in which it finds itself. This also means that some research results produced throughout the project are not presented in this thesis as they were out of keeping with the times.

Table 3-1. A research map.

Research map

Overall assumption: VR can improve the construction process

Stage	Main objectives	Work tasks	Methods	Main output	Research question
1	1. Review ongoing research – "VR in construction"	Investigate current research "VR in construction" – Scandinavia and the UK	Literature study Individual interviews	Internal report "Virtual Reality in Construction – a state-of-the-art report" (licentiate thesis)*	Preliminary information gathering
	2. Explore the potential utility of VR in supporting the construction process	– Review of VR in construction – Understand difficulties and prospects for VR in construction, e.g. construction errors	Literature study Individual interviews	Summary in licentiate thesis*	Preliminary information gathering
		Understand VR modeling	Literature study Action research Descriptive case study Case study "Centralhuset"	Results published in earlier paper* (licentiate thesis)	Preliminary information gathering
	3. Explore the credibility and applicability of VR in design and construction	Investigate how VR models are experienced and assessed by workforce at a building site	Questionnaire survey Descriptive case study Case study "Centralhuset"	Paper V	RQ 1
2		Investigate how VR models can be applied and accepted by professionals active in the design and planning process	Individual interviews Questionnaire survey Descriptive case study Case study "MK3"		
	4. Test and evaluate the use of VR for design and planning	Investigate how VR can facilitate worksite planning	Literature study Individual interviews Evaluative case study Case study "MK3"	Paper I	RQ 2
		Describe a practical approach to use VR to facilitate design reviews	Individual interviews Evaluative case study Case study "MK3"	Paper II	RQ 2
		Describe a practical approach to use VR to facilitate decision-making	Individual interviews Evaluative case study Case study "MK3"	Paper II	RQ 2
		Explore and document the practical work from using VR in design and planning	Individual interviews Evaluative case study Case study "MK3"	Paper III	RQ 2 and 3
		Investigate the type of projects in which VR is most useful?	Literature study Evaluative case study Case study "MK3"	Thesis	RQ 5
	5. Develop an evaluation model for ICT investments	Review common practice for evaluating ICT investments	Literature study	Paper IV	RQ 4
		Develop a novel model for evaluating ICT investments	Literature study Action research	Paper IV	RQ 4

*Not included in the thesis. However, the results are used to develop the overall assumption.

4 SUMMARIES OF PAPERS

In this chapter, each of the five appended papers is summarized with the intention of providing an insight into the research work and its results. The summaries include the title of the paper, the authors, which of the five research questions in the thesis that is in focus, keywords, introduction, purpose, methods, a summary of the main contents and the results and contributions.

4.1 Summary of Paper I

Title:

Applying virtual reality and 4D CAD models in the scheduling process of a large pelletizing plant

Authors:

Stefan Woksepp, Rogier Jongeling and Thomas Olofsson

Research question in focus:

RQ2: How can VR be used for decision-making?

Keywords:

Virtual Reality, 4D CAD, Virtual Prototypes, Construction Planning

Introduction:

Worksite planning is still a document-oriented process in which the planners rely on conventional scheduling tools, such as Gantt charts, 2D CAD drawings, paper documents and face-to-face meetings. The traditional work process imposes rigorous demands on the planners, especially in large, complex projects in which they have to compile and evaluate a large amount of documentation in order to perform the actual planning. It is also difficult for the planners to communicate an easy view of the work that is going to be executed. The lack of a continuous, structured information flow in construction projects is traditionally accepted as a natural part of the process and problems are dealt with on the construction site as they arise.

Although many previous case studies have produced good results from using VR models at different stages of the construction process, few have focused on the planning and scheduling part. It was believed that the complexity of this project, the number of multidisciplinary participants and the need to coordinate and facilitate the construction site activities according to a tight schedule would make VR models exceptionally useful in the planning process.

Purpose:

This paper is a report from a case study of the use of VR [and 4D] models to facilitate worksite planning in a large-scale construction project. The research work was performed and evaluated in concordance with the actual work on the building site, including the research group, planners and site managers. The paper attempts to answer the question: how can stakeholders exploit VR models as alternative forms of communication? Note: the use of 4D models was part of a more exploratory study and was not used in practice in this study.

Methods:

Literature study, individual interviews, evaluative case study

Summary of the main contents:

Most of the information that was used in the VR models originated from 3D CAD models developed by the different multidisciplinary design teams in the project. The VR system consisted of a low-cost approach to commercial software, PCs and projectors. VR was mainly used at design coordination and review meetings, as well as for planning purposes. All demonstrations of VR models were made using computer monitors or projectors (2D).

The VR models were mainly used by the planners for overviews and examinations of details. They also used various software features such as distance measuring, user positioning, turning objects on/off via layers, gravity, impenetrable objects and avatars. In addition, a number of VR models were produced in the project to show the general phases of the project during construction in order to support the scheduling process. These VR models of the construction process, which we define as phase models, were considered useful by the project team. However, it was noted that the phase models were limited in the sense that they are approximate representations of a certain state of the construction process, with no direct link to the project schedule (4D).

According to the planners, the greatest value when it comes to using VR models was the support of the planning process by including the setting-out grid (created as “VR solids”) in the VR models. The setting-out grid provided them with a starting position from where distances to the construction parts could be measured and it consequently provided a better spatial understanding of production alternatives, such as the preproduction of larger assemblies.

Results and contributions:

The case study provided good working experience and knowledge of practical implementation, usage and benefits achieved. However, this contribution supported RQ 2 rather than confirming it.

The case study showed that the use of VR models has the potential to increase the performance and reliability of the information according to the various interviews and tests performed on the construction site. In addition to facilitating decision-making and coordination in the scheduling process and visualizing the site activities, the VR models also improved the understanding of construction and collaboration among all the stakeholders who were involved. In comparison with the traditional 2D and document-based working methods, it was clear that the planners obtained a higher degree of spatial understanding from the VR demonstrations in the planning meetings on site.

My main contribution to this paper was describing and analyzing the application of VR models in the planning process. Rogier Jongeling made the exploratory location-based 4D model and analyzed the approach and Thomas Olofsson supervised and reviewed the work. I was the main author.

4.2 Summary of Paper II

Title:

Design reviews and decision-making using collaborative virtual reality prototypes; a case study of the large-scale MK3 project

Authors:

Stefan Woksepp, Thomas Olofsson and Rogier Jongeling

Research question in focus:

RQ2: How can VR be used for decision-making?

Keywords:

Virtual Reality, Design Review, Decision-making, Collaborative Working Environments, Client Requirements, Concurrent Engineering

Introduction:

Decision-making support is critical in complex projects, especially for the client in this project for whom the decisions that are made will have a long-term impact in terms of the opportunity to generate revenue on the invested capital. The decision makers – in this case, the client and the different design teams – base their decisions on large, heterogeneous, multidisciplinary sets of data. These data sets need to be effectively coordinated and communicated in the design process. The challenge is continuously to keep the decision-makers up to date on all the options and criteria that are important in enabling the decision to be made, especially in the briefing and preliminary design phase, when the most crucial decisions are taken. For this purpose, it was decided at an early stage to introduce VR models as a complementary source of information to 3D CAD models and extracted 2D drawings.

The previous paper focused on using VR models in the planning and scheduling process. This paper was designed to provide supplementary input regarding decision-making in the design process with the aim of substantiating RQ2.

Purpose:

This paper is a report from a case study of the use of VR models in the MK3 project to facilitate decision-making and coordination and to communicate client requirements in the design process. Special attention is paid to design reviews. The model-based working methods are discussed in the context of concurrent engineering.

Methods:

Individual interviews, evaluative case study

Summary of the main contents:

The use of VR models facilitated two important processes in the design process, especially in the design reviews; it facilitated the decision-making and the identification of client needs and requirements. The VR models made the communication during review meetings more effective, focusing on issues essential to the moment, thereby gaining valuable time and reducing the risk of misinterpretation. The client and the design teams were able to explore different alternatives by predicting and evaluating the impact on the project as a whole in order to come up with the best solutions. Several examples that illustrate the benefits are documented. They make it possible to:

- Make quick, well-founded decisions
- Understand the multidisciplinary consequences of a decision
- Match the decisions to the main goals of the project
- Present information to a wider audience in order to obtain input on issues such as the maintenance and operation of the plant

Results and contributions:

The case study provided excellent working experience and knowledge of practical implementation, usage and benefits achieved. This contribution provided substantial input to RQ2.

The use of VR models made it easier for the client and the design teams to become more actively involved in the multidisciplinary design process:

- In evaluating and making decisions about design alternatives
- In communicating the design aims to involved stakeholders

– In coordinating the different specialty designs.

This paper was written together with Thomas Olofsson and Rogier Jongeling, who provided empirical input and reviewed the work.

4.3 Summary of Paper III

Title:

Using virtual reality in a large-scale industry project

Authors:

Stefan Woksepp and Thomas Olofsson

Research question in focus:

RQ2: How can VR be used for decision-making?
RQ3: How can VR be implemented in the design process – prerequisites?

Keywords:

Client Requirements, Construction Planning, Construction Project, Design Process, Virtual Reality

Introduction:

Some of the most common mistakes when introducing new ICT tools, such as VR, in the design process are that the objectives are not clarified and established, the benefits not understood and planned for and the prerequisites for a successful implementation not complied with. Instead, most interest has traditionally focused on the technical issues – the applications and their features. This focus needs to be wider and include issues related to collaboration forms, organizational structure, ICT evaluations, et cetera. It is clear that there are no perfect scenarios for a successful implementation that suits every type of project. Instead, it is necessary to adapt to the situation and carry out the planning according to the current conditions.

The previous two papers focused on using VR models in the design and planning process. This paper summarizes the benefits of using VR in a concurrent engineering design and planning process and provides some prerequisites for successful implementation in construction projects with the aim of substantiating RQ2 and providing valuable input to RQ3.

The qualitative study was based on field studies and informal interviews.

Purpose:

The research objectives were to provide a deeper insight into and knowledge of the values and methods applied when using VR models in a construction project with the emphasis on the design and planning process. Implementation and usage, as well as the values obtained, are described in detail and discussed in the context of project prerequisites.

Methods:

Individual interviews, evaluative case study

Summary of the main contents:

This case study focuses on the same project as the two previous papers, with the same conditions regarding creating and demonstrating the benefit of using VR in a concurrent engineering process.

This paper provides a complementary detailed description to the two previous papers relating to the way VR models have been integrated in the design and planning process. The values obtained are described and discussed in order to provide a better insight into the potential of VR.

Experience and lessons learned:

- Most value has been derived from the use of VR as a decision-making support in the conceptual design of the plant layout and from detecting collisions in the detailed design phase
- The VR models were considered reliable because they originated directly from the different design teams' 3D CAD models
- Computer monitors and projectors (2D) were considered to be sufficient for displaying the VR models
- Using VR has had a positive effect on the final project costs and quality. A rough estimate based on previous experience from a similar project using 2D drawings by the design coordinator showed that the cost of using VR is much lower compared with the savings in design coordination alone, see also Paper IV. The number of staff dedicated

to design coordination was halved (from 15 to 7 designers) compared with a similar project using only 2D. In spite of this, the quality of the design coordination was deemed to be higher in the MK3 project
- The VR models have improved the understanding of the construction and collaboration of all the stakeholders involved in the project
- Partnering was believed to be successful in creating the climate of trust and collaboration necessary for sharing information among the involved stakeholders
- The working process, concurrent engineering, was considered to be a successful design method to reduce lead times and produce a coordinated multidisciplinary information flow.

Results and contributions:

The main contribution from this paper is the detailed description of the way the VR models were introduced and used successfully in the concurrent design process. The result is discussed in the context of the project features. As stated above, there are no perfect scenarios for the successful implementation, but the process described here could be described as "general", i.e. suitable for a variety of possible prerequisites.

This paper was written together with Thomas Olofsson, who reviewed the work and assisted in drawing conclusions.

4.4 Summary of Paper IV

Title:

An evaluation model for ICT investments in construction projects

Authors:

Stefan Woksepp and Thomas Olofsson

Research question in focus:

RQ4: How can we assess the value of VR in design and construction?

Keywords:

Benefits, Construction project, Costs, Evaluation, ICT, Investment, Virtual Reality

Introduction:

Several studies indicate that the ICT utilization ratio is still relatively low in the construction industry. It was suggested that some of the main causes of this were deficient understanding and a lack of knowledge about the potential of ICT, unsuccessful implementation in project organizations and limitations of software functionality. Another reason is most likely that construction companies often find it difficult to justify ICT investments in an industry that suffers from low profit margins and that many managers often view ICT investments as a process of consumption rather than capital expenditure and do not realize the importance of evaluating the IT investment.

The evaluation and justification of ICT investments is a complicated process, not only in the construction industry but also in all major industries, since the costs and benefits associated with the investment are uncertain and difficult to measure. In general, early estimates are typically plagued by limited scope definition and are often prepared under pressure of time. Moreover, many of the tools and methods used today have been shown to be inadequate and/or difficult to apply.

Several studies identify the process of investment justification as a major barrier to implementing ICT.

Purpose:

This paper presents a novel project-oriented evaluation model that has been developed in order to provide a structure and a work routine to be used by a multidisciplinary project team to evaluate the implications of realizing ICT investments in construction projects.

To support development towards practical applicability, the model was used to evaluate how VR models have facilitated the design process in a large-scale construction project. Interest focused on applicability, to establish whether or not it is a valid approach and, of course, to evaluate the implications of using VR models. The evaluation was carried out from a project perspective.

Methods:

Literature study, action research

Summary of the main contents:

The model is designed to provide a structure and a work routine to be used by a multidisciplinary working team throughout the process of assessing, planning and managing the implementation, utilization and follow-up of an ICT investment in a project organization.

The predefined benefit category structure and variable list is an extension of DeLone's and McLean's theoretical framework Information System Success Model (ISSM). The predefined cost category structure is a theoretical framework developed from a project perspective and the work procedure and risk handling were inspired by the PENG model.

The evaluation activities are divided into three main phases: (1) Prepare; (2) Analyze; and, (3) Secure. The first phase, "Prepare", includes identifying the scope of the evaluation, creating a multidisciplinary evaluation team and involving the management. The second phase includes drawing up three sets of checklists in order to identify, quantify and classify benefits and costs, as well as identifying and handling the risks. The third phase of the process includes securing the benefits. This phase begins as soon as the decision to realize the ICT investment has been taken.

The evaluation presents a gross result – benefit and cost variables are categorized, quantified in monetary terms and classified depending on the likelihood of their happening. The model differs from most other financial evaluation tools in that it is project oriented and includes intangible benefits.

Results and contributions:

The overall research objective was to present a novel project-oriented model for evaluating ICT investments in construction projects. Its applicability was validated in one case study. This research suggests that the proposed model is a highly applicable and valid approach. As shown in the case study, both the evaluation and the presentation of results met the requirements for successfully identifying and explaining the implications of realizing an ICT investment. The model was demonstrated by calculating the net benefit of using a new ICT tool (VR) in the design process in a large-scale construction project.

This paper also presented a review of common practice for evaluating ICT investments.

The co-author was Thomas Olofsson, who assisted in developing the evaluation model and reviewed the work.

4.5 Summary of Paper V

Title:

Credibility and applicability of virtual reality models in design and construction

Authors:

Stefan Woksepp and Thomas Olofsson

Research question in focus:

RQ1: How is VR perceived?

Keywords:

Construction Project, Design Stage, Field Survey, Planning, Questionnaire, Virtual Reality

Introduction:

From a general point of view, today's information flow is considered to be insufficient and the hypothesis is that using VR models in the construction process has the potential to minimize waste in construction projects and improve the quality of the end project. Although, applications of virtual prototyping have clearly been an area of increasing research and development activities in architecture and construction (Kähkonen 2003), the proper use of VR models in the different phases of a construction project is still not clear (Westerdahl et al. 2006).

Purpose:

The aims of these case studies are to explore and provide an insight into and knowledge of the way VR models are perceived and used by AEC professionals in their everyday work.

Methods:

Individual interviews, questionnaire survey, descriptive case study

Summary of the main contents:

This paper presents the two cases.

- The first case study is a questionnaire study that aimed to investigate how a visualized VR model was experienced and assessed by the workforce in the construction of a large hotel and office block and the extent to which VR was able to complement the use of traditional 2D CAD drawings. In this case, the operational use of VR at the building site was the primary target.

- The second case study is a field study. A qualitative research methodology was used. The study is based on field studies and informal interviews with 12 respondents involved in the design and planning of the construction project. The interviews were conducted on a one-to-one basis in conjunction to the participants' everyday work. This informal method helped us to map out the working process and to obtain a deeper knowledge of the experience of using VR in a systematic way throughout the design and construction process.

The conclusions in the paper are based on these two cases.

Results and contributions:

Using two case studies made it easier to go into greater depth when investigating the use of VR models in large construction projects. The study showed that the VR models in both projects were useful and well accepted by the users.

The results of the first case study indicate that there is a need to improve the information flow at building sites. The usefulness of virtual prototyping technologies, such as VR, appears to be obvious. This was also confirmed by the users who considered the VR models useful and felt confident about them. Indications that can inhibit the integration of VR into the building process were found in limited technical knowledge and financial considerations. Moreover, designing in 2D rather than directly in 3D considerably increases the cost of producing a VR model. Additional comments also revealed that it is important to inspire and create confidence in new ICT tools, such as VR models; otherwise, there is always a risk of a low utilization ratio.

In the second case study, it was found that the client and the vast majority of the designers and planners accepted and were positive about using VR models as a tool for improving information processing. The usefulness in both the design and planning process was acknowledged. At the beginning of the project, both fascination with and scepticism about VR technology was noted and this was thought to influence the acceptance and credibility of VR models. However, these symptoms quickly vanished when the use of VR models become a natural part of daily work. Moreover, several respondents argued that the use of VR would probably increase in future projects and that more built-in intelligence in the VR model would extend its use in design, planning and process simulation.

The paper was written together with Thomas Olofsson, who supervised and reviewed the work.

5 DISCUSSION AND CONCLUSION

This chapter discusses and concludes my research work. The research questions are addressed and the scientific and practical contributions of my research are presented. Furthermore, the trustworthiness, generalizations and limitation, relevance to industry and possible barriers to industry uptake of my research findings are discussed. Finally, some suggestions for future research are presented.

The objective of my research has been to investigate how VR (and thereby 3D) can be used during the planning, design and realization phase of a construction project, with the emphasis on complex building products. The main hypothesis during my research has been that the use of digital mock-ups of the product design visualized using VR technology enhances the opportunity to identify, analyze, coordinate and communicate the product design in order to improve the decision-making and thereby the final product. This hypothesis has been substantiated in five research questions where a combination of methods in two case studies has been applied to search for the answers.

5.1 Answering the research questions

The five research questions defined from the main hypothesis form the core of the research presented in this thesis. The answers to each of these research questions are derived from the appended publications and summarized along with information about the paper that contains further information relating to these results.

Research question 1

How is VR perceived?

Paper V presents the findings from an extensive case study of the use of VR models in large construction projects. The study has two parts. The first part presents a quantitative questionnaire designed to investigate how VR models are experienced and assessed by the workforce at a building site and the second part includes a qualitative field survey of how VR models can be applied and accepted by professionals in the design and planning process of a large pelletizing plant.

The results of the first part indicate that the present procedure of distributing design information by means of 2D CAD drawings is ineffective and that there is a need to improve the information flow at building sites. The usefulness of virtual prototyping technologies, such as VR, appears to be obvious. This was also confirmed by the users who considered the VR models useful and felt confident about them. Indications that can inhibit the integration of VR into the building process were found in limited technical knowledge and financial considerations. Moreover, designing in 2D rather than directly in 3D considerably increases the cost of producing a VR model. Additional comments also revealed that it is important to inspire and create confidence in new ICT tools, such as VR models; otherwise, there is always a risk of a low utilization ratio. In the second part, it was found that the client and the vast majority of the designers and planners accepted and were positive about using VR models as a tool for improving information processing. The usefulness in both the design and planning process was acknowledged. At the beginning of the project, both fascination with and scepticism about VR technology was noted and this was thought to influence the acceptance and credibility of VR models. However, these symptoms quickly vanished when the use of VR models become a natural part of daily work. Moreover, several respondents argued that the use of VR would probably increase in future projects and that more built-in intelligence in the VR model would extend its use in design, planning and process simulation.

In the end, confidence comes from keeping the information valid and reliable, not from presenting design information in the most convincing way possible. Failing to keep information up to date will have an immediate effect on the way users perceive VR models. For a more detailed discussion regarding this research question, see Paper V.

Research question 2

How can VR be used for decision-making?

Decision-making is a fundamental process in any construction project. In this context, the main intention is to provide an understanding of how VR can be used in decision-making in the design process. This second research question is dealt with in Papers I-IV.

The MK3 case study shows that the use of VR enriches information processing and thereby provides a better basis for decisions. One of the greatest benefits lies in the ability to improve the understanding of the multidisciplinary consequences of a decision. Different design alternatives can be explored by predicting, understanding and evaluating the impact on the project as a whole in order to come up with the best possible solution. This is particularly important in the early design stage when decisions often have a major impact on the final outcome. A more reliable and easily understandable decision-making basis at this stage increases the chances of achieving a positive effect on the final costs and quality. Using VR models also makes it easier to keep design teams and clients informed of options and decision criteria during every phase of the decision-making process. The client can become more involved in the design process and is thereby able to make faster decisions based on an understanding of the design rather than spending time trying to interpret 2D drawings. Information can be presented in a way that enables users to pay attention to what is essential and consequently gain valuable time and reduce the risk of misinterpretation.

Most VR applications can provide a certain level of interactivity and functionality that makes it possible for users to use some unorthodox methods to analyze or test different design solutions and present design intentions. Some good examples of these opportunities and the way VR models can be used in the decision-making process and more detailed discussions regarding this research question can be found in Papers I-IV.

Research question 3

How can VR be implemented in the design process – what are the prerequisites?

This third research question, which aims to provide an insight into the prerequisites for achieving the best possible implementation of VR in the design process, is mainly dealt with in Papers III-V, with some additional input in Chapter 2 in this thesis.

The implementation of VR in the design process requires an holistic approach. Implementing VR in the construction process is not primarily a technical challenge. Any successful implementation of new collaborative tools (such as VR) will affect the methods that are used, the working processes and the structure of the organization and will thereby challenge the business culture and vice versa. Change management must address all these levels when implementing VR in the construction project.

Interdisciplinary collaboration and coordination of the design is critical for implementing a concurrent engineering design process. In a design environment of this type, virtual prototypes using digital mock-ups of the different specialty designs provide the tool for the coordination and review of the design. In the MK3 project in particular, the VR tool also made it possible for the client actively to take part in the design and review of the operation and maintenance of the pelletizing plant.

Furthermore, the VR models must be based on and continuously updated from the different discipline-specific models if they are to be trustworthy in the review process. As a result, the different design disciplines must deliver 3D design models that can be easily integrated in the VR tool. This means that it is necessary to use a common coordinate system and delivery format from the discipline-specific 3D designs to make the models ready to be integrated in the VR models. There is simply not enough time to allow 2D specialty design models to be translated into 3D before they can be imported by the VR tool. Moreover, the risk of introducing errors in the design increases if these translations are to be made when the models are updated.

The project organization should aim to set up multidisciplinary design teams and create an open, collaborative environment that encourages and supports the sharing of information, risks and profits between the participants in the project. Research suggests (Eriksson 2007) that different procurement models affect the governance and organization of construction projects. The contractual form of partnering in combination with a concurrent engineering process has been shown to be an effective solution when it comes to providing a base for the successful implementation of a concurrent engineering process. Partnering facilitates problem-solving, support collaboration and cost reimbursement using incentives to realize common objectives in the project (Eriksson 2007, Toolanen et al. 2005).

Research question 4

How can we assess the value of VR in design and construction?

In addressing this fourth research question, I have used theories from the general field of evaluating ICT investments rather than focusing on assessing the values of using VR in design and construction. I found it difficult to distinguish between procedures of assessing values from using VR to other ICT tools. Nor did the literature review reveal any such efforts. ICT evaluation activities generally involve several multidisciplinary measures of both tangible and intangible variables that must balance each other if the evaluation is to be a success in terms of creating a well-described understanding of the implications in a project organization. The literature review also shows that the methods used today often fail to meet these requirements. In order to address this deficiency, I developed a novel project-oriented model for evaluating ICT investments in construction projects. The purpose is to provide a structure and a work routine to be used by the project teams in a construction project to evaluate the costs/benefits of realizing a new ICT investment for the project as a whole as opposed to evaluating cost/benefit for a specific partner organization. To support a development towards practical applicability, the application of the model is illustrated using a case study. The result of this case study indicates that the proposed model is applicable and produces a satisfactory result. The case study shows that both the evaluation and the presentation of results met the requirements for successfully identifying and explaining the impact of an ICT investment at project level.

For the specific case studied in Paper IV, the benefits of using VR were estimated to exceed the estimated costs by a large margin. However, isolating the benefits from using the tool (VR) is difficult, as it was part of an overall strategy which also affected the work processes (e.g. concurrent engineering). Furthermore, since all the benefits and costs are incurred by the project (in this case, due to the contractual arrangement of partnering), the estimated values at project level were not split between the stakeholders. Nevertheless, it is clear that the client is the main beneficiary in the case that was studied.

Research question 5

In which type of construction projects is VR most useful?

The last research question attempts to identify the types of construction project in which VR would be most useful. This fifth research question is an integration of previous research questions, as they are strongly interrelated. It aims to collate the knowledge acquired from dealing with previous research questions.

Since this study focused on large, complex building projects and the simplified cost/benefit analysis made in Paper IV showed that the benefits largely exceeded the costs in the project, the obvious conclusion is that VR in the design process used in a concurrent engineering setting adds substantial value to the project. This reasoning is supported by the results of a recent study from CIFE, Stanford University, which demonstrates the significant value that applying Virtual Design and Construction tools, such as 3D/4D and automated clash detection tools, can bring to a large, complex project (Khanzode et al. 2007).

However, determining how large and complex the construction project should be before new investment in VR tools and methods is profitable for the project is far more complex. Figure 5-1 shows general curves of ICT-evaluated costs/benefits versus project size.

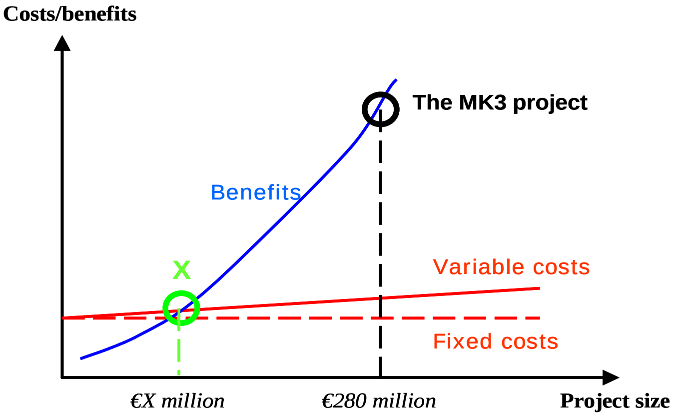

Figure 5-1. Cost and benefits of ICT investments versus project size.

The figure is highly speculative, but the general experience is that the benefits of an ICT investment increase when the project size increases. In addition, if the initial investments can be depreciated over several projects, the profitability should increase. Since the evaluated project benefits in the MK3 project were so large, a qualified guess is that, at the present time, the construction project must be in the order of €2-4 million to be profitable at project level. This estimation of benefits and costs also raises a question for the main beneficiary of such an investment – the client: how should the project be procured and organized so that the estimated costs, risks and benefits of the ICT investment can be shared in the project?

5.2 Contributions of this research

Research in the field of VR in construction is an applied science where the aim is to contribute to the development of the area, both scientifically and in practice. As far as the author of this thesis is aware, the following contributions are new in the field of VR in construction.

- Insight into the way AEC professionals experience and assess VR models in their everyday work. VR is considered in the context of being a carrier of design information in the design and planning phase.

- Guidelines for and examples of the way VR can be utilized in complex building projects during planning, design and realization in order to be beneficial to the project. What are the main benefits and how should the construction project be organized in order to make use of the potential benefits the technology offers?

- A newly developed model for evaluating the benefits and cost to the construction project associated with the introduction of new ICT tools. The model is intended to provide a structure and a work routine to be used by a multidisciplinary working team throughout the process of assessing, planning and managing the implementation, utilization and follow-up of an ICT investment in a project organization.

5.3 Trustworthiness of research results

This study applies a mixed method approach; a combination of qualitative and quantitative research methods, see Chapter 3. The reliability and validity of research findings is addressed. Within the scope of this research, the terms reliability and validity are conceptualized as trustworthiness.

The reliability and validity of the qualitative research findings were enhanced by involving other researchers and “objects of the study” to discuss and criticize the findings, as well as comparing the results with similar projects. Moreover, different types of triangulation were used to enhance validity, data were collected from different sources, other researchers were involved in gathering data and different data collection methods were used in the research.

The reliability and validity of the quantitative research findings presented in this thesis (i.e. the questionnaire survey in Paper V) were enhanced by using well-established and reliable test methods, execution and sampling methods, measuring and demonstrating mean values and standard deviations with a reliable and valid method (author's comment: relatively low standard deviation values were obtained in the questionnaire survey – Paper V – which indicates a fairly high degree of reliability) and involving other researchers to discuss and criticize the test and its results.

This research project has mainly used triangulation of data between the two case studies (the MK3 and Centralhuset projects), using different investigators in the MK3 project and the use of several data collection methods in order to strengthen the reliability and validity of research findings. A more detailed discussion of the reliability and validity of research and triangulation can be found in Chapter 3.

5.4 Generalization and limitation

Using only two case studies – two construction projects – to collect data made it possible to analyze things in depth, but it also limited the research. The conclusions presented in this thesis should be interpreted in relation to this limited scope. Extensive literature studies and comparisons with similar studies have, however, confirmed that the results are confirmed in similar types of construction project.

The greater part of my research work focuses on large and complex projects and sometimes conclusions are drawn and linked to construction projects. Needless to say, construction projects vary considerably in type, size and complexity and generalization to all types of construction projects is therefore not possible. Nevertheless, I do make some generalizations, especially when I am illustrating the possible benefits of using VR models, e.g. clash detection, since I believe that generalization in this specific context is valid for a wide range of construction projects. Furthermore, the illustrated benefits are sometimes linked to a particular stakeholder but most often to the benefits that are incurred by the project organization as a whole.

Very few follow-ups regarding the project impact of using VR in construction have been made in real projects and it is therefore difficult to verify the success factor.

Although many of the findings are applicable to far smaller, simpler projects, no such connections or guidelines are given.

The applicability of the newly developed evaluation model for ICT investments presented in Paper IV was validated in one case study and, as a result, the data set is limited in scope and scale. However, the theoretical framework and work procedure on which the model is based is well known and well established. My achievement is to adapt the theoretical structure and refine the evaluation process to fit the purpose and scope of the thesis. I therefore believe that the development work is well founded and the presented evaluation model can be used in other types of project.

Finally, I am aware that using deductive reasoning as a scientific method to study a fascinating tool such as VR can affect objectivity. I am also sure that this has occasionally blurred my scientific integrity.

5.5 Relevance to industry

Several years of research have resulted in an abundance of literature that describes ICT development and applications in the construction industry. However, only a few research results and tools developed for visualization are currently being applied in industrial applications in construction. Among the possible reasons, the most relevant is that, while the majority of the research focuses on developing new tools and computational models, there is a noticeable dearth of research that focuses on issues and factors that impinge on the uptake of ICT systems in construction, including stakeholders' perceived benefits and the costs and risks of ICT systems in practice (Ugwu and Kumaraswamy 2007). As discussed in the "Introduction" section, the scope of my research comes from the recognition that any successful implementation of new ICT tools, such as VR, will affect the methods that are used, the working processes and the structure of the organization and will thereby challenge the business culture and vice versa. Change management must address all these levels. I believe that the results of the research presented in this thesis can contribute to a better understanding of how and why the construction industry can use and benefit from advanced ICT, such as VR.

5.6 Barriers to industry uptake

Conducting applied research enabled the identification of some of the current key barriers to industry uptake. The uptake of advanced ICT tools, such as VR, is not primarily a technical challenge but rather a comprehensive process which requires an holistic approach with clearly defined aims and all-embracing efforts. It is hampered not so much by barriers in the VR technology itself as by barriers arising from traditional working processes and structures in the project organization, which are not adapted to take advantage of the new ICT tools offered in the market. Another barrier is the lack of a clear business case for the changeover from communicating design information using traditional documents, such as 2D drawings and written specifications, to using model-based information processing. Project stakeholders often find it difficult to recognize the benefits for their own organization and thereby justify such a change. The use of advanced ICT tools is often viewed as a process of consumption rather than an investment with benefits and costs. In addition, the importance of a fair cost reimbursement scheme is not recognized. The benefits are usually distributed throughout the value chain to the client, but it is the stakeholders who create the design information – the architect and designers – that often carry the costs of implementation and use alone. This leaves little incentive to encourage uptake. The impact of these barriers is evident in current findings from benchmarking studies indicating a low uptake of ICT; they include the e-Business w@tch EC report (2007) and InPro (2007).

5.7 Suggestions for further research

It is only recently that VR has started to be adopted as an enabling technology in construction projects and there are many directions in which the work described in this thesis can be extended. During my research work, several ideas regarding new research projects have come to mind.

It is recognized that implementing and using VR in the construction process is more than a technical challenge. Any implementation and utilization will affect the methods that are used, the working processes, the structure of the organization and the business culture and vice versa. However, these aspects of change management, which have a decisive influence on the success or failure of an implementation, are not well understood. As a result, there is a need to further investigate the prerequisites that should be met to ensure a successful implementation. I would like to highlight two areas of special importance in this context: *Processes* – adapted to fit into model-based information processing and which could challenge the traditional sequential construction process; and *Contractual forms* – which, for example, have a decisive influence on strengthening the incentives to carry out the implementation.

Secondly, the benefits of using VR in construction projects are still a relatively unexplored field of research. In this context, I would like to propose two main areas of research. The first area to investigate is in the areas in which the most benefits can be exploited when using VR in the building process. In my experience, these benefits from a quantitative and qualitative point of view can be acquired in the early stages of a construction project. The second area is to apprehend the benefits of VR in a lifecycle perspective and to link these benefits to specific players in the building process.

Finally, research in the field of VR in construction is an applied science where the aim is to contribute to the development of the area, both theoretically and in practice. I therefore believe that it is important for the researcher to carry out research work in close collaboration with practitioners who can apply and evaluate according to current conditions and to whom knowledge can be transferred. Collaboration of this kind is rewarding for both the researcher and the industry partner involved and can help reduce the gap between the R&D results and the current needs in the construction sector.

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Paper I

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Applying Virtual Reality and 4D CAD models in the scheduling process of a large pelletizing plant

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Abstract

LKAB, a large mining company in Sweden, has decided to invest €290 million in a new pelletizing plant in Malmberget, Sweden (MK3). The complexity of the project, the number of multidisciplinary participants and the necessity to coordinate and facilitate the construction site activities according to a tight schedule makes Virtual Reality (VR) and 4D CAD prototyping exceptionally useful in the planning process.

This paper describes a case study to explore a practical approach of using VR and 4D CAD to facilitate work site planning in a real large-scale construction project. The research work was performed and evaluated in concordance with the actual work on the building site including the research group, planners and site managers.

The evaluation of the case study shows that the use of VR and 4D CAD have facilitated the construction planning process. Besides coordinating and visualizing of the site activities, the virtual prototypes have also improved the understanding of the construction and collaboration among all parties involved. The main drivers for collaboration have been the time pressure in the project resulting in a concurrent engineering approach and a set of common goals, making the involved stakeholders to focus on the overall project performance.

Keywords

Virtual Reality, 4D CAD, Virtual Prototypes, Construction Planning

1. INTRODUCTION

The Swedish state owned mining company LKAB has recently initiated the design and planning process of a new pelletizing plant in Malmberget, northern Sweden. The plant, called Malmberget Kulsinterverket 3 (MK3), is planned to be operational by October 2006 and involves an investment of €290 million. It will be complementary to an existing pelletizing plant for the purpose of increasing the production capacity.

This paper presents the findings from the design and scheduling process of the pelletizing plant. At the start of the project it was decided by the project team to use model-based methods and Virtual Reality (VR) in the design and scheduling process of the project as tools to meet the client's requirements. A team of researchers from the Center for Information Technology in Construction (eBygg) at Luleå University of Technology is closely monitoring and studying this application of modeling software and VR walkthrough environments. In addition to these analyses, prototype software is developed and applied for 4D simulations in which the 3D models of the project are integrated with schedule data that follows from the project's construction schedules. The 4D simulations are experimental in the project, but are closely monitored by the project team, mainly as a result of the positive experiences with the use of VR in the project.

2. RESEARCH AIM AND SCOPE

The scale of the project, the extent to which the modeling tools and VR environments are used, and the very tight project delivery schedule make the project an interesting environment to study the application of VR and 4D modeling. Our aim is to report the practical approach that is applied by the project team to facilitate the scheduling process in the preconstruction stage. We illustrate this approach with a number of VR and 4D models of the project. The impact of these models will only be measured qualitatively since it is difficult to estimate the impact on economy and time in a project such as MK3. We will instead estimate the effect by evaluating how the client and the other stakeholders have been using VR and

4D as alternative forms of communication and also provide the readers with some case examples.

We first introduce the concept of virtual prototyping after which we briefly describe the case study project. We then outline and evaluate the application of virtual prototyping in the case study project. Concluding remarks and recommendations for future research follow this section.

3. VIRTUAL PROTOTYPING

"A virtual prototype is a computer simulation of a physical product that can be presented, analyzed, and tested from concerned product life-cycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model. The construction and testing of a virtual prototype is called virtual prototyping", [Wang2002]. The two main virtual prototyping technologies that are used in the design and scheduling process of the MK3 project are VR and 4D modelling.

3.1 Virtual Reality for coordinating designing and scheduling

One way to approach the challenge of providing a good understanding of the construction and its facilities would be to exploit the potentials advanced visualization techniques such as VR provides. VR is a spatial and communicating medium well suited to facilitate collaboration and understanding about the construction and the processes needed to erect it [Woksepp2004]. Even though VR today primarily is used for visualizing the final product [Woksepp2001] there is also a great potential to use it as a universal interface to all design applications [Aouad1997; Issa1999]. It might seem that we are evading the issue of "lack of trust" by suggesting a technical solution, but the fact is that VR has proven to promote collaboration in e.g. the design process through its ability to allow team members to create a design and evaluate it simultaneously for function, cost and aesthetics [Issa1999]. Actually, some of the major business drivers for VR identified by lead users are just coordinating design and design reviews [Whyte2002], which also leads us to the possibilities to facilitate effective processing of client requirements and planning of site activities.

3.2 4D modeling

4D modeling is a process method in which 3D CAD models are visualized in a 4-dimensional environment. Construction plans can be represented graphically by adding the time dimension to the 3D model to allow project planners to simulate and analyze what-if scenarios before commencing work execution on site [Mallasi2002]. A 4D model of a project allows project stakeholders to review the planned or actual status of a project in the context of a 3D CAD model for any day, week, or month of the project [Fischer2004]. In several studies 4D has proven to be a good visualization and schedule review tool by which project stakeholders are able to better understand a construction schedule with 4D visualization than traditional construction management tools [Songer2001; Yerrapathruni2003; Chau2004]. Koo [2000] identifies 4D modeling as a tool to convey planning information (visualization tool), enhance collaboration among project participants (integration tool), and to support users to conduct additional analyses (analysis tool).

Although geometrical data and temporal data are present in commercial 4D software, the utilization of these models has so far mainly concentrated on the visualization of construction processes. Planning supported by visual analyses of 4D models is considered more useful and better than traditional planning [Heesom2004; Jongeling2004], but does not take advantage of the quantitative data contained by 4D models. Recent research efforts in 4D modeling show an increasing interest in providing an integrated 4D environment to support a variety of quantitative analyses of for example work spaces, work flows and use of resources [Akbas2004; Akinci2002; Li2003].

In this paper we describe the relevance of 4D modeling as an instrument to facilitate the scheduling process of the MK3 project. We study the use of a location-based modeling approach as a method to facilitate 4D modeling and quantitative analyses from 4D models.

4. THE MK3 CASE STUDY

4.1 General

The client's (LKAB) three key goals in the MK3 project are to obtain a plant with required *Capacity* in *Time* within the *Investment frame*. The time period from the decision of investing in the construction of a new pelletizing plant to its completion is limited to two years. This puts great demands on the project organization and project performance. The preliminary study and the preliminary design, which both formed the basis for the investment decision, were also carried out during a very short period of time.

Normally in construction projects, the spatial needs govern the preliminary design, which in its turn is transferred into a real concept via the architects drawings and documents. However, in the MK3 project the priorities in the planning and design process are the following:

1. The manufacturing process (dictating)
2. Layout (the plant and its surroundings)
3. The construction process of the plant

This leads to a situation where the focus lies on assembly and functionality of machinery in the plant instead of the actual building. All separate design processes including construction, HVAC, electrical installations, et cetera, occur simultaneously in a concurrent design approach. Because of the complexity of the project the contract is based on incentives to meet the client's requirements in function, time and costs.

The contractual form in the MK3 project is called *Partnering* and is used to form an open collaborative environment. Partnering often involves cost reimbursable forms (transparency) for remuneration either with some incentives or without. The incentive is often based upon sharing savings and overflows of the target price. In the MK3 project the incentives are based on a combination of the three project goals to make all major stakeholders focused on the overall project performance. This facilitates problem solving and shift focus from the individual goals for the involved partners to the overall project goals. It was also decided to use model-based methods (3D and VR) in the design and planning process of the project to enhance the communication and reduce the risk.

4.2 Modeling tools and work process

Most of the information that makes up the VR prototypes of the plant originates from 3D CAD models developed by groups of multidisciplinary design teams. These teams work together with a common goal to fulfil the client's design intents of the pelletizing plant. Apart from forming the base for the VR prototype, the 3D CAD models are also being used for other purposes such as: spatial planning, extracting 2D CAD drawings and further processing in order to extract more detailed 2D CAD drawings as well as for updating 2D CAD drawings. The 2D CAD drawings are only used for production.

The VR system used in the MK3 project is a low-cost approach that consists of commercial software, PC computers, servers and projectors. The system is mainly used for coordination and review of the design, but is also applied for scheduling purposes. The VR software being used is Walkinside™, for which VR files are created via an add-on to Microstation. An independent VR consultant is appointed to work full-time managing the VR model and the information that is passing through.

The design teams who extract and choose the parts to be included in the VR prototypes are responsible for the development of the 3D models. These are then transferred into a common FTP server that works as a hub for exchanging and storing all visualization information. Every design team has their own dedicated folder with assigned authorization to facilitate the exchange administration and also to secure those parts of the information that is, for example, protected by patent. It is also common that the designers do not want to share all the information they create [Staub1999]. They simply want to share the relevant information for a particular situation [Liston2001]. The design teams are also responsible that the latest updated version should always be available.

The modeling is carried out in 3D CAD software such as, Solidworks, AutoCAD, Tekla Structures, Microstation (where most of the mapping of material and textures is done), Intergraph's PDS system, Inventor, SteelCAD and Enterprixe Structural. The common exchange format is primarily DWG. At the start of the project the VR consultant and design team set a number of minimal specifications for the contents of the DWG files to facilitate the information exchange and creation of VR models. It was decided that they should work in the same coordinate system and to model objects of the same type with the same colour. File sizes are kept down by dividing the project in several DWG files per design discipline. These specifications are rather basic and minimal, but are sufficient for the information exchange and VR modelling process.

After a new set of 3D CAD models has been transferred to the FTP server they are converted into VR format by the VR consultant. Large models are converted independently, optimized and integrated with the other models in the VR prototypes. Smaller models are converted in groups. The aim is to present updated versions every week, however, the reality is that this occurs every two weeks or when some major changes have been made. To smooth the progress of integration, all 3D CAD models are modelled using the same coordinate system. The total amount of information describing the VR prototypes of the pelletizing plant is extensive, including the construction (prefabricated and cast in place concrete, and the steel structure), its installations (machinery, HVAC, electrical installations, etcetera) and its surroundings. The VR prototypes are considered to be reliable because they origin directly from the design teams' 3D CAD models and have not been regenerated via some supporting 2D CAD drawings.

After the transfer, storing, converting and optimizing have been completed, the VR consultant then produces different VR prototypes for different purposes. For example; design reviews, construction site planning, production, mounting, working environment, presentations, exchange of experiences, etcetera. After having produced the prototypes the consultant transfers these back to the design team's folders at the FTP server. Focus is also on producing suitable VR prototypes for the customer to use for e.g. spatial planning, understanding the construction and its machinery, training of workforce, reconstruction, new work activities, handling hold-up in production, etcetera.

4.3 The project scheduling process

Effective planning throughout the construction project is essential for achieving a high level of quality and profitability. A comprehensive and parallel information exchange process characterizes the multi-disciplinary and concurrent project scheduling process in the MK3 project. Traditionally, as well as in the MK3 project, this is a document-oriented process where the planners rely on conventional scheduling tools (e.g. Gantt charts), 2D CAD drawings, paper documents and personal meetings. This work process is putting great demands on the planners, because they have to determine whether the accessible information is reliable or not besides performing the actual planning work. In consequence of this procedure one planner described that he had considerable difficulty in achieving an overall picture and understanding of the project. The lack of a continuous and structured information flow in construction projects are traditionally accepted as a natural part of the process and problems are dealt with on the construction site as they arise.

In this study we will focus on the preconstruction stage. Waly et al [Waly2002] describe this stage as the *macroplanning process*, which involves selecting major strategies, reviewing the design for constructability improvement, site planning for major operations and construction path, and arranging for the primary means, methods and resources required for the execution of the work packages. Our hypothesis is that this process can be facilitated by the use of VR and 4D.

4.4 The Virtual Reality approach

All demonstrations of the VR prototypes are done with computer monitors or projectors (2D) (often referred to as 'Desktop VR'). Screenshots and movies are produced and distributed via the FTP server. In addition to overviewing and detail examining, the VR software is used for ocular clash detection (automatic clash detection is being carried out in the 3D CAD software by the design teams themselves), distance measuring, user positioning (via XYZ coordinates or marked on a general map, updated in real-time), turning objects on/off via layers, gravity, impenetrable objects and avatars, see Figure 1.

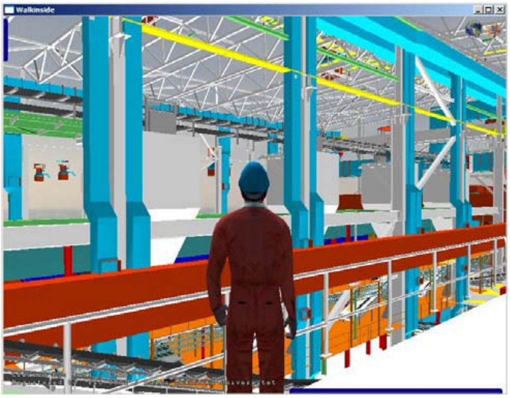

Figure 1: A screenshot extracted from a VR prototype showing the avatar inside one of the main facilities in the pelletizing plant.

An especially practical functionality of the VR system is that the users can mark areas within the VR prototype and write notes in a separate text entry window that is connected to the marked area, but logged in a separate text file. The text and its connection can later be resumed by clicking the notes. A number of people can also interact collaboratively in the VR environment over the network.

Figure 2 outlines the iterative design and planning process and use of VR in the MK3 project. The client is responsible for the overall design and planning process while the design teams, here denoted DS 1 to n, is responsible for the design of the sub-systems in the plant, i.e. process equipment, building structure, installations etcetera. All design teams is also responsible for providing correct and updated input data to the "VR database" and "4D CAD database". An independent VR consultant working for the client manages all the VR data and also makes updated and corrected VR prototypes accessible for everyone to use in the project.

The provided VR prototypes, denoted VR1 to VRn, are also used in the design review meetings that take place once every fortnight. Errors discovered during these design review meetings are instantly delegated to the design teams concerned. All errors that have been attended to are logged and later confirmed in the next following meeting. Decisions on major changes in the design are taken after conducting a risk analysis on the three goals in the project; the capacity, the time and the economical impact. These decisions are always taken in the risk management group consisting of the client and the main subcontractors in the Partnering contract. However, the greatest value for the customer comes from the ability to supervise, interact and provide input to the design teams in the design reviews during the entire design process.

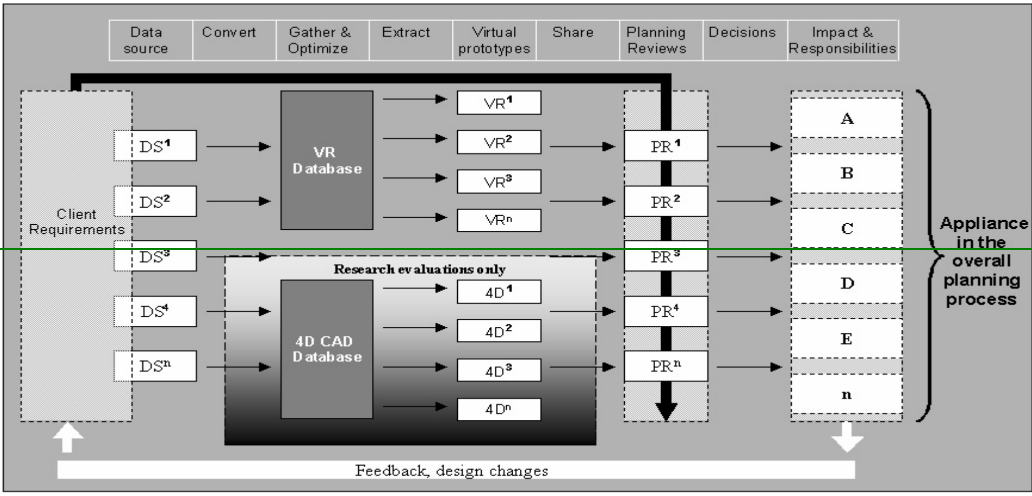

Figure 2: Specified and collaborative VR and 4D models in a continuous design and planning process in the MK3 project

According to the planners, the biggest value from using VR models to support the planning process is obtained from including the setting-out grid (created as “VR solids”) in the VR models. The setting-out grid provides them with a starting position from where distances to the construction parts can be measured and consequently brings forth a better spatial understanding.

In addition to the work processes related to VR, the use of 4D CAD is also outlined in Figure 2. As mentioned in the introduction, the use of 4D CAD is experimental in the project, but is closely monitored by the project team. Many project team members consider 4D as a logical next step in the application of a model-based design and scheduling approach. A number of VR models were made in the project that showed the general phases of the project during construction in order to support the scheduling process. These VR models of the construction process, which we define as phase models, are considered useful by the project team. However, it was noted by the MK3 project team that the phase models are limited in the sense that they are approximate representations of a certain state of the construction process, without a direct link to the project schedule.

4.5 The 4D CAD approach

The evaluation of the use of VR, described in the previous section, was mainly conducted throughout interviews with the project team and studies of the VR models. The application of 4D is studied in cooperation with the MK3 project team, where 4D prototype tools and 4D methods are developed and tested that suit the conditions of the MK3 project. Before we describe the 4D modelling process in further detail, we introduce the project settings for which the 4D models are made.

4.5.1 Balling station

The pelletizing plant consists of two main parts:

- A machinery section, consisting of a single large process installation, mainly delivered by one supplier and constructed by one contractor.
- A balling section, consisting of five sub-stations in which the actual steel pellets are rolled. Each balling station consists of a large tilting drum that measures 3 meters in diameter and 12 in length, connected by several conveyor belts. The conveyor belts of each balling station connect to conveyor belts that run throughout the plant.

Within this study a focus is made on the balling station as the design, scheduling and construction are the most complicated part of the whole pelletizing plant. There are a number of conditions that make the balling station an interesting environment for application of 4D:

- The design models are complex as they involve many different disciplines and complex geometries. For example, almost all conveyor belts are sloping away in different directions, often crossing and connecting to parts of the plant that are designed by several other suppliers and designers. The complex design raises questions about the constructability and order of assembly of the balling section.
- The construction space is limited. The drums and conveyor belts are almost completely preassembled when they arrive at the construction site and have to be fit in a steel structure that will support them. One main contractor conducts the work on the steel structure, but the work on the balling stations involves about 10 different suppliers and contractors at the same time, in the same area.
- The construction time is limited and requires from all involved contractors and suppliers to work with several crews at the same time. The limited construction time only allows minor buffers in time between the different installation activities, of which many are in fact planned to be carried out concurrently.

These conditions force the project team to carefully schedule and coordinate the construction process, but due to the complexity and amounts of data the conventional planning methods appear to difficult to apply. To illustrate; LKAB employs two planners in the project that solely work with the coordination of schedules, for which they use a master schedule in Gantt format. This master schedule contains at the time of writing about 5000 activities, but is expected to contain 15000 activities when the project advances. The main interests of the MK3 project team in 4D modeling are therefore the following:

- 4D models are needed that describe the overall construction of balling section of the pelletizing plant. The main aim of these models is to analyze the constructability of the plant. To illustrate: will the drums fit in when the work on the steel structure advances?
- In addition to 4D models that show general construction process, there is a need to model the space usage of suppliers and contractors during the construction of the balling stations. This 4D model should show construction operations in detail and spaces that are needed and available during construction.

The process of preparing and analyzing the 4D models requires an alternative approach to 4D modeling compared to a straightforward linking process of 3D objects with schedule data that subsequently is browsed visually in time. The conditions in the MK3 project force us to think of a 4D modeling method that suits the project.

The volume of available 3D data is considerable and not prepared to be used for 4D simulations. The structural engineers, for example, use SteelCAD in which they have structured the project data hierarchically in a database. From SteelCAD they export to the Enterprixe model server, which in its turn uses AutoCAD as a client to create DWG data of the project. This conversion to DWG does not include the object hierarchy that was created by the engineers. All the 26000 objects are saved in a flat manner, without any property data by which objects can be identified. The only identifier is the layer on which an object is located, but the total number of layers amounts only 9 different layers.

The model by the process engineers is created in Autodesk Inventor and consists of about 50000 objects that are grouped in blocks in the DWG. Some of the objects in this model have properties defined, but most of them are limited to just geometry.

The schedule data is available in Gantt charts that together contain between 5000 and 15000 activities. Most of the activity names are rather cryptic as they directly result from data systems used by suppliers that connect to the project-scheduling database with their internal planning systems.

The MK3 project team is interested in modeling and analyzing space usage and availability with 4D models, but the available 3D models from the design process do not contain these types of objects.

4.5.2 Location-based 4D modeling approach

A location-based approach to the 4D modeling process is applied in order to be able to work with the amount of data and to be able to extract quantitative data from the resulting 4D models. By using locations as a common denoter for both 3D CAD objects and activities, the information modeling and retrieval process is greatly facilitated. The locations for the 3D CAD models are specified according to the grid lines, which are used by the structural engineers. The grid ranges from H to X in one horizontal direction and from 10 to 18 in the other horizontal direction. The average distance between the gridlines is 7 meters. The vertical specification for locations is based on the coordinate system that is used by the MK3 project team. Each vertical level amounts between 3 and 5 meters. Based on the horizontal and vertical distribution of locations, locations are located in the form of transparent 3D mass objects as shown in Figure 3.

The 3D CAD objects from the various design disciplines are mapped according to the 3D locations. A property set is created for all 3D CAD objects, called location, which specifies to which location(s) in the grid the objects are placed. Objects can be contained by multiple locations and one location can contain multiple objects. After having specified the locations for all objects in the vertical and horizontal plane, the objects are hierarchically arranged according to object type, vertical position and horizontal position. This process is automated by using an experimental add-on program to AutoCAD that publishes the CAD objects according to a user-defined structure in a database as VRML files. All CAD objects are published in this way, resulting in a hierarchical database with one VRML file per object assembly for which a location is specified.

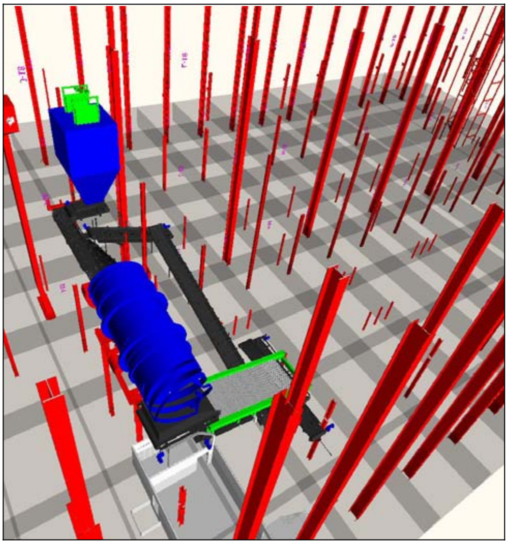

Figure 3: A location-based 4D modeling approach in the MK3 project

The production scheduling is carried out using the line-of-balance method, [Kenley2004]. Locations are distributed on the Y-axis of the diagrams and have several different levels. The first level is the vertical level and the second level the horizontal distribution of locations. Construction time is presented on the X-axis of the diagrams. Lines in the diagram that enable users to quickly detect time-space conflicts present activities. Time-space conflicts can result from different activities going on at the same time, at the same place. The use of line-of-balance diagrams is a first step in the analyses of time-space conflicts, but provides also a limited insight in the complex spatial configuration of the project. The line-of-balance diagram is a powerful instrument to distribute an activity from one location to another. This process of distributing activities over locations is done in combination with the hierarchically organized 3D model on a parallel screen.

The activities and locations are exported as schedule data to the 4D software, which directly connects to the database with 3D model data. The process of linking the activities and 3D model data is a straightforward process as a result of the matching data structure of the 3D and schedule data. The 4D model that follows is the 4D base model of the study. This model shows the overall construction process and is useful to analyze the constructability of the balling station. It facilitates the planners to evaluate several schedule alternatives and to communicate the schedule intent to the suppliers and contractors.

The 4D base model is limited to 3D CAD components from the design models and does not include information about workspace usage. This information is added to the 4D base model in the 4D environment. The 3D space objects that represent locations are used as workspace objects in the 4D model and are published to the database where they are sorted by vertical and horizontal location. The 3D location objects are added to the 4D base model by manually linking them as resources to activities. This is done for every construction day by stepping through the 4D model with a one-day interval.

An activity has the following properties and links in the 4D model, Figure 4:

```
Activity Name
   ├── Properties (locations)
   ├── Material (links to design objects)
   └── Resources (links to workspaces)
```

Figure 4: Links and properties in the 4D environment

For every workspace a type and duration can be specified. There are a number of research efforts that have looked into the generation and planning of space usage on construction sites [Akinci2002, Mallasi2002]. Akinci [2002] identifies for example the following types of space needed during construction activities:

- Building component space; the physical space occupied by the building component to be installed.
- Labor space; the space used by a labor crew installing the components.
- Equipment space; the space used by the equipment supporting a labor crew or a component during installation.
- Hazard space; the space generated when an activity creates a hazardous situation.
- Protected space; the space required to protect a component from possible damage for a certain period of time.
- Temporary structure space; the physical space occupied by temporary structures, such as scaffolding and shoring.

The 4D model in this study is limited to visualizing and analyzing the building and labor spaces during construction. For certain critical activities there are spaces added for equipment. 3D objects from the design models visualize building components. 3D location objects visualize labor and equipment spaces, with a unique color per space type.

The workspace loaded 4D model that results from this linking process is more detailed than the 4D base model and shows activities down to crew level per construction day. The space loaded 4D model is not created for the whole construction as this would result in considerable modeling efforts and large amounts of data. A number of critical phases are therefore modeled to show the potential of this 4D modeling approach. The critical phases are selected by using the line-of-balance diagram and the 4D base model. The workspace loaded 4D models are subsequently used for quantitative analyses in which distances between concurrent activities are analyzed and workspace usage by different crews and contractors.

4.6 Combining techniques provides further values

By combining VR and 4D techniques the users can derive further advantage in the planning process. This is, however, practically difficult to manage because of the additional resources this approach calls for. The 3D information originates from the same 3D CAD models, but is converted into and used in two different systems (see section 3.1 “Virtual Reality for coordinating designing and scheduling” and 3.2 “4D modeling”), thus managed by professionals with different skills. A schematic picture of the VR and 4D information handling in the continuous designing and planning process is shown in Figure 2. What is not clear in this figure is that the users constantly have to verify that they are using the latest versions of the 3D CAD models as a basis for their VR and 4D models. This puts heavy demands upon users how the information is managed and distributed, especially in large and complex projects. We therefore recommend this approach when facing particular problematical situations, e.g. advanced technical design solutions or narrow spaces (HVAC, et cetera), i.e. when the project planning is performed in more detail or when the consequences are considerable. Combining VR and 4D have not had any practical application in the MK3 project, only as experimental work.

5. CONCLUSION

The planning process in a multi-disciplinary and concurrent large-scale project such as the MK3 project is a complex and difficult process to manage. However, the use of VR and 4D models, individually or combined, has the potential to increase the performance and reliability of the information according to the several interviews and tests performed on the construction site. By comparison to the traditionally used 2D and document-based working methods the designers and planners can obtain a higher degree of spatial understanding from the VR demonstrations and better understanding of how and when the construction is going to be built from the 4D demonstrations. As a result the planners are able to foresee future consequences from different decisions and they can test and evaluate different solutions, further develop exchange of experience, and plan and manage the time schedules.

The reliability of the information has been obtained by continuously updating the VR and 4D models using the different design teams’ 3D CAD production models. In the MK3 project, one person was appointed to manage all information that was exchanged between all project participants. This proved to be a good investment. As a consequence, the rich information environment has facilitated the planners to focus on ‘priority of consideration’.

The technical interoperability between the different design teams and planners has not been an obstacle despite the variety CAD system used in the project. The propriety format DWG provided 'enough' interoperability for the users in this project. The technical interoperability has been identified as one of the main barriers in several research project conducted over the last decade. Instead the project management focused on selecting the best designers available using the CAD software of their choice. The interoperability was then a technical matter of selecting the common format and to overcome some of the spurious errors that occurred in the exchange of the DWG files to the VR prototype as well as linking the 3D CAD models to the tasks in the 4D systems. Most of these exchange errors could easily be detected.

The reluctance to share information is also a major identified barrier in the construction sector. Even though the Partnering contract facilitates the cooperation between the different stakeholders by trust, the main cause for the intense information flow and willingness to share has been the time pressure forcing the different design teams to act concurrently.

Based on the experience from the MK3 project, the client LKAB, has decided to use the same contractual concept and working method provided by VR in the next project – the construction of a new pelletizing plant in Kiruna, Sweden, twice the size of MK3. 4D will still remain at the experimental stage.

6. RECOMMENDATIONS FOR FUTURE RESEARCH

Despite the rapid technical progress during the last decades both VR and 4D can still be regarded as unexploited resources in the construction industry. Much remains to be investigated. Rather than suggesting tangible proposals for future research projects we will instead try to point out (some of) the most important areas to explore the impact of using VR and 4D in – as standalone working methods or applications or in conjunction with the most commonly used design and planning tools and methods in the construction industry today.

Project characteristics:

- Collaboration forms, e.g. Partnering
- Organisation, concurrent engineering, the need for champions and specialist function (VR/4D coordinator)
- Client value
- Risk management

Model-based working methods:

- Working guidelines for 3D, VR and Location-based planning in combination with 4D
- Handling of updates and modeling errors – data reliability
- Communication and design reviews using model-based environment

Technical issues:

- Recommendation for hardware and software related to the modeling efforts
- Interoperability issues

7. ACKNOWLEDGEMENTS

This paper is based on a field investigation where several people involved in the MK3 project were interviewed. These people represent the client (LKAB) and a number of subcontractors with liabilities within project management and planning, design management, business management and development, technical engineering and VR modelling. We thank them for their invaluable commitment and patience in sponsoring our work and providing access to project data and methods as well as their own knowledge and experiences. We also acknowledge the financial support from the Swedish research fund for environment, agricultural sciences and spatial planning (Formas), the Lars Erik Lundbergs Stipendiestiftelse, the Swedish construction development fund (SBUF) and the European regional funds.

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DESIGN REVIEWS AND DECISION-MAKING USING COLLABORATIVE VIRTUAL REALITY PROTOTYPES; A CASE STUDY OF THE LARGE-SCALE MK3 PROJECT

Stefan Woksepp[1], Thomas Olofsson[2] and Rogier Jongeling[3]

ABSTRACT

LKAB, a large mining company in Sweden, is investing 290 million Euros in a new pelletizing plant in Malmberget, Sweden (MK3). The complexity of the project, the number of actors involved and the desire to involve end users such as industrial workers responsible for the future plant operations in the design makes VR an excellent enriched source of communication in the design review process.

This paper describes a practical approach to facilitate decision-making, coordination and to communicate client requirements in the design review process using a number of collaborative VR (Virtual Reality) prototypes of the plant including the construction and installations. The model based working methods that are used in the case study is discussed in the context of lean construction.

The case study shows that the use of VR has increased the value for the client and the reliability in the design process. VR mock-ups have also minimized the waste in the production phase by eliminating collisions between the different designs. Even though the Partnering concept facilitates the cooperation between the different stakeholders the main cause for the intense information flow and willingness to share the information has been the time pressure forcing the different design teams to act concurrently.

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KEY WORDS

Virtual Reality, design review, decision-making, collaborative working environments, client requirements, concurrent engineering.

INTRODUCTION

ICT IN CONSTRUCTION

Even if the introduction of computers in the construction industry has changed the way we work its full potential is yet to be reached. Information management in construction projects is still a document-based process. Communicating, coordinating and maintaining up-to-date information is very difficult to achieve, especially in large construction projects. A great number of paper and reports emphasize the need for change in order to increase the effectiveness of the AEC industry (e.g. Egan 1998; Koskela et al., 2003). In a recent report "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry" (NIST GCR 04-867, 2004) by the National Institute of Standards and Technology (NIST) it is indicated that the cost for inadequate interoperability in the U.S. Capital Facilities run up to $15.8 billions annually. This report contributes to the awareness of interoperability-related issues, not only for owners and operators in the capital facility industries, but also for the construction industry at large. This might not be a technical-related problem but rather a consequence of the reluctance to share information and knowledge between the stakeholders in a construction project. Lack of trust and lack of adequate tools for communication are considered to be two of the most important factors for information losses in traditional construction projects (Blokpoel, 2003). Building trust is not an easy task, especially in an industry, where the relationship between parties is often characterized by shifting risk, contracts and adversarial perspectives (Busch and Hantusch, 2000). Since the communication between actors in a construction project is mainly based on documents the breakdown of the project and its presentation can only provide some basic information transfer between the stakeholders of the project (Kähkönen, 2003).

Changing the industry does not necessarily rely on the introduction of new advanced information and communication technologies (ICT); however, many of these systems have proven to be very efficient in other sectors. The result from the EC project ESPRIT CICC (1999) indicates that the efficiency can increase of 30 % is possible by exploiting the possibilities of different ICT tools. However, to act as a facilitator the ICT systems have to support the business processes (Björnsson, 2003). Since today's constructions process is developed to produce documents and 2D drawings, these procedures also have to change when new design methods based on technologies such as 3D, VR and product-models is introduced. Several European Information Society Technology (IST) projects have taken the challenge to introduce new ICT tools and model based work methods in the construction industry, e.g. OSMOS, eConstruct, Divercity, ISTforCE, eLegal, GLOBEMEM, etcetera. The results from the ICCI project (ICCI, 2004), where one of the objectives was to improve the coordination between these IST projects, revealed that there is also a need to overcome social and technical barriers in the construction industry. Some of the recommendations of especially importance are:

- Improvement of trust and social cohesion between all stakeholders involved in the construction process and product lifecycle.
- Changing the attitude and perceptions of the industry towards ICT
- Improvement of reliability and security of data and information exchange, as well as their underlying ICT systems.

One way to of improve communication and to provide a good understanding of the construction and its facilities is to exploit the potentials of advanced visualization such as Virtual Reality (VR). VR is a spatial communicating medium well suited to facilitate collaboration and understanding about the construction and the processes needed to erect it. Even though VR is primarily used for visualizing the final product (Woksepp, 2001) it has great potential to be a universal interface to all design applications (Aouad, et al., 1997; Issa, 1999). VR has also proven to promote collaboration in e.g. the design process through its ability to allow team members to create and evaluate designs simultaneously for function, cost and aesthetics (Issa, 1999). Actually, some of the major business drivers for VR identified by lead users are design coordination and design reviews (Whyte, 2002), including the possibilities for processing of client requirements.

RESEARCH ISSUES

Given the fact that VR constitutes an unexploited resource in the construction industry makes it particularly interesting to study how it can be used in a large and complex construction project as the MK3. Our aim is to describe how VR is used in the design process. Especially to facilitate coordination, decision-making and processing of client requirements in the design review process. The impact has only been measured qualitatively in interviews since it is difficult to estimate the impact on economy and time in a project as MK3.

THE MK3 PROJECT

BACKGROUND

The Swedish state owned mining company LKAB has recently initiated the design and planning process of a new pelletizing plant (MK3) in Malmberget, located in the north of Sweden. The plant is planned to be operational by October 2006 and involves an investment of €290 million. It will be complementary to an existing pelletizing plant for the purpose of increasing the production capacity. The Centre for Information Technology in Construction (eBygg) at Luleå University of Technology is closely monitoring and studying the design, planning and construction process of the plant as it involves the application of advanced IT systems, such as process-plant design software and VR walkthrough environments.

The client's, LKAB's, three key goals in the MK3 project is to obtain a plant with required *Capacity* in *Time* within the *Investment frame*.

THE UNIQUE CHARACTERISTICS OF THE PROJECT

To discuss whether a construction project can be classified as unique or not often leads to different standpoints. Nevertheless, one can certainly assert that the MK3 project is has set of conditions that all together have an effect on the project performance in a way that separates this project from other similar projects.

The time period from the decision of investment to completion of a the pelletizing plant is limited to two years. This put great demands on the project organization and project performance. Also the preliminary study as well as the preliminary design, which both formed the basis for the investment decision, was carried out during a very short period of time. In "normal" construction projects, the spatial needs govern the preliminary plans. These are transformed into a concept by the architect in form of drawings and documents. In the MK3 project the priorities in the planning and design processes are as follow:

1. The manufacturing process (leading)
2. Layout (the plant and its surroundings)
3. The construction of the plant

This leads to a situation where the focus is on the manufacturing process and functionality of the machinery in the plant instead of the actual building. All separate design processes including construction, HVAC, electrical installations, process, etcetera occurs simultaneously in a concurrent design approach. Because of the complexity of the project the contract was based on incentives to meet the client’s requirements in function, time and costs. This contractual form is called Partnering and forms an open collaborative environment for reaching a common goal for all major stakeholders in the project. It was also decided to use model-based design tools, such as 3D CAD and VR, in the design and planning process of the project to enhance the communication between the stakeholders and reduce the risk. The different design teams was free to use the 3D CAD tool they considered to be the most suitable as long as it could export the 3D CAD model in DWG format. Different VR prototypes were then assembled from the exported DWG models. A screenshot of a “VR environment” presenting an avatar inside one of the main facilities is shown in Figure 1.

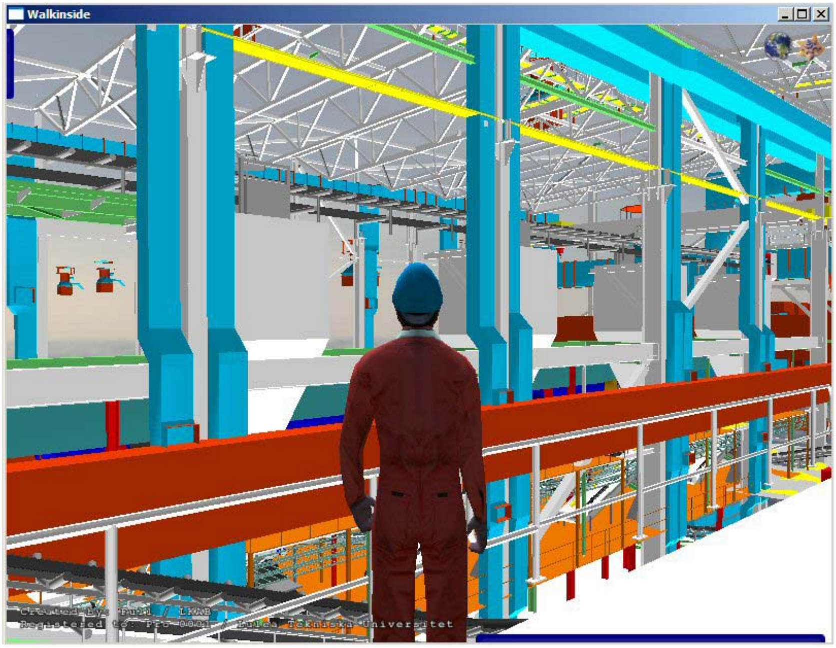

Figure 1: A screenshot extracted from a VR prototype showing an avatar inside one of the main facilities in the pelletizing plant.

The 2D CAD drawings are in most cases extracted from the 3D CAD models to be refined and used for production purposes. The project has also employed a number of retired local staff who has experience from the existing pelletizing plant constructed during the 1970s. Otherwise, lack of local competence could have been a problem considering that the plant is being built on a remote and sparsely populated place.

DESIGN TOOLS AND WORK METHODS

The VR environment used in the MK3 project is a “low-cost” approach that consists of commercial software, PC computers, servers and projectors. The VR software is Walkinside that is compatible with the most of the major CAD formats. The cost for producing and exploiting the virtual prototypes, and the consequences from this (read: the savings), is impossible to estimate as this comes within the scope of the Partnering agreement. An independent VR consultant working for the client is especially appointed to work full-time managing all VR prototypes. Most of the information that makes up the VR prototypes of the plant originates from 3D CAD models developed by groups of multidisciplinary design teams. These teams work together with the goal to fulfill the client’s requirements and design intents of the pelletizing plant. The electrical installations are modeled in 2D and later remodeled into 3D path for the cabling. The 3D CAD models are also being used for other purposes such as: spatial planning, extracting 2D CAD drawings and further processing in order to extract more detailed 2D CAD drawings as well as for updating 2D CAD drawings. The 2D CAD drawings are mainly used for production. The design teams who also extract chosen parts of the models to be included in the VR prototypes are responsible for the development of the 3D CAD models. These are then transferred into a common FTP server that works as a hub for exchanging and storing all visualization information. Every design team has their own dedicated folder with assigned authorization to facilitate the exchange administration and also to secure those parts of the information that is, for example, protected by patent. It is also common that the designers do not want to share all the information they create (Staub et al., 1999). They simply want to share the relevant information for a particular situation (Liston et al., 2001). The design teams are also responsible that the latest updated version should always be available. The modeling is carried out in 3D CAD software such as, Solidworks, AutoCAD, Tekla Structures, Microstation (where most of the mapping of material and textures is done), Inventor, Steelcad, EPX and Intergraph’s PDS system. The common exchange format is primarily DWG.

After a new set of 3D CAD models has been transferred to the FTP server they are converted into VR prototypes by the VR consultant. Large models are converted independently, optimized and integrated with the other models. Smaller models are converted in groups. The aim is to present updated versions every week, however, the reality is that this occurs every two weeks or when a big revision been made. To smooth the progress of integration, all 3D CAD models are modeled using the same coordinate system. The total amount of information making up the VR prototypes of the pelletizing plant is extensive, including the construction (prefabricated and cast in place concrete, and the steel structure), its installations (machinery, HVAC, electrical installations, etcetera) and its surroundings. The VR prototypes are considered to be reliable since they originate directly from the different design teams 3D CAD models and not remodeled via supporting 2D CAD drawings.

After the transfer, storing, converting and optimizing have been completed, the VR consultant then produces different VR prototypes for different purposes, for example, design reviews, construction site planning, production, mounting, working environment, presentations, etcetera. The updated prototypes are then transferred back to the design teams folders in the FTP server. Focus is also on producing suitable VR prototypes for the customer to use for e.g. spatial planning, understanding the construction and its machinery, training of workforce, reconstruction, new work activities, handling hold-up in production, etcetera. All demonstrations of the VR prototypes are done with computer monitors or projectors (2D). Low qualitative screenshots and movies are also produced and distributed via the FTP server. Besides overview and detail examining, a number of functionalities in the VR software are also used, e.g. ocular clash detection (automatic clash detection is being carried out in the 3D CAD software by the design teams themselves), distance measuring, user positioning (via XYZ coordinates or marked on a general map, updated in real-time), turning objects on/off via layers, gravity, impenetrable objects, avatars, etcetera. An especially practical functionality of the VR system is that the user can mark areas within the VR prototype and write notes in a separate text entry window that is connected to the marked area but logged in a separate text file. The text and its connection can later be resumed by clicking the notes. A number of people can also interact collaboratively in the VR environment over the network.

DECISION-MAKING AND CAPTURING THE CLIENT'S REQUIREMENT IN THE DESIGN REVIEW PROCESS

The use of VR prototypes facilitates two important processes in the design review; the *Decision-making* and *Capturing the Client needs and requirements*. The decision makers base their decisions on large, heterogeneous and multidisciplinary sets of data (Liston et al. 2001). These data sets need to be effectively coordinated and communicated in design reviews with the multidisciplinary design teams and the client (Christiansson, 2001).

The time-pressure in the project and the use of Partnering as a stimulus to enhance the collaboration between the stakeholders, resulted in a concurrent design process where the use of digital VR mock-ups where selected as the main tool for coordination and communication of client requirements in the design review process.

AN ITERATIVE DESIGN PROCESS

Figure 2 outlines the iterative design process in the MK3 project. The client is responsible for the overall design process while the design teams, here denoted Design team *1* to *n*, is responsible for the design of the subsystems in the plant, i.e. process equipment, building structure, installations etcetera. All design teams are also responsible for providing correct and updated input data to the "VR database". An independent VR consultant working for the client manages all the VR data and also makes updated and corrected VR prototypes accessible for everyone to use in the project. The provided VR prototypes, VR *1* to VR *n*, are used in the 'formal' design review meetings, Design review *1* to *n,* that takes place once every fortnight and includes representatives from the client and the design teams. Errors discovered during these design review meetings are either immediately dealt with by the representatives themselves or delegated to the design teams concerned. All errors that have been attended to are logged and later confirmed in the next following meeting. Decisions on major changes in the design are taken after conducting a risk analysis on the three goals in the project; the capacity, the time and the economical impact. These decisions are always taken in the risk management group consisting of the Client and the main subcontractors in the Partnering contract. However, the greatest value for the customer comes from the ability to supervise, interact and provide input to the design teams in the design reviews during the entire design process.

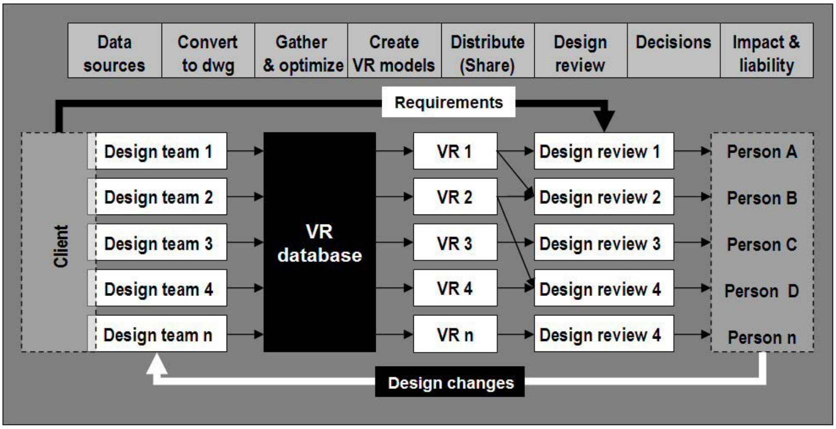

Figure 2: An iterative design review process with specified VR models in a concurrent and multi-disciplinary design situation.

‘Informal’ design review meetings are also conducted continuously throughout the design process. These informal meetings main objectives are to function as a complement to the formal meetings and to speed up the design process. One of the drawbacks of using VR as a communication platform has been that the access been limited to the VR software and the computing power needed to visualize the large VR prototypes. Therefore most of the information in these informal meetings has been based on 3D models, extracted 2D paper drawings communicated through emails and telephone meetings. However, the lack of VR has not impacted the information sharing, since theses informal meetings occurs between the regular design reviews where the coordinated VR prototypes are presented. The partners in the Partnering group have encouraged the sharing of information in informal meetings between the different design teams. All VR prototypes are collectively shared and owned by the partners.

DECISION-MAKING

Howard et al. (1984) defined the term *decision analysis* as the discipline comprising the philosophy, theory, methodology, and professional practice necessary to address important decisions in a formal manner. They continues to argue that the term includes the procedures, methods, and tools for identifying, clearly representing and formally assessing the important aspects of a decision situation. Decision-making in the MK3 project is a critical procedure, especially for the client where the decisions in the project will have a long-term impact on the opportunity to make revenue on the invested capital. The decision making and the design sequencing can affect the design process negatively. To reduce the risk for negative design iterations Ballard (2000) suggest among other measures; team problem solving, the share of incomplete information and concurrent engineering. Decisions made early in the design process have also a greater impact on the final outcome. Therefore, by focusing on the preliminary design stage, the greater are the chances to achieve a positive effect on the final costs and quality. This applies to this project as well to most construction projects. In view of the wide range of technical inputs, the client and the designers must provided information in an informative way so it can be assimilated into other decision criteria, e.g. risks, costs and milestones. The challenge, according to Kam et al. (2004), is to keep the decision makers (in this study - the client and the design teams) informed of all the options and decision criteria during all phases of the decision-making process, particularly in the briefing phase. It is therefore vital that the design teams prepare the information in a way so that the client can pay attention to what is essential, thus gaining valuable time and reducing the risk for misinterpretations. The design teams themselves need to explore different alternatives by predicting and evaluating the impact on the project as a whole in order to come up with the best solutions.

Today the communicating in most construction projects is based on 2D drawings and paper documents. This is clearly not sufficient as regarding to the requirements mentioned above. The participants need better and more effective tools to share and communicate project information. To support the needs of the collaborative multi-disciplinary design and decision-making process in the MK3 project, the client and the different design teams has used a number of VR prototypes for communication of comprehensible project information. Early in the project the decision to use 3D CAD and VR was taken by the Partner group. The project management foresaw the difficulties of gathering and communicating easily comprehensible multi-disciplinary information.

In the MK3 project, the VR prototypes constituted the most vital source of information together with 2D drawings and paper documents for continuous decision-making. There are several examples in the MK3 project where the VR prototypes been facilitating the decision-making in the design process. For example, because of the tight time schedule, sometimes the different design teams needs to take quick internal decision often without consulting the other design teams on a regular design review meeting. The VR prototypes help them to better understand the *multi-disciplinary consequences* of a decision. From the client's perspective, the impact of the decision on the manufacturing processes has the highest priority. All other decisions regarding e.g. construction, HVAC, etcetera, is of subordinate significance. Therefore, when the client had chosen the plant process and the machinery that supported the required capacity, it was then possible to define the spatial needs. These needs were describe to the construction design teams using a VR prototype of the plant process design. The construction design teams could then begin to plan the layout of the construction and make decisions about technical solutions, which would later be discussed, followed up and evaluated in the succeeding design review meetings. Besides making it easier for the client to make crucial decisions, the VR prototypes have also involved the client in the everyday design work. Being able to quickly sort out the information that is relevant for the moment and present it in an easy and comprehensible way to a wider audience such as the plant operating and maintenance staff, have facilitated the decision-making processes for the client.

ADDING VALUE AND MINIMIZE WASTE

Several papers and reports have pointed out the role of ICT in facilitating the processing of client requirements (e.g. Kamara, 1996; Worthington, 1994; CIT, 1996). Client requirements and the processing of these involves the communication of needs, wishes and expectations of the person or firm responsible for commissioning and paying for the design and construction of a facility in a format that enhances the understanding and implementation of what is desired (Kamara et al., 1999 and Miron et al., 2003).

As mentioned earlier, the use of VR prototypes in the MK3 project have facilitated for the client to become more actively involved in the design process. However, it is difficult to give an overall estimation of the value added and the waste saved caused by the use of VR in the design process. Here, we will give the reader just a few examples on how the technology been utilized to add value to the final design and to minimize the waste in the production phase.

In the analysis of the plant working environment and safety a special designed avatar of ample size (210 cm of height) was let to mimic the behavior of the operational and maintenance staff. This was primarily a spatial analysis where working spaces, escapes routes and risky areas in the plant were investigated. The result of the analysis was forwarded to the involved design teams for redesign of the problematic areas in question.

The second example also concerns a spatial analysis but with a total different purpose. The operation of a highly automated industrial process is to a large extent dependent on the maintainability of the process equipment. Measures to prevent production losses have high priority in such facilities due to the economical consequences. Therefore, to make sure that maintenance could be conducted, the maintenance personal was asked to participate in a spatial analysis using avatars and VR prototypes of the process machinery and layout. Problematic areas from a maintenance point of view could as a result be taken care of in the design phase.

Much of the non-productive work during the production phase is generated in the design phase. Rework caused by collisions between different objects, such as HVAC and the building construction, is mainly due to incomplete coordination and information flow between different design teams. The use of 3D and automatic collision detection can be a remedy to this problem, but this implies the all design teams should use the same CAD system. Furthermore, in large construction projects containing a huge amount of CAD objects, the use of automatic collision detection generates in many cases too much collision information to be practicable. Instead the same technique of probing avatars was used to detect collisions in special areas of the plant. Since the major risk for collisions occurs in the interface between different design teams, e.g. mainly between installation and construction, a visual detection technique was used. For example the avatar was made to craw inside the ventilation system to detect colliding objects penetrating the ventilation shaft, see Figure 3. This last example also shows how natural/visual interfaces to large data sets can inspire the interaction with VR systems that mimics the strategy that would be taken in the real world.

DISCUSSION AND CONCLUSIONS

Howell (1999) pointed out the essential principles of lean construction; to include a clear set of objectives for the delivery process, aimed at maximizing performance for the customer at the project level, concurrent design of product and process, and the application of production control throughout the life of the product from design and delivery. Even if not explicitly evaluated, we still want to stress the correlation between some of the main principles of lean construction, especially the use of VR to facilitate decision-making, coordination and communication in the design review process. According to several interviews the use of VR has increased the reliability in the design process to fulfill the client's needs and requirements or as Howell (1999) put it "Partnering is about building trust, and lean is about building reliability". The reliability has been obtained by continuously updating the VR model using the different design teams' production models.

The rich information environment has facilitated the client and the design teams to focus on 'priority of consideration'. The interactivity has enabled the use of unorthodox methods to test for maintainability, working environment and to minimize waste in the production phase caused by collisions in the design.

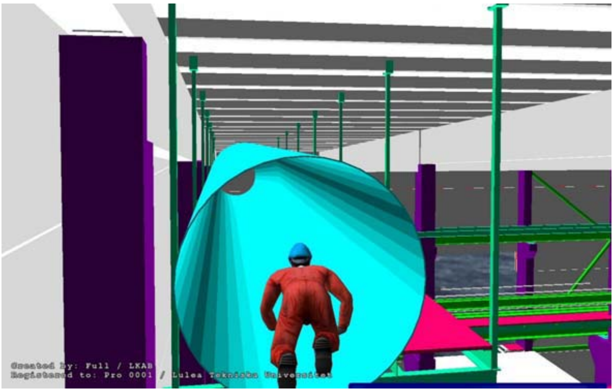

Figure 3: A screenshot extracted from a VR prototype describing how visual clash detections of installations can be made.

The technical interoperability between the different design teams has not been seen as a major obstacle despite the variety CAD system used in the project. The rather primitive propriety format DWG provided “enough” technical interoperability for the users in this project to compile and integrate the various design teams 3D CAD models into VR model. The technical interoperability has been identified as one of the main barriers in several research project conducted over the last decade. Instead the project management focused on selecting the best designers available using the CAD software of their choice. The interoperability was then a technical matter of selecting the common format and to overcome some of the spurious errors that occurred in the export of the DWG files to the VR prototype. Most of these exchange errors could easily be detected and corrected.

The reluctance to share information is also a major identified barrier in the construction sector. Even though the Partnering concept facilitates the cooperation between the different stakeholders by trust the main cause for the intense information flow and willingness to share has been the time pressure forcing the different design teams to act concurrently.

Based on the experience from the MK3 project, the client LKAB, has decided to use the same contractual concept and working method in the next project – the construction of a new pelletizing plant in Kiruna, Sweden, twice the size of MK3.

ACKNOWLEDGEMENTS

This paper is based on a field investigation where several people involved in the MK3 project were interviewed. These people represent the client (LKAB) and a number of subcontractors with liabilities within project management and planning, design management, business management and development, technical engineering and VR modeling. We thank them for their invaluable commitment and patience in sponsoring our work and providing access to project data and methods as well as their own knowledge and experiences. We also acknowledge the financial support from the Swedish research fund for environment, agricultural sciences and spatial planning (Formas), the Swedish construction development fund (SBUF) and the European regional funds.

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Paper III

Woksepp, S. and Olofsson, T. (2006). Using Virtual Reality in a large-scale industry project. ITcon, Vol. 11, pp. 627-639.

USING VIRTUAL REALITY IN A LARGE-SCALE INDUSTRY PROJECT

SUBMITTED: December 2005

REVISED: May 2006

PUBLISHED: August 2006

EDITOR: B-C Björk

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SUMMARY: The Swedish state-owned mining company LKAB has recently initiated the process of building a new pelletizing plant (MK3) in Malmberget, northern Sweden. The total expenditure will amount to €280 million and the new plant is expected to be operational around the turn of the year 2006-2007. Contractors are expected to employ a workforce of about 250 in connection with the construction of the plant, while some 150 consultants and engineers are engaged in the design phase. Since time to market is a crucial factor for LKAB, the contractual agreements for cooperation in the project support collaborative working methods such as concurrent engineering, open information flow and introduction of innovations in the design process. The complexity of the project, the number of actors involved and the desire to involve the client and the end-users, such as industrial workers responsible for the future plant operations, in the design work makes Virtual Reality (VR) an excellent enriched source of communications. This paper describes findings from a case study that sought to explore and document the practical work and experiences achieved, including some good examples, from using VR in the design and planning process.

KEYWORDS: Client requirements, construction planning, construction project, design process, virtual reality

1. INTRODUCTION

A great number of papers and reports emphasize the need for change in order to increase the effectiveness of the construction industry (e.g. Egan 1998, Koskela et al 2003 and Kunz et al 2005). Changing the industry does not necessarily depend on the introduction of new advanced information technology (IT) tools; however, many of these aids have proven to be very efficient in other sectors. For example, results from the EC project ESPRIT CICC (1999) indicates that an efficiency increase of 30 % is possible by exploiting the possibilities of different IT tools.

Even though the introduction of new IT tools in the construction industry has changed the way we work, the full potential on project level is yet to be reached. The pragmatic communication in construction today is often based on traditional media where the breakdown of the project and its presentation can only provide some basic information transfer between the stakeholders of the project (Kähkönen 2003). To be able to act as a facilitator and to provide new opportunities these tools have to be adapted to the business processes (Björnsson 2003 and Lindfors 2003). However, today's processes are constructed to support an information flow mainly based on documents and 2D drawings.

Several European Information Society Technology (IST) projects have taken the challenge to introduce new IT tools and model-based working methods in the construction industry, e.g. Manubuild, OSMOS, eConstruct, Divercity, ISTforCE, eLegal, GLOBEMEM, et cetera. The results from the ICCI project (ICCI 2004), where one of the objectives was to improve the co-ordination between these IST projects, revealed that there is a need to overcome business, social and technical barriers before model based working methods can be introduced.

It is also vital to find enough incentives in order to justify the introduction of new IT tools and model-based working methods. The report "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry" (NIST GCR 04-867 2004) by the National Institute of Standards and Technology (NIST) indicates that the cost for only for the inadequate interoperability in the U.S. Capital Facilities ran up to $15.8 billion annually. This report contributes to creating an increased awareness about interoperability-related issues, not only for owners and operators in the capital facility industries, but also for the construction industry at large. This is not believed to be a technical issue but rather a consequence of the reluctance to share information and knowledge between the stakeholders in a construction project. Basically the lack of trust, and also the lack of adequate tools for communication are the two most important factors for information losses in traditional construction projects (Blokpoel 2003 and Blokpoel et al 2004).

Virtual Reality (VR) models are one way to improve information handling, communication and understanding in construction projects. VR offers a natural medium for the users providing a three-dimensional view that can be manipulated in real-time and used collaboratively to explore design options and simulations of the construction process (Bouchlaghem et al 2005). Already during its introduction in the construction industry in the 1990s VR was considered to have a great potential in construction providing new possibilities for improving the construction processes (e.g. Retik 1997 and Cochrane 1997). However, it is only recently that VR have started to be used in construction projects as tool to support the design and construction process. Although, the proper use of VR models in the different phases in a construction project is still not clear (Westerdahl et al 2006). This paper describes a case study of the use of VR in a real construction project and will hopefully contribute to the understanding on how VR can be utilized for improving the construction process.

2. RESEARCH OBJECTIVES AND METHODOLOGY

The case study was launched to explore and document the use of VR in a construction project by providing values achieved and good examples from how the client, design teams and planning teams have been using VR models as a complementary source of information to 3D CAD models and 2D CAD drawings in the construction of a large-scale pelletizing plant (MK3) in northern Sweden. The research objective was to provide new insights and knowledge about the values of using VR models in a construction projects with focus on the design and planning process.

A qualitative research methodology was used. The study is based on field investigations and informal interviews with 12 respondents involved in the design and planning process in the construction project. The interviews were mostly conducted on a one-to-one basis in conjunction to the participants' everyday work. This informal method helped us to map out the working process as well as to obtain a deeper knowledge of the experience of using VR in a more systematic way throughout the design and construction process. Since the project is still on-going the possible impacts on overall targets in the project have not been evaluated.

The paper is organized as follows: The next section provides the reader with some background and review of the use of VR in construction projects. The case study project, MK3, where VR has been used in the design and planning process, is then presented followed by a description of working methods and some examples of benefits found the in the design and planning process. Finally, the uses of VR in the MK 3 project are discussed and some conclusions are made regarding the prerequisites and benefits of using VR in construction projects.

3. CURRENT RESEARCH ON VR IN CONSTRUCTION

Applications of VR have clearly been an area of increasing research and development activities in architecture and construction (Kähkonen 2003). Below are some examples of research on the use of VR models in construction projects. The examples are structured in reversed chronological order.

A study by Westerdahl et al (2006) investigated how employees of a company experienced a VR model of their yet-to-be-built workplace. The use context for the VR model was the late stage of the architectural planning process. The results indicated that the employees provided them a good understanding of their future workplace and that the VR model helped them in the decision-making process of the design.

Bouchlaghem et al (2005) reviewed the applications and benefits of visualisation in construction projects from three research projects covering collaborative working and design in the conceptual design stage, marketing process in the house building sector and modelling of design details in the construction stage. The paper concluded that visualisation applications are becoming more available and accessible to construction professionals largely because of the continuous decreasing cost of software and hardware and leading construction firms now have invested large resources realizing its business benefits.

Ganah et al (2005) presented a research project with the aim to develop a visualisations system for graphical communication of constructability information between design and construction teams. The objective was to improve the lack of communication between design and construction using visualisation tools.

Janols (2005) studied how 3D visualisation can be used for improving timber construction by communicating the aesthetical properties. The results showed that structural complexity, intended viewer and current building phase influence the benefits of the visualisation and that the need for 3D visualisations with high realism and high level of detail is higher for external communication compared to internal communication between professionals.

Woksepp et al (2004) investigating how a VR model was experienced and assessed by the users in the construction of a large hotel and office building, and the extent to which such model could complement the 2D CAD drawings that are mainly employed in such a context. The operational use of VR at the building site was of primary concern. The study involved a total of 93 participants all involved in the building project. It was concluded that the VR model in question was realistic, a majority of the participants being positive regarding use of VR in their profession. The participants also were of the opinion that the information flow at the building site is insufficient and that use of VR models would be beneficiary for the communication and coordination at the building site.

The use of VR in the construction of a new lecture hall in Helsinki was studied by Savioja et al (2003). The study described the process starting from a relative simple VR model for presentation of the concept and layout. The model was further detailed until a photo realistic model of the building could be presented and used for detailed studies of the design. All participants, especially the design team and the end users, were enthusiastic over the possibilities the VR model could bring to the project. Some technical problems were reported, especially when the complexity of the model increased. One conclusion worth mentioning was the necessity of early planning of the model structure, especially when realistic VR models are going to be created.

The use of 4D/VR in the construction of a high-rise apartment and commercial store building project in South Korea is described in Kim et al (2001). The biggest gain from using 4D/VR models was achieved from improving communication between managers and workers which led to reducing the construction time from 43 months to 39 months.

Calderon et al (2000) studied the use of VR as a communication medium for building design. A review of the literature showed there to be a lack of adequate research and there being relatively few practical applications there thus far.

To conclude, research has indicated that VR at the present time has become more accessible and available as well as appreciated and accepted by the stakeholders in the construction process. Knowledge of benefits and method of application in the construction process is relatively good, especially the use of VR for communication of design intents to the client. New VR applications such as visualisation of the erection process (4D) (e.g. Fischer et al 2004 and Jongeling et al 2004) are starting to be introduced in the construction sector. Westerdahl et al (2006) suggest that there is a demand for further research on the use and value of VR in the design and construction process; especially since the construction industry is starting the transition from a traditional document supported process using 2D drawings to a model based supported design and construction process.

4. THE MK3 PROJECT CASE STUDY

4.1 Background

The Swedish state owned mining company LKAB has recently initiated the building of a new pelletizing plant (MK3) in Malmberget, in the north of Sweden, which will be complementary to an existing pelletizing plant for the purpose of increasing the production capacity. The total expenditure will amount to €280 million and the new plant is expected to be operational in October 2006. Contractors are expected to employ about 250 persons in connection with the construction of the plant, while some 150 consultants and engineers are engaged in the design. Since time to market is a crucial factor for LKAB, the contractual agreements for cooperation, partnering, in the project support collaborative working methods such as concurrent engineering, open information flow and introduction of innovations in the design and construction process. The Center for Information Technology in Construction (eBygg) at Luleå University of Technology is closely monitoring and studying the design, planning and the construction process of the plant as it involves the application of advanced IT systems, such as process-plant design software and VR walkthrough environments.

The client's three key goals in the MK3 project are to obtain a plant with required *Capacity* in *Time* within the *Investment frame*.

The 12 interviewees, all men, represented the client (LKAB) and a number of subcontractors with responsibilities within project management and planning, design coordination, business management and development (representing the client), technical engineering and VR modeling. All but one, the VR consultant, had several years of experience from similar construction projects. Also, the VR consultant was the only one that had some experience of working with VR models. Everyone uses computers frequently and agreed that the amount of information in construction projects is probably enough but needed to be more structured and easier to communicate to the different stakeholders in the project.

4.2 Project characteristics

Discussions about whether a construction project can be classified as unique or not often leads to different standpoints. Nevertheless, one can certainly assert that the MK3 project is carried through based on a combination of conditions that all together have an effect on the project performance in a way that separates this project from other similar projects. For example, the time period from the decision of investing in the construction of a new pelletizing plant to its completion is limited to two years. This put great demands on the project organisation and project performance. The conceptual stage of the project, the base for the investment decision (business conditions, manufacturing process and preliminary layout of the plant), was carried out during a very short period of time.

Normally, the spatial needs govern the preliminary plan in a construction project. However, the design of the plant in the MK3 project is affected by the following parameters:

1. The design of the manufacturing process;
2. The plant layout (the plant and its surroundings);
3. The construction of the plant.

This leads to a situation where the focus is on the assembling and functionality of the machinery in the plant instead of the actual building. All separate design processes including construction, HVAC, electrical installations, process, et cetera, occur simultaneously in a concurrent design approach. The project has employed a number of retired local staff who has experience from the existing pelletizing plant constructed during the 1970s. Otherwise, lack of local competence could have been a problem considering that the plant is being built in a remote and sparsely populated place.

Due to the complexity and the time pressure in the project the contract was based on incentives to meet the client's requirements in function, time and costs. This contractual form is called Partnering and is used to form an open collaborative project environment. Partnering facilitates problem solving and shift focus from the individual goals for the involved partners to the overall project goals. Also, changes in the design beneficiary for the project can be implemented without renegotiation of the contract. Partnering often involves cost reimbursable forms (transparent) for remuneration with incentives for reaching project goals. The incentive is often based upon sharing savings and overflows of the target price. In the MK3 project the incentives are based on a combination of the three project goals to make all major stakeholders focused on the overall project performance. The project management introduced a number of team building activities in order to improve the working climate and trust between the different parties. Early in the project the decision to use 3D CAD and VR was taken by the Partnering group. The project management foresaw the difficulties of gathering, coordinating and easily communicating comprehensible multi-disciplinary information to all stakeholders in the project.

4.3 The VR system

The VR system used in the MK3 project is a low-cost approach that consists of commercial software, PC computers, servers and projectors. Walkinside™, which was selected as VR platform in the project, can import most of the major CAD formats. An independent VR consultant is especially appointed to work full-time managing the VR models and the information that is passing through.

4.4 Creating and displaying the VR models

Most of the information that makes up the VR models of the plant originates from 3D CAD models developed by groups of multidisciplinary design teams. The only exception in the project is the electrical installations that were modelled only in 2D. However, the cabling was later remodelled in Microstation as 3D CAD objects to show the location of the cable ladders in the plant. The design was carried out using a number of 3D CAD applications such as: Solidworks, AutoCAD, Tekla Structures, Microstation (where most of the mapping of material and textures is done) and Intergraph's PDM system. Apart from the use in creation of VR models, most 2D CAD shop drawings are directly generated from the 3D models.

The different design teams responsible for the development of steel, concrete, machinery, ventilation, et cetera, extract chosen parts of the 3D models to be included in the VR models. These are then transferred into a common FTP server that works as a hub for exchanging and storing design information. The common exchange format used is DWG. Each design team has a dedicated folder with a given assigned authorization to facilitate the exchange administration and to secure those parts of the information that is protected by patent. The design teams are responsible that the latest updated version should always be available on the FTP server.

The VR consultant converts the uploaded 3D models into VR format. Larger 3D models, consisting of many objects, are first converted and optimised separately to reduce the size of the VR model. Smaller models are converted and optimised in groups before the complete VR model is put together. The aim was that to produce updated versions every week. However, in reality this occurs every two weeks or when a large design change has been made. To facilitate the process of integration, all 3D CAD models uses the same coordinate system. Also, during the course of the project the design become more detailed and objects describing smaller parts of the machinery such as bolts or similar that has less significance for the visualisations are filtered out in the DWG exchange file before they are uploaded to the FTP server.

The total amount of information describing the VR models of the pelletizing plant is extensive, and includes the construction (prefabricated and cast in place concrete, and the steel structure), the installations (machinery, HVAC, electrical installations, et cetera) and its surroundings. The VR models are considered to be reliable because they directly origin from the different 3D CAD models and are not re-constructed from supporting 2D CAD drawings.

After the transfer, storing, converting and optimising have been completed, the VR consultant then produces different VR models for different purposes, e.g. design reviews, construction site planning, production, mounting, working environment for safety and maintenance et cetera. After the VR models have been produced they are transferred back to the to the FTP server.

All presentations of the VR models are done with computer monitors or projectors (2D). Screen-shots and movies are also produced and distributed via the FTP server. Besides overview and detail examining, the VR software is also used for ocular clash detection (automatic clash detection is being carried out in the 3D CAD software by the design teams themselves), distance measuring, user positioning (XYZ coordinates or on an overview, updated in real-time), turning on/off objects layers, gravity, impenetrable objects, avatars, et cetera. An especially practical functionality of the VR software is that the user can mark locations in the VR model and write notes. These notes are connected to the marked location and logged in a separate text file. The description and its connection to the location can be retrieved by clicking on the note symbol in the VR model. A number of people can also interact collaboratively in the VR models over the network. A typical example of a VR model of the plant can be seen in Fig. 1 - showing an avatar inside one of the main facilities in the pelletizing plant.

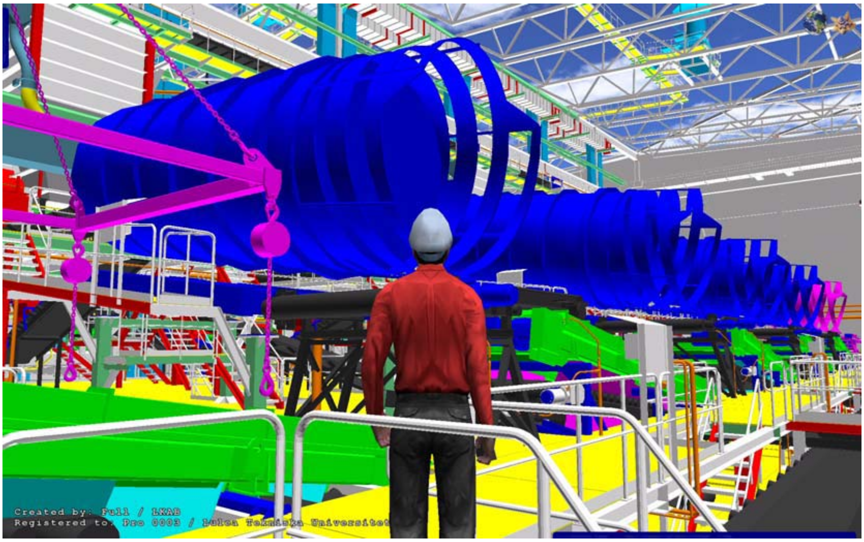

FIG. 1: A screenshot extracted from a VR model showing an avatar inside one of the main facilities in the pelletizing plant.

4.5 A concurrent design process

4.5.1 VR models in the design process

Fig. 2 outlines the iterative and concurrent design process in the MK3 project. The client is responsible for the overall design process while the design teams within Construction, Mechanics, HVAC, et cetera, are responsible for the design of the subsystems in the plant, i.e. process equipment, building structure, installations, et cetera. All design teams are also responsible for providing correct and updated input data to the "VR database". The VR consultant working for the client manages all the VR data and also makes updated and corrected VR models accessible for everyone involved in the design process.

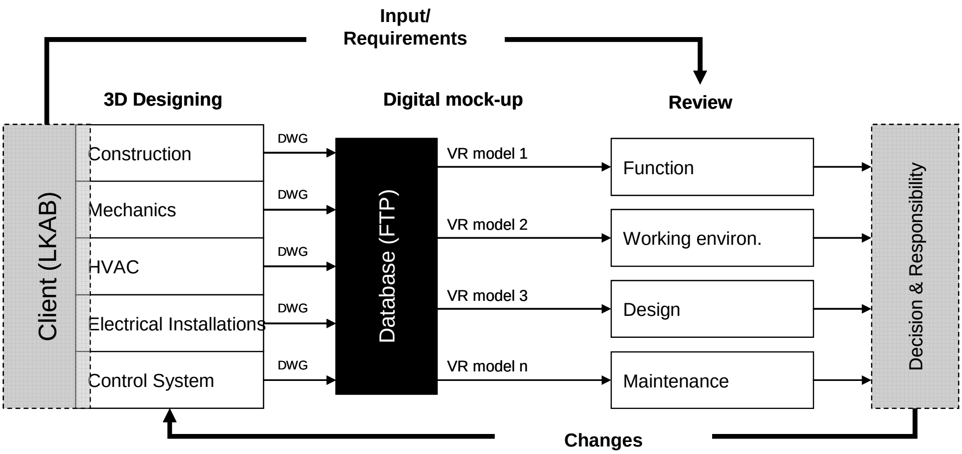

FIG. 2: An iterative design process with specified VR models in a concurrent and multi-disciplinary design situation.

The VR models, in Fig. 2 denoted VR model 1 to VR model n, provided the design teams with structured and easy-to-understand design information in a way that is not possible using a traditional design process using 2D CAD drawings. The stakeholders could analyse the design both from a perspicuous as well as detailed perspective by navigating freely in the VR models. Moreover, using VR models made it easier to explain and discuss different design solutions with a larger group of stake-holders with different knowledge and experience in interpretation of 2D design drawings. This facilitated the collecting of views from different perspectives that could be used get a better and more production adapted design. Also, a number of collisions and design errors could also be discovered and corrected in the design process.

The interviewees involved in the design process concluded that one of the major benefits was the increased level of understanding; especially within areas outside the scope of their own profession, or to quote one of the design managers: “I was sceptical at first but when I realized that by studying one VR model instead of spending time searching through piles of paper drawings could save me a lot of valuable time thus I could focus on what is important”. To illustrate his point, he mentioned how much easier it was to design the concrete foundations of the machinery when you get a clear picture from the VR model of how the mounting frames were designed.

Since a model based design process using VR had not previously been tested by the different design teams the design coordinator made sure that if the 3D design process should come to a dead end during the course of the project due to problems for the software to handle the amount of 3D data there was always the option to go back to the traditional way of working using 2D drawings. In the beginning of the project both fascination and scepticism over the VR technology was noted which was thought to effect the credibility of the VR models. However, these symptoms quickly vanished when the use of VR models become a natural part in the daily work.

4.5.2 Design review meetings

The VR models were extensively used in the reviews meetings that occurred every two weeks. Here, design solutions were examined from the different perspectives and requirements on function, work environment and maintenance. Clashes between the different design disciplines was also discussed and resolved. The use of VR made the review work much easier and minimised the risk for misinterpretations. This implies that more valuable time could be spent on finding solutions and opportunities.

The usability of any information is strongly connected to its trustworthiness, especially in a decision-making situation. Since the VR models was one of the main sources of information in the design review meetings the VR consultant put a lot of effort in making these models up to date.

However, one of the greatest advantages in design reviewing as well as in the individual design work was the increased understanding for the overall design. The design teams could, interactively, in a virtual environment, explore different alternatives by predicting, understanding and evaluating the impact on the project as a whole in order to come up with the best solutions. VR was especially valuable in the conceptual design of the plant layout and in the detailed design phase.

Much of the non-productive work during the production phase is generated in the design phase. Re-work caused by bad design or collisions between different objects, such as HVAC and the building construction, is mainly due to incomplete coordination and information flow between different design teams. The use of 3D and automatic collision detection can be a remedy to this problem, although this implies that all design teams should use the same CAD system. Furthermore, in large construction projects containing a huge amount of CAD objects the use of automatic collision detection generates in many cases too much collision information to be practicable. Instead, the technique including probing avatars was used to detect collisions in special areas of the plant. Since the major risk for collisions occurs in the interface between different design teams, e.g. mainly between installation and construction, a visual detection technique was used. For example, an avatar was made to crawl inside the ventilation system to detect colliding objects penetrating the ventilation shaft, (see Fig. 3). This example also shows how natural/visual interfaces to large data sets can inspire interaction with the VR model that mimics the strategy that would be taken in the real world.

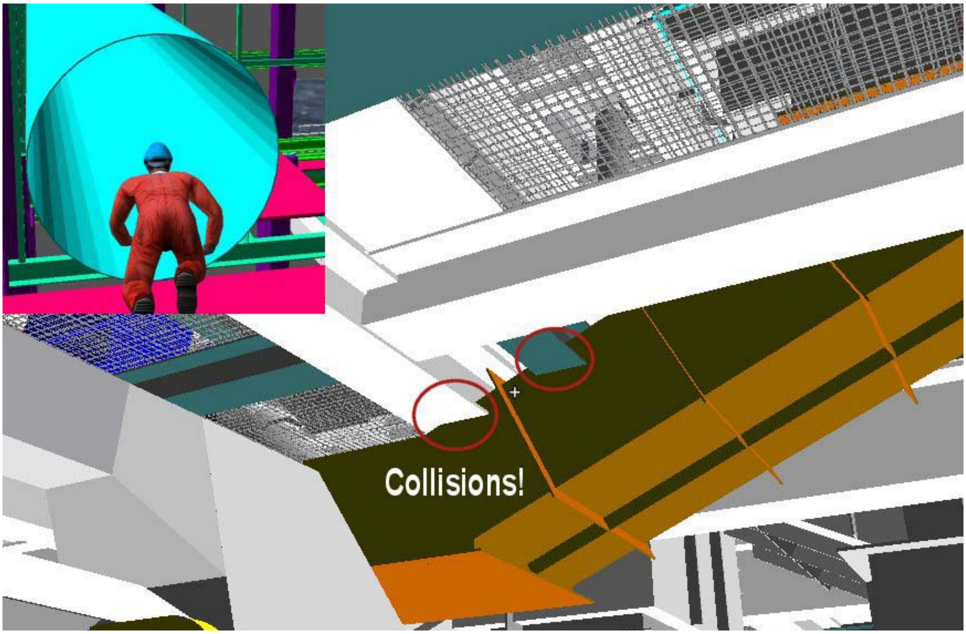

FIG. 3: Screenshots extracted from a VR model showing a detected clash between the ventilation system and the structural system. These types of clashes are much easier to detect from the inside of the ventilation system.

Fig. 4 shows a detected bad design solution where the process water outlets were placed in such a way that would have hindered the access to the area. These types of errors are often costly to take care of in the production phase. They will also affect the production rate generating delays in the production schedule and re-planning of activities.

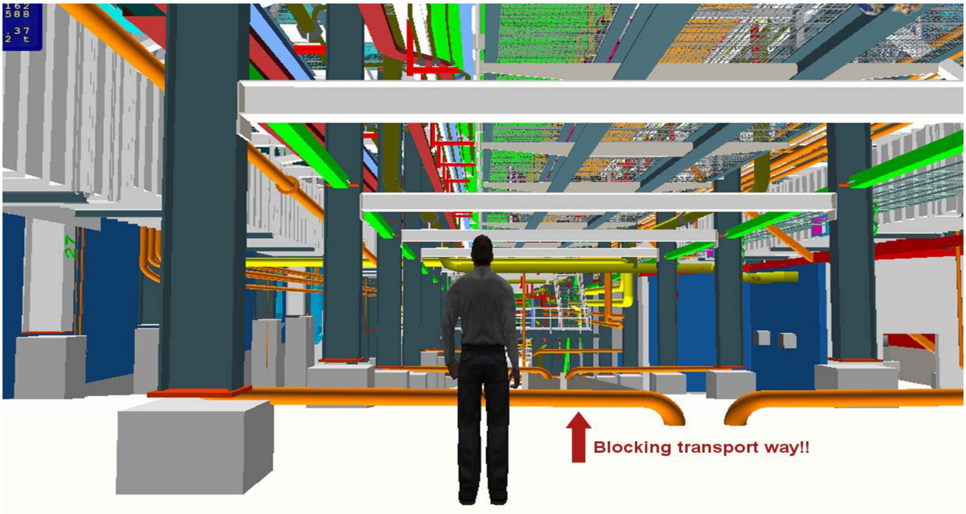

FIG. 4: Screenshots extracted from a VR model showing a design solution that would have blocked the access.

Errors discovered during the design review meetings were immediately delegated to the design teams concerned. All errors that were attended to were logged and later confirmed in the next meeting. Decisions on major changes in the design were taken after conducting a risk analysis on the three goals in the project, i.e. *Capacity*, *Time* and *Investment frame*. These decisions were always taken in the risk management group consisting of the client and the main subcontractors in the Partnering contract.

'Informal' design review meetings were also conducted continuously throughout the design process. The main objectives of these informal meetings were to function as a complement to the formal meetings and to speed up the design process. One of the drawbacks of using VR as a communication platform in the project has been the limited access to enough computing power to handle and visualise the increasingly larger VR models. Therefore most of the information in these informal meetings has been based on 3D models, extracted 2D paper drawings and screen shots from the VR models communicated through emails and telephone meetings. However, the lack of VR has not impacted the information sharing since these informal meetings occur between the regular design reviews where the coordinated VR models are displayed. The partners in the Partnering group have encouraged these informal meetings between the different design teams and sharing of information.

4.5.3 Capturing the client's needs and requirements in the design process

The most important task for the client in the MK3 project was to ensure to that needs and requirements of the pelletizing plant were implemented in the design. The time-pressure in the MK3 project and the use of Partnering as a stimulus to enhance the collaboration between the stakeholders, resulted in a concurrent design process where the VR models been used to coordinate and communicate the design to the client. Besides making it easier for the client to make crucial decisions; the VR models have also involved the client in the everyday design work. Being able to quickly sort out the information that is relevant for the moment and present it in an easy and comprehensible way have enabled the client to collect opinions from a wider audience, such as the plant operating and maintenance staff, and to concentrate on the actual decision making.

Decision-making in the MK3 project is a delicate procedure, especially for the client where the decisions in the project will have a long-term impact on the opportunity to make revenue on the invested capital. The decision-making and the design sequencing can affect the design process negatively. To reduce the risk for negative design iterations Ballard (2000) suggests among other measures: team problem solving, the share of incomplete information and concurrent engineering. These measures were encouraged by the Partnering group.

Decisions made early in the design process have a great impact on the final outcome. Therefore, by focusing on the preliminary design stage, the greater are the chances to achieve a positive effect on the final costs and quality. This applies to this project as well as to most construction projects. In view of the wide range of technical inputs, the client and the designers must be provided with information that can be assimilated into decision criteria's regarding, e.g. risks, costs and milestones.

There are several examples in the MK3 project where the VR models have been used to facilitate the client's decision-making in the design process. For example, due of the tight time schedule, the client and the different design teams needed to take quick internal decisions often without consulting the other design teams on a regular design review meeting. The VR models have helped them to better understand the multi-disciplinary consequences of a decision. From the client's perspective, the impact of the decision on the manufacturing processes has the highest priority. All other decisions regarding for example construction, HVAC, et cetera, are of subordinate significance. Therefore, when the client had chosen the plant process and the machinery to produce the required capacity, the spatial needs can be defined. These needs were described to the construction design teams using a VR model of the plant process design. The construction design teams could then begin to plan the layout of the construction and select technical solutions to be discussed, followed up and evaluated in the succeeding design review meetings.

As mentioned above, the use of VR models in the MK3 project have facilitated the client and the design teams to become more actively involved in all of the different designs of the plant. This has promoted coordination and fostered a common view on the overall project goals. However, it is difficult to give an overall estimation of the value added and the waste saved caused by the use of VR. Here, we will give the reader a few examples on how VR has been utilized to add value to the final design and to minimize the waste in the production phase:

In the analysis of the plant working environment and safety a specially designed avatar of ample size (210 cm of height) was allowed to mimic the behaviour of the operational and maintenance staff. This was primarily a spatial analysis where working spaces, escape routes and risky areas in the plant were investigated. The result of the analysis was forwarded to the involved design teams for redesign of the problematic areas in question.

The second example also concerns a spatial analysis but with a totally different purpose. The operation of a highly automated industrial process is to a large extent dependent on the maintainability of the process equipment. Measures to prevent production losses have high priority in such facilities due to the economical consequences. Therefore, to make sure that maintenance could be conducted, the maintenance personnel were asked to participate in a spatial analysis using avatars and VR models of the process machinery and layout. Problematic areas from a maintenance point of view could as a result be taken care of in the design phase, see Fig. 5.

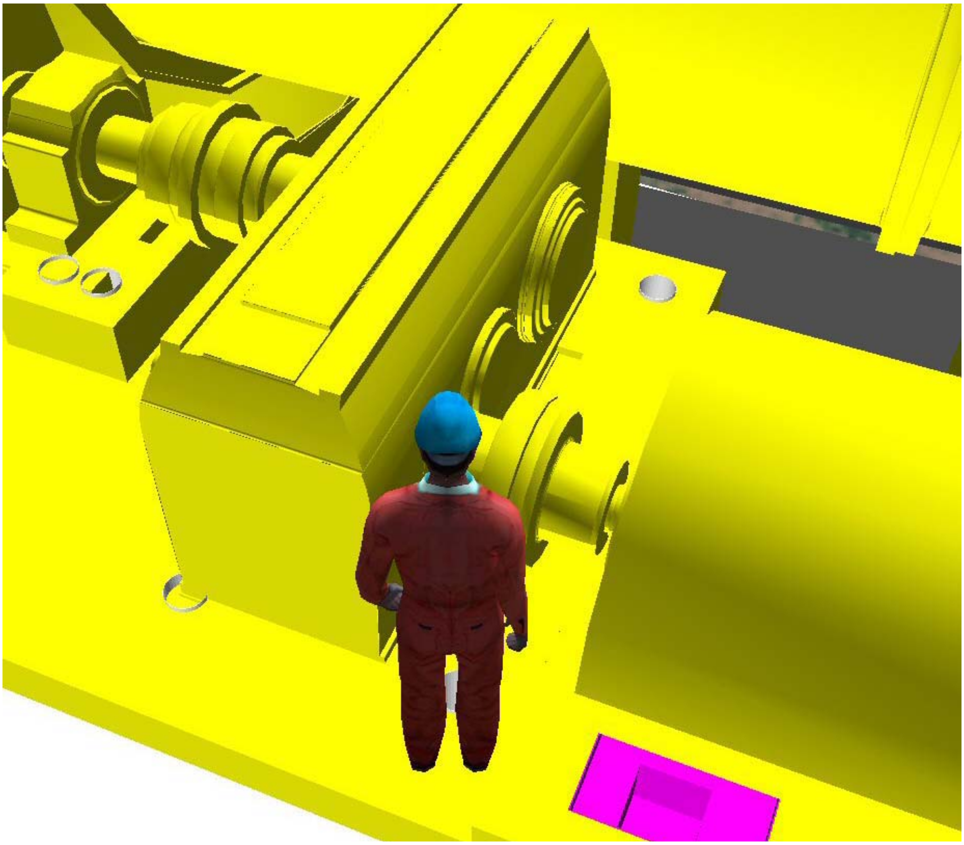

FIG. 5: A screenshot showing the use of avatars for investigating the maintainability of the process machinery in the dressing plant.

The design of the new plant process could also be exemplified in an early stage of the project, where alternative solutions from a production capacity point of view and the impact on the layout and logistics could be visualised for the client. These layouts were also part of the information on which the board of LKAB took the decision to invest in the MK3 project.

Currently the VR models are used to speed up the CE-marking procedure of the plant and to get an earlier production start. The CE-marking procedure is normally carried out when the plant is finished. Also, the VR models are planned to be used to train operational and maintenance workers.

The client and the involved design teams are very positive to the use of VR in the MK3 project. Several respondents argued that the use of VR will probably increase in future project and that more built-in intelligence in the VR model will extend its use in planning (4D) and process simulation. Some preliminary investigations of the use of 4D in the MK3 project have been conducted by Jongeling et al (2006) and Woksepp et al (2005).

4.6 The planning process

Effective planning throughout the construction project is essential for achieving a high level of quality and profitability. A comprehensive and parallel information exchange process characterises the multi-disciplinary and concurrent project planning process in the MK3 project. Traditionally, as well as in the MK3 project; this is a document-oriented process where the planners rely on conventional planning tools (e.g. Gantt charts), 2D CAD drawings, paper documents and personal meetings. This work process puts great demands on the planners, because they have to determine whether the accessible information is reliable or not besides performing the actual planning work. A consequence of this procedure as described by one planner participating in the study was that he had considerable difficulty in achieving an overall picture and understanding of the project. The lack of a continuous and structured information flow in construction projects is traditionally accepted as a natural part of the process and problems are dealt with on the construction site as they arise.

In this study we have focused on the preconstruction stage. Waly et al (2002) describe this stage as the macro planning process, which involves selecting major strategies, reviewing the design for constructability improvement, site planning for major operations and construction path, and arranging for the primary means, methods and resources required for the execution of the work packages. Our hypothesis is that this process can be facilitated by the use of VR models.

According to the planners, the biggest value from using VR models to support the planning process was obtained from including the setting-out grid (created as “VR solids”) in the VR models. The setting-out grid provided the planning teams reference positions from where distances to the construction parts could be measured. This created a common frame of reference and a better spatial understanding. The VR models also facilitated the structuring and handling of the massive amount of information in the planning process. This took some of the work load off the planners.

VR models were also utilised to support planning and decision-making of prefabrication. For example, to speed up the production it was decided that larger parts of the belt conveyor system could be assembled off-site after it was checked in the VR model that these preassembled belt conveyor parts could safely be lifted in the plant.

Even though the planners considered the VR models to be reliable and well-structured most of the planning work was nevertheless done using traditional methods. The two main reasons for this are believed to be that the traditional way of working is still firmly established and that the “right” VR models often were inaccessible when much of the planning work was conducted. There was simply not enough time to produce and present production adapted VR models to the planning team.

5. DISCUSSION AND CONCLUSION

The design and planning process in a multi-disciplinary and concurrent large-scale project such as the MK3 project is a complex and difficult process to manage. However, the uses of VR models have provided the potential to increase the performance and reliability of the information according to the several informal interviews performed on the construction site. By comparison to the traditionally-used 2D and document-based working methods the designers and planners have obtained a higher degree of spatial understanding and a better understanding of how and when the construction is going to be built from the VR demonstrations. As a result the designers and planners have been able to foresee future consequences from different decisions and test and evaluate different solutions, further develop exchange of experience, and plan and manage the time schedules.

The reliability of the information has been obtained by continuously updating the VR models using the different design teams’ 3D CAD production models. In the MK3 project, one person was appointed to manage all information that was exchanged between all project participants. This proved to be a good investment. As a consequence, the rich information environment has facilitated the users to focus on 'priority of consideration'.

The team that has been coordinating the design claims that VR has really facilitated the design coordination in the project. It gives better quality and communication and compared with traditional design methods lower costs for design coordination. The number of people involved in the design coordination has been reduced by 50% in this project compared with a similar project 10 years ago where all design was made in 2D.

Neither realistic VR models (lighting, texture, et cetera) nor the experience of presence was considered to be essential in the design and planning process. Computer monitors and projectors (2D) were believed to be sufficient for the VR presentations.

The technical integration between the different design teams and planners has not been an obstacle despite the variety of CAD systems used in the project. The propriety format DWG provided 'enough' integration for the users in this project. The technical integration has been identified as one of the main barriers in several research projects conducted over the last decade. Instead the project management focused on selecting the best designers available using the CAD software of their choice. The integration was then a technical matter of selecting the common format and overcoming some of the spurious errors that occurred in the exchange of the DWG files to the VR models. Most of these exchange errors could easily be detected, see a typical example in Fig. 6.

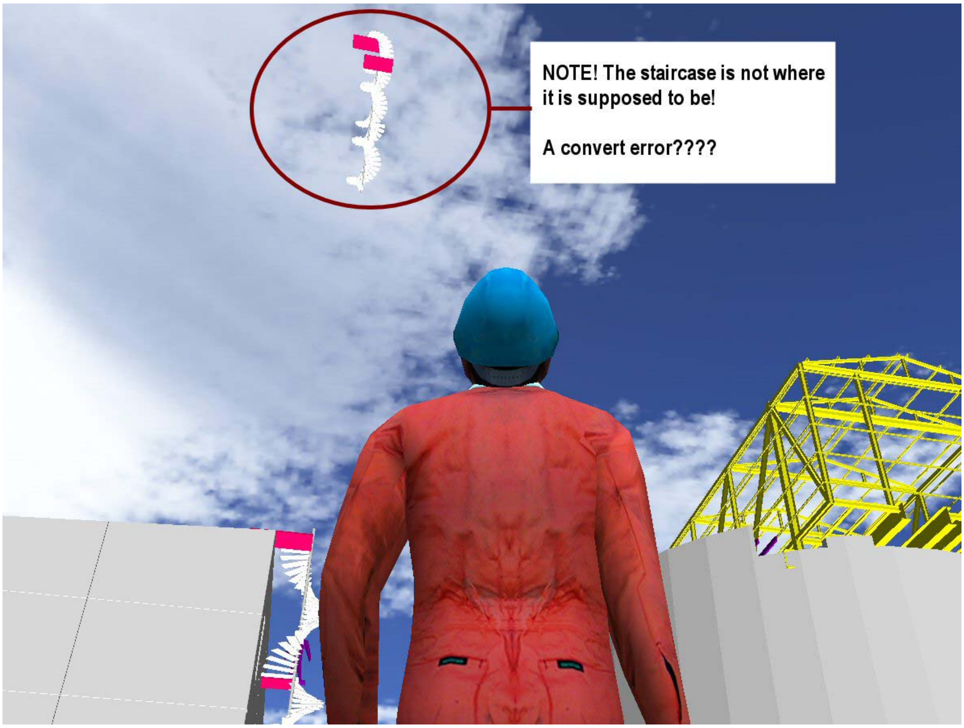

FIG. 6: An example of exchange error that occurred between the CAD and the VR software used in the project.

The reluctance to share information is also a major identified barrier in the construction sector. Even though the Partnering contract facilitates the cooperation between the different stakeholders by trust, the main cause for the intense information flow and willingness to share has been the time pressure forcing the different design teams to act concurrently.

In conclusion:

- VR has been used throughout the project and has been integrated in the design process and to some extent used in the planning process.
- The use of VR has facilitated the concurrent design process in the MK3 project. Especially in the design coordination process, the design review process and the capturing of client requirements on the final design.
- Most value has been derived in the use of VR as a decision support in the conceptual design of the plant layout and in detecting collisions in the detailed design phase.
- The VR models were considered reliable because they directly origin from the different 3D CAD models.
- Computer monitors and projectors (2D) were considered to be sufficient for displaying the VR models.
- Using VR has had a positive effect on the final project costs and quality. A rough estimate based on previous experience from a similar project using 2D drawings by the design coordinator showed that the cost of using VR is much less compared with the savings in design coordination alone. The staff devoted to design coordination was halved (from 15 to 7 designers) compared to the 2D design project. Still, the quality of the design coordination was deemed to be higher in the MK3 project.

Based on the experience from the MK3 project, the client LKAB has decided to use the same contractual concept and working method provided by VR in the next project – the construction of a new pelletizing plant in Kiruna, Sweden, twice the size of MK3. Also, the use of 4D CAD technology is also discussed to improve the production coordination of the new project.

6. ACKNOWLEDGEMENT

This paper is based on a field investigation where several people involved in the MK3 project were interviewed. These people represent the client (LKAB) and a number of subcontractors with responsibilities within project management and planning, design management, business management and development, technical engineering and VR modeling. We thank them for their invaluable commitment and patience in sponsoring our work and providing access to project data and methods as well as their own knowledge and experiences. Special thanks goes to Per Lundström, Jaakko Pöyry AB and Anders Lundgren, LKAB without whose help the study would have been far less rich in information. We also acknowledge the financial support from the Swedish research fund for environment, agricultural sciences and spatial planning (Formas) and the Swedish construction development fund (SBUF).

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Paper IV

Woksepp, S. and Olofsson, T. (2007). An evaluation model for ICT investments in construction projects. Accepted for publication in ITcon, Special Issue on Case studies of BIM use (October 2007).

AN EVALUATION MODEL FOR ICT INVESTMENTS IN CONSTRUCTION PROJECTS

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SUMMARY: Even though Information and Communication Technology (ICT) investments in construction projects generally represent minor commitments of project resources by comparison to the full project cost, it have serious consequences on the profitability. Despite this, many of the investment decisions are poorly thought through or examined. Taken during the procurement phase often merely based on intuition and rough estimations of the future costs and risks. Also, many of the traditionally used appraisal approaches have been shown inadequate in anticipating the consequences of such an investment. As a result, the investment is too often assumed to be negative since the benefits are not proper evaluated, included and weighted against the costs and risks the investment is expected to generate. Poor decision-basis does not only affect the actual decision-making in a particular project but also, in the long run, the motivation to innovate and to introduce new ICT tools and working methods into the construction industry.

In view of this, a new project-oriented evaluation model is developed for the purpose to provide for a structure and a work routine to be used by a multidisciplinary project team to evaluate the implications of realizing ICT investments in construction projects. Although primarily aimed at establishing future benefits and costs the model may very well be used for follow-ups. The models' application is illustrated using a case study.

KEYWORDS: Benefits, Construction project, Costs, Evaluation, ICT, Investment, Virtual Reality.

1. INTRODUCTION

Information and Communication Technology (ICT) has been widely applied across many sectors in order to increase competitiveness and reduce costs (e.g. Marsh et al 2000), and is today seen as a vehicle to gain a competitive advantage (Ives et al 1991, Earl 1993). The average annual growth rate of ICT investment in the construction industry is increasing every year and constitutes now a significant part of the total project cost. However, some studies indicate that the ICT utilization ratio is still relatively low in the construction industry. For example, a comprehensive study within the EU project InPro (Open Information Environment for Knowledge-based Collaborative Processes throughout the Lifecycle of a Building), which investigated the use of ICT tools in the European construction industry (InPro internal report D2, 2007), revealed a lack of use of ICT tools in construction projects, especially in the early stages, despite several good alternatives available. Some of the main causes for this were suggested to be deficient understanding and lack of knowledge about the possibilities of ICT, unsuccessful implementation into project organizations and limitations of software functionality. Another reason is most likely that construction companies often find it difficult to justify ICT investments in an industry that suffers from low profit margin (Alshawi et al 2003) and that many managers often view ICT investments as a process of consumption rather than capital expenditure (Irani et al 2002) and do not realize the importance of evaluating the IT investment (Willcocks et al 1997). Moreover, the traditional approaches to evaluate investments have been shown inadequate (e.g. Peacock et al 2005, Love et al 2001, Andresen 1999, Irani et al 1999, Shank et al 1992). DeLone et al (1992) argues that commonly used benefit and cost analyses are often found lacking due to difficulty of quantifying intangible benefits. The lack of effective evaluation models does not only have an influence on individual projects but also, in the long run, the motivation to innovate and introduce new ICT tools in the construction industry.

The main purposes of using ICT in construction projects are to improve operational efficiency of an organization, to improve quality and to reduce project time and to increase profit levels (Gunasekaran et al 2001). Intangible effects could be sustainable competitive advantage (e.g. Barney 1991, Powell et al 1997, Henderson et al 1999), better project control and understanding, marketing, customer service, et cetera. Carefully evaluated and considered ICT investments with established objectives can boost an organization forward with the increased likelihood to achieve successful implementation and improved project performance while reducing costs. Equally, poor investments, those that are inadequately justified or whose costs, risks, and benefits are poorly managed can hinder and even restrict an organization's performance (GAO 1997). The effects associated with an ICT investment are uncertain and difficult to measure (Ekström et al 2003) and the benefits and value of IT investments are being questioned by researchers and practitioners (Dadayan 2006). However, a great number of researchers have shown the values of using ICT in construction projects (e.g. Dawood et al 2005, Bouchlaghem et al 2005, Fischer et al 2004, Björk 2001).

The process of investment justification has been identified as a major barrier to implementing ICT (Love et al 2000, Andresen et al 2000, CIRIA 1996, Enzweiler 1996) and because of the growing concern about the effectiveness of information systems expenditure there is an increasing need to re-think approaches to the evaluation of information systems in order to demonstrate business benefits from these investments (Remenyi et al 1999).

2. EVALUATING ICT INVESTMENTS

ICT systems are multidimensional constructs requiring multiple measures to evaluate (Etezadi-Amoli et al 1996, DeLone et al 1992). Any major ICT investment must be preceded by a careful evaluation of its direct and indirect benefits and costs (Gyampoh-Vidogah et al 1999). Farbey et al (1999a) defined the evaluation process as “a process that takes place at different points in time or continuously, for searching for and making explicit all impacts of an IT project.“ Willcocks et al (1996) define ICT investment evaluation as “Taking a management perspective, evaluation is about establishing by quantitative and/or qualitative means the worth of ICT to the organization.” According to Farbey (1992), the evaluation is envisaged to serve different objectives, such as:

1. Being used as a part of the process of justification of a system;
2. To enable an organization to make comparisons between different projects competing for resources;
3. To provide a set of measures that enables the organization to exercise control over the project.

Moreover, evaluation and the subsequent measurement and comparison with actual achievements will provide the learning experience which is necessary if the organization is to improve its system evaluation procedures and development capability.

Evaluation and justification of ICT investments is a complicated process, not only in the construction industry but also in all major industries, since cost and benefits associated with the investment are uncertain and difficult to measure (Ekström et al 2003). Early estimates, in general, are typically plagued by limited scope definition and are often prepared under time pressure (Trost et al 2003). Traditionally, specialists in different areas have been engaged in the task of evaluating the benefits and costs of future ICT investments. Many times these specialists have little or no knowledge of the overall consequence of the investment. Andresen et al (2000) describe the IT managers’ large influence on the selection of data management systems on which the senior management uses to support their decision making. Specialists such as IT managers have mostly poor understanding of the company’s overall business goals and are often excluded from the decision-making process. The senior management on the other hand is well acquainted with the company’s business but has little insight into the fast-changing ICT development and often lacks feedback from previous strategic ICT projects. Anandarajan et al (1999) pointed out the influence of the accountants in ICT investment decisions. They usually focus on analyses that can be measured in monitory terms but lack insight into the effects on the work processes. Instead of making the analysis of ICT investment the task of a specific profession, general methods and tools should be developed to assist the decision-making process. Even though substantial efforts have been made to develop such evaluation methods (e.g. Sethi et al 1994, Chismar et al 1985) there is still room for improvements.

There are several methods available for evaluating ICT investments spanning from simple computational formulas to complex techniques that comprise both quantitative and qualitative attributes. Traditional early investment appraisal methods, such as Cost Benefit Analysis (CBA), generates non-discounted estimate of benefits and costs, i.e. the cash flow, that the investment is expected to generate. Both the Discounted Cash Flow (DCF) and the Net Present Value (NPV) method calculate the net cost of the investment in monetary terms. The Internal Rate of Return (IRR) method calculates the discount rate where NPV is set to zero. NPV and IRR are basically used for the same purpose and can be viewed as complementary methods for the purpose of evaluation. Conducted correctly the IRR and NPV methods should give in an equal estimation of the effect of the investment. One of the most popular methods to use when comparing different ICT investments is the Return on Investment (ROI) method which measures how effectively a business uses its capital to generate profit – the higher the ROI the more profit.

The above-mentioned methods are well-established and relatively easy to use. However, many users argue that these methods are difficult to apply in estimations of ICT investment (Kumar 2000), probably due to an insufficient identification and evaluation process of benefits and costs (Powell 1992). Other criticism against these methods are that they fail to grasp the impact on the construction process and organization and fail to capture hidden costs, intangible benefits (Love 2006) and risks (Anandarajan, 1999). Andresen et al (2000) argues that more complex methods, such as Information Economics (IE) and Return On Management (ROM), have failed to be put into practice in the construction industry because of three main reasons: there is little awareness of the methods; the methods requires large operation requirements; and, the methods need to improve.

Despite the range of different evaluation alternatives little practical use has been made of these (Bannister et al 2000, Farbey et al, 1999b, Smithson et al 1998). Slow adoption can depend on several factors, e.g. inadequate methods – as discussed above; the methods are costly and require staff with special skills; or organizational culture (Brown 2005). Andresen et al (2000) and Marsh et al (2000) argue that the problems most likely are due to construction industry's structure and undercapitalization.

In order to address this above-mentioned deficiency, a new evaluation model is presented in the next section. The intention is to develop an easily-understandable and easily-comprehensible tool which would help the users understand the implications of an ICT investment in a construction project. To support a development towards practical applicability, the model has been applied to evaluate how Virtual Reality (VR) models have facilitated the design process in the large-scale construction project. Focus was on applicability, to establish whether or not it is a valid approach and, of course, to evaluate the implications from using VR models. The evaluation was carried out from a project perspective. The result was twofold. The evaluation model was considered highly applicable and valid approach and the net benefit from using VR in the design process was demonstrated.

3. THE ICT INVESTMENT EVALUATION MODEL

This paper presents a new evaluation model. The model is intended to provide for a structure and a work routine to be used by a multi-disciplinary working team throughout the process of assessing, planning for and managing the implementation, utilization and follow up of an ICT investment in a project organization. The evaluation presents a gross result – benefit and cost variables are categorized, quantified in monetary terms and classified depending on the likelihood of it happening. The model differs from most other financial evaluation tools since it is project-oriented and includes intangible benefits, such as process and information quality – which often provides a significant contribution to the final result. Other features include for example risk assessment. Besides presenting a monetary result, the process of carrying out the evaluation also helps the participants to obtain a clear insight into the characteristics and potential of the ICT tool in question as well as the processes and other tools of the project.

The predefined benefit category structure and variable list is an extension of the DeLones' and McLeans' theoretical framework Information System Success Model (ISSM) from 1992 (Lindfors 2003, DeLone et al 1992). The work procedure and risk handling is inspired by the PENG model (Dahlgren et al 1997), which has become a popular method in Sweden to evaluate IT investments in companies and organization. The biggest difference is that the model proposed in this paper is project-oriented and ICT investment "specific". In addition, in the PENG model the benefit and cost variables and category structure are established by the evaluation group, which means that every evaluation is unique in its disposition, whereas the proposed model provides a predefine structure. We believe that the combination of a pragmatic evaluation procedure and a predefined category structure and variable list not only makes it easier for the users to identify, evaluate and secure the tangible benefits and costs but also the intangible and hidden effects from realizing the investment proposal. Also, we believe that this combination facilitates the implementation process, follow-ups, the re-use of knowledge and the information process as a whole.

3.1 Basic assumptions

The proposed model is intended to be used in construction projects by multi-disciplinary evaluation teams before an ICT innovation is implemented, during its implementation and afterwards when the results can be assessed. The primary objectives for using the evaluation model are to:

- Facilitate for organizations to justify an ICT investment;
- Facilitate for managers and users to reach a better understanding of the impact of an ICT investment on organizational performance - which can help the organization utilize its resources better (Clemons 1991);
- Facilitate for managers and users to plan for, monitor and accomplish benefit realization as well as identify potential further benefits;
- Facilitate for managers and users to handle and restrict risk and costs associated with benefit realization; and
- Facilitate for managers and users to gather data for benchmarks that later can be used to provide a measure of the actual implementation success of the ICT investment (Farbey et al 1992).

The proposed model assumes that all benefits and costs – tangible as well as intangible - can be identified, categorized and measured in monetary terms and that all cost are incurred within the project and all returns (read: benefits) are received by the project.

The results from using the evaluation model will provide identification, categorized and classification of:

- Benefits that are expected to arise during and after the construction project life cycle. The benefit variables are predefined and structured into seven categories: ‘System quality’, ‘Process quality’, ‘Information quality’, ‘System use’, ‘User satisfaction’, ‘Individual impact’ and ‘Project impact’; and
- Costs that are expected to arise during the construction project life cycle and that are generated as a result from the implementation and use of the ICT tool in the construction project. The cost variables are predefined and structured in two categories: ‘Investment costs’ and ‘Operational costs’.

The model also assesses diffuse and intangible factors making them visible and traceable. However, many of these benefits or costs are hard to estimate and must be classified as risky.

As the costs and benefits associated with the ICT investment influence the project result, the decision to evaluate should involve the owner of the project and the affected stakeholders preferable prior to the procurement procedure.

4. THE EVALUATION MODEL FRAMEWORK AND PROCESS

The evaluation process is a joint effort between the project stakeholders which is characterized by a series of activities that vary in scope and intensity depending on the nature of the investment being evaluated. The activities are divided into three main phases:

1. Prepare
2. Analyze
3. Secure

4.1 Prepare

The first phase of the evaluation process – “Prepare” – includes identifying the scope of the evaluation, establishing a multidisciplinary evaluation team and getting the management involved. The preparation phase answer questions such as:

- What type of IC investment is to be evaluated?
- What is the purpose?
- Which stakeholders will be affected by the investment?

The preparation phase is necessary for establishing a multi-disciplinary group of people with a designated evaluation leader who possess the competence to assess the ICT investment – system functionality, effects on the multi-disciplinary work routines, et cetera. The first tasks for the evaluation team is to define scope and aim, describe the IT investment - its purpose and effect, collect knowledge of previous use, establish evaluation plan as well as setting up evaluation identification and history including (proposed guideline):

Evaluation ID - Set unique integer sequence number identifier, alt. use a hierarchical form: X.Y. Group related evaluations in the hierarchy.

Evaluation Name - State a concise and results-oriented name for the evaluation.

Evaluation History - Document created by; date created; last updated by; date last updated.

This phase also involves notifying the strategic, tactical and operational expectation of the ICT investment to the project organization’s immediate stakeholders and to involve the decision-makers therein. A go/no-go decision is made by the project owner about whether to proceed with the evaluation or not (see Fig. 1).

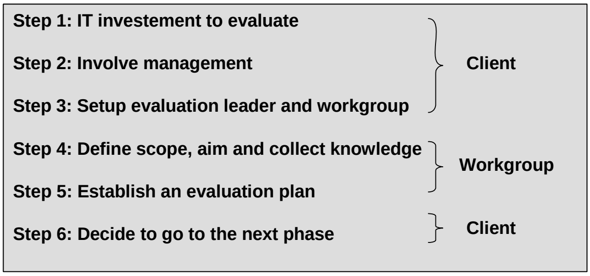

FIG. 1: Steps in the preparation phase.

4.2 Analyze

When a decision is taken to continue the evaluation process, the team proceeds to establish three sets of checklists in order to identify, quantify and classify benefits and cost as well as identify and handle the risks.

4.2.1 Benefit assessment

The expected project benefits from realizing an ICT investment are identified, structured and quantified using the theoretical framework Information System Success Model (ISSM) presented by Lindfors (2003), see Fig. 2. The proposed ISS model is an extension of the DeLone and McLean ISS model from 1992 (Lindfors 2003, DeLone et al 1992).

Benefits refer to all positive returns of an ICT investment.

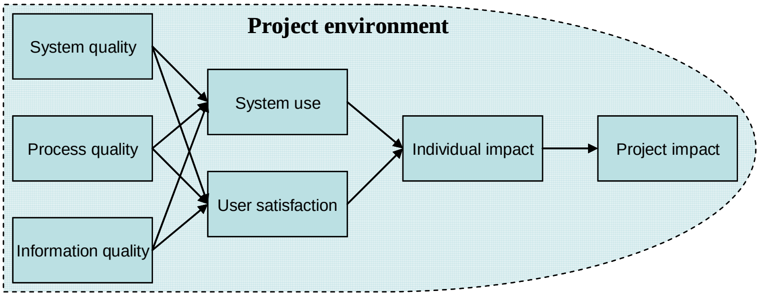

FIG. 2: The extended ISS model in a project environment (Lindfors 2003).

The DeLone and McLean ISS model from 1992 derives from Shannon’s (1948) and Shannon and Weaver’s (1949) initiative on the theory of communication and Mason’s (1978) work on information influence theory (Lindfors 2003). It is basically a mathematical approach to the theory of communication where an information system acts as the information source that is sending information through a system to a recipient. Divided into three basic levels: first, a technical level that represent the accuracy and efficiency of the system; second, a semantic level that addresses the success in conveying the message; and third, an effectiveness level which measures the effect the information has on the recipient, see Table 1.

Source	**Categories**						
Shannon and Weaver (1949)	Technical level		Semantic level	Effectiveness or influence			
Mason (1978)	Production		Product	Receipt	Influence on recipient		Influence on system
DeLone and McLean (1992)	System quality		Information quality	System use	User satisfaction	Individual impact	Project/organisational impact
Lindfors (2003)	System quality	Process quality	Informati on quality	System use	User satisfaction	Individual impact	Project/organisational impact

TABLE 1: Categories of Information System Success (Lindfors 2003, DeLone et al 1992).

Mason (1978) adopted this theory and revised it according to a product-oriented approach. Instead of effectiveness or influence, Mason presented the categories of receipt of information, influence on receipt and the influence on system, also renaming technical level and semantic level to product and production level (Lindfors 2003). Following the basic approach of assessing the value of a system, numerous researchers have drawn up different models from various viewpoints. DeLone and McLean reviewed these previous studies and developed their taxonomy using six major dimensions of categories of information system success: System quality; Information quality; System use; User satisfaction; Participant impact and Organization/Project impact (DeLone et al 1992). Based on both process and casual considerations, these six dimensions of success are proposed to be interrelated rather than independent (DeLone et al 2003). Lindfors (2003) extended this model to include measures for the perceived quality of the information management process (the Process quality category in figure 2). Each of the categories in figure 2 consists of a number of variables that recognize the effects according to (DeLone et al 1992):

- **System quality** – effect on the information system itself which produces the information.
- **Information quality** – accuracy, meaningfulness and timeliness of the information produced.
- **System use** – use of the information system.
- **User satisfaction** – interaction of the information system with its recipients: users and project owner.
- **Participant impact** – influence on the management decisions.
- **Organization/Project impact** – effect on the organizational performance.
- **Process quality** – effect on the information management process quality (Lindfors 2003).

Lindfors (2003) argues that it is essential to adopt a more project- and process-oriented evaluation approach because of the nature of construction projects and construction industry as a whole. These features along with a logical and comprehensive list of variables, see Table 2, seems most promising when appraising the full effect of a future information system investment or performing a follow up. By being able to link each measurement to a structure of predefined variables a deeper level of understanding can be brought to the evaluation process.

System quality variables	Process quality variables	Information quality variables	System use variables
Database content Ease of use Ease of learning Convenience of access Usefulness of system features and functions System flexibility System reliability Integration of systems System efficiency Response time	Information development Information acquisition Information identification Information preservation Information utilisation Information dissemination	Relevance of information Usefulness Usableness Understandability Clarity Format Content Accuracy Sufficiency Completeness Reliability Timeliness	Frequency of report request Appropriate use Purpose of use Number of reports generated Regulatory of use Amount of connect time Frequency of access
User satisfaction variables	Participant impact variables	Project impact variables	
Software satisfaction Decision-making satisfaction Satisfaction with specifics Information satisfaction Overall satisfaction	Information understanding Learning Information awareness Decision effectiveness Decision quality Improved decision analysis Correctness of decision Time to make decision Confidence of decision Improved individual. productivity Change in decision Task performance Personal valuation of IS Information management	Operating cost reduction Staff reductions Overall productivity gains Increased work volume Product quality Contribution to achieving goals Service effectiveness Time effectiveness Improved information management Increased profits	

TABLE 2: ISS categories with adjacent benefit variables (Lindfors 2003, DeLone et al 1992).

The process of assessing future benefits is carried out by exploiting the collective experiential knowledge of the multi-disciplinary evaluation group and data from earlier evaluations or any other relevant available information. Basically, the benefit evaluation procedure is a group activity that consists of four levels of benefit variable aggregation. First, the benefits are identified. The evaluation group proceeds methodically and uses the list of ISS categories and their adjacent variables in table 2 to establish project specific benefits and make sure that no intangible benefits are overlooked. One variable can include several different benefits and one benefit can be divided into several variables. Undoubtedly, it is difficult to ascertain all benefits at a given time, but using the “benefit variable structure” makes it easy for the evaluation group to include or change the input at a later stage. Secondly, the benefits are grouped into appropriate category (if not already done). In the third level, quantification of variables is performed in monetary terms. This is probably the most difficult part of the process and will surely lead to many discussions. Nevertheless, monetary assessment is essential and the discussions can be used in a positive way to exploit the collective knowledge and expertise of the group to bring about best possible result – assuming that the composition of the evaluation group promote collaboration and together strive to achieve best possible outcome. The quantitative variables are classified into one of three grades: 1 – ’Most likely’; 2 – ’Likely’; and 3 – ’Unlikely’, in the fourth level, depending on the likelihood of the benefit being realized.

Only those benefits that directly or indirectly affect the project are dealt with. The sum of the cumulated categories together with respective classifications represents the gross benefit for the evaluated investment. The prerequisites can be adjusted on all four levels, giving the users a maximum of flexibility to adapt the evaluation to new conditions.

4.2.2 Costs

The expected project cost from realizing an ICT investment are identified, structured and quantified using a theoretical framework developed from a project perspective. All costs are incurred and accounted for in the project. Costs can be defined as the expenditure necessary to achieve the benefits.

Table 3 illustrates how the project costs can be structured. The costs are divided into three categories, 'Capital costs', 'Operational costs' and 'Indirect costs'. Each of the categories in table 3 consists of a number of variables that recognize the effects according to:

- **Capital costs** – Up front costs, e.g. software and hardware.
- **Operational costs** – Start-up and on-going costs, e.g. personnel and consultants.
- **Indirect costs** – Indirect expenses, e.g. support and productivity losses.

This structure intends to enable easier identifying, quantifying and grading of the costs and it also facilitates an easier management and follow-up of the results. The capital costs – including the up front costs that can be attributed to expenses such as acquisition of software and hardware - have been separated from the operational costs so that the project owner can readily calculate the depreciation time. Capital costs also include additional hardware accessories, such as increased processing performance, memory or similar. The operational costs - including the start-up and on-going costs, e.g. personnel and consultancy costs, are often underestimated and exceeding 'obvious' costs such as hardware and software costs. Operational costs also include the costs for carrying out the evaluation. Indirect costs are those expenses that are not classified as direct, e.g. support and productivity losses (e.g. when introducing a new ICT system or tool into an organization).

The process of assessing the costs is similar to that for analyzing benefits using the collective experiential knowledge of the multi-disciplinary evaluation group. The cost evaluation procedure consists of four levels of cost variable aggregation. First, the costs are identified. The evaluation group proceeds methodically and uses the list of cost categories and their adjacent variables to establish the costs, see table 3, and to ensure that no hidden costs are overlooked. Now, in practice, this is nearly impossible because the hidden costs are often related to future events which yet can not be anticipated, e.g. staff hours for maintaining the system, cost for communication, et cetera. However, additional input can be added in a later stage. Second and third level; the identified costs are grouped into appropriate category (variable) and quantified in monetary terms. And fourth level, the variables are classified into one of three grades: 1 – 'Most likely', 2 – 'Likely' and 3 – 'Unlikely', depending on the likelihood of that happening. The structure and procedure facilitates for the users to identify individual costs – effect and size – as well as take in the overall result. It also facilitates pinpointing the most significant costs, which in an early stage could be enough in order to put together a preliminary budget.

Only those costs that directly or indirectly affect the project are dealt with. The sum of the cumulated categories together with respective classifications represents the total cost for the evaluated investment. The prerequisites can be adjusted on all four levels, giving the users a maximum of flexibility to adapt the evaluation to new conditions.

Capital costs	Operational costs		Indirect costs
Hardware and software	Personnel	Cost for evaluation	Support (network, data administration, etc.)
Compensation	Consultants	Education	Productivity losses
Acquisition	Travelling	Workplace	Other costs
Transition/changeover	Communication	Account	
Other costs	Administration	Security	
	Adaptation/converting	Other costs	
	Upgrading		

TABLE 3: Project cost categories with adjacent variables.

4.2.3 Risk management

The risk management process aims at anticipating uncertainties (read: defining Risks) in a potential ICT investment, assessing the degree of the risk, and identifying possible mitigation actions. The overall aim with the risk management process is to secure the project commitments.

Risks refer to exposure to such consequences as failure to obtain some, or all, of the anticipated benefits from utilizing an ICT investment. Risks also refer to consequences to the costs. Only those risks that directly or indirectly affect the project are considered. The risk management process helps managers and users to gain a better understanding about the consequences from the ICT investment and of the project as a whole. The risk management process also enables assessment of overall project risks and identifies and manages special risks. This could be general risks associated with ICT systems or applications (McFarlan 1981, Willcocks et al 1994), such as implementation costs; technical systems performance; or incompatibility of the system; et cetera or risks associated with using the systems or applications, such as functionality; compatibility; applicability; staff competence; et cetera.

The risk management process is a joint effort between project stakeholders represented in the evaluation group. The process, which is supported by a basic risk management structure, see table 4 (Dahlgren et al 1997), is carried out simultaneously to the benefit and cost assessment, before and during implementation of the ICT investment and when the ICT system or application is being used and for follow ups. The process is divided into three parts:

1. **Identifying and Assessing:** Identify and assess risks to the project's ability to obtain anticipated benefits and manage costs. Typically, these risks arise from lack of control or changes in the initial objectives.
2. **Mitigation actions:** Identify measures to mitigate risks and consolidate success. Estimated time schedule and cost for actions should be included, if possible.
3. **Monitoring and Follow up:** Gather information in a joint database – monitor and follow up in order to achieve best possible results.

The first part of the risk management process – "Identifying and Assessing" – aims at ensuring that every risk associated with the ICT investment are fully identified and assessed. Risks can be identified using a variety of approaches, e.g. continuously write down risks discovered during benefit and cost assessment; review previous evaluations; assess requirement specifications; interview users; brainstorming, et cetera. Identifying includes describing the risk and what benefit or cost variables it will affect. The next step is to assess them, i.e. appraise their significance for the project's outcome. The risks are assessed using a High-Medium-Low grading depending on whether they are more or less likely to occur, and whether the harm is more or less serious. The degree of significance given to any risk varies from situation to situation, thus every risk – new or existing – must be carefully considered/reconsidered by the evaluation team. This grading provides a list of priorities to future actions. Risks which could have a major effect on future benefits or impact critical tasks in the construction process should, as a suggestion, have highest priority. Other risks can be more difficult to appraise such as the life span of the ICT investment or factors that may lie outside the sphere of organizational control. Risks could also be external factors not directly related to the ICT investment, e.g. long time before a benefit occurs (Love et al 2005).

The second part – "Mitigation actions" – includes actions, time schedule and delegation of responsibilities to counteract identified risks, see table 4. The evaluation team can also consider alternative mitigation actions to address possible future changes of conditions and/or mitigation objectives. The risks/mitigation actions plan should be discussed and integrated with the overall project risk management to ensure accurate ranges are attached around benefits estimates affected by mitigation strategies.

The "Responsible person" is responsible for the third part – "Monitoring and Follow up": provide information to a joint database to see that all risk mitigation actions are carried out and all risks are acceptably mitigated. This information will also be used when performing follow ups.

Even though implementing a risk management process adds stability; risks and the risk assessment process will evolve over time. Risks may be added to the list and/or combined into others giving the users a maximum of flexibility to adapt the evaluation to new conditions.

Benefit/Cost	Risk/Obstacle	Priority	Measure	Time schedule	Responsibilities
Early quantity take off	Estimators/Purchasers not involved in project at this early stage	Medium	Look over project organisation and…	-month 0	Project leader
Hardware performance	Insufficient performance	High	Possible upgrading	-month 0	IT Manager
Etc.				-month n	

TABLE 4: Risk management structure (Dahlgren et al 1997).

Cooperation between the evaluation team and other project stakeholders in conjunction with transparency in the risk management process is vital in order to consolidate the foreseen benefits and avoid risks. Risk mitigation is important to the project as the odds of a future investment being successful are increased.

4.2.4 The evaluation results

The monetary result from using the evaluation model is presented as gross benefits and costs. The net benefit is calculated by subtracting the costs from the gross benefits. The decisions how to interpret and use the results is taken by the evaluation team or/and the project owner depending on the objectives with the evaluation. For example, the cash flow can be presented using illustrative and easily-understandable bar graphs where the benefits and costs are compiled and presented according to the classification grades, see Fig. 3. The colours represent here different levels of uncertainty. The results can also be further processed using methods such as DCF, NPV or IRR, mentioned earlier in the introduction, (see e.g. Ekström et al 2003, Andresen et al 2000). Other means to measure success could be to express the benefits as Key Performance Indicators (KPIs) and use the results for other evaluation purposes or for benchmarking.

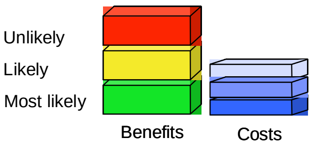

FIG. 3: Bar graph presentation of costs and benefits (Dahlgren et al 1997).

4.3 Secure

The process of securing benefits begins as soon as the decision to realize the ICT investment has been taken. However, while ICT investment evaluation is important, it is insufficient in terms of ensuring that the benefits identified and expected by the project organization are realized and delivered (Ward et al 1996a). ICT on its own does not deliver benefits (Ward et al 1996b). Active work throughout the project life cycle securing the benefits is required to achieve success. “Secure” includes a number of activities such as result estimation, planning before implementation- plan, secure, identify obstacles (obstacle analysis), preparation of follow-up, allocation of responsibility, etc. Typically, these activities fall short due to lack of insight about the importance of securing the realization of the benefits and uncertain allocation of responsibilities. However, securing the benefits are project activities subsequent to the evaluation process that lies beyond the scope of the proposed model.

A selection of methodologies for realizing ICT investments (Lin et al 2005) are listed below:

- Cranfield Process Model of Benefits Management (Ward et al 1996b);
- Active Benefit Realization (ABR) (Remenyi et al 1997);
- DMR’s Benefit Realization Model (Truax 1997);
- Model of Benefits Identification (Changchit et al 1998); and
- The IT Benefits Measurement Process (Andresen et al 2000).

5. IDENTIFYING AND STRUCTURING THE BENEFIT VARIABLES FROM USING VIRTUAL REALITY IN THE MK3 PROJECT – LESSONS FROM A CASE STUDY

The case is typical of constructing a large process plant: several companies jointly trying to comply to the basic needs of a client. The MK3 project was aimed at exploiting the potentials from growing market demands for iron pellets. Time was important in order to effectively take advantage of the market situation and achieve an edge over competitors. The purpose of the case study is to test the evaluation model presented in this article on a new ICT aid in used in the MK3 project. A short description of the case background follows. A more comprehensive description of the use of new ICT aids in the MK3 project can be found in Woksepp et al (2007), Jongeling et al (2007) and Woksepp et al (2006).

5.1 The MK3 project

5.1.1 Background

The Swedish state-owned mining company LKAB has recently increased their capacity by finishing the building of a new pelletizing plant (MK3) in Malmberget, northern Sweden. A workforce up to 250 people was employed by the constructors at the building site, while some 150 consultants and engineers were engaged in the design. The total expenditure was approximately EUR 280 M. The complexity of the project, the number of actors involved and the desire to involve the client and the end-users, such as industrial workers responsible for the plant operations, in the design work made Virtual Reality (VR) models excellent enriched sources of communications. Fig. 4 shows a screenshots from the VR models including an overview of the plant and a design review from the aspect of work environment.

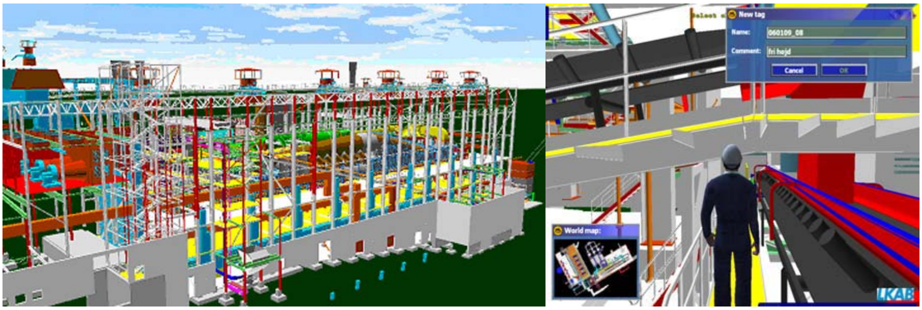

FIG. 4: Screenshots from the VR models of the MK3 project.

5.1.2 VR system and VR models

The technical equipment and VR platform used in the MK3 project was a low-cost approach that consisted of commercial software, PC computers and servers. The visualization tool Walkinside™, which was selected as VR platform in the project, can import most of the major CAD formats. All presentations of the VR models were interactive and done with computer monitors or 2D-projectors.

It was decided early in the project that most of the design should be in 3D and that the different 3D designs should be assembled and integrated in VR models for communication and coordination purposes. The client was responsible for the overall design process while the different design teams were responsible for the design of the subsystems, i.e. process equipment, building structure, installations, et cetera, and for providing correct and updated input data to the VR models. The design was carried out using a number of 3D CAD applications such as: Solidworks, Tekla Structures, AutoCAD, Microstation and Intergraph's PDS system. A VR consultant converted 3D models into VR format to produce different VR models for different purposes, e.g. design reviews, site planning, production, mounting, working environment for safety and maintenance. The VR models were also used for ocular clash detection, distance measuring, user positioning (XYZ coordinates or on an overview, updated in real-time), turning on/off objects layers, simulation of workforce and trucks using avatars, et cetera. The different design team exported updated 3D models to a FTP server every two weeks. Updated VR models were available on the FTP server to the design teams throughout the project. The total amount of information describing the VR models of the pelletizing plant is extensive, and includes the construction - prefabricated and cast in place concrete, the steel structure, the HVAC and electrical installations and machinery.

The VR models provided the design teams with structured and easy-to-understand design information continuously through the design process. The stakeholders could analyze the design both from a perspicuous as well as detailed perspective by navigating freely in the VR models. Moreover, using VR models made it easier to explain and discuss different design solutions with a larger group of stakeholders with different knowledge and experience. This facilitated the collecting of views from different perspectives that could be used to get a better and more production adapted design. The VR models were also used in the reviews meetings that occurred every two weeks. Here, design solutions were examined and discussed from the different perspectives and requirements on function, work environment and maintenance. Clashes between the different design disciplines was also discussed and resolved. It was concluded that one of the major benefits from using VR models to facilitate the design process was the increased level of understanding; especially within areas outside the scope of their own profession.

5.2 Case study procedures

The goal of the case study was to investigate the applicability of the evaluation model. This was done by using the model to assess the benefits and costs from utilizing VR models in the design process. The evaluation was carried out from a project perspective and the results were handled, analyzed and discussed with professionals with a thorough knowledge and experience of project management and technical engineering. The research objective was to support the development of the evaluation model.

No specific evaluation team was established; instead data from the case study were obtained from field investigations and informal interviews with 12 construction professionals involved in the design process. The interviews were conducted on one-to-one basis in conjunction to the participants' every day work at the construction site. This informal method helped us to obtain a deeper knowledge about using the VR models as well as capturing and understanding the benefits. Additional data was provided by a questionnaire which was sent out to additional professionals involved in the design process - thirty-one persons responded. The questionnaire was designed to investigate stakeholders' experiences working with VR models in the MK3 project. The interviewees and questionnaire respondents, all men, represented the client and a number of subcontractors with responsibilities within project management, design coordination, business management, technical engineering and model-based information handling. Only one had earlier experiences from working with VR models.

The data collected from field investigations, interviews and questionnaire were located into proposed benefit and cost structures in table 2 and 3. This procedure makes its also possible to capture benefits that does not belong to any specific stakeholder. Only the benefits belonging to the Project impact category are presented.

5.3 Case study results

The result presented here are a summary of the main identified benefits in the Project impact category and costs (all). An attempt is also made to quantify the results in monetary numbers on project impact level. The biggest values in the design process were:

- The VR models provided the stakeholders with design information in a way that is not possible using 2D CAD drawings. For example, large amount off complex interdisciplinary data could be gathered and presented in an easily-understandable way. The stakeholders could then analyze the design both from a perspicuous as well as detailed perspective by navigating freely in the virtual environment.
- Also, using VR models increased the level of coordination and understanding and made it easier to explain and discuss the overall design and different design solutions with a larger group of stakeholders with different knowledge and experience. The design teams could, interactively, in a virtual environment, explore different alternatives by predicting, understanding and evaluating the impact on the project as a whole in order to come up with the best solutions.

- VR was especially valuable in the conceptual design of the plant layout and in the detailed design phase which facilitated the collecting of views from other stakeholders that could be used get a better and more production adapted design.
- Also, a large number of collisions and design errors could be discovered and corrected in the design process which reduced re-work on-site.

However, the most important value for the client was to ensure to that needs and requirements were implemented in the design process. The time-pressure in the MK3 project and the ambition to enhance collaboration between the stakeholders, resulted in a concurrent design process where the VR models were used to coordinate and communicate the design to the client. Besides making it easier for the client to make crucial decisions, the VR models involved the client in the everyday design work. Being able to quickly sort out the information that is relevant for the moment and present it in an easy and comprehensible way have enabled the client to collect opinions from a wider audience and to focus on the actual decision making.

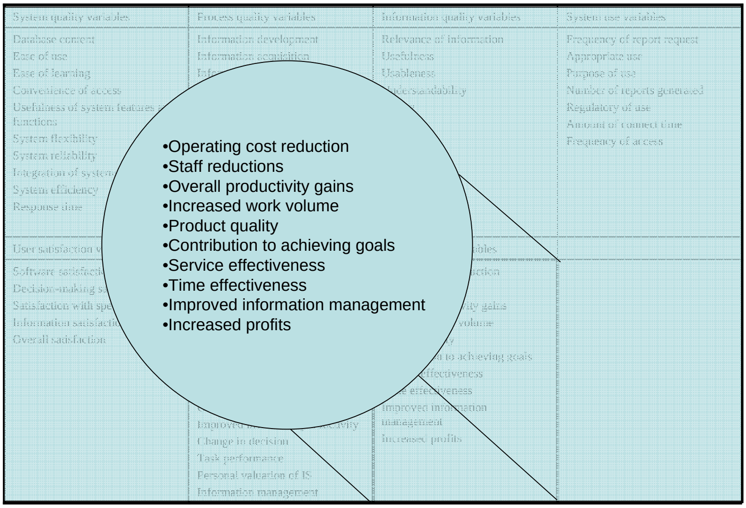

TABLE 5: Identified benefit variables in the Project impact category.

Table 5 shows the affected benefit variables in the Project impact category of using VR in the MK3 project (Project impact category). Most benefits are project specific and do not contribute specifically to any individual stakeholder. The major benefits came from the following variables in the category *Project impact variables*:

Staff reductions: Experience from a similar project using 2D drawings showed that staff devoted to design coordination was halved from 15 to 7 designers compared to the 2D design project. Nevertheless, the quality of the design coordination was considered to be higher in the MK3 project.

Product quality: The operation of a highly automated industrial process is to a large extent dependent on the maintainability of the process equipment. Measures to prevent production losses have high priority in such facilities due to the economical consequences. Therefore, to make sure that maintenance could be conducted, the maintenance personnel were asked to participate in a spatial analysis using avatars and VR models of the process machinery and layout.

Contributing to achieving goals: The design of the manufacturing process is of first priority for the client (before the plant layout and the construction of the plant). This leads to a situation where the focus is on the assembling and functionality of the machinery in the plant instead of the actual building. All separate design processes occur simultaneously in a concurrent design approach. The uses of VR models have facilitated the concurrent design process in the MK3 project. Especially in the design coordination process, the design review process and the capturing of client requirements on the final design.

Time effectiveness: The CE-marking procedure is normally carried out when the plant is finished. However, by using VR models the client could speed up the handling of CE-marking in order to get an earlier production start. Moreover, VR models were used to support planning and decision-making of prefabrication. For example, to speed up the production it was decided that larger parts of the belt conveyor system could be assembled off-site after it was checked in the VR model that these preassembled belt conveyor parts could safely be lifted in the plant.

Increased profits: Using VR models as a part of the partnering strategy in the project also including, e.g., concurrent working methods, facilitated the design, planning and construction processes thus advancing the date of completion. One of the project leader estimated that the coordination of the design and construction using VR in the project made it possible to advance the date of completion by at least two weeks (approximately 3% faster than planned).

To isolate the benefits from using VR is hard since it was part of an overall strategy also affecting the work processes (e.g. concurrent engineering). However, since all benefits and costs fall to the project (in this case due to the contractual arrangement – Partnering) we do not have to split these values between the stakeholders which makes it easier to quantify them. Also, in most cases it is not necessary to quantify all benefits. In this case study, we limited the quantification to a few variables where the project manager and the design coordinator estimated the benefits in quantifiable terms. If the estimated benefits are much higher than the costs of using the VR tool in the design process, it has been worthwhile. The estimated benefits are summarized in Table 6. The total benefits are estimated to EUR 10 630 K, including costs that are most likely, likely and unlikely to occur.

Project impact				
Benefit variable	**Benefit identified from…**	**Quantification**	**Likelihood to occur**	**Comment**
Staff reduction	Interview – Project manager	8 prs x 40 weeks x EUR 4K = EUR 1 280 K	**Most likely**	Well-supported figures
Clashes	Questionnaire/Interviews – Project manager	300 pcs x EUR 4 K = EUR 1 200 K	**Most likely**	Another project manager estimated the value to EUR 500. The number of clashes are estimated somewhere between 200 and 400 by the design coordinator
Earlier completion of project due to better coordinated shop drawings	Questionnaire – Project manager	2 weeks x EUR 3000 K = EUR 6 000 k	**Likely**	The plant's estimated profit per week when it has reached full capacity is EUR 3M!
Coordination montage	Questionnaire – Project manager	EUR 2 000 K	**Likely**	
Better information quality	Questionnaire – design coordinator	EUR 50 K	**Not likely**	Very difficult to confirm
Better insight into all aspects of the project	Questionnaire – design coordinator	EUR 100 K	**Not likely**	Very difficult to confirm

TABLE 6: Identified benefits in the Project impact category and their estimated values.

The operational cost to create the VR models in the design process can be estimated on the safe side to one person working fulltime during 60 weeks (the VR consultant), According to the design coordinator, this was only true in the beginning of the project and when the models become more complex, i.e. when the level of detailing increased. In between these periods in the project the VR consultant works approximately 8h/week on updates of the models. Also, the cost for doing the design in 3D was estimated to be the same as for 2D modelling, since much of the design made by the installation and machinery consultants are already delivered in 3D. Table 7, shows the estimated costs for the use of VR. The estimated costs are summarized in Table 7. The total costs are estimated to EUR 355 K, including the costs that are most likely, likely and unlikely to occur.

Project impact				
Cost variable	**Cost identified from…**	**Quantification**	**Likelihood to occur**	**Comment**
Capital cost	Interview – Project manager	EUR 15 K	**Most likely**	HW, SW
Operational cost	Interviews – Project manager, VR consultant	1 prs x 60 weeks x EUR 4 K = EUR 240 K	**Most likely**	VR consultants (Hög uppskatting)
Indirect costs	Interviews – project manager, VR consultant	EUR 100 K	**Likely**	Other costs – support, administration, personnel, training. Estimated sum.

TABLE 7: Identified costs and their values.

Comparing the benefits [in one category – the Project impact category] with all costs, see the bar graph presentation in Fig. 5, shows that the benefits are clearly higher than the costs, even if we only compare the most likely outcome. This conclusion is shared by the client, LKAB, who has decided to use the same working method provided by VR in the next project – the construction of a new pelletizing plant in Kiruna, Sweden, twice the size of the MK3 project. Even if the evaluation model is project-oriented, it is clear that the client is the main beneficiary.

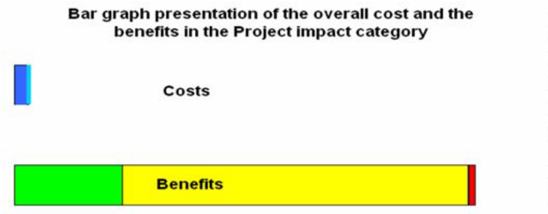

FIG. 5: Bar graph presentation of the overall costs and the benefits in the Project impact category.

A variety of inputs have been used to derive the findings presented in this paper, including data from interviews, observations and one questionnaire. The authors gathered this data during a period of one and a half year. Of course, things change during such a period: the project evolves, there is a turnover of staff, the users becomes more skilled at exploiting the VR models, new benefits emerges, "old" benefits changes, and so on. However, both performance and results feels nevertheless satisfactory. Even though a majority of the participant saw value in the use of VR models, still a few remained sceptical of the financial benefits of using VR. Since, the evaluation was made mainly based on interviews of a few key persons in the project the financial result is only a rough estimate. However, since most estimates are on the safe side and not all benefits have been finically estimated it is likely that the total benefits are much higher.

6. CONCLUSIONS

ICT evaluation activities involve several multi-disciplinary measures that must balance each other if the evaluation is to be a success in terms of creating well-described understanding of the implications of ICT investment to a project organisation. However, literature review shows that the methods used today often fails to meet these requirements; hence, the relationships between the ICT investment and project impact remain unclear.

In order to address this above-mentioned deficiency, the overall research objective was to present a new project-oriented model for evaluating ICT investments in construction projects. Its applicability was validated in one case study. This research suggests that the proposed model can be applicable and give satisfactory result. As shown in the case study, both the evaluation as the presentation of results met the requirements for successfully identify and explain the impact of an ICT investment project level. However as many ICT investment also involves changes in the process, the traditional construction processes has to be changed to take advantage of the benefits that the ICT tools can offer. In the case study, this was evident where the VR tool was an integral part of the concurrent engineering approach.

Since the evaluation model is one of the results of the case study, the evaluation was not made according to the proposed strategy. Still, the shift in focus from individual stakeholders to benefits for the project gives a momentum to optimize the benefits in the use of a new ICT tools in construction. This will surely affect the processes and the contractual environment in the project, since it has to support sharing of information and achieved benefits and the costs of the investment in the project.

Nevertheless, the proposed model needs to be further developed and tested in practice. Especially, how the individual variables in the different categories in Table 2 can be merged and measured at project level.

7. ACKNOWLEDGEMENTS

The authors wish to thank many people for their contribution to this research. This paper is based on field investigations, interviews and a questionnaire study were several people were involved. These people represent the client LKAB and a number of subcontractors involved in the MK3 project. We thank them for their invaluable commitment and patience in sponsoring our work and providing access to project data and methods as well as their own knowledge and experiences. Special thanks go to Per Lundström, Jaakko Pöyry AB, Håkan Melander, NCC and Anders Lundgren, LKAB without whose help the study would have been far less rich in information. We also acknowledge the financial support from the Swedish research fund for environment, agricultural sciences and spatial planning (Formas) and the Swedish construction development fund (SBUF).

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Paper V

Woksepp, S. and Olofsson, T. (2007). Credibility and applicability of Virtual Reality models in design and construction. Submitted to Advanced Engineering Informatics (October 2007).

Title
Credibility and applicability of virtual reality models in design and construction

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ABSTRACT
In this article, we present the findings from an extensive case study of the use of Virtual Reality (VR) models in large construction projects. The study has two parts. The first part presents a quantitative questionnaire designed to investigate how VR models are experienced and assessed by the workforce at a building site. The second part includes a qualitative field study of how VR models can be applied and accepted by professionals in the design and planning process of a large pelletizing plant. By mainly studying persons who had little or no experience of advanced IT, we hoped to reveal the attitudes of the average person working at a construction site rather than of an IT expert.

To summarize, the study shows that the VR models in both projects have been very useful and well accepted by the users. From a general point of view, today's information flow is considered to be insufficient and the hypothesis is that using VR models in the construction process has the potential to minimize the waste of resources and improve the final result.

KEY WORDS
Construction project, Design stage, Field survey, Planning, Questionnaire, Virtual Reality.

1. INTRODUCTION
The information processing in construction projects is often based on traditional media, such as drawings, Gantt schedules and written specifications, which only provide limited information transfer between the stakeholders in the project [1]. These conditions do not provide a solid foundation for an effective construction process, e.g. [2-4]. Advances in Information Technology (IT), especially computer graphics and CAD systems, have changed the way we work. However, the full

potential at project level is yet to be realized, e.g. [5]. VR offers a natural medium for users, providing a three-dimensional view that can be manipulated in real time and used collaboratively to explore and analyze design options and simulations of the construction process [6]. It is only recently that VR has started to be used in construction projects and there has been little empirical investigation of VR technologies by companies in the construction sector [7]. For example, the appropriate use of VR models in the different phases of a construction project is still not clear [8].

2. RESEARCH AIM AND OBJECTIVES

The aim of the case studies presented here is to explore and provide an insight into and knowledge of the way VR models are apprehended and used by AEC professionals in their everyday work. The two cases included:

1. A quantitative questionnaire about the way VR models were experienced and assessed by professionals involved in the construction of a large building project and the extent to which VR could complement the use of traditional 2D CAD drawings. In this context, the operational use of VR at the building site was the primary target

2. A qualitative field study of the way VR models were applied and accepted by professionals in the design and planning process of the construction of a large process plant.

Conclusions are drawn from these two cases.

3. RELATED WORK

Bouchlaghem et al. [6] studied the applications and benefits of visualization in construction projects covering collaborative work and design at the conceptual design stage, the marketing process in the house-building sector and the modeling of design details at the construction stage. Their study concluded that visualization can improve communication and collaboration between designers during conceptual design; in housing development, site layout models could be used as marketing tools or for planning consultations with planners. Westerdahl et al. [8] studied the way employees at a company perceived a VR model of the architectural design of their yet-to-be-built workplace. The results indicated that the VR model helped the decision-making process and provided a good representation of the future workplace. Savioja et al. [9] studied the use of VR models in the construction of a new lecture hall in Helsinki. The process started from a basic VR model presenting the concept and layout. The model was further detailed until a photorealistic model of the building could be presented and used for detailed studies of the design. The study concluded that VR improved communication and the project participants were enthusiastic about the potential of VR. Messner et al. [10] studied the value of visualizing design and construction information in the decision-making process. The use of visualization tools for design tasks was found to improve collaboration and communication between the involved stakeholders. Dawood et al. [11] presented a visual planning tool (VIRCON) with the objective of assisting construction planners to make accurate, informed planning decisions with particular emphasis on the allocation of work space. In particular, space planning in combination with visualization was found to be useful in tests evaluated by professionals.

4. THE CENTRALHUSET PROJECT - CASE 1

The first case study is a questionnaire study that aims to investigate how a visualized VR model was experienced and assessed by the workforce in the construction of a large hotel and office block, Centralhuset. The new 34,000 square-meter building at the bus and rail station in Göteborg was constructed between the spring of 2001 and the fall of 2003. Up to 230 people were employed at the site and the construction cost was approximately EUR 50 M. The building includes a hotel block, an office block and commercial and restaurant premises. *Figure 1* shows three screenshots from the VR model, including the steel structure, foundations and piles and a proposal for office space.

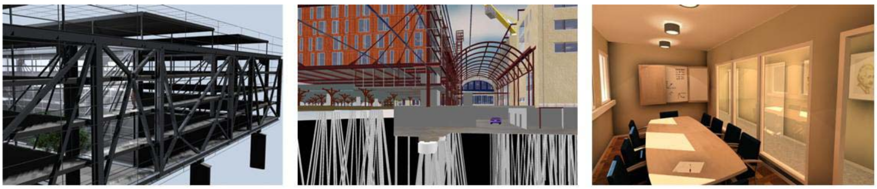


Figure 1 Screenshots from the VR model of Centralhuset

4.1 THE VR SYSTEM

The VR demonstrations can be described as desktop immersive. A standard 2-dimensional projector visualized the VR model on a screen. Two PCs and the Division MockUp (PTC) visualization tool were used for the VR visualizations and a Magellan Space mouse was used to navigate in the interactive virtual environment. The software and hardware used in the study are commercial and available on the market and were chosen for their functionality, price, flexibility and full compatibility with the most common CAD formats. The investment can be described as reasonable, i.e. suitable not only for large but also for small and medium-sized enterprises.

4.2 THE VR MODEL

The VR models of the Centralhuset were constructed from 2D CAD drawings, 3D CAD models and objects supplied by the architects, designers and other subcontractors. Additional sources detailing the surroundings, such as orthophotos and photos of building exteriors, were purchased from the National Land Survey of Sweden (LMV) or produced using digital cameras. Imported into the VR software, the model could be structured in an assembly manager with hierarchical and parent-child relationships (tree structure). This made it easy to break down the VR model into modules or "sub-models" depending on the application. This also allowed the users to create VR object catalogs and to distribute (via LAN, internet, CD et cetera) streamlined VR models for different purposes. Additional features and objects, such as textures, orthophotos, the construction crane, site office, rail area and existing rail station, were subsequently added. The VR model of Centralhuset includes the adjacent surroundings, excavations, the cast-in-place basement, piles and pile footings, prefabricated and cast-in-place supporting structures (steel and concrete), pre-fabricated and cast-in-place floors, parts of the façade, rail area (platforms, railway tracks et cetera), site office and a moving crane. The exact locations and angles of all 347 cohesion pilings were visualized. The equipment, together with the VR model, was installed at the building site. During construction, the VR model was maintained and updated with vital information. To facilitate the distribution of information, a local website was created at which the users could present data for downloading. This website also served as a meeting place at which images and animations could be downloaded and studied. Approximately 350 working hours were spent on constructing the 10,000-object VR model, at a cost of approximately EUR 35,000. This expenditure was financed by the research project and the main contractor, NCC Construction Sverige AB. The benefits of exploiting the VR model – primarily as a tool for planning site activities and incoming and on-site logistics – were accrued by the construction project.

4.3 RESEARCH METHODOLOGY

A questionnaire consisting of 20/21 questions or statements (21 directed at the representatives of the building owner) was used to evaluate the way the different types of player perceived and assessed the use of VR in the project. The first three questions pertained to individual characteristics – age, profession and computer skills. Statements for investigating participants' attitudes towards the use of the VR model and the information flow at the building site were then presented. The questionnaire closed with a section containing general statements about the use of a VR model in the respondents' own profession. Although leading questions or statements should be avoided in a questionnaire – as they could reflect the position of the researcher, we nevertheless decided that an approach of this kind was best for this study:

1. How will the VR prototype be envisaged, experienced and assessed by the users?
2. To what extent can a VR model complement the use of 2D CAD drawings?

The participants were asked to express agreement or disagreement on a five-point Likert scale: “Strongly agree” (5), “Agree” (4), “Undecided” (3), “Disagree” (2) or “Strongly disagree” (1). The Likert scale was used for all the questions in the questionnaire, with the exception of questions relating to personal characteristics, first contact with VR, information flow and the final questions directed at the representatives of the building owner. The mean and the standard deviation for the participant group as a whole were calculated for each statement.

4.4 PARTICIPANTS

In all, 93 people participated in the study. The majority of the people involved in the construction of Centralhuset participated in the study. *Table 1* and *Table 2* show the distributions of occupation and age of the 93 respondents. The occupations fell into the following categories (see columns 1-8 in *Table 1*): 1. construction workers; 2. site managers; 3. constructors; 4. architects; 5. handling officers; 6. representatives of the building owner; 7. sub-contractors; and 8. “others” – “others” included assessors, economy assistants and external specialists.

Table 1 Participants'occupation

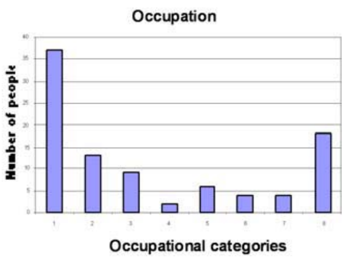
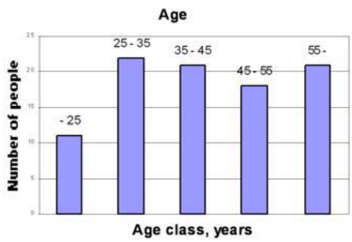


Table 2 Age class distribution



The construction workers were in the majority. Their ages ranged from 20 to 62 years. Differences due to gender could not be investigated, since too few females participated in the study. Fifty-seven per cent of the participants considered themselves to “have good computer skills”. For 75%, this was their “first contact with Virtual Reality". The majority of the participants that previously had experience of 3D modeling and/or VR were designers.

4.5 RESULTS

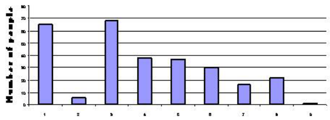
The main goal of the study was to establish whether or not a VR model could be used as a practical, reliable tool to improve communication at the building site. The results of the questionnaire are presented as means and standard deviations in Tables 3, 4 and 5. Unless otherwise stated, the response format was a five-point Likert scale (n=93).

Table 3 Investigating how participants experience use of a VR model

Virtual Reality (VR)	**Mean value (S.D.)**
1. First impressions at the VR demonstration	
1a. The VR model provides a better overview of Centralhuset than 2D CAD drawings do.	4.57 (0.54)
1b. The VR model of Centralhuset has an appearance that inspires confidence in it.	4.30 (0.69)
2. Help of navigation in the handling of details	
2a. Details show up better in VR than in 2D CAD drawings.	4.12 (0.68)
2b. It is easier for me to explain details I am involved with professionally using a VR model than using 2D CAD drawings.	4.16 (0.80)
2c. Having the ability to navigate within the VR environment and thus being able to scrutinize the model involved from different angles helps me to understand details.	4.50 (0.70)
3. Cooperation using a virtual environment	
3a. The cooperation I have with my colleagues within the same occupational group is facilitated by using a VR model.	4.01 (0.73)
3b. The cooperation I have with colleagues from other occupational groups is facilitated by using a VR model.	4.20 (0.72)
3c. Details in areas outside my professional areas of expertise are easier for me to understand with the aid of a VR model.	4.30 (0.73)

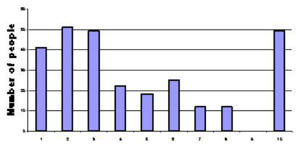
Table 4 The participants' present and desired future access to information

Information processing 4. Personal situation	Mean value (S.D.)
4a. I already receive enough information in my job without the help of VR models.	3.55 (0.77)
4b. I'm satisfied with the way information is distributed to me now, without the help of VR models.	3.40 (0.75)
4c. In my occupation, I receive information primarily from the following sources (multiple alt. can be selected):	



1.2D CAD drawings
2.3D CAD drawings
3.Personal contacts
4.By telephone
5.By fax
6.Through the internet
7.LAN (Local Area Network)
8.From literature, brochures etc.
9.From other sources

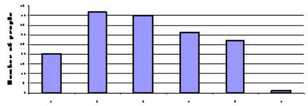
4d. In my future job situation, I would like to receive information mainly from the following sources (multiple alternatives can be selected):



1. 2D CAD drawings
2. 3D CAD drawings
3. Personal contacts
4. By telephone
5. By fax
6. Through the internet
7. LAN (Local Area Network)
8. From literature, brochures etc.
9. From other sources
10. From Virtual Reality models

Table 5 Summary of the participants' attitudes toward use of the VR model in work

Final section* 5. Using VR models in one's own work	Mean value (S.D.)
5a. I think it would be of benefit to me to use VR models in my work.	4.30 (0.68)
5b. I could imagine using VR models in my work.	4.28 (0.75)
5c. Convincing me of the benefits of Virtual Reality would require (several alternatives can be selected):	



1. Nothing, I am already convinced
2. Successful pilot projects
3. Economic analysis
4. VR presentations at the workplace
5. Better technical knowledge
6. Other factors

* Two additional questions for the representatives of the building owner are presented at the end of Section 4.5. All the participants apart from the representatives of the building owner answered the first statement in the "Final section".

The result shows that the participants received a good first impression and have confidence in the VR model (1a, 1b). The potential of using the VR model to navigate and to scrutinize and explain details was also considered to be useful (2a, 2b, 2c). The participants also felt that a VR model could facilitate cooperation and understanding within or between occupational groups. However, some participants expressed doubts about being able to create VR models of detailed 3D CAD information in good time for reviewing before performing related site activities. “The time between detailed design and construction is often too short,” they said. The result was more ambiguous regarding the use of VR for facilitating information processing (4a and 4b), although 52% stated that they would like to receive information from VR models in a future job situation (4d). The last part of the questionnaire, “Using VR in one’s own work”, generated comments such as, “This is great, but how do we implement it in our everyday work?” or “Interesting, but can we save any money by using a VR model at the building site? How?”. In spite of this, the majority of the respondents considered VR models to be useful (5a) and could imagine using them in their work (5b). However, some concerns were expressed about the financial benefits and management of VR.

Most of the comments related to the level of detail, costs and possible benefits of VR. The greatest potential was believed to be associated with the performance of an unfamiliar task (planning site activities). The rest of the comments related to foreseen problems associated with keeping the VR model updated and the need for adaptation to the conditions on the building site. Other comments related to the time at which the major breakthrough for VR in construction was likely to occur. Representatives of the building owner responded to two additional statements:

1. I believe that using VR models can give me a more favorable position in relation to a client.
2. I believe that, by using VR, I can reduce the costs of errors sufficiently to cover the costs of the modeling work.

The participants strongly agreed with the first of these two statements (M=4.5). The second statement received a slightly positive response (M=3.25). Since only four representatives of the building owner participated, the response is only indicative. A much larger number of participants are needed to ensure reliable responses. However, the estimated cost of the VR model in the Centralhuset project was approximately 2‰ and, according to Josephson (1990), the errors generated at the site are estimated to account for 10% of the total construction cost.

5. THE MK3 PROJECT - CASE 2

The second case concerned the way VR models were applied and accepted by the client and design and planning teams in the construction of a large pelletizing plant, the MK3 project. Due to increased demand for upgraded iron ore products for steel-making, the Swedish state-owned mining company LKAB recently increased its capacity by finishing the building of a new pelletizing plant (MK3) in Malmberget, northern Sweden. A workforce of up to 250 people was employed by the constructors at the building site, while some 150 consultants and engineers were engaged in the design phase. The total expenditure was approximately EUR 280 M. Since time to market is a crucial factor for LKAB, the contractual agreements for cooperation in the project support collaborative working methods such as concurrent engineering, open information flow and the introduction of innovations in the design process. The complexity of the project, the number of players involved and the desire to involve the client and the end-users, such as industrial workers responsible for the plant operations, in the design work make VR an excellent enriched source of communication. ***Figure 2*** shows three screenshots from the VR models, including an overview of the plant, a typical collision detected between different teams' design (cable ladder and pipes) and a part of the machinery section representing a design review from the aspect of maintenance.

Figure 2 Screenshots from the VR models of the MK3 project

The purpose of using concurrent engineering in the project was to reduce the lead times. It was decided early in the project that most of the design should be in 3D and that the different 3D designs should be assembled in digital mock-ups (integrated VR models) for communication and coordination purposes. Design engineers with experience of 3D modeling were recruited to the project and the different design teams selected the 3D CAD tools of their choice. The selection of CAD tools was based on people's experience not on technical demands!

The design of the plant in the MK3 project was affected by the following parameters:

– The design of the manufacturing process.
– Process layout – maintenance, logistics, working environment.
– The construction of the plant.

The client was responsible for the overall design process, while the different design teams were responsible for the design of the subsystems in the plant, i.e. process equipment, building structure, installations et cetera, and for providing correct and updated input data for the VR models. A VR consultant working for the client managed all the VR data and provided updated VR models that were accessible to everyone involved in the design process. The different design teams exported updated 3D models to a FTP server every two weeks. Various VR models were produced and used in design reviews for different purposes, e.g. design coordination, work environment, clash detection and planning. Updated VR models were available to the design teams on the FTP server throughout the design phase.

5.1 THE VR SYSTEM AND VR MODELS

The VR system used in the MK3 project is a low-cost approach that consists of commercial software, PC computers and servers. The visualization tool Walkinside™, which was selected as a VR platform in the project, is able to import most of the major CAD formats. All presentations of the VR models were interactive and made with computer monitors or 2D projectors. Most of the information that makes up the VR models of the plant originates from 3D CAD models developed by different design teams. The only exception in the project is the electrical installations that were only modeled in 2D. However, the cabling was later remodeled as 3D CAD objects to show the location of the cable ladders in the plant. The different design teams responsible for the development of steel, concrete, machinery, ventilation et cetera extract chosen parts of the 3D models to be included in the VR models. The design was carried out using a number of 3D CAD applications such as Solidworks, Tekla Structures, AutoCAD, Microstation (where most of the mapping of material and textures was done) and Intergraph's PDS system. Apart from the use in creating VR models, most 2D CAD shop drawings were directly generated from the 3D models. The VR consultant converts the uploaded 3D models into VR format and produces different VR models for different purposes, e.g. design reviews, site planning, production, mounting, working environment for safety and maintenance. The VR models were also used for ocular clash detection (automatic clash detection is carried out in the 3D CAD software by the design teams themselves), distance measuring, user positioning (XYZ coordinates or on an overview, updated in real time), turning on/off object layers, gravity, impenetrable objects, the use of avatars for simulations of workforce and trucks et cetera. The total amount of information describing the VR models of the pelletizing plant is extensive and includes the construction (prefabricated and cast-in-place concrete and the steel structure), the installations (machinery, HVAC, electrical installations) and the surroundings. All expenditures for creating, using and handling the VR models were financed by the client.

5.2 RESEARCH METHODOLOGY

Qualitative research methodology was used. The study is based on field studies and informal interviews with 12 respondents involved in the design and planning of the construction project.

5.3 PROCEDURE AND PARTICIPANTS

The interviews were conducted on a one-to-one basis in conjunction to the participants' everyday work. This informal method helped us to map out the working process and to obtain a deeper knowledge of the experience of using VR in a systematic way throughout the design and construction process. The 12 interviewees, all men, represented the client and a number of subcontractors with responsibilities within project management and planning, design coordination, business management and development (representing the client), technical engineering and VR modeling. All but one, the VR consultant, had several years' experience of similar construction projects. However, the VR consultant was the only one that had some experience of working with VR models. Everyone uses computers frequently and agreed that the amount of information in construction projects is probably enough but needed to be more structured and easier to communicate to the different stakeholders in the project.

5.4 RESULTS

The following section summarizes the main findings on the use and benefits of VR from the field study and interviews with the 12 respondents.

A number of VR models were produced throughout the project in order to support the design and planning process. These VR models were fully accepted and considered useful. According to the interviewees, the VR models provided well-structured, easy-to-understand design information throughout the project in a way that is not possible using traditional documents and 2D CAD drawings. The users were able to analyze the design from different perspectives by navigating freely in the VR models, which made it easier to explain and discuss different design solutions with a larger group of professionals with different knowledge and experience.

The VR models were extensively used in the review meetings that were held every two weeks. Here, design solutions were examined from the different perspectives and requirements on function, work environment and maintenance. Clashes between the different design disciplines were also discussed and resolved. The use of VR made the review work much easier and minimized the risk of misinterpretation. This implies that more valuable time could be spent on finding solutions and opportunities. However, one of the greatest advantages in design reviewing, as well as in the individual design work, was the increased understanding of the overall design. The design teams were able interactively, in a virtual environment, to explore different alternatives by predicting, understanding and evaluating the impact on the project as a whole in order to come up with the best solutions for the client. In addition to making it easier to make crucial decisions, the VR models involved the client in the everyday design work. The use of VR enabled the client to collect opinions from a wider audience, such as the plant operating and maintenance staff. There are several examples in the MK3 project where the VR models were used to facilitate the client's decision-making in the design process. For example, due to the tight time schedule, the client and the different design teams needed to take quick internal decisions, often without consulting the other design teams at a regular design review meeting. The VR models helped them better to understand the multidisciplinary consequences of a decision. From the client's perspective, the impact of the decision on the manufacturing processes has the highest priority. All other decisions regarding construction, HVAC et cetera are of subordinate significance. So, when the client had chosen the plant process and the machinery to produce the required capacity, the spatial needs could be defined. These needs were described to the construction design teams using a VR model of the plant process design. The design teams were then able to start planning the layout of the construction and select technical solutions to be discussed, followed up and evaluated at the subsequent design review meetings.

The interviewees concluded that one of the major benefits to the design was the increased level of understanding, especially within areas outside the scope of their own profession, or to quote one of the design managers: "I was skeptical at first, but then I realized that, by studying one VR model instead of spending time searching through piles of paper drawings, I could save a lot of valuable time and could thus focus on what is important". To illustrate his point, he mentioned how much easier it was to design the concrete foundations of the machinery when he had a clear picture from the VR model of the way the mounting frames were designed. Using VR models was also considered especially valuable for providing data for the clients' investment decision, in the conceptual design of the plant layout, in the detailed design phase and for speeding up the CE labeling of the plant.

A number of VR models that showed the general phases of the project during construction were also produced in order to support the scheduling process. These VR models, which we define as phase models, were accepted and considered useful by the planners. However, it was noted by the planners that the phase models are limited in the sense that they are only approximate representations of a certain state in the construction process, without any direct link to the project schedule. The following examples illustrate the use of VR in the planning of the work:

– The design models are complex as they involve many different disciplines and complex geometries. For example, almost all the conveyor belts in the baling section slope away in different directions, often crossing and connecting to parts of the plant that are designed by several other suppliers and designers. VR models could certify constructability and order of assembly. Moreover, VR models have been used in advance to identify critical areas or parts of the plant and have used that information in order to speed up the CE-labeling process

– The construction space is limited, e.g. the work often involves many different suppliers and contractors at the same time, in the same area. For example, to ensure that the pipe installation would not be clustered in cramped spaces without space for maintenance, VR models were used to plan and coordinate the site activities and ensure future access

– Construction time is limited and requires all the involved contractors and suppliers to work with several crews at the same time. The use of VR models facilitated a concurrent approach and helped reduce the lead time (from investment decision to start of production) to two years

– VR models were used to support the planning and decision-making relating to prefabrication. For example, to speed up production, it was decided that large parts of the belt conveyor system could be assembled off site after a check had been made in the VR model to ensure that these preassembled belt conveyor parts could be safely lifted in the plant.

According to the planners, the greatest value of using VR models was obtained from including the setting-out grid (created as “VR solids”) in the VR models. The setting-out grid provided the planning teams with reference positions from which distances to the construction parts could be measured. This created a common framework of reference and an improved spatial understanding. The VR models also facilitated the structuring and handling of the massive amount of information in the planning process. This took some of the work load off the planners.

6 DISCUSSIONS

6.1 The Centralhuset case study

The aim of the questionnaire study was to investigate the way work force at a large building site experienced and assessed the VR model as well as the intended use for information purposes. The VR model focused primarily on the supporting structure, the foundations and the prefabricated floor components of the building. We expected that some of the occupational groups could have more use for the model than other groups. Therefore, we endeavored to perfect the original version of the VR model to make it as suitable as possible for all the occupational groups involved.

In the questionnaire, three objective personal characteristics of the participants, age, occupation and computer skills, were determined. Only some relationships between these characteristics and the views or attitudes that the participants expressed in their responses could be found; e.g. younger respondents with greater computer skills were slightly more positive about VR and all the architects liked the idea of communicating their work using VR models. Although the construction workers were the group whose computer skills were most limited, they were particularly positive in their assessment of the advantages of using VR in the construction process. The fact that they receive information largely from 2D CAD drawings and personal communication may well have contributed to their positive attitude to new and richer forms of communication media. Although we did not perform any significance tests, the reasonably high mean values, combined with low standard deviations obtained for most of the test items relating to the participants' attitudes and assessments, indicate a high degree of consensus. This gives a strong indication of the conclusions drawn.

6.2 The MK3 case study

According to the interviewees, the use of VR facilitated the concurrent design process, especially in the design coordination process, the design review process and the capturing and definition of client requirements for the final design, plus, to some extent, the planning process. By comparison with the traditional 2D and document-based working methods, both designers and planners stated that they had obtained a higher degree of spatial understanding and a better understanding of how and when the construction was going to be built. As a result, they had been able to evaluate different solutions and better understand the future consequences of a decision. A rough estimate based on previous experience of a similar project using 2D drawings by the design coordinator showed that the cost of using VR is much less compared with the savings on design coordination alone once the design is made in 3D. The staff devoted to design coordination were halved (from 15 to 7 designers) compared with the 2D design project. In spite of this, the quality of the design coordination was deemed to be higher in the MK3 project.

The VR models were accepted and considered reliable, largely because they directly originate from the different 3D CAD models. However, although the planners considered the VR models to be reliable and also well structured, most of the planning work was done using traditional methods. The two main reasons for this are believed to be that the traditional way of working is still firmly established and that the "right" VR models were often inaccessible when much of the planning work was conducted. There was simply not enough time to produce and present production-adapted VR models to the planning team.

Neither realistic VR models (lighting, texture et cetera) nor the experience of presence was considered to be essential for designing and planning. Computer monitors and projectors (2D) were believed to be sufficient for the VR presentations. According to the client, most value has been derived from the use of VR as decision-making support in the conceptual design of the plant layout and from detecting collisions in the detailed design phase.

7. CONCLUSIONS

Focusing on two case studies – two construction projects – made it possible to go into greater depth when investigating the use of VR models in large construction projects. However, it should be noted that the conclusions that have been drawn should be interpreted while taking account of this limited scope.

The results of Study 1 indicate that there is a need to improve the information flow at building sites. The usefulness of technical aids, such as VR, appears to be obvious. Indications that can inhibit the integration of VR into the building process were also found in limited technical knowledge and financial considerations. The present procedure of distributing information by means of 2D CAD drawings is ineffective. Moreover, designing in 2D rather than directly in 3D considerably increases the cost of producing a VR model. Additional comments also revealed that it is important to inspire and create confidence in new aids, such as VR models. Otherwise, there is always a risk of a low utilization ratio.

The results of Study 2 indicate that the client and the vast majority of the designers and planners accepted and were positive about using VR models as a tool for improving information processing in the MK3 project. The usefulness in both the design and planning process was acknowledged. At the beginning of the project, both fascination with and skepticism about VR technology was noted and this was thought to influence the acceptance and credibility of the VR models. However, these symptoms quickly vanished when the use of VR models became a natural part of people's daily work. Moreover, several respondents argued that the use of VR would probably increase in future projects and that more built-in intelligence in the VR model would extend its use in designing, planning and process simulation.

8. ACKNOWLEDGEMENTS

This paper is based on field studies where several people involved in the Centralhuset and MK3 project were interviewed or participated in a questionnaire study. These people represent the clients and a number of subcontractors with responsibilities within project management and planning, design management, business management and development, technical engineering, VR modeling, site management and construction activities. We thank them for their invaluable commitment and patience in sponsoring our work and providing access to project data and methods as well as their own knowledge and experiences. We also acknowledge the financial support from the Swedish research fund for environment, agricultural sciences and spatial planning (Formas) and the Swedish construction development fund (SBUF).

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