The use of Virtual Reality in a large scale industry project

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ABSTRACT: LKAB, a large mining company in Sweden, has decided to invest in a new pelletizing plant in Malmberget, Sweden (MK3). 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 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 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 review process.

1 INTRODUCTION

1.1 A document based information process

Communicating, coordinating and maintaining up-to-date construction information is very difficult to achieve since the information process in typical construction projects is based on documents. Even if the introduction of computers in the construction industry has radically changed the design and planning work the full potential on project level is yet to be reached. 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). Changing the industry does not necessarily rely on the introduction of new advanced information technology (IT), however, many of these systems 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. But to be able to act as a facilitator the IT systems have to be adapted to the business processes (Björnsson, 2003).

The business processes the construction industry is using today are developed to produce documents and 2D drawings, these procedures also have to change when implementing model-based design methods.

Several European Information Society Technology (IST) projects have taken the challenge to introduce new IT tools and model based 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. 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 Information and Communication Technologies (ICTs)
- Improvement of reliability and security of data and information exchange, as well as their underlying ICT systems.

However, we need to find enough incentives in order to justify the introduction of new 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 inadequate interoperability in the U.S. Capital Facilities run up to $15.8 billions 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 might not be a technical-related problem at first hand but rather a consequence of the reluctance to share information and knowledge between the stakeholders in a construction project. Basically the lack of trust, but also, the lack of adequate tools for communication is the two most important factors for information losses in traditional construction projects (Blokpoel, 2003 and Blokpoel et al., 2004). 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).

1.2 *Virtual reality for review and coordination*

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 Virtual Reality (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 (Wokseep et al, 2004). Even though VR today primarily is used for visualizing the final product (Woksepp, 2001) there is also a great potential to use it as a universal interface to all design applications (Aouad, et al., 1997; Issa, 1999). 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 (Issa, 1999). Actually, some of the major business drivers for VR identified by lead users are just coordinating design and design reviews (Whyte, 2002), which also leads us to the possibilities to facilitate effective processing of client requirements.

1.3 *Aim and scope of the case study*

Given the fact that VR still constitutes an unexploited resource within 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 a practical approach to facilitate decision-making, and coordinate and communicate client requirements in the design review process via a number of collaborative VR prototypes of the construction and its installations.

The impact will only be measured qualitatively since it is difficult to estimate the impact on economy and time in a project as MK3. We will instead estimate the effect by evaluating how the client and the other stakeholders have been using VR as an alternative form of communication and also provide the readers with some good examples.

2 THE MK3 PROJECT

2.1 *Background*

The Swedish state owned mining company LKAB has recently initiated the design and planning process of a new pelletizing plant (MK3) in Malmberget, northern Sweden. The plant is planned to be operational by October 2006 and involves an investment of €280 million. It will be complementary to an existing pelletizing plant for the purpose of increasing the production capacity. The Center 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 three key goals in the MK3 project are to obtain a plant with required *Capacity* in *Time* within the *Investment frame.*

2.2 *Project characteristic*

Discussions 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.

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 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.

Normally, the spatial needs govern the preliminary plan in a construction project. However, the design 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, etcetera occurs simultaneously in a concurrent design approach.

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.

2.3 *Contractual form*

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 is used to form an open collaborative environment. The involved partners can make a lot of deals in order to improve the working climate and trust in order to find prerequisites for a closer cooperation. This facilitates problem solving and shift focus from the individual goals for the involved partners to the overall project goals. Partnering often involves cost reimbursable forms (transparent) 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. 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.

3 THE DESIGN PROCESS

3.1 *Modeling tools and work process*

The VR system used in the MK3 project is a low-cost approach that consists of commercial software, PC computers, servers and projectors. The VR software being used is Walkinside™ that is compatible with the most of the major CAD formats. An independent VR consultant is especially appointed to work full-time managing the VR model and the information that is passing through.

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 fulfill the client's design intents of the pelletizing plant. The cabling are modeled in 2D and later remodeled into 3D CAD path for the electrical installations.

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 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 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) and Intergraph's PDM 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 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 big change has been made. To smooth the progress of integration, all 3D CAD models are modeled using the same coordinate system. The total amount of information describing the VR prototypes of the palletizing 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 not 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 and transfer them 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). Screenshots 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 (via XYZ coordinates or marked on a general map, updated in real-time), turning objects on/off via layers, gravity, impenetrable objects, avatars, etcetera, see Figure 1. 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.

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

3.2 A concurrent 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 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 is 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, 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 immediately 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.

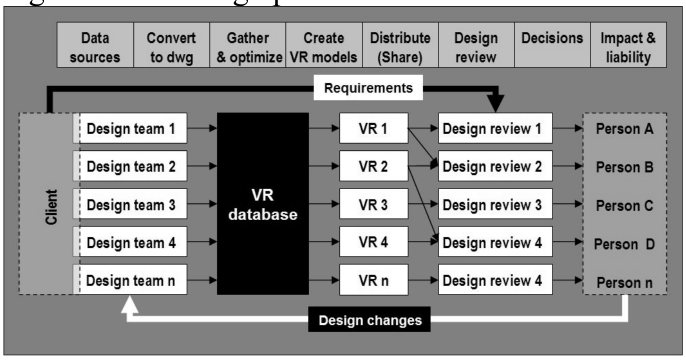

Figure 2. An iterative design review process with specified VR models in a concurrent and multi-disciplinary design situation.

'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 to the VR software and the computing power to visualize the growing VR prototypes been limited. 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 these informal meetings between the different design teams and sharing of information.

4 DECISION-MAKING

4.1 Introduction

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 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) 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 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 saving a lot of 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.

4.2 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.

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.

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 have 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 and 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 for the client to concentrate on the actual decision.

4.3 Adding value and minimize waste

Several papers and reports have pointed out the role of IT 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 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, see Figure 3.

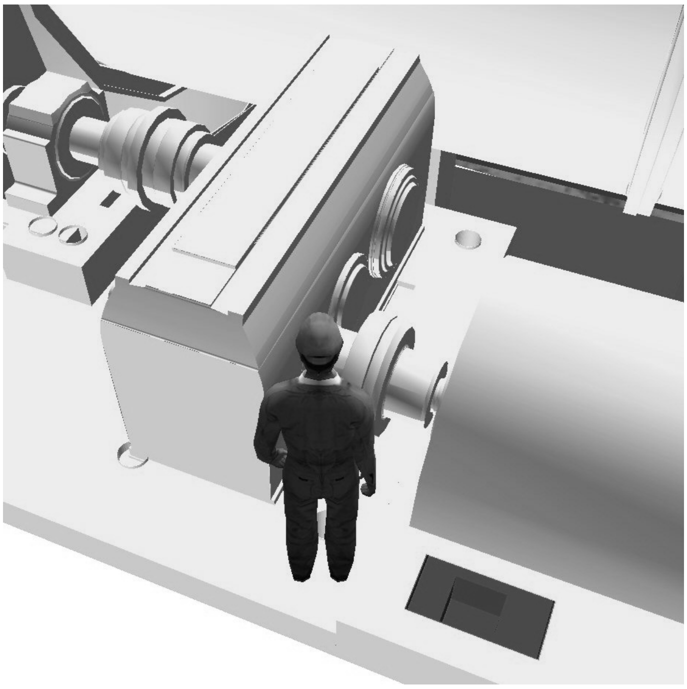

Figure 3. A screenshot showing the use of avatars for investigating the maintainability of the process machinery in the dressing plant.

Many 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. This last example is also shows how natural/visual interfaces to large data sets can inspire to interaction with the VR system that mimics the strategy that would be taken in the real world, see figure 4.

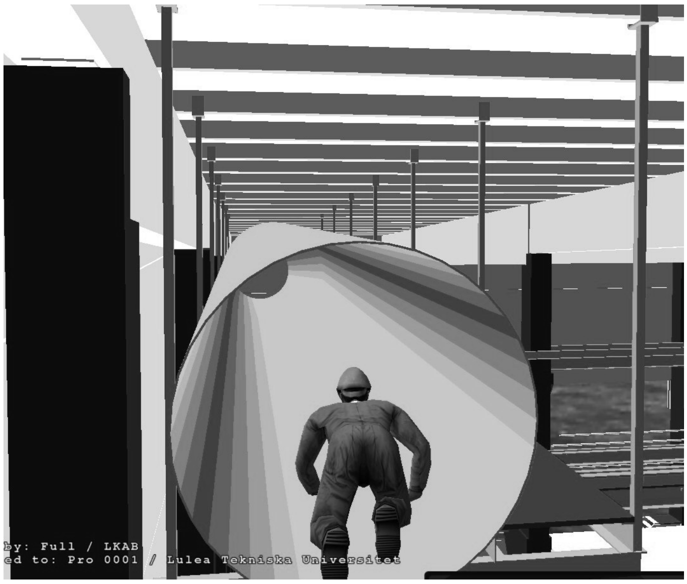

Figure 4. Screenshots extracted from a VR prototype describing how visual clash detections and spatial analyse of the installations with the help of an avatar was carried out.

5 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 especially in capturing the client's needs and requirements. 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.

The technical interoperability between the different design teams has not been an obstacle despite the variety CAD system used in the project. The rather primitive 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. Most of these exchange errors could easily be detected, see Figure 5.

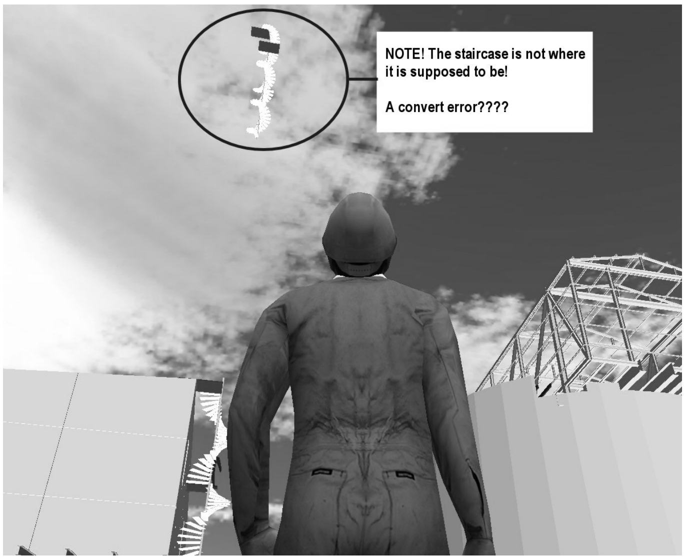

Figure 5. An example of exchange error that occurred between the CAD and the VR software used in the project.

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.

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.

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 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.

REFERENCES

Aouad, G., Child, T., Marir, F. and Brandon, P. (1997). "Developing a Virtual Reality Interface for an Integrated Project Database Environment." *Proceedings of the IEEE International Conference on Information Visualization (IV'97)*, London, UK.

Ballard, G. (2000). Positive vs negative iteration in design", *Proceedings of the International Group for Lean Construction 8th Annual Conference, (IGLC-8)*, Brighton, U.K.

Björnsson, H. (2003). *Byggandets informationsteknologi*, Örjan Wikforss (editor), AB Svensk Byggtjänst, Stockholm, Sweden (in Swedish).

Blokpoel, S. (2003). *Cooperation and Product Modelling Systems - The Application of Product Modelling Systems in the Building Process*, Research report 2003:17, Luleå University of Technology, Luleå, Sweden.

Blokpoel S., Jongeling R., Olofsson T. (2004). Cooperation and product modelling systems. *Proceedings of European Conference on Product and Process Modelling in Construction (ECPPM 2004)*, Istanbul Turkey, 8-10 September 2004.

Christiansson, P. (2001). Capture of user requirements and structuring of collaborative VR environments. *Proceedings of the AVR II & CONVR 2001 Conference on Applied Virtual Reality in Engineering & Construction*, Chalmers University of Technology, Gothenburg, Sweden, 4-5 October.

CIT (1996). *Benchmarking Best Practice Report: Briefing and Design*. Construct IT Centre of Excellence, UK.

Egan, J. (1998). *Rethinking Construction: The report of the Construction Task Force to the Deputy Prime Minister, John Prescott, on the scope for improving the quality and efficiency of UK construction*, London, Department of the Environment, Transport and the Regions, UK.

ESPRIT and CICC (1999). *The CICC final report*. (http://www.vers.co.uk/cicc.htm)

Howard, R. A. and Matheson, J.E. (editors) (1984). *Readings on the Principles and Applications of Decision Analysis*, 2 Volumes, Menlo Park CA: Strategic Decision Group.

Howell, G.A. (1999). What is Lean Construction?, *Proceedings of the International Group of Lean Construction 7th Annual Conference*, Berkeley, USA.

ICCI (2004). *ICCI Final Report*, The ICCI Consortium, edited by Alain Zarli (CSTB). (http://icci.vtt.fi)

Issa, R. (1999). *Virtual Reality in Construction – state of the art report*, TG24 Final report, UK.

Issa, R. (1999). Virtual Reality: A solution to seamless technology integration in the AEC industry?, *Proceedings of the Berkley-Stanford CE&M Workshop: Defining a Research Agenda for AEC Process/Product Development in 2000 and Beyond*, Stanford University, USA.

Kam, C. and Fischer, M. (2004). Capitalizing on early project decision-making opportunities to improve facility design, construction, and life-cycle performance – POP, PM4D, and decision dashboard approaches. *International Journal of Automation in Construction*, Vol. 13, pp 53-65.

Kamara, J.M., Anumba, C.J. and Evbuomwan, N.F.O. (1996). *A review of existing mechanism for processing client requirements in the construction industry*. Technical Report

No. 96/11, School of Science and Technology, University of Teesside, UK.

Kamara, J.M., Anumba, C.J. and Hobbs, B. (1999). From briefing to client requirements processing, *Proceedings of the 15th Annual Conference of the Association of Researchers in Construction Management*, UK,

Koskela, L., Ballard, G., et al. (2003). Achieving change in construction, *Proceedings of the International Group of Lean Construction 11th Annual Conference*, Virginia Tech, USA.

Kähkönen, K. (2003). Editorial: Virtual Reality Technology in Architecture and Construction. *Electronic Journal of Information Technology in Construction (ITcon)*, Vol. 8, pp 101-103.

Liston, K., Fischer, M. and Winograd, T. (2001). Focused sharing of information for multi-disciplinary decision making by project teams. *Electronic Journal of Information Technology in Construction (ITcon),* Vol. 6, pp 69-81.

Miron, L.I.G. and Formoso, C.T. (2003). Client Requirement Management in Building Projects. *Proceedings of the International Group of Lean Construction 11th Annual Conference*, Virginia Tech, USA.

NIST GCR 04-8687 (2004). *Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry*. U.S. Department of Commerce Technology Administration, National Institute of Standards and Technology, USA.

Staub, S., Fischer, M. and Spradlin, M. (1999). Into the Fourth Dimension. *International Journal of Civil Engineering, ASCE*, 69(5), pp 44-47.

Whyte, J. (2002). Industrial Applications of Virtual Reality in Architecture and Construction. *Electronic Journal of Information Technology in Construction (ITcon)*, Vol. 8, pp 43-50.

Woksepp, S. (2001). Centralhuset – A Virtual Reality project at the building site. *Proceedings of the AVR II & CONVR 2001 conference on Applied Virtual Reality in Engineering & Construction*, Chalmers University of Technology, Gothenburg, Sweden.

Woksepp Stefan, Tullberg O., Olofsson, T., (2004), Virtual reality at the building site: investigation how the VR model is experienced and its practical applicability. *Proceedings of European Conference on Product and Process Modelling in Construction (ECPPM 2004)*, Istanbul Turkey, 8-10 September 2004.

Worthington, J. (1994). "Effective project management results from establishing the optimum brief." Property Review, November, pp 182-5.