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Credibility and applicability of virtual reality models in design and construction

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ABSTRACT

In this paper, we present the findings from an extensive study of the use of virtual reality (VR) models in large construction projects. The study includes 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 pelletizing plant. Through mainly studying persons who had little or no experience with advanced information technology (IT), we hoped to reveal the attitudes of the average person working at a construction site rather than of an IT expert. In summary, the study shows that the VR models in both projects have been very useful and well accepted by the users. Today's information flow is, from a general point of view, considered to be insufficient and the hypothesis is that using VR models in the construction process have the potential to minimize waste of resources and improve the final result.

1. Introduction

The information handling in construction projects are often based on traditional media, such as drawings, Gantt schedules and written specifications, which only provide a limited information transfer between the stakeholders of the project [1]. These conditions do not provide a solid foundation for an effective construction process, e.g. [2–4]. Advances in IT, especially computer graphics and CAD systems have changed the way we work. However, the full potential on project level is yet to be reached [5].

VR offers a natural medium for the users providing a 3D view that can be manipulated in real-time and used collaboratively to explore and analyze design options and simulations of the construction process [6]. Users can navigate freely in real time and interact with virtual objects in a 3D 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 [7]. The use of VR in design applications – VR prototyping – require that the 3D CAD 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 VE 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 CAD models [8]. CAD and VR could be regarded as complementary technologies in design visualization. However, the 3D CAD 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 3D 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 [8].

It is only recently that VR have started to be used in construction projects and there has been little empirical investigation of VR technologies by companies in the construction sector [9]. For example, the proper use of VR models in the different phases of a construction project is still not clear [10].

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 are:

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- 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.
- 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

Applications of VR have been an area of increasing research and development activities in construction. Bouchlaghem et al. [6] studied the applications and benefits of visualization in construction projects covering collaborative working and design in the conceptual design stage, marketing process in the house building sector and modeling of design details in the construction stage. The study concluded that: visualization can improve communication and collaboration amongst 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. [10] made a study of how employees of a company of their yet-to-be-built workplace apprehended a VR model of the architectural design. The results indicated that the VR model helped the decision-making process and provided a good representation of the future workplace. Savioja et al. [11] studied the use of VR models in the construction of a new lecture hall in Helsinki. The process started from a basic VR model for presentation of 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 the communication and the project participants were enthusiastic about the possibilities of VR. Messner et al. [12] studied the value of visualizing of design and construction information in the decision process. The use of visualization tools for design tasks was found to improve collaboration and communication between involved stakeholders. Dawood et al. [13] presented a visual planning tool (VIRCON) with the objective of assisting construction planners to make accurate and informed planning decisions with particular emphasis on the allocation of work space. Especially, space planning in combination with visualization was found useful in tests evaluated by professionals. Other relevant studies are: Whyte [14] who presents a study that assesses the benefits and limitations of VR and its application at different stages of the construction process; Fernandes et al. [15] who investigate the barriers that affect the adoption of VR; or [16–18] that are focusing on developing VEs or databases. Howard and Björk address the state of building information models (BIM) and the conditions necessary for them to become more widely used in [19].

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 m^2 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. Fig. 1 shows three screenshots from the VR model, including the steel structure, foundations and piles and a proposal for office space.

4.1. The VR system

The VR demonstrations can be described as desktop immersive. A standard 2D 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

Fig. 1. Screenshots from the VR model of Centralhuset showing (from left to right) the steel structure, foundations and piles and a proposal for office space.

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. The estimated cost of the VR model in the Centralhuset project was approximately 2‰ of the total construction cost. This expenditure was financed by the research project and the main contractor, NCC Construction Sverige AB.

The VR model was used to improve communication among constructors and non-constructors on-site. The main aim was to reduce construction errors in the production phase, which, consequently, will reduce the construction costs. Special attention was given to installations provided by different kinds of subcontractors, such as ventilation, drainage and water supply, elevator shafts and temporary installations. Communication between people involved in the construction work was taken place within the virtual environment, which formed a connection between theory and practice on-site. 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. The questionnaire comprised a total of nine pages, also including a description of its aims, a statement regarding the confidentiality of the results, and space for participants to write in any additional comments they wished to make.

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. Procedure and participants

The questionnaire was administered to participants in situ at "Centralhuset" in groups of 1–20 individuals at a time. The fact that the building was half-completed made it particularly easy for participants to compare the VR model with how the building was erected, facilitating comparison of the expressions virtual reality and reality. A testing occasion began with the project leader's greeting participants and providing an introduction to the research project. The questionnaires were then handed out and the participants began by answering the questions pertaining to personal facts or characteristics. A visualization of the VR model and a short introduction to the concept of VR were then provided. The participants continued then by answering the questions, or the statements to be responded to, that remained. The project leader was present throughout so as to provide support if participants considered any of the questions or statements to be difficult to understand. Participants took approximately 20 min to complete the questionnaire; the time the VR demonstration took being included here. Most questionnaires were filled out directly at the building site, although some few were filled out later and were sent to the project leader by mail.

In all, 93 people participated in the study. The majority of the people involved in the construction of Centralhuset participated in the study. Tables 1 and 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.

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

Table 1
Participants' occupation

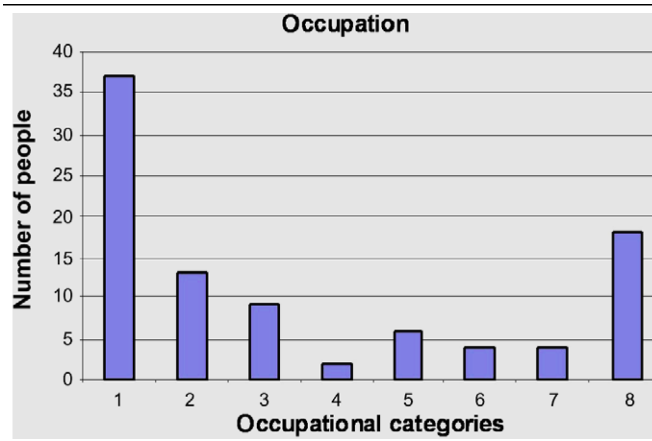
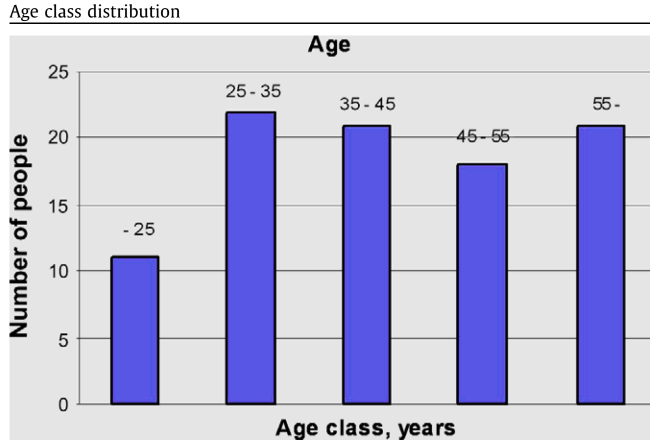


Table 2
Age class distribution



communication at the building site. The results of the questionnaire are presented as means and standard deviations in Tables 3–5. Unless otherwise stated, the response format was a five-point Likert scale ($n = 93$).

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.

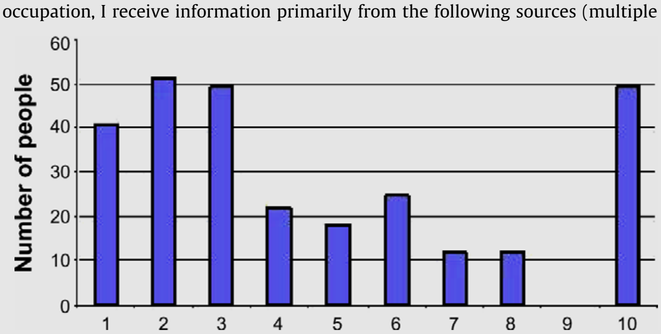
Most of the comments related to the level of detail, costs and possible benefits of VR. The greatest potential was believed to be associated with the performance of an unfamiliar task (planning site activities). The rest of the comments related to foreseen problems associated with keeping the VR model updated and the need for adaptation to the conditions on the building site. Other com-

Table 3
Investigating how participants experience using a VR model

Virtual reality (VR)	Mean value (SD)
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 group is facilitated by using a VR model	4.20 (0.72)
3c. Details in area outside my professional areas of expertise are easier for me to understand with the aid of a VR model	4.30 (0.73)

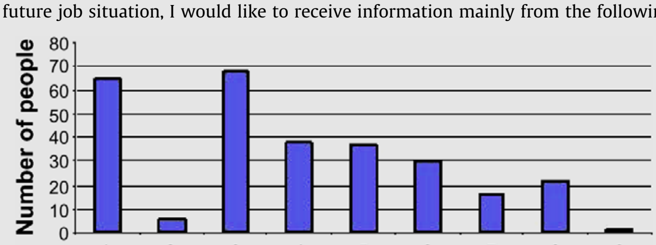
Table 4
The participants' present and desired future access to information

Information processing	Mean value (SD)
4. *Personal situation*	
4a. I already receive enough information in my job without the help of VR models	3.55 (0.77)
4b. I am satisfied with the way information is disturbed 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

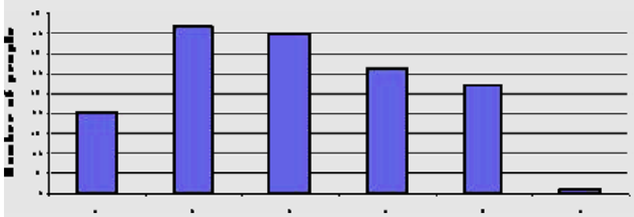
4d. In my future job situation, I would like to receive information mainly from the following sources (multiple alternatives can be selected):



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 the use of the VR model at work

Final section[a]	Mean value(SD)
5. *Using VR models in one's own work*	
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



[a] Two additional questions for the representatives of the building owner are presented at the end of Section 5. All the participants apart from the representatives of the building owner answered the first statement in the "Final section".

ments 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.

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. Fig. 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.

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:

1. The design of the manufacturing process.
2. Process layout – maintenance, logistics, working environment.
3. 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

Fig. 2. Screenshots from the VR models of the MK3 project showing (from left to right) an overview of the plant, a typical collision detected between different teams design (cable ladder and pipes) and a part of the machinery section.

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. An especially practical functionality of the VR software was that the user can mark locations in the VR model and write notes. These notes were connected to the marked location and logged in a separate text file. The description and its connection to the location were then retrieved by clicking on the note symbol in the VR model.

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 a field study 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 2 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 pre-assembled 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. Discussion

This study investigated the use of VR models in two real-life construction projects. The use contexts of the models were the construction stage (case study 1) to support site operations and the design stage (case study 2) to support design and planning. Below we discuss the results in each case study with regards to usefulness and acceptance of the VR models and trustworthiness and limitations of research results. In the section thereafter, conclusions are drawn.

The choice of construction projects was based on three fundamental prerequisites: VR was extensively used in the construction processes; the authors had access to these processes; and the study found strong support as well as attracted attention from stakeholders, thus ensured participation, in both projects. Research methods (quantitative and qualitative approaches) were chosen so that the results from each case would provide a supplementary angle to the research objective as well as confirmation of results. And it turned out that, when interpreting the results, we could provide some general conclusions (confirmation) of some findings. For example, that VR indeed improved the information flow and that it was a high acceptance of using VR models in an everyday work situation.

6.1. The Centralhuset case study

The aim of the questionnaire study was to investigate the way the workforce 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 would have more use for the model than other groups. We therefore 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.

The choice of a questionnaire as opposed to interviewing was based primarily on the suitability of the former for reaching a large number of respondents who could give a particular set of questions in a standardized way with as limited an expenditure of time and effort as possible. Also, the questions with which we were concerned, those of the general attitudes of these persons towards use of the VR model and of the flow of information between persons under such conditions were such that answers could be obtained without our going into depth, as in an interview. One should note, however, that use of a questionnaire rather than conducting interviews provides less emphatic answers and limits opportunities to prevent people from avoiding questions. Also, respondents cannot ask for an elucidation of individual questions and are not under any pressure to give well thoughtout answers to complex or difficult questions.

Leading questions or statements should be avoided in a questionnaire as they could reflect the position of the researcher and jeopardize the strive for objectivity. When writing the questionnaire the authors tried to keep this in mind and not phrase the questions in such a way that forces or implies a certain type of answers. Positive phraseology was used and the authors did not receive any indications from the discussions prior and subsequent to the testing occasion or from the additional comments in the questionnaire documents that the respondents experienced the questionnaire to be leading.

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.

6.3. Trustworthiness and limitations of results

The choice of research methods and the way they are implemented affect the reliability and validity of findings. McMillan and Schumacher [20] argue that a combination of strategies should be used to enhance the reliability and validity of the research results. 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 according to [21,22]. Within the scope of this study, the terms reliability and validity are conceptualized as trustworthiness.

The reliability and validity of the quantitative research results presented in case 1, the questionnaire study, were enhanced by using well-established and reliable test methods, execution and sampling methods and measuring and demonstrating mean values and standard deviations with a reliable and valid method. Relatively low standard deviation values were obtained which indicates a fairly high degree of reliability. The reliability and validity of the qualitative research results in case 2 were enhanced by involving other researchers and the interview respondents to discuss and criticize the findings, as well as comparing the results with similar projects. Methodological triangulation confirmed general conclusions.

Focusing on two construction projects made it possible to go into depth when investigating the use of VR models in large construction projects, but it also limited the research. The conclusions presented in this paper should be viewed as preliminary and interpreted in relation to this limited scope. Literature studies and comparisons with similar studies have, however, confirmed that the results are confirmed in similar types of construction project.

7. Conclusions

The results of case 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 case 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.

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