Virtual Models Linked with Physical Components in Construction

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Preface

The present thesis is the written outcome of an Industrial PhD project completed from September 2006 to August 2009 at Ramboll Denmark Aalborg University. The thesis is submitted to the Department of Civil Engineering, Aalborg University, Denmark, in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

The focal points of this thesis are information and communication technology (ICT) in construction including new applications of virtual modelling, automatic object identification by means of radio frequency identification (RFID), mobile technology, ontology development, ubiquitous computing, project progress management, quality management, facility management, future user needs analysis and Contextual Design of ICT systems.

The research project is funded by Ramboll Denmark and the Danish Ministry of Science, Technology and Innovation to whom I am grateful.

I would like to thank my supervisors Professor Per Christiansson and Associate Professor Kjeld Svidt at Aalborg University, and Head of IT Kim Jacobsen and Head of Department Thomas Simoni at Ramboll Denmark for their guidance and cooperation throughout the study. I have been fortunate to be able to combine the worlds of academia and business for the last three years, and I would like to thank all of my supervisors for their great enthusiasm and many fruitful hours of inspiring discussions.

I would also like to acknowledge the companies MT Højgaard, Spæncom, M_Solution, and DIO Systems for their participation and involvement in the practical experiments.

As part of the project, I spent a three months period at the Center for Integrated Facility Engineering (CIFE) at Stanford University under the supervision of Professor Martin Fischer. I would like to express my gratitude to Professor Fischer, the researchers and students at CIFE for the very inspiring stay.

Finally, but definitely not least, I would like to thank my family, friends, and colleagues for their support and patience. Most of all, I want to thank Lisbeth, my wonderful fiancée, for her endurance, support and love.

Aalborg, August 2009

Kristian Birch Sørensen

Abstract

The use of virtual models supports a fundamental change in the working practice of the construction industry. It changes the primary information carrier (drawings) from simple manually created depictions of the building under construction to visually realistic digital representations that also reflect the behaviour and properties of the building and its surroundings. Today it is practicable and sensible to create complete virtual models of buildings or infrastructures before they are created in real life. Leading architects, engineers and contractors already benefit from it today and create virtual models that thoroughly mirror the performance of the final facility and its construction process.

However, the potential of the virtual models in construction has not yet been fully utilised. One way to take more advantage of the virtual models is by digitally linking them with the physical components in the construction process and thereby improving the information handling. The present PhD project has examined the potential of establishing such a digital link between virtual models and physical components in construction. This is done by integrating knowledge of civil engineering, software engineering and business development in an iterative and user needs centred system development process.

The analysis of future business perspectives presents an extensive number of new working processes that can assist in solving major challenges in the construction industry. Three of the most promising of these business perspectives were selected for further investigation through system analysis, development and evaluation. They include combining virtual models with automatic object identification by means of radio frequency identification (RFID) in 1) quality management of buildings under construction, in 2) project progress management, and 3) in operation and maintenance.

Experiments and implementations in real life projects showed that mobile technology and passive RFID technology delineate an efficient and practically implementable ways to establish the digital links in construction and are ready for use. Among other things it is demonstrated how the digital link can be used with advantage for documentation of the quality of accomplished work, real-time update of production status in the virtual models, and on-site inspection work in facility management.

The prototype developments and implementations also showed that a lot of development work is still required before the full potential can be realised in form of improved quality, cost and reliability of the construction projects where the technology is adapted. The major barriers identified were related to the working culture, changing industry practices and development of new ontologies. Based on the experiences gained in this PhD project, some of the important future challenges are also to show the benefits of using modern information and communication technology to practitioners in the construction industry and to communicate this knowledge among all the stakeholders. Therefore, future implementations must be driven through strong leadership and a solid methodical approach to change the current practice.

Sammenfatning (Danish Abstract)

Anvendelsen af virtuelle modeller understøtter en fundamental ændring af gængs praksis i byggeriet. Det ændrer den primære informationsbærer (tegninger) fra at være simple manuelt udarbejdede afbildninger til at være visuelt realistiske digitale repræsentationer, som afspejler bygningen og dens omgivelsers opførsel og egenskaber. Det er i dag muligt og fornuftigt i praksis at udarbejde komplette virtuelle modeller af bygninger eller anlæg inden de udføres i virkeligheden. Førende arkitekter, ingeniører og entreprenører drager allerede nytte af det i dag, og skaber virtuelle modeller som detaljeret beskriver performance af den færdige bygning og dens opførelsesproces.

Det fulde potentiale af de virtuelle modeller er imidlertid endnu ikke udnyttet. En måde at få flere fordele ved anvendelse af modellerne er ved digitalt at linke dem med de fysiske komponenter, der indgår i byggeprocessen og derved forbedre informationshåndteringen. Mulighederne for at etablere et sådant digitalt link mellem de virtuelle modeller og de fysiske komponenter i byggeriet er undersøgt i dette Ph.d.-projekt. Det er gjort ved at integrere viden om bygningsteknik, softwareudvikling og forretningsudvikling i en iterativ og brugerorienteret systemudviklingsproces.

I denne afhandling beskrives i analysen af fremtidige forretningsmuligheder en række nye arbejdsprocesser, der kan være medvirkende til at løse nogle af de største udfordringer inden for byggebranchen. Tre af de mest lovende af disse forretningsmuligheder blev udvalgt til den videre systemanalyse, -udvikling og -evaluering. Dette omfatter kombinationen af virtuelle modeller med automatisk objektidentifikation ved hjælp af radio frequency identification (RFID) i 1) kvalitetssikring af bygninger under opførelse, i 2) styring af projekters fremdrift samt i 3) drift og vedligeholdelse.

Eksperimenter og implementering i aktuelle projekter viste, at mobilteknologi og passiv RFID teknologi er klar til anvendelse og en egnet samt praktisk implementerbar måde at etablere digitale links på i byggeriet. Blandt andet demonstreres det i denne afhandling hvordan det digitale link kan udnyttes i forbindelse med dokumentationen af kvaliteten af det udførte arbejde, realtidsopdatering af produktionsstatus i de virtuelle modeller og inspektion af bygningers vedligeholdelsestilstand.

Prototypeudviklingen og implementeringerne viste også, at en del mere udviklingsarbejde kræves før potentialet kan realiseres i form af forbedret kvalitet, omkostninger og pålidelighed af byggeprojekter, hvor teknologien indføres. De største barrierer blev identificeret i relation til arbejdskulturer, ændring af gængs byggebranchepraksis og udvikling af nye ontologier. Baseret på erfaringer opnået gennem dette Ph.d.-projekt vil vigtige fremtidige udfordringer også være at synliggøre fordelene ved at anvende moderne informations- og kommunikationsteknologi i byggebranchen og kommunikere dette til alle interessenter. Som det argumenteres i afhandlingen er det nødvendigt at fremtidige praktiske implementeringer drives af stærkt lederskab og en sund metodisk tilgang til at forandre gængs praksis.

List of Scientific Publications

Paper I: Ontologies to Support RFID Based Link between Virtual Models and Construction Components, accepted for publication in *Journal of Computer-Aided Civil and Infrastructure Engineering*, March 2009

Paper II: Prototype Development of an ICT system to Support Construction Management Based on Virtual Models and RFID, Published in *Journal of Information Technology in Construction*, Vol. 14, Special Issue Next Generation Construction IT: Technology Foresight, Future Studies, Roadmapping, and Scenario Planning, pp. 263-288, http://www.itcon.org/2009/19

Paper III: Radio Frequency Identification in Construction Operation and Maintenance – Contextual Analysis of User Needs, published in *Proceedings of the 12th International Conference on Computing in Civil and Building Engineering & 2008 International Conference of IT in Construction*, Beijing

Paper IV: ERP Application of Real-Time VDC-Enabled Last Planner System for Plan Reliability Improvement, published in *Proceedings of 2009 ASCE IT Workshop*, Texas.

Paper V: A Method for Updating Production Status in Computer Based Four Dimensional Models, Patent application No PA 2009 00801 submitted to *Danish Patent and Trade Office*, July 2009

Paper VI: Evaluation and Guidelines for Implementation of ICT Systems to Support RFID in Construction, submitted to the *Journal of Information Technology in Construction*, August 2009

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Part 1

Introduction, Summaries, and Conclusions

1 Introduction

People are migrating globally from rural areas to urban areas in their pursuit of a different life and better opportunities. In 2008 a landmark was reached as the urban population matched the size of the rural population for the first time in history and it is expected to nearly double by 2050 (UN, 2008). This urbanization is putting stress on the infrastructure of already large urban cities and particularly on the way they are designed and constructed. Well designed and properly operated buildings and infrastructures are essential for the survival and well-being of people living and working in urban areas.

Despite the growing size and complexity of building and infrastructure projects the most common information handling method among stakeholders in the construction industry is more than 4000 years old – drafting of design solutions. In fact the oldest known architectural plan of a temple in Babylon dates from around 2130 BC and is inscribed in stone. Drafting was further developed by the Romans to include plans as well as sections of buildings. Additionally Leonardo da Vinci's 15th century architectural and engineering drawings predate the sketches and design communication seen from the 18th century to present day by hundreds of years (Garner, 2004).

The consequences of this old-fashioned communication and information handling methodology are devastating. The construction industry is responsible for creating the world's stationary assets but has major challenges in improving: cost of defects (Josephson and Hammarlund, 1999), predictability of construction project estimates (Flyvbjerg, 2007), data reuse and information exchange (interoperability) (Gallaher et al., 2004), 40 years of stagnation in productivity (Teicholz, 2004; Danish Government, 2003) and waste of energy and nature resources (Sustainable Build, 2009).

The reasons or excuses for the lack of revival in construction are many, and the industry has several practices that limit the ability of organisations, teams and individuals to innovate and thereby change practice. One of the reasons is that the ever-changing multidisciplinary project basis of the industry contributes to slow innovation diffusion, rather than systematic learning and innovation (Taylor and Levitt, 2004). Another reason is that sub-optimization is dominant in the construction industry and as argued by Kunz and Fischer (2009): *"Architects, engineers and contractors all have a culture and methods that minimize cost. With notable exceptions, many lack a culture that seeks to maximize value. This culture follows owner preference, but it also represents a culture that some AEC players accept in order to minimize their short-term project risks."* No single solution exists to the challenges in the construction industry, but in recent years the multifaceted implementation of virtual design and construction have proven to significantly improve reliability, latency, communication, and information handling in building projects and thereby to reduce costs or increase the quality of the buildings (Kunz & Gilligan, 2007; Eastman et al., 2008).

The use of virtual models supports a fundamental change in the working practice of the construction industry. The primary information carrier is changing from simple manually created depictions of the building under construction to visually realistic digital representations which also reflect the behaviour and properties of the building and its surroundings. It is now practicable and sensible to create complete virtual models of buildings or infrastructures before they are created in real life. Even in the construction industry with individual order production, virtual models are created which detailed mirror the performance of the final facility and its construction as illustrated in Figure 1.

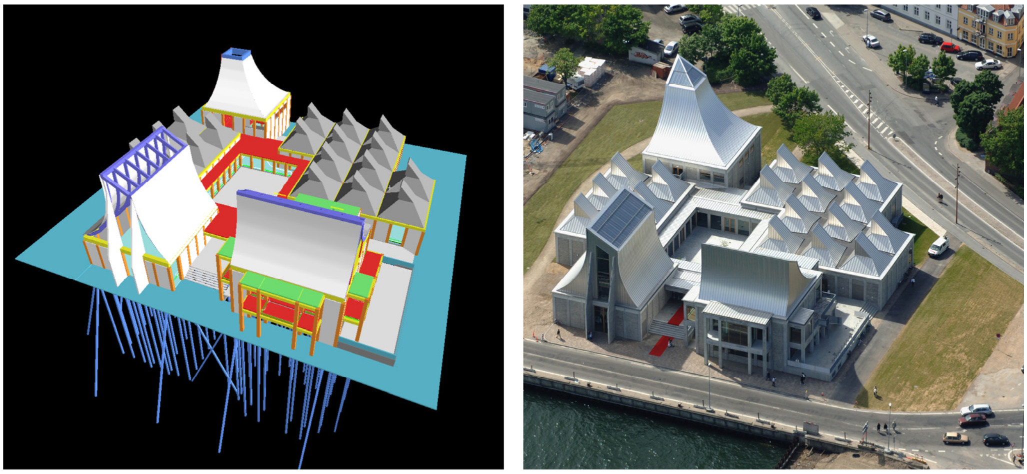

Figure 1 Virtual model and physical building of the Utzon Center at the Aalborg Harbour Front.

The potential of the virtual models in construction has not yet been fully utilised. The virtual models with their supporting structured data representation and today's ubiquitous availability of information and communication technology (ICT) provide basis for new applications and services. It is expected that such new virtual model based ICT applications and services can support the construction industry in solving the challenges earlier mentioned.

One way to take more advantage of the virtual models is by digitally linking them with the physical components in the construction process and thereby improving the information handling. The aim of this PhD project is to investigate what a digital link between the virtual models and the physical construction components is useful for and to investigate how it can be established technically as well as practically. The project is motivated by a desire to improve the working practice and information handling further in the construction process. The research questions answered in this thesis are:

- What are the user needs and business perspectives in relation to virtual models linked with physical components in construction?
- Can new ICT systems support the user needs?
- Can ontologies support the ICT system development?
- How can such new ICT systems be implemented in the construction industry?

1.1 Virtual Model and Context Definition

Virtual models and virtual modelling in construction are not new inventions. Hence the terms have been used in many contexts and also under different names since the mid 1970s. Today, in construction practice and in research, terms like object-oriented model, virtual design and construction (VDC) model, information model, 3D model, building information modelling (BIM) model and virtual building model are often used interchangeably. According to Merriam-Webster's dictionary the term "virtual" means *"being on or simulated on a computer"*. Therefore the term "virtual model" is used in this thesis to describe a digital object-oriented product and/or process model of a physical object (e.g. a person, a building part, a work description, a room, a house, a city or a planet, etc.). The term "virtual model" is used rather than e.g. "BIM model" or "virtual building model" to reflect that the subjects discussed are not only applicable to buildings, but also generally applicable in the construction industry. The virtual model often, but not necessarily, contains a geometrical 3D representation of the modelled objects. When the terms "virtual 3D model" or "virtual building model" are used, it is done in order to emphasize the 3D or building aspects of the context.

The virtual model objects can be enriched with data or linked to data in other systems such as activities from schedules, unit prices from enterprise resource planning (ERP) systems, and static models in finite element software. When the virtual model is used for planning and monitoring the progress of the project, the virtual model often is called a four dimensional (4D) model (3D+time).

In advertising campaigns for new virtual modelling applications, there is an ongoing competition for reaching even higher dimensions of the virtual models. 5D is often used for cost estimation, 6D for energy simulation, 7D for sustainability simulation, and even nD for multipurpose simulations. However, from a scientific point of view the terms from 5D and up are not appropriate because cost, energy, and sustainability are not orthogonal dimensions to each other or to the first four dimensions of the virtual models. The objects of the virtual 3D model are rather enriched with new attributes and used for various performance simulations.

Figure 2 illustrates how the building process is supported by a heterogeneous set of technical services in the form of ICT hardware and software systems. It is also illustrated how the underlying virtual model resources are interrelated and can be linked. An important prerequisite for the new services and applications under development is their ability to work in this context and take advantage of or improve the technical services already in use. A virtual model of e.g. a building can in some situations be represented in a single non-redundant parametric model, but as illustrated in Figure 2 it will often be represented in multiple related data models (databases, photos, hypertext, documents etc.).

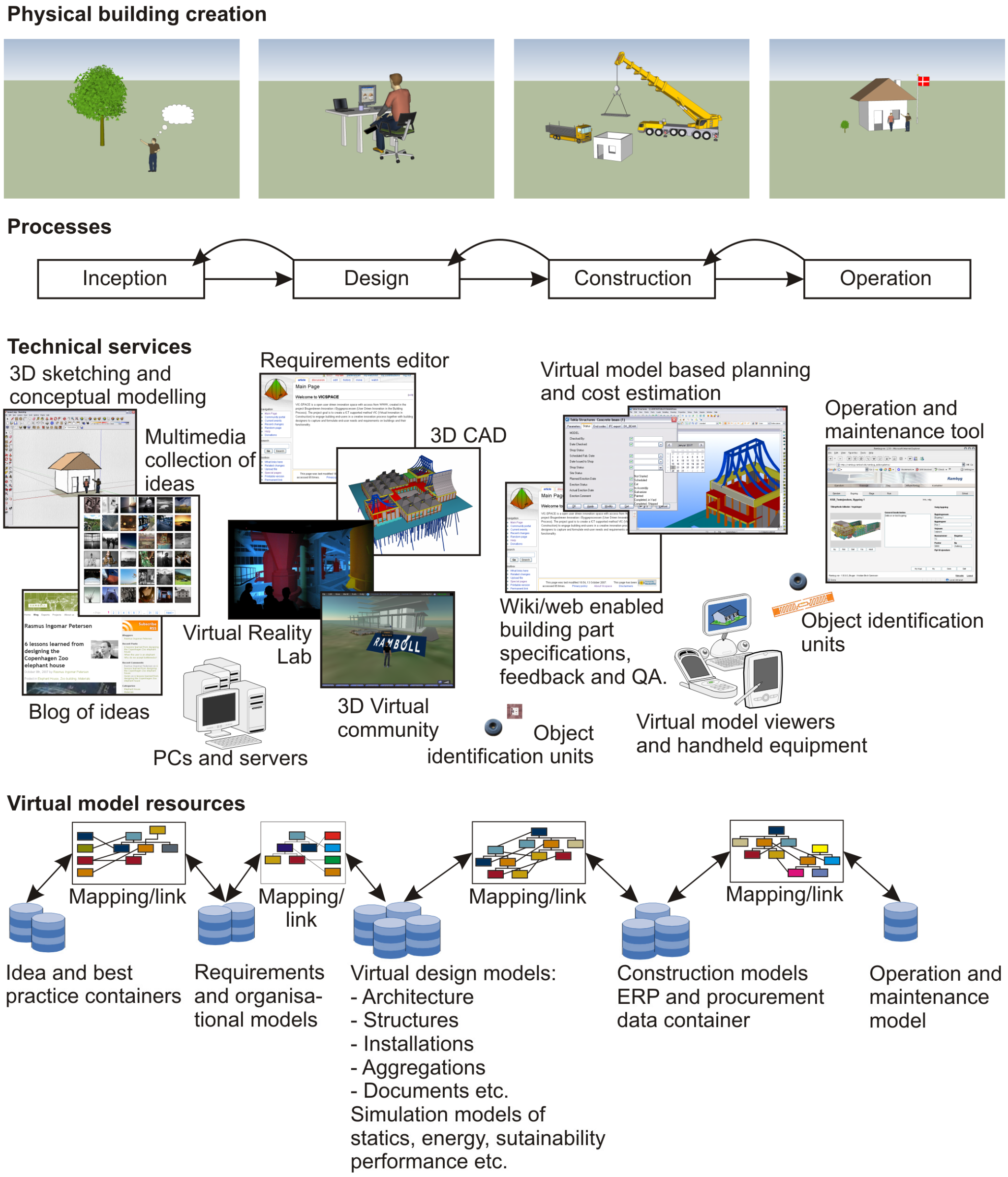

Figure 2 The virtual model context. Illustration of how the building process is supported by a heterogeneous set of technical services in the form of ICT hardware and software systems.

1.2 Research Methodology

This research project is an Industrial PhD in the tension field between research and business. It is a Mode 2 knowledge production and as argued by Gibbons et al. (1994) "*… characterised by a constant flow back and forth between the fundamental and the applied, between the theoretical and the practical*".

The methodologies used in the project reflect the multi-disciplinary research domain at the intersection of civil engineering, software engineering and business development.

Several methodologies are used in the project and described in the papers throughout the thesis. Among them, the Contextual Design methodology (Beyer and Holtzblatt, 2000) is used as an overall guidance for the project. It is an efficient methodology to handle the collection and understanding of data from field studies to design of ICT based prototypes and products. It involves observing users in their working environment, conceptual modelling of their behaviour and evaluation through practical experiments at construction sites. In Figure 3 photos taken during observations, sketches of an early conceptual user environment and an interactive prototype developed in the project are illustrated.

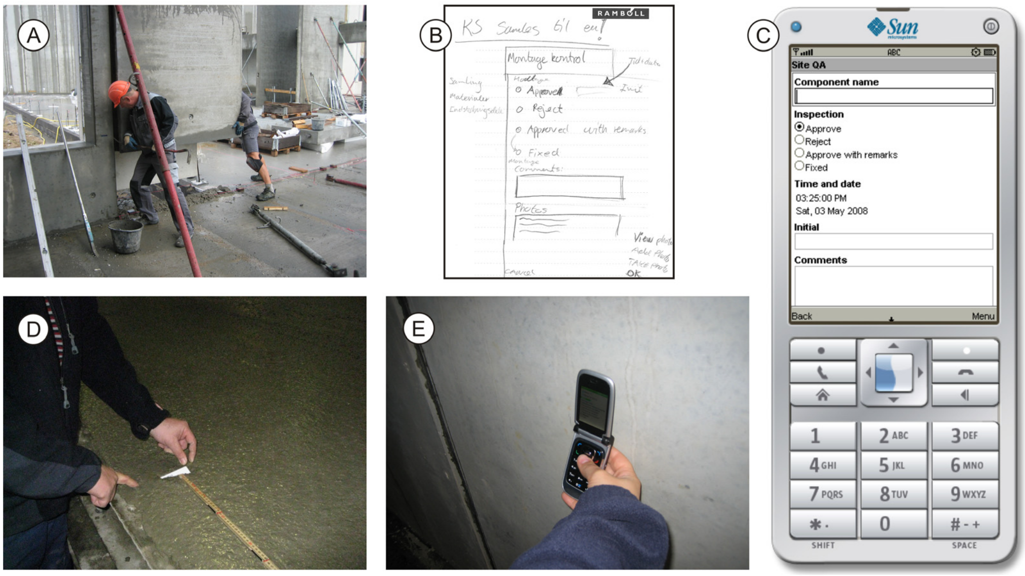

Figure 3 Photos, sketches and prototype captured and developed during the project. A: Photo taken during observation of precast concrete element mounting. B: Early conceptual sketch of a quality management system. C: Interactive prototype of a mobile phone application for quality management. D: Photo of experiments with embedment of RFID tags in precast concrete. E: Photo of experiments with reading RFID tags embedded in precast concrete elements.

The Contextual Design methodology is described further in relation to the prototype development described in Paper II. The methodology is, among others, supplemented with literature reviews to understand the research domain, portfolio management and SWOT analysis to judge and understand the business perspectives, story telling using scenarios to communicate between scientists, developers and practitioners, and rational unified process (RUP) in the software development (Jacobson et al., 2005).

1.3 Outline of the Thesis

This thesis is subdivided into three parts.

Part 1: "Introduction, Summaries and Conclusions" contains a brief introduction to the research field, methodology and definition of the virtual model related terms used in the thesis. This is followed by a description of the background of the supporting technologies and point of departure of the project in relation to virtual models in construction, automatic object identification, and future business perspectives. A summary and discussion is then given of the six papers included in the thesis. Finally, conclusions and future research are presented based on the research presented in the papers.

Part 2: "Scientific papers" includes the collection of papers written by the author during the research project. Each paper, presents a self-contained part of the research addressed in the PhD project and can be read independently. The papers are published or in process of being published in peer reviewed journals and conference proceedings.

Part 3: "Appendices" supplements the introduction and scientific papers with further analysis of business perspectives, details about software specifications and ontology development and finally a list of other publications to which the author has contributed. The supplementary details of the appendices are intended the reader with particular interest in these topics. In addition Appendix A is a business report accepted in fulfilment of the industrial part of this Industrial PhD project.

Figure 4 gives an overview of this thesis and illustrates dependencies between sections, papers and appendices included.

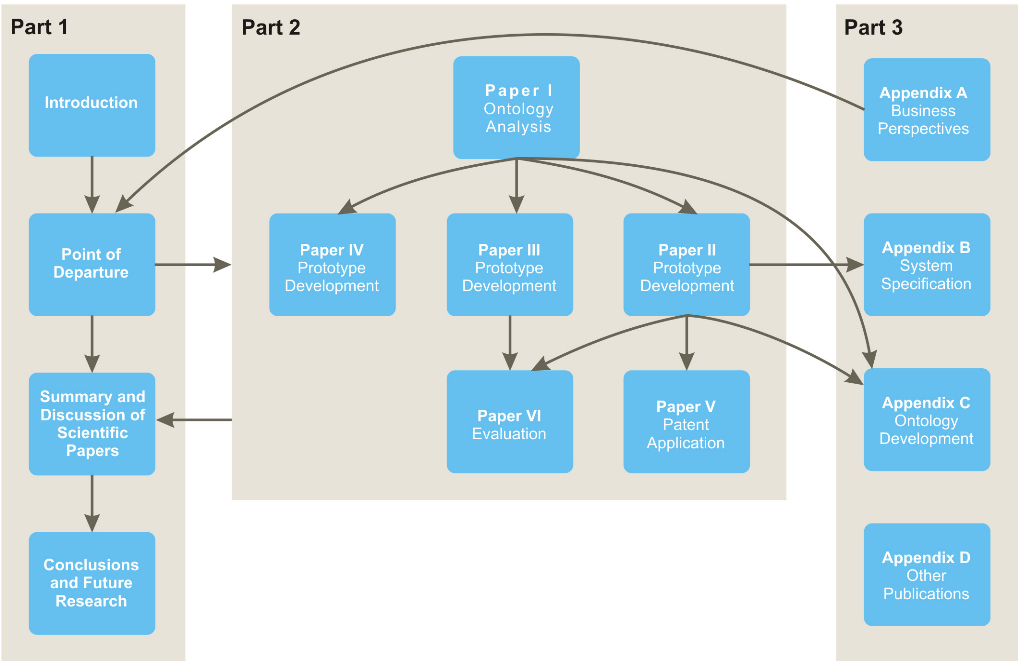

Figure 4 Overview and dependencies between sections, papers and appendices included in this thesis.

2 Point of Departure

In the following sections the point of departure of this PhD project is described by introducing the background of the supporting technologies, related research projects, and business perspectives.

2.1 Background of Supporting Technologies

The Computer Aided Design (CAD) tools used today for drafting in design and construction originate from Ivan Sutherland's research in the 1960s. In 1963 Sutherland developed the software tool Sketchpad and a light-pen – predecessor of the mouse, allowing the user to point at and interact with objects displayed on the screen (Sutherland, 2003). Drafting tools for CAD were commercialised in the early 1970s, and in the late 1970s they also supported 3D modelling with surfaces and solids (Eastman, 1999). The benefits of moving from 2D drafting to 3D modelling in industries such as manufacturing, aerospace and process plant design and construction were improved quality because all drawings extracted from the same 3D model were guarantied to be coordinated, and also improved communication through 3D visualisation. It also facilitated the integration of design and analysis applications as well as automated fabrication. However the construction industry did not pay much attention to 3D modelling before the late 1990s.

Several efforts were made from the mid 1970s to develop single virtual building model solutions. Before the wide introduction of personal computers in 1982, 3D modelling of buildings could only be done on very expensive work stations attached to mini computers with software like BDS, Intergraph, Medusa and Computervision (Christiansson & Carlsen, 2005). Principles from these early systems are reflected in the functionalities of today's authoring tools for virtual models. Object-oriented design tools usable in the construction industry were introduced in the mid 1980s, but their distribution was limited due to many restrictions in the designer's work.

In recent years, focus has increased on the use of virtual design in the construction; including Ramboll to a large degree. This is mainly because the 3D CAD tools used in the design by now have matured enough to be used in practice without introducing limitations or additional costs compared to traditional 2D drafting tools. The 3D object-oriented CAD tools were originally introduced in the design and shop drawing production for steel structures. However, today they are widely used within both architectural and engineering design.

The PDES/STEP (STandard for the Exchange of Product model or ISO 10303) standardisation process and later IFC (Industry Foundation Classes) is today's foundation of the possibilities in 3D object-oriented design collaboration and important in future information handling in the construction industry.

To encourage the use of digital working methods in the construction industry, the Danish government initiated the project "Digital Construction" (DC), in Danish called "Det Digitale Byggeri", in 2002. The project ran from 2003 to 2006, and the focal point of DC was the vision of an object-oriented working method, where all project data are associated with the virtual 3D model that gradually develop through the life cycle of the building. Similar initiatives have been launched in other Nordic countries and in the USA, where The National Institute of Building Standards (NIBS) has set up a committee to formulate the National Building Information Model Standard (NBIMS). The first version of an NBIM Standard defining a framework for the project, principles and methods was published in March 2007. Common for DC and NBIMS is that they focus on implementation and practical adaptation of digital working processes rather than development of new technologies.

The governmental projects in Denmark only represent about 2% of the annually constructed gross area, and therefore the direct measureable impacts of the requirements are rather limited. Nevertheless, the process of preparing the requirements and supporting standards for working methods has had a positive influence on the overall use of IT in the Danish architectural and engineering industry. Hence, today virtual models are widely used by leading firms in the sector.

The Internet and WWW, as we know it today, dates back to 1992 and is now facing some comprehensive paradigm shifts that will introduce new applications. First of all, the introduction of XML cleared the way for separating the storage and the presentation medium for digital information on the Internet. The following introduction of Semantic Web from 2000 with its supporting standards forms the basis of efficient future handling of information associated with meta-data and data stored in information containers distributed globally on the Internet (Berners-Lee et al., 2001).

Another paradigm shift is the introduction of IPv6. The internet protocol (IP) specifies a hierarchical addressing system that enables unique identification of all units connected to the Internet. The present version 4 of IP is from the 1970s and consists of a 32 bit address, which will not continue to be sufficient for identification of all units connected to the Internet. The forthcoming IPv6 uses 128 bit addressing which gives 4 millions unique addresses per square metre surface of the earth, which should be sufficient for supporting the growth of the Internet for at least the next 50-100 years.

These paradigm shifts form the potential for an Internet of Things. That means a network where all physical objects such as humans, clothes, machines, building components etc. have a unique identification, and information about them can be structured and used rationally by humans and machines. There will be great potential in using the next generation of the Internet in interaction with virtual models in the construction industry.

Several existing suitable technologies can be used to create a digital link between the virtual models and the physical components such as GPS, photo and video recognition, bar codes, RFID etc. These technologies are often given the generic term “automatic identification and data capture” and commonly referred to as “AIDC” or “Auto-ID”. RFID technology is of particular interest in this research project because of low cost and good possibilities to function in a harsh environment like a construction site – but the recommendations given in this thesis can be useful in connection with the other technology domains as well. RFID denotes any identification system in which electronic devices are employed which use radio waves or pulsating magnetic fields to communicate with identification units fastened to objects.

2.2 Virtual Models in Design and Construction

As described in Section 1 and 2.1, the use of virtual models in design and construction is based on many years of development from drafting to computer-based 3D modelling. Point of departure for this research project is today's leading engineers, architects, contractors, and researchers' use of virtual models. In architectural and engineering practice, virtual models today are used from early sketches to the detailed design for visualisation, coordination, drawing creation, quantity take-off, and recently directly in simulation of a building's energy and static performance etc. (Eastman et al., 2008). An example of that is Ramboll's new Head Office near Copenhagen and virtual models from the project are illustrated in Figure 5. The figure illustrates how discipline models are created with different authoring tools by the architects and engineers during the design phase and through IFC export collected to aggregated models. This is a commonly used practice in Ramboll Denmark and described by bips (2007). The applications used in this project were AutoCAD Architecture, Tekla Structures and Progman MagiCAD respectively used for the architectural, structural, and ventilation and MEP (mechanical, electrical, and plumping) design. Aggregated models were made with Solibri Model Checker for coordination and clash detection, Autodesk Navisworks for interactive walkthroughs and Tekla Web Viewer for overview and dynamic sectioning.

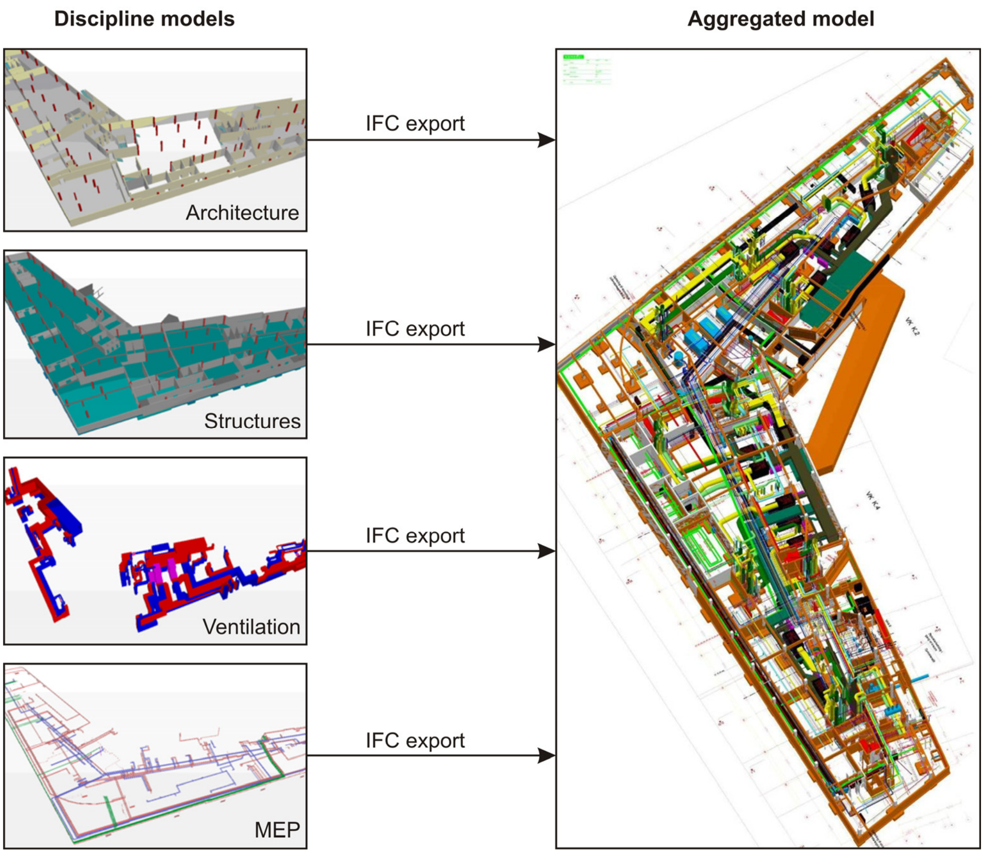

Figure 5 Discipline and aggregated models of one floor in the Ramboll Head Office, Copenhagen, Denmark.

In the construction phase, contractors can use the virtual models to analyse, plan and monitor the erection and progress of the project. It is done by linking the components of the virtual 3D models with activities from the design, procurement and construction schedules. As described by Fischer (2001): "*The resulting 4D production model of a project allows project stakeholders to view the planned construction of a facility over time on the screen and 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.*" Cost estimation and follow-up are other important aspects of the virtual model use during the construction phase and together with 4D modelling it has proven to add significant quantitative and qualitative value to construction projects as documented in several articles (Haymaker and Fischer, 2001; Khanzode, 2008; Zang et al., 2008).

A major Achilles' heel in the ICT systems used in virtual construction is the integration of the 3D model with the schedule and the cost estimates. Current practice in many systems (e.g. Tekla Structures and Autodesk Navisworks) is to create a direct relationship between the components in the virtual 3D model and a task in the schedule or cost item in the estimation software. It is useful in cases such as structural or mechanical component installation where this 1-to-1 relationship between the virtual model, the physical component and the installation task exists. In other cases there is a need for intermediate objects between the virtual model, the schedule and the cost estimate. It is necessary when construction components consist of several materials assembled at the construction site (e.g. drywalls or precast concrete) or when a tradesman works on components installed by others (e.g. painting or finished floors). Various research projects have focussed on developing this intermediator between virtual model components and processes in construction (see e.g. Froese, 1992; Myllymäki, 1998; Laitinen, 1998), where the latter has evolved to the Virtual Construction software suite of VICO software, today used by contractors for construction management. In VICO software's applications the intermediator is called a recipe and is a link between the virtual 3D models, the schedules and the cost estimates. Other related efforts have studied how data collection and performance control can be automated (Navon and Sacks, 2007) and how the working processes and planning can be improved (Ballard, 2000).

The application of virtual modelling in construction is still a major research domain with many scientific publications each year. Within the research domain standardisation of information exchange, automation of working practices, virtual model representations, 3D parametric modelling, integration of analysis and design etc. are eternal topics that have and will form the basis of many research projects. In order to focus this research project, initial analysis of business perspectives is used to establish a point of departure. This is done so to have the research project grounded in practical issues and actual user needs rather than a solely theoretical point of departure. The business perspectives are described further in Section 2.4 after the introduction of automatic identification in construction in Section 2.3.

2.3 Automatic Object Identification in Construction

Automatic object identification technologies are used to create the digital links between virtual models and physical components. The digital link can e.g. be created by adding a unique electronic RFID tag to the physical components, and include the ID(s) of the tag(s) as an attribute value in the virtual model of the component. It enables the user to in real-time and at any location access and update information in the virtual models such as production status, component locations, work instructions etc.

RFID is, as mentioned in Section 2.1, of particular interest in this project, but other technologies have shared features with RFID. Bar codes are for instances crucial in point of sales solutions in the retail industry but have limited impact on the construction industry. At the end of the 1990s, Marsh and Finch (1998) investigated the attitudes towards automatic object identification in construction using bar codes. They found the major industry barriers against the adoption of automatic identification within the United Kingdom supply chain to be in 1) lack of awareness of technologies and benefits, 2) technology conservative organisations, 3) temporary project organisations, 4) lack of motivation to apply labelling to the benefit of others, 5) failed client technology enforcement, and 6) challenges in technology standardisation due to diversity in construction components. Similar barriers still exist and they are equally relevant for the introduction of the RFID technology. Other parallels between the application of RFID today and bar coding one or two decades ago can also be drawn. In retail, automotive manufacturing, and aerospace bar codes were widely used and have proven effective (Marsh and Finch, 1998 and sources herein) while the construction industry was still waiting a wider introduction. Today, RFID in these industries is introduced at a steadily increasing pace for new significant applications such as the systems for luggage handling in airports (IID, 2009), process optimization in golf car production (Collins, 2004) and prototypes of new mobile web-based services to customers of meat (DMA, 2008).

In the construction industry, significant use of the RFID technology has only been implemented in a single country (Korea), although as described in Paper I, several research projects and proof of concepts demonstrate the potential of using RFID in construction. This paradox indicates that not all challenges in implementing the technology have been tackled. Various research projects have since the mid 1990s (sources referenced in Paper I) addressed the application of RFID in construction in contexts as precast concrete element fabrication, tracking the receipt and delivery of pipe spools, inspection and management in test laboratories, on-site tool tracking, project progress management, etc. All the research projects conclude that the technology has potential in construction, but the industry impact of the research projects is so far limited. Therefore, a main goal of this research project is to capture and analyse user needs to avoid only encouraging a technology push but also identify potentials of customer pulls and thereby address challenges of implementing automatic identification in construction.

2.4 Business Perspectives and Ideation

A digital link between virtual models and physical components has many potential applications in construction. Through brainstorming and observations of current practice in construction, a gross list of potential applications was developed in the opening phase of the PhD project. Ten of the more promising of these ideas for new applications in construction are listed below (not in order of priority) and further ideas to new services and ICT products are described in Appendix A:

- Supply chain management of building components
- Documentation and support of operation and maintenance
- Easy mobile access to context and location dependent information
- Navigation in buildings in emergency situations
- Real-time optimization and control of working processes
- Patient and equipment management at hospitals
- Identification of drawings and specifications
- Tracking of material and components in the full lifecycle from fabrication to demolition
- Physical hyperlink to World Wide Web (WWW) content e.g. in virtual communities or product catalogues
- Wireless measurement of temperature, moisture and movement

Because of limited resources for research and development (R&D), it is always important to select the right potential applications for further R&D projects. It includes long-term projects with high risk and high potential value as well as short-term projects with lower potential but greater chance of success. Diversity in the research project portfolio ensures the highest possibility for success short-term as well as long-term (Cooper et al., 2006). Projects with both a low expected value and low probability of success should of course be closed as soon as possible or never initiated, and the investment should be spent on projects with better potential. Portfolio management was as described in Appendix A used to analyse the business perspective of the ideas and thereby select focus areas for the PhD project. Among the short-termed ideas it was found most promising to continue the work with applications for integrating automatic object identification and virtual models in operation and maintenance. Use of the virtual models to support automatic object identification in construction management activities such as quality management and automated project progress was found most promising among the long-termed ideas. These subjects are therefore addressed in the scientific papers presented in this thesis.

3 Summary and Discussion of Scientific Papers

The following sections summarise the findings of the research presented in the six scientific papers included in this thesis.

3.1 Paper I: Ontologies to Support RFID Based Link between Virtual Models and Construction Components

The first paper presents a state of the art review of RFID in construction and of ontologies to support the development of a digital link between virtual models and physical components. As defined by Gruber (1993): *"An ontology is an explicit specification of a conceptualization"*. This means that ontologies are all the certified and upcoming standards, commonly accepted working methods and services that enable unambiguous identification of entities in heterogeneous systems. Furthermore, ontologies are also the assertion of applicable named relationships that connect these entities. Adequate and widely accepted ontologies are needed, especially when developing ICT systems where scalability and interorganizational interoperability are of importance.

The goal of this paper is therefore from an ontology consumer's (system developer) point of view to review the existing ontologies relevant for supporting a digital link between virtual models and physical components in construction to identify if they are sufficient for a future system implementation or if there is a need to develop new ontologies. It was found useful to categorise the ontologies according the meta-ontology shown in Figure 6.

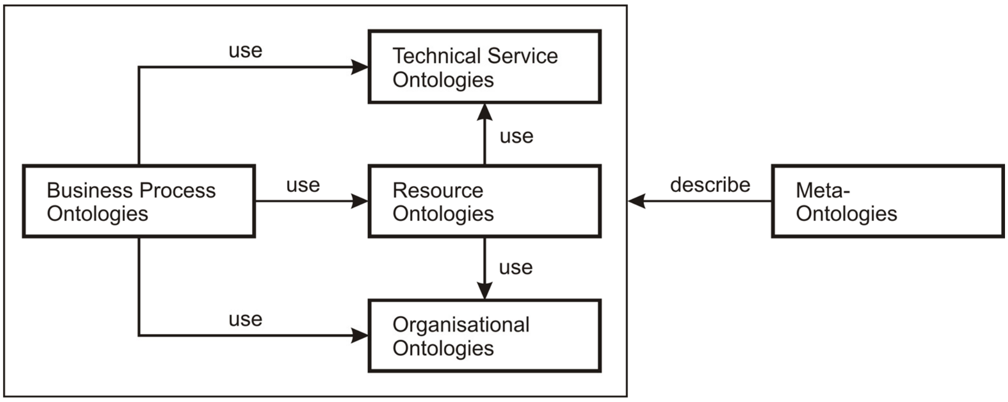

Figure 6 Overview of ontology domains and their relations.

Within each ontology domain a brief description of existing ontologies is given and existing implementations are examined. Afterwards, the ontologies are evaluated according to their usefulness in supporting a proposed future scenario where automatic object identification is used in production management and component element installation.

The main conclusions of this review are that, with a few modifications for industrial use, the technical service and resource ontologies are applicable. The meta, organisational and business process ontologies need further development and industrial maturity to be applicable for use in the system development. The important technical service technologies for the construction industry regarding the RFID technology are, ISO 14443 and ISO 15963 for HF (high frequency) RFID technology, and EPC and ISO 18000-6 for UHF (ultra high frequency). These ontologies enable interoperable access to data stored in the RFID tags. Here, the critical task is to select the right ontology because they are not all compatible.

The upcoming edition, 2x4 of the resource ontology IFC, supports representation of identification numbers from RFID tags and can therefore be valuable in future implementations. Combined with the formalised resource ontologies, it is also proposed to use search engines with automatic full-text indexing and keyword tagging (folksonomies). This can function as a quick way to provide users in construction projects with widely used information such as work instructions, documentation, and schedules.

Business process ontology development is a discipline requiring new development and specification of e.g. functional building systems before it can be used in relation to linking virtual models with physical components. This paper highlights the need for business process ontologies to at least support project progress management, work instruction delivery, quality inspection, inventory management, construction planning, procurement and facility management. Development of new ontologies starting at meta-levels and an increased use of internationally accepted ontologies will enable the structuring and reuse of information for the great benefit of the whole industry. Nevertheless, it is also one of the most complicated hurdles to overcome for the industry, and an increased focus from major universities, companies and property owners is needed for progress in this area.

To follow-up on the findings of Paper I, it is in Appendix C illustrated how an ontology to support virtual models linked with physical components in construction can be developed. Ontology development methods, tools and recommendations are described in Appendix C and demonstrated by initialising the development of the OWL (Web Ontology Language) based ontology: "Virtual Physical Link". It is also the author's expectation that Appendix C will inspire researchers and developers in the development of future ontologies for the construction industry (e.g. classification systems) to focus on modern ICT usage rather than looking backwards for solutions to support outdated information handling methods.

3.2 Paper II: Prototype Development of an ICT System to Support Construction Management Based on Virtual Models and RFID

Three of the papers in this thesis describe prototypes of new ICT systems taking advantages of the link between the virtual models and the physical components. Paper II is the first of them and the initial idea of the research presented in this paper is to formalise user needs in relation to construction management by means of virtual models and RFID.

Based on three case studies and involvement of more than 20 future users, an extensive list of future user needs was discovered. They are in the paper presented in an affinity diagram respectively as challenges to be addressed and as potential that can be utilised e.g. by new ICT systems. For a successful future system development and implementation, the main challenges to be addressed were identified to be; 1) a need to integrate interorganizational and conflicting working processes, 2) lack of interoperability and de facto standards, 3) need for better integration of the traditional paper document/drawing based working practice into modern virtual model based working paradigms, and 4) need for new competences at the middle management level or a project information officer (PIO) service function who would be responsible for the implementation of the technology at the construction site.

However, great potential was also identified, e.g. 1) mobile phones can be an important key to introduce a wider introduction and use of RFID in construction, 2) a combination of automatic identification technology and lean construction principles can give new possibilities for process optimisation, 3) use of automatic identification can introduce a new object-oriented paradigm for quality assurance in construction, and 4) the combination of RFID and GPS technology can enable real-time tracking and location of machines and materials.

Main outcomes of the research presented in this paper are ICT system prototypes that demonstrate how the challenges and potential could be addressed. First of all, a prototype was developed of a simple and implementable system with supporting work processes for real-time project progress management, quality assurance and inventory management. By this prototype it is illustrated how today's manual and paper-based checking and project follow-up can be done digitally by means of RFID enabled mobile phones and virtual models. Screen dumps from the prototype are illustrated in Figure 7. Further details about this prototype can also be found in Appendix B.

Figure 7 Screen dumps from a mobile phone based prototype application for project progress management and quality assurance. The screen dumps are from mobile phone emulator executed on a PC. From left the screen dumps show 1) a part of the menu, 2) input window used by the manufacturer of prefabricated components, 3) output from an inquiry of a component's current location and production status, and 4) output from a full component attributes inquiry.

Secondly, a prototype of a new tool for Virtual Collaboration in Construction (V2C) is presented. It illustrates a possible user-interface of a collaboration tool that can support the link between virtual models and physical components in construction. Figure 8 illustrates V2C and gives an example of how it supports the link between the virtual models and the physical components.

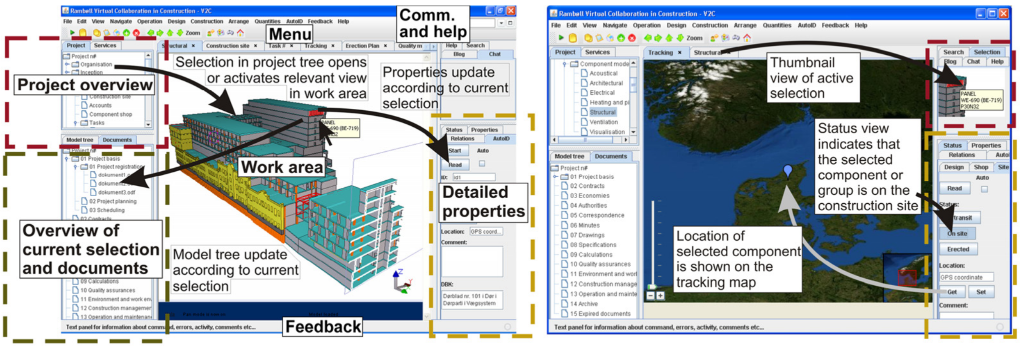

Figure 8 Screen dumps illustrating the prototype system Virtual Collaboration in Construction (V2C) and how it supports the link between a virtual model and the physical components.

The prototypes presented in this paper are preliminary conceptual works which have to be implemented, and further validated by full-scale tests. Evaluation of the prototypes and guidelines for the future implementations are described further in Paper VI. The author expects the prototypes can act as a basis for future developments of interfaces to e.g. model server managers, and development of mobile data capturing equipment. The research and development was done as a highly iterative and user involving process, and was based on a well-documented methodology (Contextual Design), which improves the validity of the findings.

3.3 Paper III: Radio Frequency Identification in Construction Operation and Maintenance – Contextual Analysis of User Needs

As described in Section 2.4, operation and maintenance (O&M) was identified as one of the areas where short-term benefits can be achieved by integrating automatic object identification and virtual models. O&M might also hold the trigger to a wider demand from building owners to require RFID tagged building components in construction. Therefore the aim of the research presented in Paper III is to identify the actual user needs for automatic identification in construction O&M.

In Paper III results are presented from a Contextual Design process in the form of an affinity diagram of captured user needs, work flow model and cultural model. It is supplemented with practical experiences from a system implementation of a prototype of an RFID supported operation and maintenance system. The system was developed as an extension to the existing mobile edition of the operation and maintenance system SMART from Ramboll Denmark. The author contributed to requirement specifications of the system extension on basis of the results derived from this contextual design process.

The main user needs identified are; demands for easier on-site information access, increased focus on documentation, education of users, and re-use of knowledge across organisations by introduction of new services. The needs can form a basis for new services and ICT systems in construction. However, the introduction of RFID in operation and maintenance may introduce many potential cultural conflicts about e.g. distribution of cost of system implementation, unwanted surveillance, and public attitude which can influence the success of a wider use of this technology. This is illustrated with the cultural model in Figure 9.

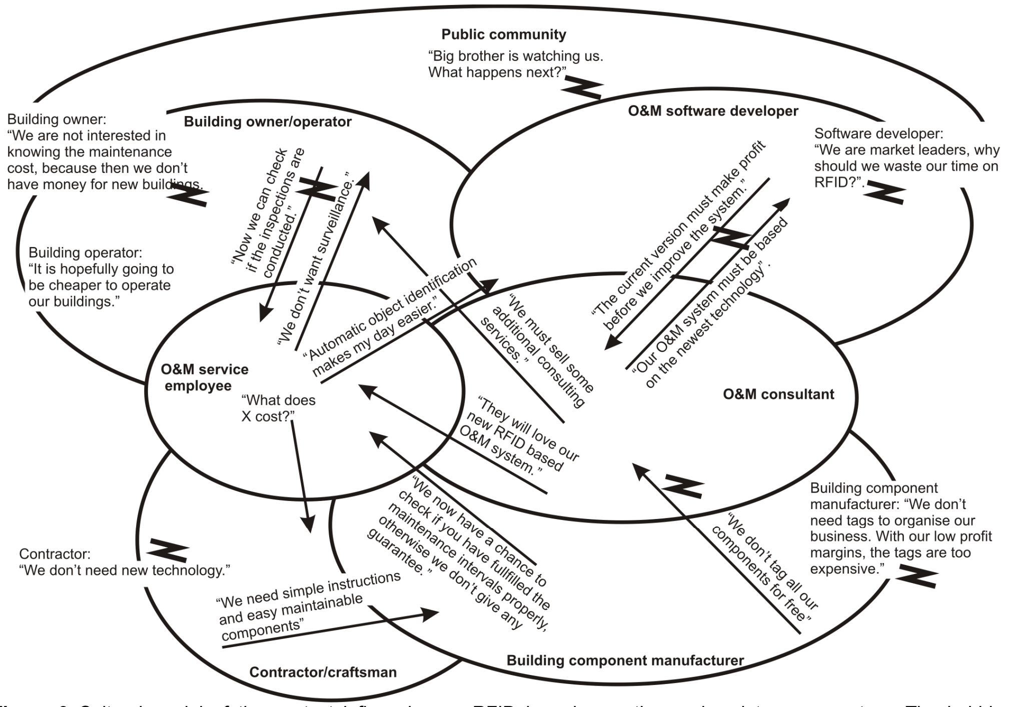

Figure 9 Cultural model of the context influencing an RFID based operation and maintenance system. The bubbles illustrate users with overlapping interests and the arrows illustrate cultural influence. Zigzags indicate conflicts.

The conclusions are that the technology works in practice and the main obstacles for using RFID in operation and maintenance are in information structuring, need for de-facto technology standards and lack in the use of general ontologies for storing and accessing the information resources. Demands from the property owners to implement component tagging are important to overcome these obstacles and gain benefits from implementing the technology in the construction process.

3.4 Paper IV: ERP Application of Real-Time VDC-Enabled Last Planner System for Plan Reliability Improvement

Paper IV describes a concept of how the combination of virtual models, ERP systems and RFID can be used to create real-time work plans according to the Last Planner System (LPS) of production control (Ballard, 2000). It is a continuation of the work presented in Paper II.

The Last Planner System has since its introduction in 1994 become a widely used method of architectural, engineering and contractor (AEC) practitioners for improvement of planning reliability and tracking and monitoring of project progress. The main objective of the LPS is to enhance planning reliability by utilizing three main techniques: 1) look ahead and weekly work planning, 2) make-ready process, and 3) reliable commitment of labour resources. These techniques are intended to improve mechanisms that control the organisation and the construction process, while the extent of the products or components under construction is of less importance. The authors' observations indicate that the last planners and coordinators are in need of the product aspect since current practice of the LPS implementations is guesswork-driven, textual report-generated, hand-updated, and even interpersonal trust-based, resulting in less accurate and reliable plans. Thus, this paper introduces a prototype system which improves planning reliability of the LPS by utilising automatic quantity extraction from virtual models, and generates cost and quantity based Percentage Plan Complete (PPC) reports. This is done by combining cost data from an enterprise resource planning (ERP) system with the component quantities from virtual models as illustrated in Figure 10, step 6-10.

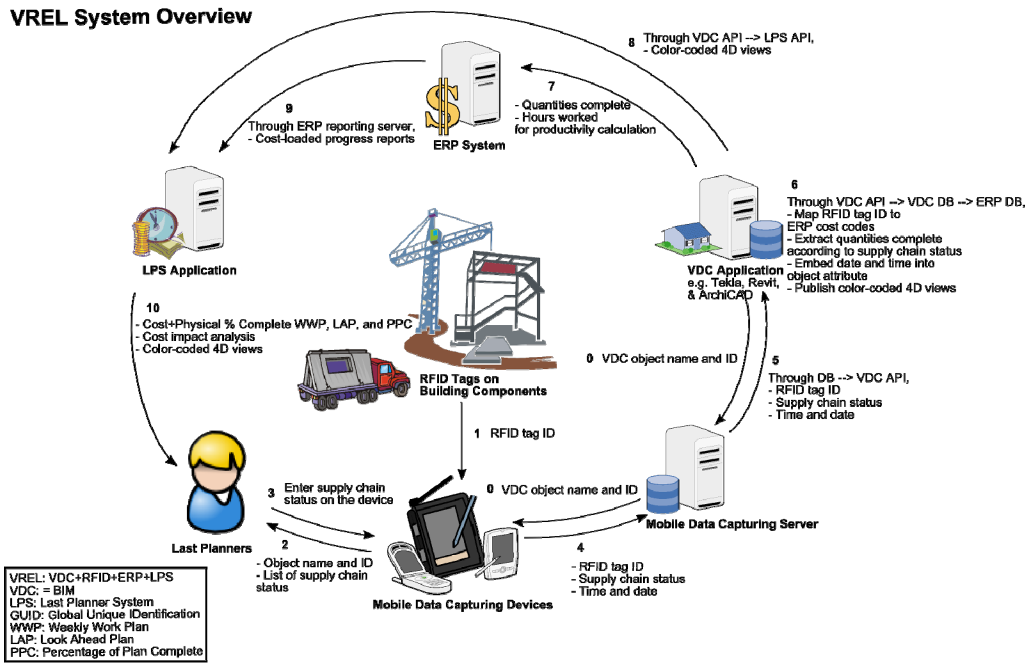

Figure 10 Overview illustrating how the VREL prototype system is used to create cost-loaded weekly work plans, look ahead plans, and PPC and how the system performs cost impact analysis.

In addition, as also illustrated in Figure 10, the system enables real-time and automatic data capturing by means of RFID tagged components. It allows the last planners to be real-time notified of interruption in the schedules and thereby take immediate action, rather than waiting until next week's coordination meeting.

The concept of the VDC + RFID + ERP + LPS integration (VREL) was developed in cooperation with researchers at the Center for Integrated Facility Engineering (CIFE) at Stanford University during the author's stay at CIFE in the autumn and winter of 2008/2009.

3.5 Paper V: A Method for Updating Production Status in Computer Based four Dimensional Models

A solution to one of the technical hurdles discovered during site observations for the prototypes presented in Paper II gave inspiration to the patent application presented in Paper V.

In practice many identical components such as doors, windows, wall elements, ventilation ducts, pumps etc. are used in the construction of a building. In the prefabrication phase and at the delivery of these components to the construction site these identical components are handled by type and not on individual basis. A prefabricated wall component is for example named and handled in the supply chain by the type name "WE 101" and not by a unique name "WE 101-07" (type name + serial number). The components can be given a unique ID tag to enable automatic progress monitoring with the 4D model, but if they are not handled as unique components in the supply chain it will result in a wrongly updated 4D model. This problem can be avoided by planning the delivery of the components to the construction site uniquely. However, this prior art method is not advisable because it leads to time-consuming micro management of the components.

Therefore, a method (computer implementable algorithm) was invented that automates the handling of unique components and saves the user time in production management. The method utilises a combination of scheduling data, global positioning (GPS) coordinates and type name to uniquely identify the monitored components. It ensures that the right component in a 4D model is updated, even if multiple components are identical and not managed individually. The method is illustrated in the activity diagram in Figure 11, using Unified Modelling Language (UML) notation.

The method is important in order to achieve benefits from using automatic object identification in construction management by means of RFID and bar code technology. The method is exemplified with a precast concrete element installation process, but it will also be applicable to other component installation or handling processes such as installation of heating, ventilation or air-condition equipment as well as steel and timber structures.

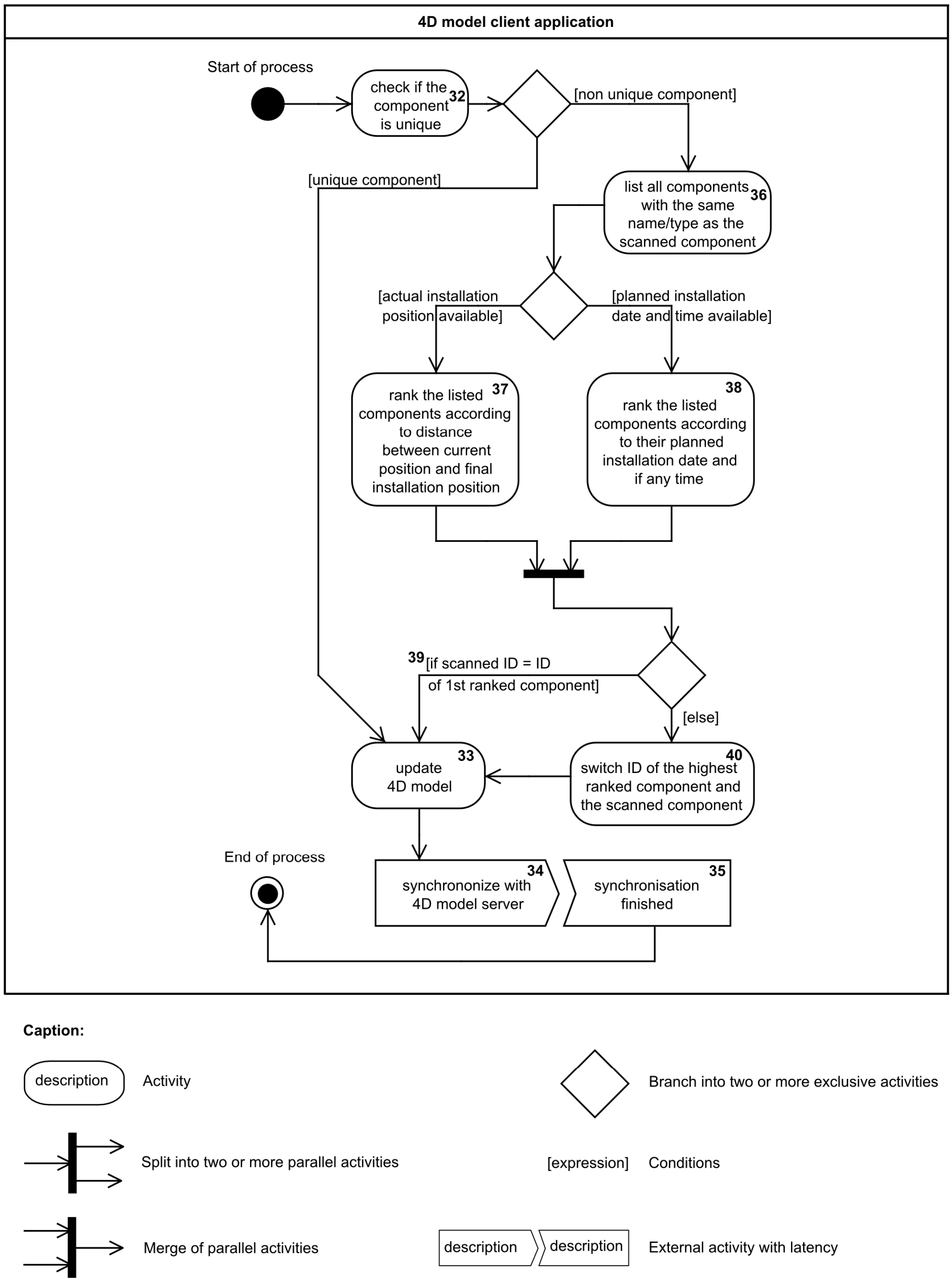

Figure 11 Activity diagram of the invented method for updating production status in virtual 4D models.

3.6 Paper VI: Evaluation and Guidelines for Implementation of ICT Systems to Support RFID in Construction

Paper VI evaluates two of the prototypes presented in Paper II and III and demonstrates usefulness of combining virtual models and automatic identification technologies in construction. Real world applications of two prototype systems for operation and maintenance and construction management are used in the evaluations.

For the automatic object identification in the first prototype system ISO 15963 compatible RFID technology is used because of good all-round properties such as availability, price, readability and size. The virtual model resource is Ramboll's operation and maintenance system SMART Mobile where PDAs are used to document inspections on-site. The author contributed to the specification of an RFID extension for SMART Mobile that has been released in its first version. It is currently used in practice by a contractor for document management, maintenance and operation reporting. It is evaluated by observing the users in action and by informal interviews about user interface satisfaction.

In the second prototype NFC / ISO 14443 compatible mobile phones are used because today they are available in some traditional (low-cost) consumer mobile phones. As a virtual model resource it is examined how the 3D/4D authoring tool Tekla Structures can be configured to interact with a Java Web application server for data capture. Figure 12 shows the building case used for the evaluation of the second prototype and photos taken during the experiments with embedment of RFID tags in precast concrete elements. RFID tags were embedded in approximately 500 precast concrete elements for the experiments.

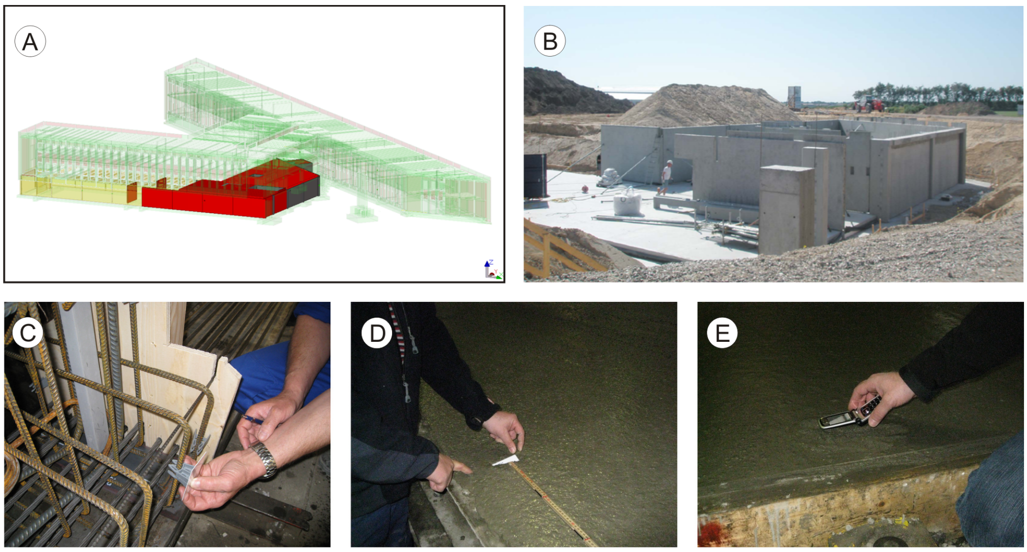

Figure 12 Evaluation of virtual 3D/4D models and RFID in construction. A+B: Virtual model and physical building of The Registration Court in Hobro. C: Experiments with fixing RFID tag to concrete reinforcement. D: Embedment of RFID tag in precast concrete wall. E: Test of RFID tag readability in wet concrete.

The main conclusions are that mobile technology and passive RFID technology are an efficient and practical implementable way to introduce digital links between virtual models and physical components in construction. It can by advantage be used for on-site inspection work and documentation, real-time project progress management, and quality assurance. These are crucial aspects of improving information handling in construction.

It is also concluded that a lot of work is still required before the potential can be realised in form of improved quality, cost and reliability of the construction projects where the technology is adapted. The main challenges for future implementation of the technology were identified to be: 1) Lack of resources for innovation projects in construction, which limited the prototype development and thereby also practical implementation of the construction management solution. 2) Cross company data network sharing, which introduces security and inter-personal trust conflicts. 3) Reuse of virtual models from design directly in construction management, which is important to avoid unnecessary duplication of work. On the other hand, the models should be sufficiently decoupled to allow flexibility in the working process so delays in the design do not affect the possibilities of planning the construction. 4) Manufactures and mid-level managers/project managers, who were found to be the most reluctant to change.

Contradictory to other research projects it is concluded that, blue-collar workers are more willing than their managers to try the new technology and expect future benefits of using it. In several on-site observations and interviews blue-collar workers showed great interest in trying the new technology and were keen to “work smarter”.

To overcome the challenges several suggestions to guide the implementation are presented. First of all, a proven methodology to run the change process should be used. It can e.g. be the framework for implementation of technology change presented in this paper. It is also argued that reuse of the RFID tags from the construction management process in operation and maintenance of the building is important to share the cost of tagging the building components among several stakeholders. Use of traditional consumer equipment such as the NFC (Near Field Communication) compatible mobile phones is also crucial to lower the cost of the technology implementation and thereby increase the chances of success with the implementation.

4 Conclusions and Future Research

This Industrial PhD project has examined the potential of establishing a digital link between virtual models and physical components in construction. This was done by integrating knowledge of civil engineering, software engineering and business development in an iterative and user needs centred system development process. The main conclusions of this work are provided in this section of the thesis, while in depth details can be found in the individual papers.

4.1 User Needs and ICT System Support

The establishment of a digital link between the virtual models and the physical components in construction supports an extensive number of new working processes which can solve major challenges in the industry.

First of all, the research concludes that the industry is in need of new practices for quality management. Quality management receives comprehensive attention in many construction companies (at least in Northern Europe) and vast efforts are put into construction projects on documentation of the building process, materials used and how components must be serviced. However, it is to almost no avail because it is all done in a document and paper based fashion where the data are almost inaccessible for experience gathering, continued learning, and performance analysis. Paper II in this thesis describes a new approach to the quality management process where automatic object identification and mobile ICT tools are used to enable a simple and real-time capturing of the information required to document quality of the conducted work with photos of the construction and comments from the inspection team. The documentation is by means of RFID tagging linked to the relevant objects in the virtual model. With this integration of the quality management documentation with the objects in the virtual model, data can easily be sorted and filtered according to specific wishes (component type, material, manufacturer, date etc.). By implementing these findings the user can to run performance analyses and thereby improve working practice.

Secondly, project progress management is in several research projects nominated to be crucial for improving reliability and reduce non-productive time in the building erection process. Based on this system development process, it can be concluded that the major challenges in the planning and follow-up in construction projects are in interorganizational settings where different disciplines and companies rely on each other. The companies observed had well-optimised processes to handle their own work (e.g. mounting of precast or installation of ducts), but they were reluctant to release detailed information about when specific task are going to be accomplished. Therefore, the overall construction manager does not have detailed information about on-going tasks and is not able to e.g. optimise working processes which with advantage could run concurrently or do location based planning. This results in an ad hoc oriented planning process which only relies on a few milestones several weeks ahead in the project and has poor optimisation of resources as a consequence.

The virtual models are particularly strong in the cross-disciplinary planning and follow-up, because the 3D visualisation improves the stakeholders' abilities to understand other disciplines than their own. In addition the digital link between the physical components and the objects in the virtual models is powerful to real-time automate a continuous update of the virtual models. Paper II and V describe how this can be done by means of RFID technology and mobile phones. In Paper IV the approach is extended further to also include unit cost data from ERP systems to further improve reliability of the percentage plan completed reporting.

To benefit from the virtual models in the planning and construction process it is concluded that the virtual models must always reflect the reality, with the right level of detail. For that reason continuously and real-time model update are crucial. The right level of detail cannot be generically quantified because it very much depends on the capabilities of the used software, hardware, and workforce. However, it is advisable early in the process to keep the models on a conceptual level to avoid unnecessary rework and continuously add more details to the model. Less detailed or inconsistent models later in the project will on the other hand not improve working practice compared to traditional drafting. With a trained workforce and virtual model authoring tools with performance to handle detailed virtual models and features to automate the modelling process, it is the author's experience that full detailing is worthwhile before beginning the construction. In other words, the conclusion is that the more challenges solved in the virtual models before construction starts, the fewer problems can be expected on the construction site.

Today's virtual models created during the design phase seldom contain the required information to be directly useful to the construction planning and project progress management. Therefore, additional effort is required to enrich the models with information on construction task, interim structures, and available resources in form of materials, machines and manpower. When this is done, the detailed virtual models are powerful in the construction phase to plan and control the erection, extract bill of materials, book required resources and overview the flow of equipment and materials from procurement to delivery of the completed facility. To avoid critical dependencies in the planning process it is important to decouple the design and construction models. However, the models should still be linked to increase the possibilities of data reuse across the disciplines.

In combination with the RFID technology for the automatic data capture and virtual model update, the interviews with the stakeholders indicate it is useful to embed positioning equipment (e.g. GPS or Wireless LAN) in the RFID readers. It enables cost-efficient component positioning every time a component is moved or inspected. It does not provide the fully automatic real-time location tracking which a GPS with GPRS data-connection attached to each component can give, but it will make a great difference compared to current practice in controlling the delivery of components and equipment to construction sites.

Thirdly, over the entire life-time of a building, the operation and maintenance (O&M) is more costly than the design and construction, but the related working processes are still based on a low level of automation, and the information handling is mainly done with a low level of digitalisation. One of the reasons is that initially it requires a lot of effort to set up the O&M systems with all details about the facility and subsequently keep the system updated with information about the conducted maintenance services. The virtual models made during the design and construction phase contain significant parts of the information required in the operation phase such as detailed information about area usage and component details. If the contractors then deliver the maintenance instructions digitally, as is required today in governmental financed building projects in Denmark, the facility owner has the fundamental basis for a digital operation. As demonstrated in Papers III and VI, the digital link between the virtual models and the physical components will then enable the facility managers to do on-site update of the O&M system, quick information retrieval of e.g. inspection check points, and avoid time-consuming office work of entering handwritten notes into the O&M system. The digital link becomes even more favourable if the RFID component tagging is already done during the construction. The cost of RFID component tagging can then be shared among multiple stakeholders to common benefit and the system can be set up and run from the day of handing-over the facility to the owner.

4.2 Ontologies to Support Future System Development

The application of a digital link between the virtual models and the physical components in building projects is a highly interorganizational process. The components are tagged by the manufacturer, the virtual models are created by the design team, and together they are used by the contractor in planning and in project progress management and subsequently used by the owner for operation management. In large building projects, hundreds of people from several different companies and thousands of components are involved in the design and construction process. In order to make the digital link useful, standardisation through internationally accepted ontologies is concluded to be of significant importance. The ontology examination presented in Paper I shows, a high level of standardisation of technical services to enable data communication among heterogeneous hardware and software components. It is concluded that future consolidation of the RFID technology through combination of two or more standards (e.g. NFC (ISO 14443), ISO 15963, ISO 18000 and EPC) in multiband (HF+UHF) RFID tags, will be of value to the construction industry. It is needed to enable the previously mentioned interorganizational process because none of the currently defined standards support all the needs of the construction industry. In this thesis, support of low-cost RFID enabled mobile phones at the construction sites was established as the key to success with implementing the digital link between the virtual models and the physical components. At present it requires support of NFC. However, in many automation cases, RFID tags with longer reading distances than the few centimetres obtainable with the mobile phones will be necessary. For this purpose UHF tags (ISO 18000) are available. The retail industry is working on the introduction of the electronic product code (EPC) defining the data content of the RFID tags. Therefore, to facilitate future digital procurement, support of the EPC specifications will also be important.

Industry Foundation Classes (IFC) is the only available serious attempt to develop and propagate a resource ontology that facilitates interoperability among the virtual models in construction. In the forthcoming edition 2x4 of the IFC specification, possibilities of a link between the physical components and the objects in the virtual models will be included. Support of IFC should therefore be integrated in future system developments.

Various proposals exist for organisational ontologies such as the Business Process Execution Language for People (BPEL4People), the Semantic Web based Friend of a Friend (FOAF), and project and actor definitions in IFC, but none of them have gained wide acceptance. FOAF is simple and originates from the widely expanding ICT-based social networking world and is therefore expected to be one of the first generally used organisational ontologies and is as such relevant in future system developments.

Business process ontology development is a discipline requiring new development and specification in relation to support the link between virtual models and the physical components in construction. This is needed to increase scalability and interoperability of the systems and future specification must define how data on about project progress management, work instruction, quality management, inventory management, construction planning, procurement and facility management should be exchanged among the systems and stakeholders involved.

It is concluded that future ontology development starting from a meta-ontology level is needed. Ontology development methods, tools and recommendations are therefore described by initialising the development of an OWL ontology named Virtual Physical Link. It is the author's expectation that this work can inspire researchers and developers in the development of future ontologies for the construction industry (e.g. classification systems) to focus on modern ICT usage rather than looking backwards for solutions to support outdated information practices.

4.3 Barriers and Practical Implementation

As argued in the reporting of the prototype development and evaluation throughout this thesis, the technologies supporting the digital link between the virtual models and the physical components are available and ready for use. Of course some further development is needed, but the technical implementation is definitely achievable with the right resources. The major barriers indentified are related to the changing industry practices and educating mid-level mangers that were found most reluctant to change. Contradictory to other research projects it is concluded that, blue-collar workers are more willing than their managers to try the new technology and expect future benefits of using it. Based on the experiences gained through this PhD project, it is believed that some of the important future challenges are to show the benefits of using modern ICT to practitioners in the construction industry and communicate this knowledge among all stakeholders. Tangible results are important for success of the technology implementation because of the practice orientation and short-term cost focus of the construction industry. As argued in Paper VI, the practical implementation must be driven through leadership and a methodical approach in order to change the current practice.

A number of cultural barriers were also identified. These are difficult to tackle but can have a major influence on the success of the technologies in construction. During the initial implementation, there will be conflicts about who should pay for adding RFID tags to components and for what purpose the detailed registration of people's behaviour can be used? Also public attitude about the RFID technology may have influence on the system implementation because the technology introduces potential risk of increased and unwanted personal surveillance.

4.4 Future Research

As previously described there are many potential applications of the combination of virtual models and automatic identification in construction, but it is important to keep in mind that focus should be kept on solving real business problems to get success with the implementation. Therefore it is recommended to start future developments with focus on the three subjects highlighted in Section 4.1 - quality management, project progress management, and operation and maintenance. When the technology is up and running within these areas, attention can be paid to other application areas.

The introduction of automatic data capturing in the quality management and project progress management process will lead to a significant increase in the amount of data collected about the building process. It will be very relevant to use these data to generate new knowledge about e.g. common errors in the building process, performance of suppliers, and long-time durability of the building components. During the construction process, new approaches can enable contractors to do real-time control based on reliable performance measures. It is also expected that research in statistic simulations on the basis of the data collected could lead to new real-time control algorithms improving construction project management.

The next steps in taking advantage of the automatic identification technology could be to have more advanced self-configuring sensor technology embedded in the building components. In the construction phase, the components could then do autonomous data exchange, keep a virtual models server updated and automatically inform the workmen about installation errors. Similarly the building components could do self-reporting about maintenance condition and required service.

Many new services can be created around the link between the virtual model and physical components to provide; automatic price estimation, automatic service instruction update, material safety certificates, hyperlink to virtual communities etc. It will require additional research to clarify how such services should be developed, accessed and made interoperable. In addition, alliances are required between universities, architectural, engineering and contractor companies, and property owners to develop and implement the international ontologies needed.

With the current rapid progress in display and mobile technology, the reasons for using significant energy on drawing and document production in construction projects will soon disappear. However, it will still require more research to understand how the step into the paperless construction process should be taken, and how all the information should be linked together as well as more ICT maturity of the society. Best practices for defining information views are still required, but they will definitely be different than yesterday's paper based drawing standards and more dynamically changing.

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Part 2

Scientific Papers

Paper I

Ontologies to Support RFID Based Link between Virtual Models and Construction Components

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Ontologies to Support RFID Based Link between Virtual Models and Construction Components

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Abstract: *Virtual models have in recent years proven their worth in practice in building design. Today, virtual models of a complete building project are often created before the project is carried out in practice. The immediate advantages of this new working process are great; it reduces the number of errors, it gives a better production basis, and it improves clarity and enhances communication compared to traditional 2D drafting methods. However, there is still much unutilized potential in the virtual models, especially for use in the construction and operation phases. A digital link between the virtual models and the physical components in the construction process can improve the information handling and sharing in construction and building operation management. Such a link can be created by means of Radio Frequency Identification (RFID) technology.*

Ontologies play an important role as the foundation for information sharing between trading partners, reuse of data from one phase in construction to the next, integration of process and product models with enterprise resource planning (ERP) systems, easily access of information, communication of data through networks, reading of data stored in electronic tags, etc. This paper reviews existing ontologies relevant in relation to creating such a digital link between virtual models and the physical components. The ontologies are reviewed from an ontology consumer (system delveloper) point of view. The ontologies are categorised according to their applicability to specification of technical services, resources, organisational relations, business processes and overall frameworks for ontology descriptions and their relations. It is concluded, with a few modifications for industrial use, the technical service and resource ontologies are applicable and that the meta-, organisational and business process ontologies need further development and industrial maturity to be applicable for use in system development.

1 Introduction

Virtual models have in recent years proven their worth in practice in building design. Today it is common practice in leading architectural and engineering firms to create a virtual model of the complete project before it is built (Kiviniemi et al., 2008). The immediate advantages of this new working process are great, and the authors' experiences show that it reduces the number of errors, gives a better production basis, improves clarity and enhances communication methods in comparison to traditional 2D drafting methods. Other researchers have recently reported and quantified similar productivity gains using virtual modelling compared to traditional drafting (Sacks and Barak, 2008; Woksepp, 2007).

There is still much unutilized potential in the virtual models, especially in the construction and building operation phases. A digital link between the virtual models and the physical components in the construction process can improve the information handling and sharing in construction and operation management (Chin et al., 2008; Sørensen et al., 2008). The link can be made by means of Radio Frequency Identification (RFID) technology, bar codes, biometrics, optical recognition, laser scanning, magnetic/electronic smart cards, and wireless low power technologies such as Bluetooth, Lon Works, Zig Bee, Memory Spot, MEMS (Micro Electro Mechanical System), Wibree and Z-wave. RFID technology is of particular interest in this research project because of low cost, and good possibilities to function in a harsh environment like a construction site – but the recommendations given through this paper can be useful in connection with the other application domains as well. The digital link can e.g. be created by adding a unique electronic RFID tag to the physical components, and include the ID('s) of the tag('s) as an attribute value in the virtual representation of the component. As illustrated in section 3.1, it enables the user to real-time, and at any location, to access and update information in the virtual models such as production status, component locations and work instructions.

Significant use of the technology in construction management has only been implemented in a single country (Korea), although as described in section 2 of the paper, several research projects and proof of concepts demonstrate the potential of using RFID in construction. This paradox indicates that not all the challenges in implementing the technology are tackled. The technology has been implemented in more than 400 projects in Korea, but there is still a need for standardisation of the technology (technical service ontologies) to reduce the barriers for collaboration across projects (Chin et al., 2008a). Similar needs and problems are expected to arise when the technology is introduced to heterogenous organisations of several companies, and into more multidisciplinary working processes than described in the prior research projects.

The goal of this paper is therefore from an ontology consumer (system developer) point of view to review the existing ontologies supporting a digital link between virtual models and physical components in construction to identify if they are sufficient for a system implementation or if there is a need to develop new ontologies.

Ontologies play an important role as a foundation for information sharing between trading partners, reuse of data from one phase in construction to the next, integration of process and product models with enterprise resource planning (ERP) systems, easily access of information, communication of data through networks, reading data stored in electronic tags, etc. The term "ontology" does not only have a single definition. Within knowledge engineering the term has been widely discussed in the 1990's (Guarino, 1996). Guarino argues that Tom Gruber's definition is the best known (Gruber, 1993): *"An ontology is an explicit specification of a conceptualization."* For use within ICT (Information and Communication Technology) in construction a similar, but more detailed definition by DLI Glossary (1998), is also valid: *"An ontology is an explicit formal specification of how to represent the objects, concepts, and other entities that are assumed to exist in some area of interest and the relationships that hold among them."*

In ICT in construction practice it means that ontologies are all the certified and upcoming standards, commonly accepted working methods and services that enable unambiguous identification of entities in heterogeneous systems. Furthermore, ontologies are also the assertion of applicable named relationships that connect these entities. Adequate and widely accepted ontologies are needed, especially when developing ICT systems where scalability and interorganizational interoperability are of importance.

Firstly, in this paper an introduction to RFID in construction is given. Secondly, the method used for evaluation of ontologies is described. This is followed by an overview and discussion of ontologies relevant for fulfilling the potential of a digital link between the virtual models and the physical components in construction within: 1) meta-ontologies, 2) technical service ontologies, 3) resource ontologies, 4) organisational ontologies and 5) business process onotologies. Figure 1 shows an overview of the ontology domains and their relations are given. The domains are further described in sections 4-8 of the paper.

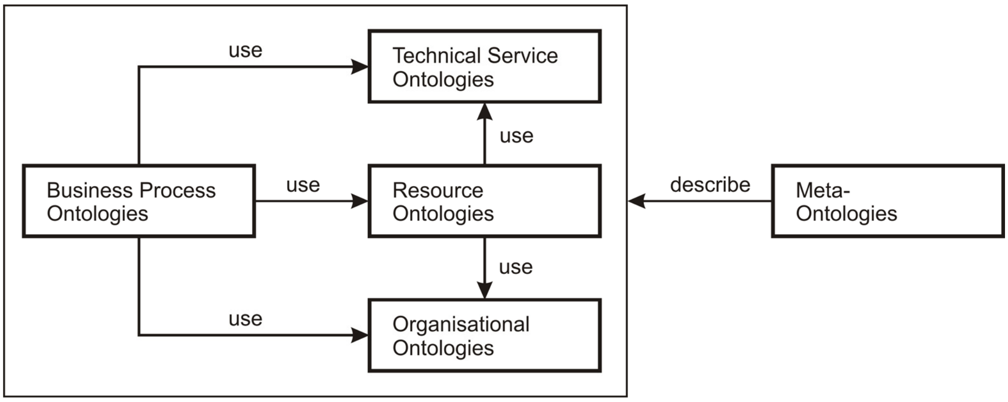

Figure 1 Overview of ontology domains and their relations.

2 RFID in Construction

RFID is the acronym for Radio Frequency Identification, and denotes any identification system in which electronic devices occur that use radio waves or pulsating magnetic fields to communicate with identification units fastened to objects. In the 1970's and 1980's RFID was first introduced in the industrial sector to keep track of railway wagons, dairy cattle, and auto chassis in production lines. Since then, it has spread to other areas such as identification of pets, clothing in laundries, ticket systems, theft protection, and admittance control. From the beginning of this century there has been an increasing focus on the application of RFID. This is, among other things, because of recommendations from the U.S. Department of Defence and the U.S. Food and Drug Administration for use of this technology. Furthermore, the world's largest retail chain, the Wal-Mart Stores, Inc., has since 2005 required its largest suppliers to use RFID on all their product pallets and larger units. The supply of RFID equipment has gradually increased, and there is now a higher degree of standardisation in the area than earlier. (Glover and Bhatt, 2006)

As early as in 1995 it was stated that automatic identification of objects using RFID technology was a promising technology for the construction industry (Jaselskis et al., 1995). However, 14 years later, the applications of RFID in the construction industry are rare and mostly used in prototype projects or for theft and access control, but not in interorganizational applications (Erabuild, 2006). Some of the reasons are the lack of widely used ontologies, and the shortcomings of virtual product and process model applications used in the construction industry. Another reasons is that the true benefits and complexity of automatic identification systems do not arise from the hardware, but from the possibilities to get information of proper time and place in a usable form (Glover and Bhatt, 2006).

A number of recently published papers describe various examples of tested RFID implementations within construction: 1) Automation of tracking the delivery and receipt of fabricated pipe spools is described by Song et al. (2006), 2) inspection and management in a concrete test laboratory is described by Wang (2008), 3) on-site tool tracking is described by Goodrum et al. (2006), 4) project progress management with virtual models is described by Chin et al. (2005), and 5) tracking and locating components in a precast storage is described by Ergen et al. (2007). In all the papers it is concluded that RFID technology can be brought to work efficiently, even in the harsh construction environment.

In other industries (e.g. hospitals) research indicates that despite the great potential of the RFID technology it must be better integrated into existing business systems to demonstrate commercial value (Tzeng et al., 2008). Lee et al. (2008) argue that in the service industry firms should seek to apply the technology to generate additional value (by new services) for the customer rather than focusing only on the effectiveness of supplier relationships. This results in a need for a redesign of existing working processes because it is not only a matter of adding a tag to a component and a database. Based on case studies from the retail industry, Wamba et al. (2008) argue that the real potential of RFID is collaboration among all the supply chain members included in the ICT supported business model, which is imperative to allow overall supply chain optimisation. It is the authors' experience that findings similar to the one described above can be done in the construction industry, and that ontology development therefore is an important research area, in which some of the challenges can be addressed.

2.1 Components in RFID Systems

The most referenced components in RFID systems are tags, readers and middleware. Tags, also termed transponders, are identification units that are attached to the objects to be localised. The interrogator, the transceiver or the RFID reader, as it is often called, is that component which via the antenna is used for scanning the data contents of the tag. The middleware is the software component which ties the RFID reader together with the other software components in an ICT system and, if necessary, also filters the data before it is relayed. RFID is a technique whose applications are far from a final development and new areas appear in a steady increasing pace (Glover and Bhatt, 2006). In Figure 2 an outline of a typical RFID supported ICT system and the information flow in the system is presented.

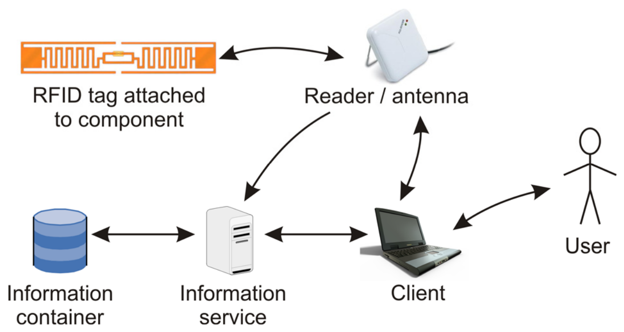

Figure 2 Outline of a typical RFID supported ICT system and the information flow in the system

2.2 RFID Tags

An RFID tag communicates by means of electromagnetic signals. RFID tags are distinguished in the way they are supplied with energy: 1) Passive RFID tags receive all their energy from the RFID reader, 2) Active RFID tags have a built-in battery supply that can supply not only the communication unit with energy but also microprocessors, storage medium and sensors, and 3) semi-active RFID tags with a built-in battery for internal processes receive energy from the RFID reader to drive the communication.

RFID tags are made in many different shapes that fit the application to which they are applied. There are practically no restrictions in relation to the shape of the tag to fit in everyday items, such as access cards, smart labels, library book labels, ticket systems, etc. Moreover, there are various specially designed tags that are suited for immersion into fluids or shaped like nails which can be hit into transportation pallets or wooden door frames. See e.g. TAGnology (2009) for an overview and prices.

The data capacity of RFID tags varies from only one-bit tags used for e.g. theft protection for products in shops, to active tags with many kilobytes of memory. The smallest tags are smaller than a grain of sand and can thus be hidden in a regular piece of paper (Hitachi, 2009). There are read-only RFID tags, and on other tags it is possible to write data once or a repeated number of times. Active tags with built-in sensors are capable of registering temperature, pressure or vibrations. In that way it is possible upon reception of a batch of products to scan the physical conditions during transportation. Compared to passive tags, the battery capacity and cost are the most significant barriers for a wide use of active tags in construction. Current lifetime for batteries for application in RFID tags is up to 10 years, and the lifetime for future lithium/thionyl chloride cells are up to 20 years (Jacobs, 2007). With the designed life time of buildings of typically 30-50 years, it is important to consider maintenance of active tags before installing them widely in buildings. It is important to realise that currently no single tag has all the features typically mentioned in connection with RFID. In the following section an overview of the RFID tag properties is given depending on communication frequency.

2.3 Communication Frequency

Besides the power supply, the communication frequency is used for classification of RFID tags and readers. There are tags and readers that operate on the frequency bands: Low frequency (LF), high frequency (HF), ultra high frequency (UHF) and microwave. The communication frequency determines the reading distance, what kind of materials that can be read through, the data transfer speed and the price. Table 1 shows an overview and assessment of the positive and negative properties for application of passive RFID technology, dependent on the communication frequency.

Table 1 Frequency guide for passive RFID technology inspired by InnovationLab (2006).

Frequency band	**Low Frequency (LF)**	**High Frequency (HF)**	**Ultra High Frequency (UHF)**	**Microwave**
Typical RFID frequency	125 – 135 kHz	13,56 MHz	433 MHz 865 – 956 MHz	2,45 GHz
Scanning distance	< 0.5 metres	< Approx. 3 metres	< Approx. 9 metres	> 10 metres
Data transfer speed	Less than 1 kbit/sec.	Approx. 25 kbit/sec.	Approx. 30 kbit/sec.	Approx. 100 kbit/sec.
Positive attributes concerning application in construction	1)Readable through most materials 2) No reflections or absorption 3) No problems with radiation 4) Low cost equipment	1) Longer reading distance than LF 2) Readable through concrete and fluids 3) Same standards world wide 4) Thoroughly tested technology 5) Small readers	1) Read many objects simultaneously 2) Relatively long scanning distance 3) Relatively high speed	1) Long reading distance 2) High speed
Negative attributes concerning application in construction	1) Short reading distance 2) Slow data transfer	1) Relatively short reading distance 2) Relatively slow data transfer	1) Signal reflection from metal 2) Impossible to read through fluids and metal 3) Expensive and large RFID readers	1) Poor readability 2) Impossible to scan through fluids and metal 3) Public attitude and fear concerning radiation
Typical areas of application	1) Tagging of animals 2) Process optimisation in production firms	1) Smart labels 2) Access and security cards 3) Process optimisation in production firms	1) Logistics at pallet level and item level 2) Smart labels 3) Tracing of animals/cattle.	1)Asset tracking and automatic payment systems

The reading distances listed in the frequency guide above concern passive RFID tags and can be improved within the same frequency area by using active RFID tags, which will affect the price per unit in a negative direction. It is also important to mention that the reading distances are guidelines for readers with fixed power supply and large antennas. Handheld readers have often significantly shorter reading distances, typically less than 5-10cm for passive HF and LF tags and less than 1-3m for passive UHF tags (TAGnology, 2009).

Tags used at the HF band have good all-round attributes and can be applied in the vicinity of fluids and metal. They are expected to have good changes for a breakthrough in the construction industry, and they are already widespread in other industries. If tags are required to be embedded in for instance steel structures LF tags should be chosen. HF tags will only work if they are put on the outside of steel structures with a sufficient separation layer between the antenna and the metal. HF tags with a ferrite based separation layer are today commercially available. UHF tags are now being introduced in the retail industry, and they have long reading range making them an obvious choice for application in construction, but they also have some significant downsides compared to HF tags. HF tags are therefore expected to have better chances for a breakthrough in construction. UHF tags are vulnerable in the vicinity of metal and fluids and can therefore be expected to make troubles during practical implementation. UHF signals are reflected by metals, and it will be difficult to ensure reliable reading at construction sites. Further development of directional antennas, methods for tag localization, filtering of the received signals, and smaller readers are important, for making UHF tags more attractive for use in construction.

2.4 RFID Reader and Middleware

Like RFID tags, RFID readers are also available in a variety of shapes, and the antenna can be integrated in the reader or be a separate and independent unit. The reader transmits a signal via the antenna and activates the tag that returns another signal with its data encoded. The RFID reader receives its signal from the antenna when one or more RFID tags are within reach of the antenna. The RFID reader transfers the pieces of information about the subject to a computer or handheld unit that handles the incoming data. The computer typically contains software (middleware) capable of filtering the incoming data, and it allows only the relevant "events" to pass through the configured filter. The middleware also enables integration of the RFID reader with underlying ICT systems such as quality management systems, ERP systems and Virtual Building Models. Fixed RFID readers can be placed at the gate to a construction site enabling automatic identification of all tagged objects passing the gate. Another approach is to use handheld readers such as mobile phones with GPRS/Edge, HSPA or Wireless LAN connection to the Internet. They provide a more flexible solution, where objects can be scanned anywhere. The major disadvantages of the handheld readers are the short reading distances, and that the object reading is only semiautomatic and therefore requires human interaction.

3 Methodology for Evaluation of Ontologies

A large number of methods exist for developing ontologies in e.g. knowledge engineering and software engineering. The methods are used to formalise a given domain into a knowledge base or to develop an ICT-system. In the early system development phases, methods like Contextual Design (Beyer and Holtzblatt, 1998) can be used to understand and formalise user needs and work flows. Rational Unified Process (RUP) (Jacobson et. al, 2005) with its Unified Modelling Language (UML) is useful in the following analysis, design, and implementation phases. UML is a result of best practice in engineering modelling and is widely used for modelling large and complex systems and ontologies.

According to Gómez-Pérez (1995) evaluation of ontologies means to judge the technical features of the ontologies and it includes; 1) check of the structure or architecture, 2) check of the syntax, and 3) check of the content (consistency, completeness, and conciseness). Similarly he argues that assessment refers to the usability and utility of the ontologies, and even a technically well-evaluated ontology will not guarantee that no errors will occur in the integration of its definitions in the system under development, but it will make the process easier.

A number of methods and tools for evaluation of ontologies under development also exist such as OntoMetric and OntoClean (Hartman et al., 2005). Another method for evaluation of ontologies is described by Grünninger and Fox (1995) and is based on user scenarios and informal questioning. However, when it comes to evaluation and assessment of ontologies seen from an ontology consumer perspective, which is the main focus of this paper, the availability of sufficient methods is much more limited. Noy (2004) argues that although the existing evaluation methods are necessary, none are helpful to the ontology consumer, who needs to discover the existing ontologies, and more important which one would be suitable for the task. In addition, she discusses useful methods to assist the ontology consumer in evaluating existing ontologies: 1) Summarization can be used to decide whether a particular ontology fits the application requirements. 2) Opinions from trusted persons are strong arguments for deciding whether to use an ontology or not. 3) The possibilities of ontology customisation or use of a subset of the ontology is important to avoid unnecessary complexity in applications under development.

Based on Grünninger and Fox (1995) and Noy (2004) the following metrics in the review of the ontologies are used:

Brief description of existing ontologies: Within the five domains: meta-ontologies, technical service ontologies, resource ontologies, organisational ontologies and business process ontologies, a summary is given of relevant ontologies to support the link between the virtual models and the physical components. A similar structure of ontologies is also proposed in (Christiansson, 2007). See Figure 1 for an overview of the ontology domains and their relations.

Existing implementations: Whenever possible, examples of existing usage of the ontologies are given and other researchers opinions about the ontologies are referenced.

Usefulness to support a scenario: In Sørensen et al. (2009) a future user scenario was developed based on the method Contextual Design (Beyer and Holtzblatt, 1998). The scenario reflects future applications of the technologies and work processes to be supported by the ontologies. It describes the use of RFID in production management and component element installation. The questions to be answered in relation to the scenario are: 1) Are the ontologies useful (capable of being put to use)? 2) What/who are they supporting? 3) When and how are they used? The scenario is described in section 3.1 of the paper.

3.1 Scenario for Future Use of RFID in Construction

A future user scenario is presented below to outline how the ontologies must support a simple method for continuous project follow up and progress management. The scenario is presented using story telling with the following fictitious protagonists: John, the virtual model coordinator, Jane the construction manager, Michael a precast concrete manufacturer and Paul the foreman. The scenario is one of the results from a contextual design process described in (Sørensen et al., 2009). The scenario is illustrated in figure 3.

Model generation and precast element management: *John is virtual model coordinator in the design and construction of a new office building. His task is to secure a smooth flow of information between all parties in the project. During the design of the building John is responsible for the 3D and 4D modelling, and works in close collaboration with the general contractor's construction manager, Jane, and the project manager, Michael, at the precast concrete manufacturer. John is also responsible for adding the ID's from the RFID tags to the objects in the virtual 3D and 4D model stored on the model server.*

When the concrete elements are ready for shipping, Michael is responsible for updating the 4D production status information on the model server. He does that by reading the RFID tag in each concrete element with his mobile phone, and subsequently presses the button "In transit". Together with the production status information the mobile application automatically updates the model server with data about time, date, user and current location from the GPS. His mobile phone has Internet access and connects to the service provided by the model server.

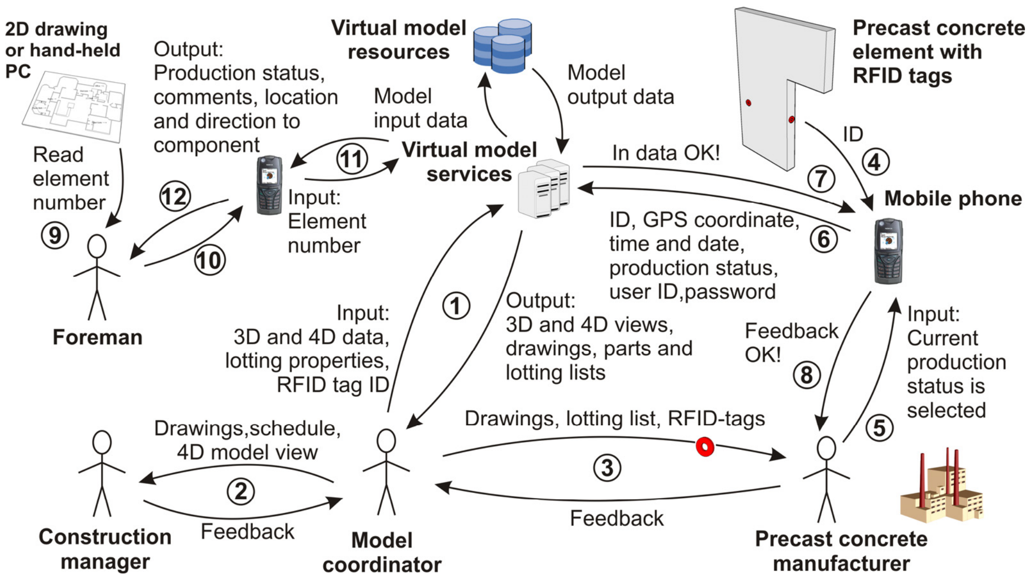

Figure 3 Rich picture illustrating future use of a digital link between virtual models and physical components in construction for model generation and precast element management. The numbered events refer to a possible sequence of the actions.

Construction site precast element acceptance and inventory management: *When the precast elements arrive at the construction site, Jane uses the RFID enabled mobile phone to identify the elements. Prior to arrival, she has already received information about the elements installation time, date, storey and gridline from the virtual model service. While making the acceptance check, Jane writes comments on the phone, if any, and updates the model server with new element data about production status, location, time, date, and user. The acceptance checking also includes finish, transportation damages and measurements of window and door holes.*

On site element location: *A continued update of the virtual model enables any user of the system to retrieve information about current production status, location, comments and direction of any of the precast concrete elements. Foreman Paul uses his mobile phone to retrieve information about where he can find the next element to be installed, and he reads the comment input during element acceptance at the construction site. In case the element is not in place on the construction site, he is notified where in the supply chain it is currently located.*

Task accomplished update: *When a precast concrete element is installed, Paul updates the virtual model with his mobile phone by reading the RFID-tag and selecting the "Task finished" button. He supplements the input with a photo for the quality assurance documentation. He now receives information about the next task, and the location of the elements to be installed.*

Ongoing information retrieval: *During the construction process contractors, engineers, architects and the client can follow the progress of the project in their own offices by means of a virtual 4D model viewer. Furthermore for elements where they have subscribed to notification, they receive an e-mail, SMS or RSS feed whenever production status of the elements is changing. The structural engineer uses this option to get information about when he has to go to the construction site to do follow-up quality checks, and the construction manager is quickly informed when new elements arrive at the construction site.*

In the following sections the scenario is used as a background in the review of the ontologies.

4 Meta-ontologies

Meta-ontologies are the ontologies for ontologies. They specify frameworks and identify languages for defining ontologies and their relations. In the following sections, a brief description of some of the available meta-ontologies relevant for linking virtual models and physical components in construction is given. Their existing implementations and usefulness in relation to the scenario are also discussed.

4.1 Brief Description of Existing Ontologies

An important meta-ontology container is the Semantic Web, with the vision of extending today's World Wide Web from being a medium for document sharing to becoming a medium for data sharing - a universal medium for data, information, and knowledge exchange. Therefore, it is considered as an important framework for future ontologies (including meta-ontologies) supporting knowledge handling in construction by RFID. The Semantic Web provides a common framework (building blocks for ontologies) that allows data to be shared and reused across application, enterprise, and community boundaries. It is a collaborative effort led by the World Wide Web Consortium (W3C) with participation of a large number of researchers and industrial partners. "The Semantic Web is an extension of the current web in which information is given well-defined meaning, better enabling computers and people to work in cooperation." (Berners-Lee et al. 2001)

Some of the important building blocks in the Semantic Web include the specifications of the Resource Description Framework (RDF) and the Web Ontology Language, which are intended to provide basis for a formal description of concepts, terms and relationships within a given knowledge domain (W3C, 2004). Triplets in RDF consist of a subject, a predicate and an object (object, attribute and value). The subject denotes the resource, e.g. a web page. The predicate denotes traits or aspects of the resource, and expresses a relationship between the subject and the object. An object may in itself be a subject.

The InteliGrid project is an example of a research project related to the construction industry that makes use of the Semantic Web to define meta-ontologies. The InteliGrid Ontology Framework (Gehre et al., 2006) describes a meta-ontology and four independent but interrelated ontologies that can be further specialised in an extensible set of domain-specific ontologies serving particular industry purposes. The four ontologies are: 1) Business process ontology, 2) organisational ontology, 3) service ontology and 4) resource ontology. This structure is similar to the one given in this paper with the exceptions that this paper does not differentiate between business process ontologies and service ontologies, and this paper also includes technical service ontologies. A comprehensive framework and supporting ontologies are described in the InteliGrid project deliverables.

4.2 Existing Implementations

The impact of Semantic Web on the construction industry is still very limited. However, a number of research projects have demonstrated the advantages of Semantic Web e.g. in collaboration and knowledge transfer in design teams (Lai, 2006), blogging between construction professionals (Wang and Xue, 2008), and mobile collaboration (Zeeshan et al., 2004). Companies like Metaweb, Ontoprise and twine are commercialising Semantic Web technologies and providing software products and services for implementation in organisations. Open source initiatives are also existing, like the Semantic MediaWiki (SMW, 2009), a free extension of the engine MediaWiki powering Wikipedia and many other wikis. This extension allows the users to add semantic annotations to the hyperlinks between pages in the knowledge management system.

One of the first adoptions of RDF is the widely used RSS news feed. RSS is an abbreviation for Really Simple Syndication (RSS 2.0), RDF Site Summary (RSS 1.0 and RSS 0.90), or Rich Site Summary (RSS 0.91)) and gives users of a website the possibility to subscribe to information e.g. about new articles on the site.

The Inteligrid project deliverables provide an extensive framework, but the practical implementations are limited to a test bed demonstrating the potential, and no companies have yet adapted the solution proposed by the Inteligrid project. From an ontology consumer perspective, it is therefore uncertain if the meta-ontology proposed in the project will have impact and success in the construction industry.

4.3 Usefulness to Support the Scenario

In relation to the scenario presented in section 3.1 the meta-ontologies are needed at a upper level to define how the business processes can make use of the technical services, the resources and people working in the related organisations as illustrated in Figure 1. The Semantic Web and its supporting standards are currently the main proposal for defining future knowledge representations. However, there are also some drawbacks; it might require too much structure to ever become useful. The authors agree with the arguments in (Priss, 2002) that "… *Semantic Web also needs to combine both formal and associative structures and in general utilize multi-strategy approaches to knowledge representation.*"

As explained above, parts of the Semantic Web are already useful today as a framework to fulfil some of the requirements in relation to the scenario presented in section 3.1. RSS feed would e.g. provide the simplest and most flexible way to provide the users with notifications about changes in the virtual model resources. Another possibility is to extend the virtual model resources by Semantic Web functionalities. A query sent from a worker at the construction site about a component would then provide him not only with the simple values of the attributes defined in one virtual model, but also with the relevant instructions, photos, and messages stored in other related resources.

5 Technical Service Ontologies

Technical service ontologies are the specifications enabling data communication through heterogeneous networks, and a standardised use and development of hardware and software from different suppliers.

5.1 Brief Description of Existing Ontologies

Technical communication service ontologies such as the TCP/IP protocol for the Internet and GPRS/EDGE for mobile phone communication are used daily by many people in construction. They are therfore also ready to support the link of virtual models with physical components in construction. The HSPA (3G) mobile broadband network gives faster data transfer speed (currently up to 7.2 Mbit/s in Europe), and is a breeding ground for new rich mobile applications and easier on-site Internet access.

The Internet and WWW, as we know it today, dates back to 1992, and is now facing some comprehensive paradigm shifts that will introduce new ICT (Information and Communication Technology) applications. First of all, the introduction of XML cleared the way for separating the storage and the access medium for digital information on the Internet. The following introduction in 2000 of Web services and Semantic Web and its supporting standards (SOAP, WSDL, and UDDI respectively OWL, RDF, RDF Schema) form a basis of efficient and interoperable future handling of information associated with metadata and data stored in information containers globally distributed on the Internet. SOAP denotes Simple Object Access Protocol, WDSL denotes Web Services Description Language, and UDDI denotes Universal Description, Discovery and Integration. See W3C (2002) for an overview of activities, specifications, working groups and recommendations related to Web services.

Another paradigm shift is the introduction of IPv6. The internet protocol (IP) specifies a hierarchical addressing system that enables a unique identification of all units connected to the Internet. The present version 4 of IP is from the 1970's, and consists of a 32 bits address which will not continue to be sufficient for all units connected to the Internet. IPv6 uses 128 bits addressing which gives 4 million unique addresses per square metre earth surface, which should be sufficient for supporting the growth of the Internet for at least the next 50-100 years, and for allowing a dense integration of IP addresses and RFID. These paradigm shifts form the potential for an 'Internet of things', that is a network where all physical objects such as humans, clothes, machines, building components, etc. have a unique identification, and where information about them can be structured and used rationally by humans and machines. A great potential is expected from the use of the next generation of the Internet in interaction with virtual models in the construction industry.

A large number of technical service ontologies exist for RFID, but only a few of them are of relevance to the construction industry. Two of the RFID ontologies for contactless smart cards, ISO 14443 and ISO 15963, working on the HF-band (13.56 MHz) have already become popular in other industries. They were originally developed for ID cards, but have experienced a widespread use in general for track and trace, cashless payment, production line optimisation and similar purposes, as a consequence of low cost tags and good all-round attributes. ISO 14443 is developed for proximity coupling (0-10 cm), and ISO 15963 for vicinity coupling (0-1m). Tags for both standards are delivered with a pre-printed unique ID, which cannot easily be changed. This ID can be used also for unique identification in interorganizational settings. However, it is important to use high quality tags because tags from less reliable manufacturers also exist where, the ID uniqueness is not definite. The advantage of ISO 15963 tags compared to ISO 14443 tags is their longer reading range which can have significant influence on the system performance. From a construction business point of view, the ISO 14443 also has a significant advantage. It is compatible with the NFC technology (Near Field Communication) which combines the function of a mobile phone, contactless smart card reader and peer-to-peer communication, and is defined in ISO 18092 (NFC Forum, 2008).

Another important ontology is the ISO 18000 series of RFID standards for item management. The six standards in the ISO 18000 series define the air interface between tags and readers on five frequency bands from 135 kHz to 2.45 GHz and a common architecture (ISO, 2004), but not the data contents or the data structure.

EPCglobal is an important developer of ontologies for RFID. EPCglobal is centred on what is called the Electronic Product Code (EPC), which is a fundamental ID system for identification of physical objects in an EPC network (EPCglobal, 2008). Possibly, it is a successor to the widespread bar codes. EPCglobal develops standards in the field to expedite a commercial use of the technology. Therefore, it feeds ISO (International Organization for Standardization) with material with the hope of a faster and wider spread use of RFID. The protocols of the EPCglobal

RFID tags are classified into seven classes according to their features ranging from 1) passive, read only and write-once tags in Classes 0 and 0+ to 2) rewriteable, semi-active tags with integrated sensors in Class III and 3) rewriteable, active, two-way tags that can communicate with each other using their own power supply and are able to supply power to other tags in Class V. The contents of tags and their coding are, at present specified for all the classes, but the methods of communication have presently been specified only for Class 0 and Class I. The classes are specified to improve the possibilities for backward compatibility when their specifications later are completed. Therefore, only passive RFID tags of the tags supporting EPCglobal are ready for use in construction.

EPC uses a URI (Uniform Resource Identifier) in URN (Uniform Resource Name) notation to represent a unique topic with a digital code. A URI is a compact string of characters used for identifying or naming a resource. A URL (Uniform Resource Locator) is also a URI that, besides identifying a resource on the Internet, also specifies with which protocol the resource can be accessed. Often, there is an overlap between URN and URL in resource identification, and it is not always possible to distinguish between them. A URN is a URI that identifies a resource or an object in a specific name space. The name space can e.g. be an ISBN number for books, MAC-address (Media Access Control Address) or IP number for computers or a Serialized Global Trade Item Number (SGTIN) identifier for objects in a supply chain. For a SGTIN-96 identification, in which the number 96 designates that a 96 bits EPC coding is applied, the URN looks as follows:

- urn:epc:id:sgtin-96:FilterValue.CompanyPrefix.ItemReference.Serialnumber

The filter value is not part of the SGTIN number system, but it is a 3 bit value that can be used to quickly identify whether the SGTIN-96 ID is a number of a single object or a whole pallet of objects. Furthermore, the SGTIN code identifies the manufacturer, the product type and, finally, the unique object by means of the serial number. The entire URN is coded into a 96 bits ID saved in the tags. Various companies have developed software tools for coding and printing tags. Examples of such programs and examples of using the coding systems in practice can be found at IDAutomation (2008).

Besides the standards for RFID tags and their contents, EPCglobal also describes the architecture for what they call the “EPCglobal network”. The idea is that this network of standardised and compatible RFID tags, RFID readers and information systems should connect the entire supply chain – from the producer to distributors, and from transport companies to the retail trade. By means of a network service, ONS (Object Naming Service), it will be possible to route requests for objects to servers containing information about the objects. The ONS system is hierarchical and similar to the DNS (Domain Name System) where a set of server functions is implemented as a large distributed database of URL names and IP addresses. Together with the IP protocol in version 6, the EPCglobal Network constitutes a cornerstone of the future 'Internet of things'.

5.2 Existing Implementations

The technical service ontologies TCP/IP, GPRS/EDGE, and 3G enabling the Internet and mobile communication technology, are mature and also widely used in construction. NFC is today available in mobile phones from e.g. Nokia, Samsung, and ARYGON, which are all aimed at the traditional consumer market, and it makes them cost effective compared to handheld RFID readers supporting ISO 15963. The mobile phone is one of a few modern ICT technologies widely accepted and generally used in construction, and therefore it can be an important key to the introduction of RFID in construction.

RFID systems based on ISO 15963 and ISO 14443 are used in many industries for supply chain management, asset tracking and access control. An extensive number of case studies can be found in RFID Journal (2009). Currently ISO 18000 is less appreciated for industrial use than ISO 15963 and ISO 14443, but can be expected to gain more success in the future because of the longer achievable reading distance of the UHF tags (ISO 18000-6) compared to HF tags (ISO 15963 and ISO 14443).

EPC is developed for supply chain management, and the two most significant implementations are at Metro, Germany, and at the world's largest retail chain, the Wal-Mart Stores, Inc., which since 2005 has required of its largest suppliers to use RFID on all their product pallets and larger units. However, as argued by Roberti (2009): "*There is a danger that the EPC RFID movement could simply weather if more retailers don't adopt the technology, and if companies fail to overcome the challenges of collaborating and sharing the benefits*."

Web services are widely used to deliver interorganizational data services for applications such as e-commerce, virtual maps, risk calculation, etc., but can as well be used to integrate internal business systems. An investigation carried out by Al-Masri and Mahmoud (2008) has identified more than 4000 valid Web services available on the Internet. Available Web services can be found by use of ordinary search engines, Web service list portals or the UDDI registry. Although UDDI and search engines provide two distinctive approaches for finding Web services, it is unclear whether they most likely will merge or co-exist (Al-Masri and Mahmoud, 2008).

5.3 Usefulness to Support the Scenario

Use of mobile technology is a core foundation of the scenario described in section 3.1. For simple text-based data transfer the GPRS/EDGE network is sufficient but while introducing more demanding multimedia applications, the need for faster transfer speeds will increase. The lack of bandwidth is however a decreasing problem in many countries.

As described in the sections 5.1 and 5.2 there is a comprehensive range of technical service ontologies available for creating the digital link by means of RFID. However, the challenge is to select the ontology that will be useful to act as a foundation for the whole scenario in section 3.1. Different requirements to the reading range, size of reading devices and portability at the manufacturer, during transportation, and at the construction site make different requirements to the RFID ontologies. Therefore, to improve interoperability and interorganisztional reuse of the data, it is recommended to use and develop RFID tags which combine several of the technical service ontologies. As a minimum a combination of NFC and EPC (HF and UHF) is needed, but it would also be beneficial to include compatibility of ISO 15963 and ISO 18000. Because LF RFID tags are readable through most materials and are better suited for embedment in construction components a combination with this technology would also be beneficial.

Web services are expected to be useful for defining future ontologies for integration of the devices presented in the scenario. However, meta-ontologies are needed to enable a better integration of the, to a large extent, separately developed technical service ontologies. Web services can be useful in the future for a smoother integration of the technical services from various RFID readers, sensors, communication devices, storage equipment, construction machines, transport equipment, etc.

6 Resource Ontologies

Resource ontologies are dedicated to represent all data sources such as files, documents, databases, product and process models, and model views. A prerequisite for interoperability in interorganizational settings is a common resource ontology for representation of data, information and knowledge.

6.1 Brief Description of Existing Ontologies

ISO 12006-2 and IFC (Industry Foundation Classes) are the two major candidates for resource ontologies for the construction industry (Ekholm, 2005). ISO 12006-2 is a framework for classification of information within construction, but does not provide a complete classification system. A number of national implementations of ISO 12006-2 are available, e.g. the North American Omniclass, the Swedish BSAB and the Danish DBK. Unfortunately, there is currently no deeper harmonisation between IFC and ISO 12006-2 or between classification systems based on ISO 12006-2. The IFD Library for Building Smart (International Framework for Dictionaries) (Bjørkhaug and Bell, 2007) is an international development addressed to connect classification systems and product models. This is an important initiative towards enabling the users described in the scenario in section 3.1 to retrieve context sensitive information such as installation instructions, maintenance instructions and other virtual model views.

Numbering systems are an important part of the mentioned classification systems and can be used for identification of physical components in buildings by adding numbering codes to the RFID tag. A digital link between the resources such as virtual models and physical components can thereby be established. However, it is not advisable to use the code for early object identification because it depends on the final placement of the components in the building and the component system of which the component is a part of. There may also be many RFID tags attached to the same object. The code is therefore dependent on an instantiated virtual model of the project which is not always available when the actual components are produced. The classification system is, on the other hand, important for organising information about the objects and their relationships. Therefore, in most cases, it is recommended to only have a global unique identifier (GUID) in the RFID tag, and to store all other data in the supporting virtual models organised by the resource ontologies. It is the simplest and most flexible way to secure the possibilities for reuse of RFID tags in interorganizational relations. The exceptions are situations where access to the virtual model can not be established or the specific applications require object related information to be stored in the RFID tags for fast real time access.

In some years paper based documentation will still be necessary, and this will require human interpretable numbering or codes on objects. A printed bar code supplemented with the object label could be the first step towards both computer and human interpretable codes on drawings that support the workflow action 9 in Figure 3. With the current development in flexible display technology (Plastic Logic, 2007) the need for human interpretable general numbering systems will however decrease and be superseded by hyperlinks on the digital views.

Another project from the construction industry worth mentioning in relation to resource ontologies is the SABLE project (Simple Access to the Building Lifecycle Exchange). The objective of this project was to enable easier access to resources stored in an IFC model server by providing a common framework for linking IFC model servers and a standardised interface for client access to the IFC model servers. (BLIS, 2005)

Because of the extreme complexity in developing an international classification system for organising information in construction, information retrieval based on keyword tagging and search machine indexing could be a useful technique for retrieval of information related to components in a building. Keyword tagging has emerged as a popular method for categorising contents on a website. Users are allowed to attach arbitrary strings to data items such as blog entries, photos or items for sale. When websites supporting metatagging grow, their structure will evolve to an ontology for the data that the website presents. The ontology is thereby developed by the users who are using the website. An ontology created in this way is called a folksonomy (Porter, 2005). It is an easy and somewhat useful way to structure and link information, but it has also some critical downsides. A folksonomy tag is typically 2/3 of an RDF triplet. The subject is known, e.g. the URL for the image being tagged, or the URL being bookmarked. The object is known from the tag, but the predicate to connect them is often missing. To enable machine readable information in folksonomy based ICT tools, the information providers must add supplementary semantics expressing the relationship between the subject and object. (Herman et al., 2008)

6.2 Existing Implementations

There are an extensive number of free and commercially available software applications supporting IFC. They are used for authoring, viewing, debugging, conversion, information exchange, simulation and software development in relation to virtual building models. Despite a certification process for IFC supporting applications, there is still no guarantee that information created in one tool can be reused in another. This uncertainty and lack of commitment from application suppliers are major challenges to overcome. See Kiviniemi et al. (2008) for further discussion about this topic. As mentioned above the implementations of ISO 12006-2 are also facing great challenges before they will become successful. An organisation consisting of the six largest consulting engineers and contractors in Denmark has e.g. tested DBK (the Danish implementation of ISO 12006-2) and conclude that the standard in the current incomplete version, with the current low level of financial resources and limited industry support has very limited chance to become a winning standard in Denmark (Digital Konvergens, 2008).

The user created ontologies (folksonomies) are widely used at social websites like del.icio.us and Flickr and as argued by e.g. Vander Wal (2007): "*These tools were causing quite a stir on many of the information science list serves as the tagging seemed to be working for finding things, more from exploration and serendipity than through searching and intent.*" Although, folksonomies are successful in other businesses their potential to improve productivity or quality in the construction industry is still not clear.

6.3 Usefulness to Support the Scenario

The product and process model ontology IFC in its current edition 2x3 supports the RFID tagging in the scenario in section 3.1 by use of the *IfcClassificationReference* class, a subtype of *IfcExternalReference*. By adding the GUID from the RFID tag to the IFC model as an *ItemReference* it can be associated with any building element in the virtual model. Unfortunately there is, no inverse relationship between an *IfcClassificationReference* and *IfcRelAssociates* declared in the IFC 2x3 schema, which would give the possibility to navigate back from an External reference to an *IfcBuildingElement (subtype of IfcObject)*. The next edition of the IFC specification (2x edition 4), currently released in alpha version, supports this inverse relationship (Liebich et al., 2008). The navigation between IfcObject and the IfcClassificationReference is illustrated in Figure 4. Future implementations of IFC product models and IFC API's (Application Programming Interfaces) are therefore expected to be able to support the scenario described in section 3.1.

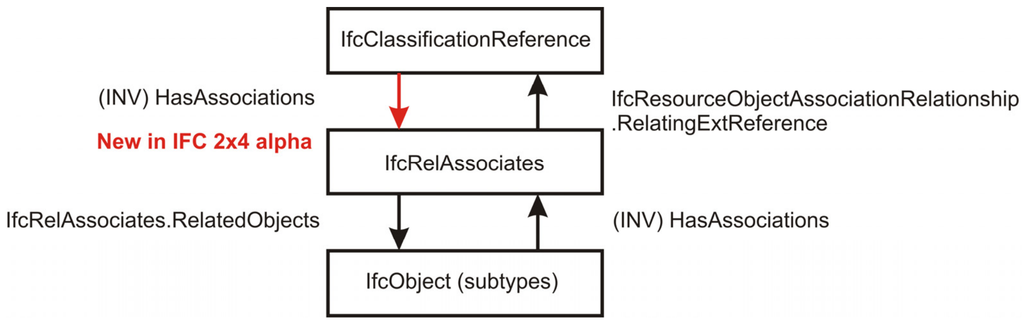

Figure 4 Illustration of navigation between IfcObject and an RFID included in an IFC model as an IfcClassificationReference.

It would also be beneficial to be able to model RFID tags not only as an ID attribute but as an object or property set in the IFC model with properties such as; GUID, current location, planned location, time and date for tag readings, user name, and active/deactivated tag.

Another approach is to add the global ID of the IFC object to the RFID tag. It is, however, not recommended because this will make the virtual model less flexible to changes. Often it is also necessary to let both one RFID tag point to several objects in the virtual model, and to have several RFID tags to point to one virtual object. Furthermore, RFID tags are often born with a fixed GUID.

For example can one RFID tag placed on a doorframe be used to identify the opening, the door, the room, the façade, and the building. Similarly it is often required to have at least two RFID tags on the same building component because with short reading distances the same tag can not be read when the component is in stock and when it is at the final location in the building. In the case with precast concrete elements, one tag is placed on the end of the element and used during transportation and storage and another is embedded in the side of the element and used after mounting of the element.

A combination of using folksonomies and the described resource ontologies will enable the users to retrieve information related to the scanned components. The response can also be made user, context, and temporal dependent. For example a construction manager and an inspection engineer scanning the same component should be presented with different information. The construction manager scanning a component at the temporary storage at the construction site should e.g. be presented with work instructions, schedule details, and progress monitoring schemas. The inspection engineer scanning the same component after installation at the construction site should be shown relevant check lists and model views.

7 Organisational Ontologies

Development of organisational ontologies is a general issue for any industry and concerns definition of concepts such as actors and their relations, hierarchies in projects and organisations, interorganizational relations, etc.

7.1 Brief Description of Existing Ontologies

In the Inteligrid project (Gehre et al., 2006) an organisational ontology is developed based on actor and project definitions from the IFC standard, developed by the IAI (IAI, 2006), authorisation from the RBAC standard (Ferraiolo et al., 2001) and supplemented by additional concepts from the CIM model (Distributed Management Task Force, 2006).

Another new organisational ontology is the Web Service Business Process Execution Language (WS-BPEL) extension designated BPEL4People (Agrawal et al., 2007). BPEL4People enables the modelling of human interaction processes using BPEL, but does not contain a complete organisational ontology. A combination of BPEL4People and the Inteligrid organisational ontology might therefore be useful for developing interoperable applications.

In relation to Semantic Web, the Friend of a Friend (FOAF) Vocabulary, gradually developed since 2000, is a different approach to an organisational ontology. Because of its simplicity and roots in the fast expanding world of ICT-based social networking, FOAF is a potential candidate for the first widely accepted organisational ontology. For this reason it should also be considered used in the construction industry. FOAF uses the Resource Description Framework (RDF) for defining persons, their ongoing projects, organisations, interests, personality, relationships, etc. (Brickley and Miller, 2007)

7.2 Existing Implementations

Usually, virtual model authoring tools supporting IFC also have implemented the organisational ontology from IFC. In practice it means that models exported from an IFC compatible tool contain information on the author/user, the company and the project. However, there is no information in the model about how the author is related to other model users and to the organisation or how the companies in the project organisation are interrelated.

The FOAF ontology enables an easy way to discover relationships between people and resources accessible on the Internet. Many social network websites have utilised the potential of FOAF to share user profiles. Google Social Graph API (2009) is an example of a developer tool to help web developers utilise public connections, which their users have already created in other websites.

7.3 Usefulness to Support the Scenario

The organisational ontologies enable administration of rights to information and context dependent information delivery to the users as described in connection with the resource ontologies in section 6.3. In relation to the example in section 6.3, it is the purpose of the organisational ontologies to define the framework for user, organisation and project profiles. The lack of existing industry implementations precludes a reliable assessment of the organisational ontologies usefulness.

There are also some negative consequences of using the organisational ontologies. Sensible information about employees and collaborators can be easily be accessed e.g. from the Internet, data security is therefore a particular subject to address.

8 Business Process Ontologies

By use of organisational and resource ontologies, the business process ontologies specify services for interorganizational communication and information exchange. They enable a direct relationship between business processes and business requirements and support workflow management.

8.1 Brief Description of Ontologies

There exist a large number of national classification systems containing business process ontologies such as the North American OmniClass, the British Uniclass or the widely accepted but outdated Swedish SfB (Samarbetskomitén för Byggnadsfrågor) (Lima et al., 2007) that is widely used in Denmark. The classification systems are used in e.g. proprietary implementations of cost estimation software and for structuring tendering material. A common limitation of these implementations of business process ontologies is the lack of support for interoperable and automated use by machines such as computers. The e-Cognos project and the Inteligrid projects are addressing this challenge by providing frameworks for implementing ICT systems based on their respective ontologies. In the e-Cognos project a platform for deploying knowledge management systems has been developed and is now available for free under the GPL license

(General Public License) (e-Cognos, 2003). The Inteligrid project describes a framework for developing interoperable business services, which can be implemented using service oriented business architecture (SOBA), and Business Process Executions Language (BPEL) (Gehre et al. 2006). The framework describes high-level business process objects, but when it comes to more detailed ontologies about actual information delivery, a reference is made to the ongoing Information Delivery Manual (IDM) and Model View Definition (MVD) projects of the BuildingSMART initiative (Wix, 2005).

In Denmark the national Digital Construction project has worked with information delivery to the construction site and to the client in a digital project handover process. The use of a production card has been proposed to represent the information needed to conduct a given task, and an XML-schema has been specified for representing the information needed in the project handover to the client. Knowledge from these projects can be valuable in relation to developing future business process ontologies based on functional building systems, but they are currently not considered to be mature enough for industrial use. See also Christiansson (2007).

8.2 Existing Implementations

One of the major drawbacks of the above described business process ontologies, frameworks and research project, is their limited impact on the digital working processes in construction. As argued in (Kiviniemi et al., 2008): "*The missing part has always been the exchange specifications, which are still under development, both to form and content. The IDM, Information Delivery Manual and MVD, Model View Definition initiatives are aiming at resolving this issue.*" and "*As for IDM/MVD, the standards are still under development, and although certain proofs of concepts exist, it is not yet ready for implementation in off the shelf software.*" The described business process ontologies are therefore not considered to be mature enough to be used in a system implementation supporting the scenario described in section 3.1.

8.3 Usefulness to Support the Scenario

Business ontologies are crucial to utilise the potential of the scenario described in section 3.1. Although the business integration between the virtual model services, the virtual model resources and the mobile devices can be developed on basis of proprietary solutions, the authors' expect interoperability in these interfaces to be vital for a wider international acceptance of the working processes described in the scenario. The integration of information between different organisations is a crucial part of the scenario. The virtual model resources (virtual model servers, ERP systems, asset management systems, facility management systems etc.) used in the organisations to handle the information are developed and used on widely different bases and the business process ontologies must define the interfaces between them. The scenario shows that there is a need for business process ontologies (e.g. Information Delivery Manuals) to support at least project progress management, work instruction delivery, quality inspection, inventory management, construction planning, procurement and facility management.

9 Conclusions and Future Work

This paper gives a review of existing ontologies relevant in relation to linking virtual models with physical components in construction. It was found useful to categorise the ontologies in five domains after their applicability to specify meta-ontologies, technological services, resources, organisations and business processes. Up till now, the proposed structure of the ontologies seems to be well-founded. The applicability of the ontologies to fulfil future requirements was reviewed from an ontology consumer (system developer) perspective by summarising available ontologies within the five ontology domains, examine existing implementations and assessment of usefulness to support a proposed future user scenario.

The conclusions are: 1) the meta-ontologies developed for the Semantic Web and the InteliGrid Ontology Framework will be important for developing future ICT infrastructures for information handling in construction. 2) Many technical service ontologies are already mature and used widely for communication through the Internet and mobile phones. Therefore, the challenges are integration of these ontologies with the remaining ontologies. Regarding the RFID technology a number of available technical service ontologies exist, e.g. ISO 14443 and ISO 15963 for HF RFID technology, and EPC and ISO 18000-6 for UHF. These ontologies enable interoperable access to data stored in the RFID tags. Here, the critical task is to select the right ontology because they are not all compatible. 3) The resource ontology IFC supports representation of identification numbers from RFID tags. However, there is a need for modifications of the current edition 2x3 of IFC, that allows object information retrieval based on registered RFID tags. It is proposed to use a combination of meta-tagged information based on specified ontologies with the use of search engines using automatic full-text indexing and keyword tagging. This can function as a quick way to provide users in construction projects with widely used information such as work instructions, documentation, and schedules 4) Various proposals exist for organisational ontologies such as the Business Process Execution Language for People (BPEL4People), the Semantic Web based Friend of a Friend (FOAF), and project and actor definitions in IFC, but none of them have gained wide acceptance. FOAF is simple and originates from the widely expanding ICT-based social networking world and is therefore expected to be the first generally used organisational ontology. 5) Business process ontology development is a discipline requiring new development and specification of e.g. functional building systems before it can be used in relation to linking virtual models with physical components. The scenario illustrate a need for business process ontologies at least to support project progress management, work instruction delivery, quality inspection, inventory management, construction planning, procurement and facility management.

Development of new ontologies starting at meta-levels, and an increased use of internationally accepted ontologies will enable the structuring and reuse of information for the great benefit of the whole industry. Nevertheless, it is also one of the most complicated hurdles to overcome for the industry, and an increased focus from major universities, companies and property owners is needed for progress in this area.

The authors' ongoing research focus on identifying the users' needs in relation to creating a digital link between virtual models and physical components in construction. This will be done through prototype development and pilot testing of an ICT system that supports the scenario described in section 3.1. The intention of this development is to increase knowledge of how the technology can support the working processes in construction and then subsequently use this knowledge to create future ontologies grounded in the actual users' needs.

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Paper II

Prototype Development of an ICT system to Support Construction Management Based on Virtual Models and RFID

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Prototype Development of an ICT system to Support Construction Management Based on Virtual Models and RFID

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Abstract: *There is a need to develop new information and communication technology (ICT) systems with better support of the contractor's working practice in order to gain more advantages from the virtual models created during the design of buildings. For this reason, a Contextual Design of a prototype (an early example) of an ICT system was carried out to identify and formalise user needs in relation to construction management based on virtual models and radio frequency identification (RFID). The prototype was developed to support working processes in real-time project progress management, quality assurance and inventory management.*

In this paper a number of user needs for future ICT systems are presented. The needs are captured during the prototype development process and include that future ICT systems must be more user-friendly, enable object-oriented quality assurance procedures, capture data to be used in process optimisation (lean construction), support a wide range of user environments ranging from mobile phones to large displays for presentation and editing data shared in virtual model resources, enable real-time tracking and location of machines and materials, and integrate traditional document/drawing based working practice with the use of virtual models to enable an easier adaptable change process for the construction industry.

1 Introduction

Lack of quality and too many defects are well-known challenges in the construction industry. Many previous research projects have identified the causes and cost of these defects in construction. The purpose of the research presented in this paper is to form a background for a future information and communication technology (ICT) system development to address these challenges. This is done by capture of user needs and prototype (an early example) development in relation to construction management, virtual models, and automatic object identification by means of radio frequency identification (RFID) technology.

1.1 Challenges in Construction

In Josephson and Hammarlund (1999) an overview of several studies of defects in building projects from 1969-1992 is given. In this overview the cost of defects occurring during production is stated to be 2-6 % of the cost of production. The cost of defects occurring during the maintenance phase is stated to be 3–5 % of the production cost. No figures are given regarding the briefing and design phase due to a limited number of studies on these phases in the construction process. Josephson and Hammarlund (1999) also present results from an extensive study on causes of defects where seven building projects was monitored during 6 months. No single reason for defects can be given, and Josephson and Hammarlunds analysis shows that on average 32 % of the defect cost derive from the early phases, i.e. in relation to client influence and design. Approximately 45 % of the defect cost derives from the site, i.e. in relation to the site management, and the workers and subcontractors' activities. Approximately 20% of the defect cost derives from materials and machines. The causes of defects are difficult to identify, but it is stated that on average 50% of the defects are caused by lack of motivation. However, only a few of these are intentional. 29% of the defect costs are caused by lack of knowledge, and 12% of the defect costs are caused by lack of information. A small part is due to lack of communication, stress and calculated risks. Josephson and Hammarlund's results show that the causes of the defects can be found in: 1) Key persons in the client organisation were often replaced, 2) client's long decision time, 3) user involvement in the late stages, 4) time pressure, 5) changing project organisations, 6) cost pressure, 7) lack of support to site managers from their main offices, 8) lack of activities aimed at motivating workers on site.

Findings from the Danish research project "Snublesten i byggeriet" (Stumble stones in construction), and a case study on a 3500 m² residential building conservatively estimate the direct and indirect costs of defects to be 8% of the production cost (Apelgren et. al, 2005). In this project the most frequent causes are stated to be: 1) Deficiencies in communication and cooperation, 2) mistakes and weaknesses in the design, 3) lacks in production planning and preparation, 4) insufficient project information handover meetings, 5) mistakes by contractors due to lack of competences and few resources allocated to instruction and control.

1.2 Information and Communication Technology to Increase Productivity in Construction

The Danish Government has in the project "Digital Construction" (DC) promoted enhanced use of modern information and communication technology (ICT) to facilitate increased productivity through better coordination between the different phases of the building project (NAEC, 2005). The project ran from 2003 to 2006, and the focal point of DC was the vision of an object-based working method, where all project data are associated with a virtual 3D model that gradually develops through the life cycle of the construction. The visible results of DC are a statutory about requirements for the use of information and communication technology in construction (NAEC, 2006) supplemented by recommendations for new working methods (bips, 2007).

The main aspect of the working methods described by bips (2007) is practised in Ramboll Denmark today. It concerns use of building information modelling (BIM) in the design phase, collecting discipline models to aggregated models, consistency check, etc. The immediate advantages are great, and the author's experiences using this new working method in practice show that it; 1) introduces fewer errors, 2) gives a better production basis, and 3) improves clarity and enhances communication methods compared to traditional 2D drafting methods. Other researchers have recently reported similar productivity gains using virtual modelling compared to traditional drafting (Sacks and Barak, 2008; Woksepp, 2007).

No single method can solve all the challenges indicated above. However, the use of modern ICT in the design phase has proven to address some of the challenges. Therefore, it is expected that improved use of similar technologies in the construction phase may reduce defects and increase quality in construction by improving knowledge and information handling, project transparency, project and quality management methods as well as knowledge capture in general. It is expected that a better link (both in digital terms and working process related) between the virtual models and the physical components in construction will be an important future development to achieve the benefits from using virtual models in construction. Such a digital link can be created by means of radio frequency identification technology (RFID). See Sørensen et al. (2009) for an introduction to this technology, its application in construction, and an overview of related ontologies.

Virtual modelling and virtual models are not new inventions, hence the terms have been used in many contexts and also under different names since the mid-seventies, where the first prototypes for use in construction were introduced (Eastman et. al, 2008). Today, in construction practice and in research, terms like object-oriented model, information model, 3D model, building information modelling (BIM) model and virtual building model are often used interchangeably. In this paper the term virtual model is used to describe any digital parametric object oriented product and process model of a physical object (e.g. a person, a building part, a room, a house, a city or a planet, etc.). The term "virtual model" is used rather than e.g. BIM model or virtual building model to reflect that the subjects discussed are not only applicable to buildings, but also generally applicable in the construction industry. The virtual model often, but not necessarily, contains a geometrical 3D representation of the modelled objects. BIM is the term used to describe the process of creating and using virtual models of buildings.

The RFID technology is today mature enough for practical implementation in construction (Sørensen et al., 2008, Chin et al., 2005) but a wider introduction to the industry is still to come. Some significant reasons for this are lack of de facto ontologies enabling easy interorganisational information exchange (Sørensen et al., 2009), as well as poor human computer interfaces and software applications enabling the user to achieve the benefits from the technology. Rather than trying to enforce a technology push on the construction industry, the intention of the research underlying this paper is to indentify the actual user needs in construction in relation to linking virtual models with physical components in construction. The acquired knowledge is then used to develop prototypes of ICT systems that can fulfil as many of the identified needs as possible. This is the first step in a system development and redesign of working processes towards enhancing construction management by means of virtual models and RFID.

1.3 Outline and Conclusions of the Paper

Firstly, this paper gives an introduction to the context of the research. Secondly, the methodology Contextual Design used for the research is presented followed by section 4. Contextual inquiry, 5. Consolidation, 6. Work models, and 7. Vision, Work-redesign and Storyboard that describes the findings from the Contextual Design process underlying the prototype developments described in section 8. Mock-ups. Finally, recommended future extensions of the functionality of these prototypes and conclusions are given.

The conclusions are that new ICT systems that support on-site working practice better than prior systems are needed. They must 1) enable the contractor to easy monitor and present project progress, 2) enable object-oriented quality assurance, 3) support a wide range of user environments ranging from mobile phones to large displays for presentation and editing data shared in virtual model resources, 4) enable real-time tracking and location (by GPS) of machines and materials, 5) capture data to be used for work process optimisation, and 6) predict constructability problems before they cause trouble at the construction site. Future ICT systems must also provide a better integration of the traditional paper document/drawing based working practice with modern virtual model based working paradigms. This is needed to enable an easier adaptable change process for the construction industry. Requirements for and prototypes of ICT systems that address these user needs are presented in this paper.

2 Context of the Research

A number of cases have been studied to identify the user needs in relation to linking virtual models with physical components in construction. The cases represent a broad segment of working processes in the construction industry, from design to construction and operation.

The research is based on studying working processes taking place in relation to the Department of Buildings, at Ramboll in Aalborg, Denmark. Ramboll Denmark is part of the Ramboll Group, which is a leading Nordic provider of knowledge services with more than 8,000 employees and activities all over the world. The company is operating in a broad international context from 130 offices in the northern European region, and from around 25 permanent offices in the rest of the world (Ramboll, 2008). The Ramboll Group provides engineering, consultancy, product development and operation services within the areas of buildings, water and environment, infrastructure, telecommunication, industry, management, energy and IT.

The Department of Buildings in Ramboll, Aalborg, has approximately 60 employees, and delivers engineering services primarily within design of buildings for power stations, hospitals, cultural activities, industry and residential purposes. It is a multidisciplinary department with competences in structural engineering, ventilation and MEP (Mechanical, Electrical and Plumbing) engineering as well as facility management. At least 20% of its revenue derives from international projects. The department has since 2004 worked on implementing BIM and is today leading in this field among engineers in Denmark.

The research reported in this paper has focussed on how contractors and clients can benefit from the virtual models created during the design process (at Ramboll). Focus has also been on identifying how this can be supported by a link between the virtual models, and the physical components and how ICT systems supporting this link should look and function. The other companies involved in this research are customers and working partners of Ramboll.

The cases studied used in this research are construction management at Aalborg Engineering and MT Højgaard, and precast concrete element fabrication at Fårup Beton Industri and Spæncom. In parallel to the research presented in this paper, future user needs in relation to facility management were also studied. For further information about this case study see Sørensen et al. (2008). After an introduction to the methodology used in this research project the three cases underlying the research are presented.

3 Research Methodology

A Contextual Design of a prototype ICT system has been carried out to identify and formalise user needs in relation to automatic object identification for construction management. Contextual Design is a method developed by Beyer and Holtzblatt (2000) to handle the collection and understanding of data from field studies to design of software based products. In the software design process, the method is here used as an important tool to collect the right input for a system specification. It is therefore a natural predecessor for an object-oriented system implementation with detailed system modelling based on e.g. Rational Unified Process (RUP) and UML modelling (Jacobson et al., 2005). As described in Göransson et al. (2003) Contextual Design and RUP can by advantage be combined in ICT system development.

The Contextual Design method is user centred, and the following techniques are used in the method:

Contextual Inquiry: Interviews, workshops and observations of future users in their actual working environment are carried out to get an understanding of the business problems that the system must support. It ensures capture of the real business practice and daily activities and not just self-reported issues and company policies.

Work-modelling: Drawn models representing the users' work practice allow the developer and end user to attain a common understanding and share their findings. It includes work flow models, sequential models of tasks, cultural models, and models of the physical environment and the used artefacts.

Consolidation: All the individual findings from interviews, brainstorming and work modelling are grouped in hierarchies and consolidated to show common patterns.

Work-redesign and visioning: Based on reviews of the models a vision of how the new system will support and streamline the working practice is sketched.

Storyboarding: A sketched and written story is created including sketches of future user environment and narrative descriptions of how it all will work in practice. The story will function as the common understanding between end users and developers of how the system will work and which functionality it will have.

User environment design: Based on the storyboard a single model of functionality and organisation of a user environment is created.

Mock-up and test with users: Paper based mock-ups/prototypes of the user interfaces are designed and evaluated in user tests. The level of detail of these mock-ups is increased through the development process starting with very simple sketches.

The above presented process is iterative and incremental, which means that findings from one step in the process will lead to updates of both the preceding and following steps in the process. The design is initiated from rough sketches, notes and simple models, which are detailed through iterations in the research and development process.

Compared to other methods from social science (see e.g. Alvesson and Sköldberg (2000) for an overview) used to study human behaviour and actions, Contextual Design offers a complete and easy to use framework. It is well organised and provides modelling tools to formalise the unstructured connections between work processes and the users' needs in relation to ICT system development. The work models developed from contextual inquiries provide a basis for a common understanding between software developers and end users.

In this research project the Contextual Design process (an applied anthropological approach) is supplemented by reviews of available literature within the field, and trail tests of software and hardware to be used in the final system and for the development. Also demonstration software applications are created and evaluated by future users.

It has been found rewarding to take the design of early paper-based mock-ups of the user interface traditionally created in the Contextual Design method, one step further by giving them some functionality and appearance like the real applications. Demonstration software applications (prototypes) with some functionality are therefore created and used for tests, and collection of user feedback and ideas. It is important to let the users know, that it is only a demonstration application being presented; otherwise they might expect the development process to be in a late state where their input does not matter any more. There is also a risk that they might be disappointed if the final release of the application has a different appearance or functionality due to findings achieved later in the system development process. Besides the end-users, it has also been found rewarding to use the work models, storyboard and prototypes in communication with software developers and other researchers. See Christiansson et al. (2002) for another approach to using the Contextual Design method for ICT system development in construction.

The contextual inquiry has been done as informal interview's and work observations of future users with different roles in relation to construction. The users involved in the inquiry are consulting engineers, construction site managers, and workmen. Observations at construction sites, factories and offices where the system is going to be used was also made. More than 20 future users have been involved in the inquiry process. The level of involvement in the Contextual Design process has varied for the users. Some construction managers have been highly involved in both the formulation of ideas, inquiry in own organisation and evaluation and development of prototypes and scenarios. Other engineers and construction workers have participated in workshops or meetings, and some have been observed during their daily work and asked for their opinion and feedback on the on-going prototype system design.

The identified needs are supplemented by input from discussions with colleagues, software developers and other researchers to form the presented requirements, consolidated work models and prototypes. In Beyer and Holtzblatt (2000) it is stated that interviews of 10-20 users are enough to collect most of the user needs. More interviews will not result in significantly more identified needs. The design process and the outcome of it are documented in the following sections 4-11 of the paper.

4 Contextual Inquiry

As described in section 3, the contextual inquiry was conducted as interviews, workshops and observations of future users in their actual working environments. The contextual inquiry has taken place in the three cases described below.

4.1 Case 1 – Construction Management at Aalborg Engineering

Aalborg Engineering is a Danish company specialised in designing and supplying steam boiler systems and heat recovery steam generators (HRSG). The company is based in Aalborg, Denmark, but its approximately 30 employees work worldwide, and most of the turnover comes from international projects. Aalborg Engineering has a standardised product package of boilers to power stations and industries with high energy consuming processes producing waste gas steams. The services often include design, procurement, production, erection and commission of the full boiler system. Each boiler system is uniquely designed and customised to the needs of each individual customer. (Aalborg Engineering, 2008)

The equipment and components for the boiler systems are purchased in various countries by Aalborg Engineering, and the erection work is carried out by subcontractors. The steel structures supporting the steam boilers and the surrounding footbridges, service decks and staircases are often designed by Ramboll, described in section 2 of the paper. Ramboll and Aalborg Engineering have an informal partnership from working together on boiler systems for 10-15 years.

The processes studied at Aalborg Engineering are those concerning management of construction and design of the steel structures in the steam boiler systems. In this case study the contextual inquiry is based on semi-structured interviews and the first author's observations from working in the Department of Buildings at Ramboll Aalborg.

Semi-structured interviews were held with head of department and assembly managers at Aalborg Engineering and with building technicians at Ramboll.

4.2 Case 2 – Construction Management at MT Hojgaard

MT Hojgaard is one of the largest general contractors in Denmark with about 5000 employees. The company works in Denmark and internationally with any kind of buildings and infrastructure projects including bridges, residential buildings, industrial and cultural buildings, roads, project development, etc. (MT Hojgaard, 2008)

The building project used in this case study is a traditional two-storey Danish office building of 3700 m^2 including a basement. It is a public-private partnership project, where MT Hojgaard is the general contractor, Ramboll is consultant on all engineering services, and the architectural firm is the company Cubo. The carcass of the building is prefabricated of concrete elements, which is the most common construction method in Denmark. The working processes concerning precast concrete element design, fabrication and erection have formed the basis of the contextual inquiry and design presented in this paper. These processes were selected because they represent a complex multi-disciplinary task. If we can develop a method to support services for this complex multi-disciplinary task, it is expected that it can be applied to many working processes in construction.

The future users involved in the inquiry from MT Hojgaard are construction site managers, IT-managers and workers at the construction site.

4.3 Case 3 - Construction Management at Faarup Beton Industri and Spaencom

Precast concrete elements are one of the most common building components for carcasses of buildings in Denmark. They are produced at approximately 30 factories widely spread in Denmark. Two of the companies producing and mounting precast concrete elements in Denmark are Faarup Beton Industri (FBI) and Spaencom. They produce walls, slabs, beams, and columns from unstressed reinforced concrete, and Spaencom also uses prestressed concrete in their slabs and beams. Contextual inquiries of the management and production processes of precast concrete have been made as observations at three of FBI and Spaencom's factories. The observations have been supplemented by informal interviews of production managers and engineers at the factories. Spaencom delivered all precast concrete elements to the building described in Case 2, and for that reason their processes concerning element mounting were studied in combination with Case 2.

4.4 Examples of Information Captured from the Contextual Inquiries

Early sketches of existing working processes and rich pictures describing ideas to new systems have been created on basis of the inquiries in the case studies. These sketches were consolidated through iterations in the design process and have formed the basis of the consolidated work models presented in section 6 of the paper. Examples of these early sketches are given in Figure 1. Notes supplementing the sketches have also been taken and these are presented in the affinity diagram in section 6 of the paper.

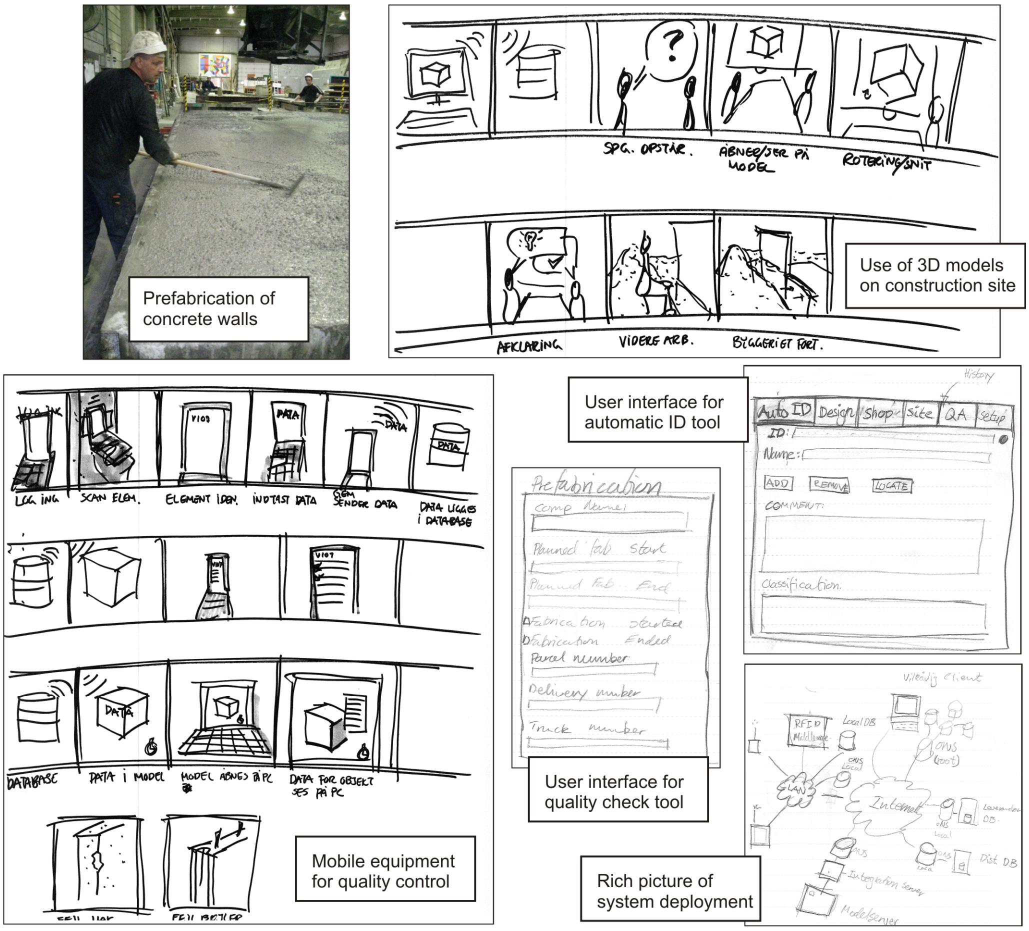

Figure 1 Examples of photos and sketches collected during the contextual inquiry.

5 Consolidation

In the Contextual Design method, affinity diagrams are used to organise the individual notes captured during interviews, observations and tests into a hierarchy of common issues. The hierarchy is built bottom up by creating a structure from the content of the notes collected during the design process. Inspiration to the structure has also been found in Wamba et al. (2007). The affinity building is the first step in consolidating the captured observations and user inputs to formalised requirements for the future system. A number of future user needs and comments have been collected. They are as earlier mentioned based on study of existing working processes and discussions with future users about working processes involving virtual models and automatic identification using RFID. Focus has been on use of these technologies in the construction management process. For a comprehensive discussion about the general use of virtual models in construction, and other recent case studies, reference is made to Eastman et al. (2008). To keep the broad understanding of the users' needs, no distinction is made in the paper between what in reality is possible or financially desirable to implement. From the affinity building it has been found useful to categorise the findings according to their relevance to overall strategy, organisation and working processes, technology and infrastructure, human resources, physical components, virtual models in construction management, quality assurance, and social and political aspects. The individual findings are grouped and presented in the diagram below. A short summary of the most important of these findings are given after the diagram.

Table 1 Affinity diagram with the captured observations categorised according to their relevance to overall strategy, organisation and working processes, technology and infrastructure, human resources, physical components, virtual models in construction management, quality assurance, and social and political aspects. For each observation it is noted whether the observation is a challenge (C) to be addressed, or a potential (P) to be utilised. (Continued on next pages)

C/P	Overall strategy
C	Alliances in business networks are needed. No single firm can drive the widespread introduction of RFID in construction themselves.
C	Individual companies in the construction industry must be less reluctant to adapt to requirements from other companies.
C	Functional split in working processes introduce waste of time in the project schedules and encourage each individual trade contractor to sub-optimise their own profit.
C	Clients often exert pressure on the project erection start-up without knowing the risk and potential extra cost they introduce to the project.
P	Procurement and prefabrication in Eastern Europe and China set new demands to logistics, planning and quality assurance in the construction process making RFID an interesting technology to link business processes in intra-organisational settings.
P	Strategic partnerships are needed at overall business level rather than on project level as current practice today.
	Organisation and working processes
C	When sharing and using 4D planning information in intra-organisational settings, new legal agreements must be made.
C	Use of RFID requires integration of interorganizational processes.
C	More focus is needed on experience gathering and knowledge sharing.
C	Start-up meetings must be held with each individual trade contractor introducing him to the new technology and working methods, and letting him know how he can benefit from it.
C	Comprehensive effort is required in the start-up phase of the implementation. Training, interorganizational shared server setup and agreement of information sharing is time-consuming.
C	Planning of work (e.g. mounting of precast concrete elements) is done prior to the arrival of the components on the construction site, while the value of instructions to the working procedure at the time of component registration is limited.
P	Component registration, virtual model update and quality assurance processes can be automated.
P	Better overview of status and production flow by use of new technology gives new possibilities for process optimization. Real-time update of the project status is now possible.
P	New possibilities for visualisation of project obstacles.
P	Improved visibility of project plans by means of 4D views improves the possibilities for involving craftsmen in the planning of their own work.
P	RFID would be useful for component acceptance checking, that is hardly done today.
P	Basic geometry information is detailed in several models. Walls are e.g. modelled by the architect, the structural engineering, and the manufacturer of precast concrete introducing many prospective errors and delays in information handling. A simpler division of modelling tasks, with fewer people responsible for modelling each component, can reduce the risk of errors.
P	New incentives are needed to gain success on implementation of ICT in construction. The ability to create continuous improvements should be rewarded.

P	Facts from measurements are more reliable than personal opinions in process optimisation. For process optimisation using Lean Construction or Six Sigma (Pyzdek, 2003), the detailed registration gives new possibilities to compare planned and accomplished construction.
P	New possibilities for linking and synchronisation of information between physical components and their associated documents, such as specifications, detailed fabrication drawings (both 2D and 3D views), and maintenance instructions.
P	Transparency of production status and defects for all parties in the project organisation.
P	Visibility of condition, place and status of each component for all parties in the project organisation.
P	Information can be shared among all supply chain players.
P	Traceability after mounting.
C/P	**Technology and infrastructure**
C	The data capturing software and its link to the virtual models are not off-the-shelf items, and therefore requires test and further development.
C	Major investments in new technology are required to gain the benefits.
C	Lack of software interoperability and need of ontology development, see also Sørensen et al. (2009).
C	Integration of CAD, procurement and management tools are required, but today there exist only a few tools that meet these requirements.
C	The network infrastructure must support both mobile and fixed RFID readers, antennas, sensors and equipment.
C	New hardware is required for visualisation at the construction sites such as big screens, projectors and screen technology working outdoor in a harsh environment.
C	Methods and tools for sharing 4D model information are needed.
P	A combination of GPS and RFID will be useful for inventory management, especially at large construction sites.
P	The mobile phone is a known technology among everyone in construction, and the resistance to use it is limited.
P	Reuse of tags from construction in facilities management would be beneficial.
	Human resources
C	New competences are required to make use of the technology on construction sites. Simple tasks for experienced ICT-users such as opening digital drawings from an ftp-server or attaching files to e-mails are often difficult or impossible to accomplish for construction site managers.
C	The middle management (project and department managers) must have the competences to drive the change process, otherwise new resources are required. It could be a project information officer (PIO) who would be responsible for introducing the technology at the construction site. (See Froese and Han (2008) for further discussion about this topic.)
C	To ensure a successful technology implementation a number of tasks to be conducted by the project information officer has been identified: 1) Ensure data quality and accessibility of discipline and aggregated models, 2) support in setting up procedures for information exchange, 3) administrate information and knowledge sharing portals, 4) conduct systematically cross-disciplinary consistency control of virtual models, 5) be the human link between the IT operation organisation and the project organisation, 6) support and influence the owner's and the contractors' use of ICT, virtual models, and ontologies 7) keep the virtual models updated during the whole construction period, 8) support construction site use of the virtual models by e.g. ad hoc creation of bill of quantities and visualisations, 9) train the construction team in the use of ICT.
C	New competences are needed on the construction site combining skills of a traditional civil engineer with the competences of an IT engineer. (See Steinmann (2005) for further discussions on this topic)
C	There is a risk of disregarding the unskilled labourer in the technology implementation process.

C	It is hard to find resources for innovation and implementation of new technology within the existing business processes. Often, when a milestone in the project must be reached the innovation and implementation of new working methods are put on hold.
C	Considerable human resources are required to keep the virtual models up to date through the construction process.
C	Managers, consultants and workers have different views on the need for new technology in construction.
P	Great possibilities to design and implement adapted human computer interfaces for different usage and contexts.
	Physical components
C	There is need to standardise the placement of the tags, especially in components where the RFID tags are hidden in the component. Inspiration could be found in currently used standards for labelling.
P	The tag can also be used for orientation of the components.
	Virtual models in construction management
C	Filtering, proper visualisation, and structuring of data are important to achieve the needed performance of the virtual models to gain benefits of RFID.
C	Lack of interoperability puts extra demands on choosing the right software because it is not possible to change the software and keep transferring all object properties from one tool to another.
C	Usability improvements are required in model viewers and in methods and tools for sharing models. Especially the aggregated multidisciplinary models and 4D models are hard to navigate for non ICT experts.
C	Standardisation of 4D views (colours of object representation) are required to make the views easier to read.
C	New method (digital or paper-based) for exchange of 4D model information is required.
C	It is difficult to print useable 4D views, objects are often hidden behind each other.
C	Automatic link between objects and schedule is required. Otherwise it is too time consuming to keep the virtual model updated.
C	The demands on the quality and time of delivery of virtual models from the design team, are increased, if the models are used as construction management basis.
C	Colour blind people can have difficulties using colour-coded 4D model views.
C	Data captured during the construction process must be reusable in operation and maintenance.
C	Virtual models must be extended with functional building system ontologies to better support the link between the building functional services and the building's component system.
C	Handling of changes or deletion of objects in the virtual model after the RFID tag has been added to the physical component can cause problems.
P	Standardised Web service interfaces to the virtual model resources are expected to reduce the implementation time for data capturing and data presentation tools.
	Quality assurance
C	2D, 3D and 4D overviews are still needed, even though quality assurance is done by use of a hand-held device such as a mobile phone.
P	Less paper is needed in the quality assurance (QA) process because of automatic object identification.
P	By adding the QA data to objects in the virtual model, the data can be reused. Today it is hard to find any useful information from the QA documentation.
P	Process optimization can be done on the basis of the structured quality assurance documentation.
P	The production of QA documentation material for project handover can be automated.
	Social and political aspects
C	Risk of undesirable surveillance

C	Radiation from the RFID reader/antennas might scare people
P	Improved documentation of the production process and delivered quality might be a client requirement as is the case with the use of virtual models and ICT today in Denmark (NAEC, 2006), Norway, Finland, Netherlands in with governmental projects.
P	New requirements for CE marking of construction components (European directive) demand unique traceability.

5.1 Summary of the Affinity Diagram

For a successful future system development and implementation, it can from the affinity building be summarised that focus is necessary on: 1) development of new partnerships and business models, 2) integration of interorganizational working processes, 3) combination of automatic identification technology and lean construction principles can enable new possibilities for process optimisation, 4) lack of interoperability and de facto standards are a considerable challenges, 5) mobile phones can be an important key to introduce a wider use of RFID in construction, 6) integration of tools for CAD, procurement and construction management, 7) new competences at the construction site to gain the benefits from ICT implementation, 8) innovation and implementation of new technology in construction require major investments, 9) standardised data interfaces to the virtual model resources, e.g. implemented as Web services, 10) use of automatic identification introduces a new object oriented paradigm for quality assurance in construction, 11) there is increased political focus on documentation and knowledge management.

6 Contextual Work Models

6.1 Workflow

Workflow models are used to define and illustrate how work is divided between people, how they coordinate work, and which artefacts (formalised messages and tools) and placeholders (information containers, meeting places, etc.) they use to assist the communication. Usually one work flow model is created per person/role interviewed. However, in this paper it has been chosen only to present one of the workflow models. The workflow model is a consolidated model of how the foreman from a precast concrete element team acts in an on-site problem solving process, see Figure 2. This workflow model illustrates currently daily practice, and therefore it shows the working processes that should be supported and hopefully improved by automatic object identification and use of virtual models. Each person or user role is shown in the bubbles annotated with their responsibilities listed below their job title. The rectangles in the workflow model show the artefacts and placeholders used for information transfer between the people. The photo placed next to the workflow model in Figure 2, shows a snapshot of the modelled work process.

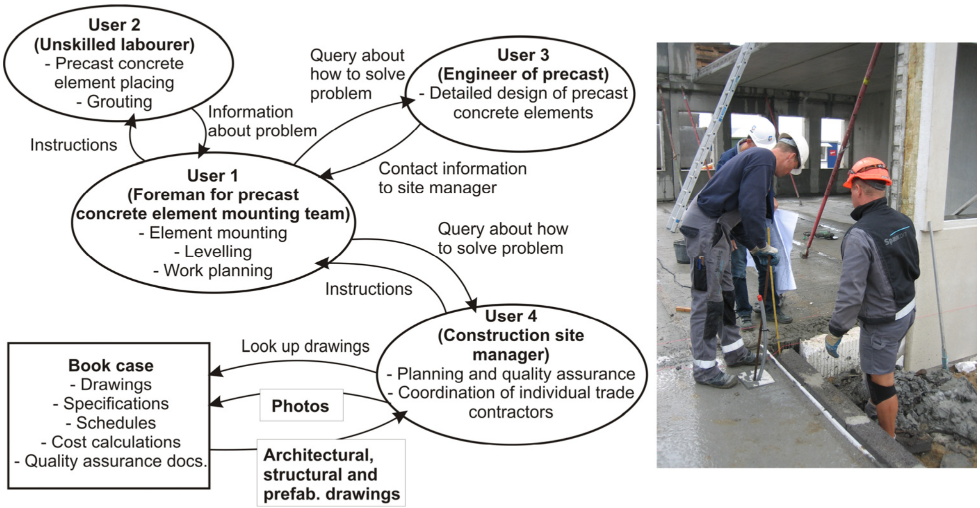

Figure 2 Workflow model of a problem solving process. The photo next to the model illustrates the process at the construction site. Bubbles illustrate roles, and rectangles illustrate artefacts (formalised messages and tools) supporting the information transfer.

The working process illustrated in Figure 2 is one out of many in construction. The more formalised of them are well described today, but in an ICT system development process it is also important to be aware of the unformalised processes like the one illustrated in the figure. In Karhu et al. (1997) a comprehensive set of $IDEF_0$ models of activities, their interconnections and the information flow between them are modelled. Reference is made to this report for a general overview of the overall processes in construction from the early design stages to completion for handover and use. From an ICT system development perspective the Contextual Design workflow are superior to the $IDEF_0$ models by being user need oriented rather than task oriented.

From studying the working processes concerning the precast concrete element design and fabrication (Case 2 and 3), it has been identified that up to now, too little effort is invested in virtual model coordination and model consistency check in the design. It has been identified during the observations that when no extra attention is paid to the subject, the first person to bring all the project material together is often the engineer or draftsmen at the precast concrete element manufacturer. Architectural drawings are used to find the right overall dimensions such as height, width and door holes of the element to be produced, and the structural drawings to find details about connections, thicknesses and reinforcement. Finally, it is checked, by use of the MEP drawings, if all mechanical and electrical parts are embedded correctly in the precast elements.

The lack of quality check of the design models results in problems at the construction site as illustrated on the work flow model in Figure 2. As shown in Figure 3, the problem could easily have been found already during the building design by executing an automatic model check.

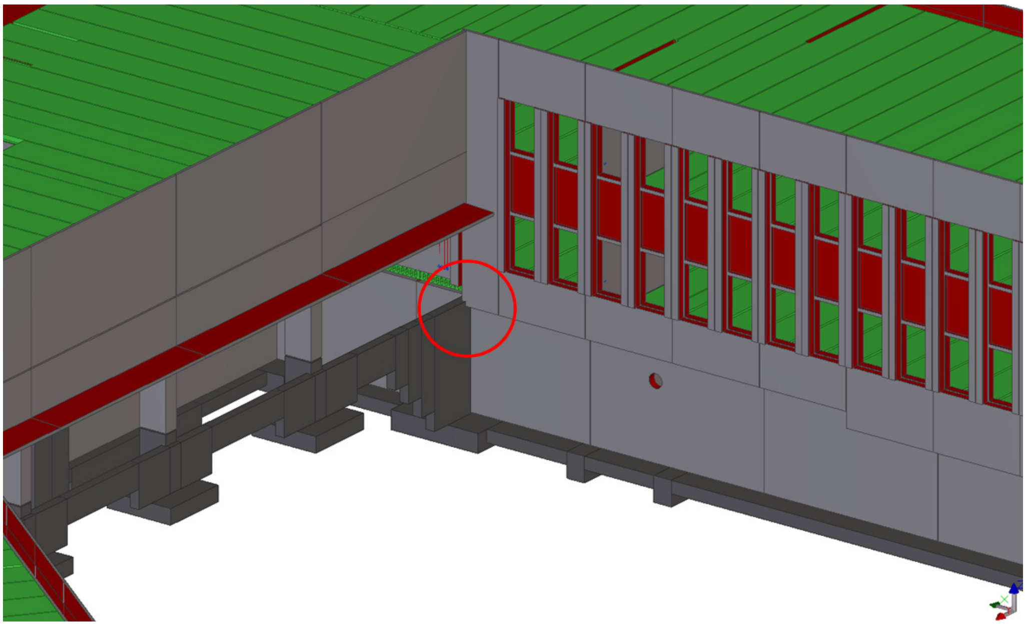

Figure 3 Virtual model of the problem to be solved at the construction site. Overlapping building components are highlighted by the circle.

An important topic to investigate further is how the virtual model can support the problem solving process illustrated in Figure 2. If the foreman or the site manager in this case should have any advantage of the virtual model he should be supported in the process of finding a solution to the problem. As illustrated with the workflow model of this process he needs information shown on drawings from various disciplines (in this case structural engineer, prefabrication engineer and landscape architect) and contact information to offices outside the construction site. In this case the snapshot from the virtual model presented in Figure 3 was not of any use because it showed only the structural model. The precast concrete element causing the troubles was modified to fit the foundation, and information about the final terrain level and reinforcement of the element was needed to make the decision of modifying the precast concrete element. This information was not included in the structural model. For the virtual models to be useful for the contractor at the construction site, they must be easily accessible as aggregated models integrating all disciplines involved in the project. Increased focus on the creation and delivery of aggregated and consistent models are therefore expected to increase the quality of the production basis significantly, and thus making it easier for the contractors to construct the buildings. Whether the consulting engineer, the architect or the contractor should be responsible for creating the aggregated model must depend on their competences, interest and contractual agreements.

6.2 Working Culture

Cultural models are used to illustrate, concretise and capture the invisible and pervasive cultural context that influences the system or product to be developed. The authors' interception of the interviewees' behaviour, their informal answers and unwritten values is presented in Figure 4.

Cultural models are relevant in any system development because cultural aspects can have significant influence on people's choices and thereby the success ratio of the new system. The introduction of automatic identification in construction management may introduce many potential conflicts, as illustrated in Figure 4 with the zigzags. In the implementation it will lead to conflicts about who should pay for adding RFID tags to components and further what can the detailed registration of people's behaviour be used for? Also public attitude about the RFID technology, which can be hard to tackle, can have major influence on the technology's success in construction.

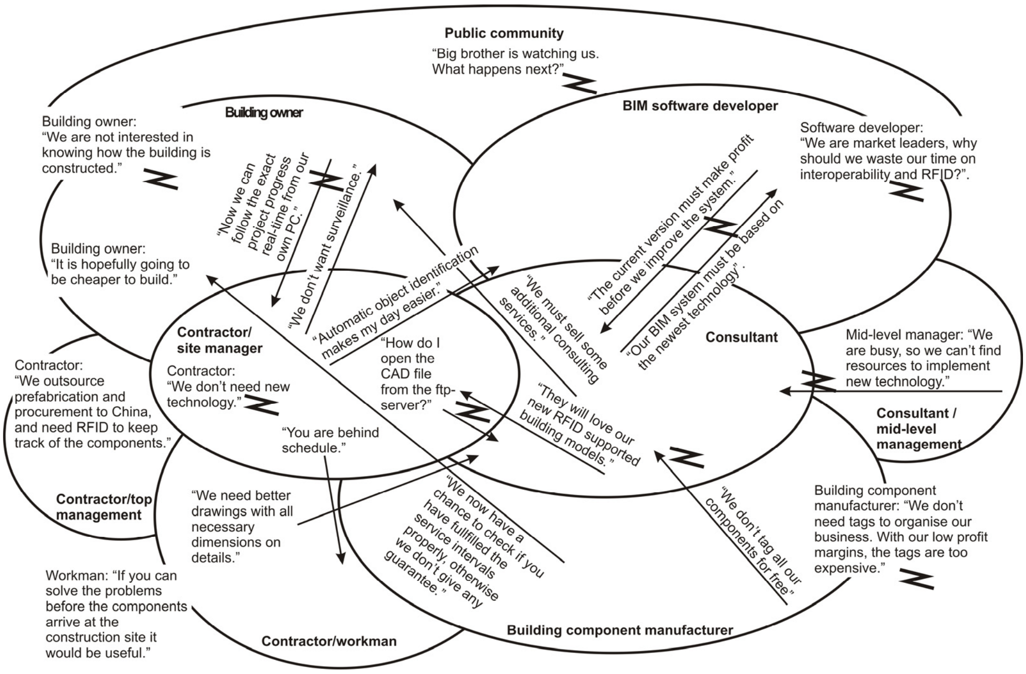

Figure 4 Cultural model of the context influencing an ICT system to support construction management based on virtual models and RFID. The bubbles illustrate users with overlapping interests, and the arrows illustrate cultural influence. Zigzags indicate conflicts.

6.3 Physical Environment

Physical models are used to illustrate the physical environment in which the future system is going to be used. It thereby illustrates the physical bindings on the system. In this case, the system under development is not only going to work in a single physical environment, therefore the physical model shown in Figure 5 illustrates a generic model of a construction site. The most important constraints illustrated in Figure 5 are that a construction site consists of a number of highly distributed physical and virtual spaces. The links between the spaces consist of access roads and supply lines for network, electricity, water and sewer system. These spaces are often moved ad hoc during the construction phase, and the ICT system must therefore be very flexible to support these changes.

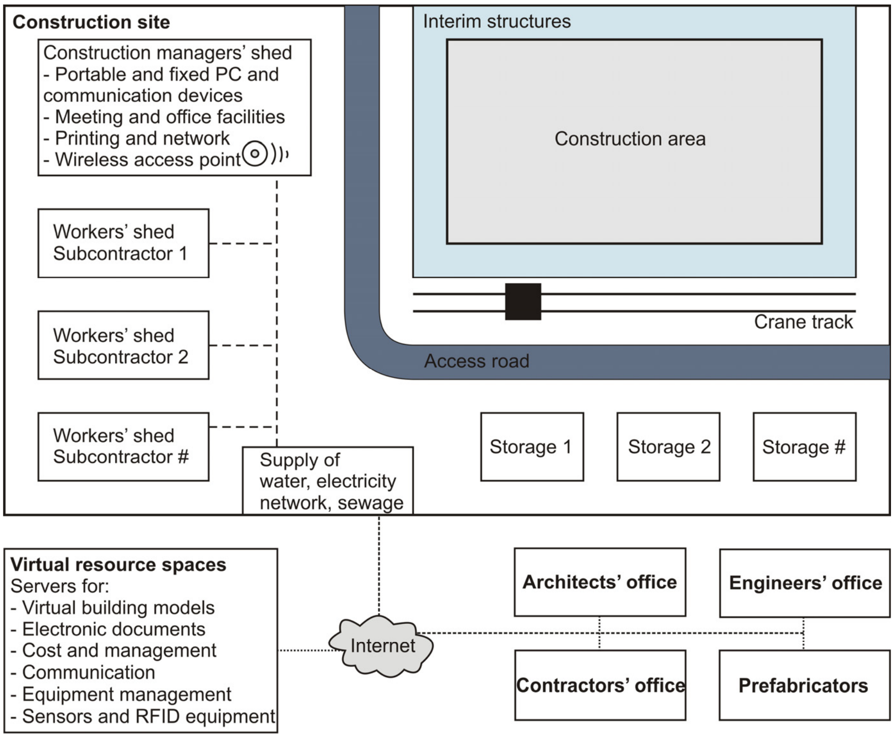

Figure 5 Generic model of the physical environment at the construction site and the nearest surroundings.

7 Vision, Work-redesign and Storyboard

The findings presented in sections 4-6 of the paper are in this section used for creating a vision of new working processes and a new ICT system. This vision is a concretising of the initially presented idea of a better link between the virtual models and physical objects in construction.

The Contextual Design based research has resulted in a vision of developing a simple and implementable system with supporting work processes for real-time project progress management, quality assurance and inventory management. The system must be flexible and give the user access to virtual model information anywhere, at anytime, and about any component modelled in the system.

Typical use cases of the system will be:

- Construction planning
- Construction site inventory management
- Quality management such as
    - Continuous follow-up
    - Registration of component flow
    - Documentation of quality of work results and project progress
- Check of compliance with schedule

- Construction process optimisation by delivering measureable input to lean construction and lean Six Sigma process optimisation (Pyzdek, 2003)
- Retrieving work instructions from a virtual model (See also Mourgues (2008))
- Real time visualisation of current project stage
- Visualisation of differences in actual and planned installation order and schedule
- On-site and office information retrieval and notification

A narrative description of how this system will be used is given below. This storyboard has proved to be very useful for presenting and discussing the future system with software developers and future users, and its content has developed through many iterations.

7.1 Storyboard

A future possible user scenario is presented below to outline how the system is intended to be used. The scenario is presented by storytelling with the following fictitious protagonists; John the virtual model coordinator, Jane the construction manager, Michael a manufacturer of precast concrete and Paul the foreman, and illustrated in Figures 6-10.

Model generation and precast element management: *John is model coordinator of the design and construction of a new office building. His task is to secure a smooth flow of information between all parties in the project. During the design of the building John is responsible for the 3D and 4D modelling and works in close collaboration with the general contractor's construction manager, Jane, and project manager, Michael, from the manufacturer of precast concrete. John is also responsible for adding the ID's from the RFID tags to the objects in the virtual model stored on the model server.*

When the concrete elements are ready for shipping, Michael is responsible for updating the 4D production status information on the model server. He does that by reading the RFID tag embedded in each concrete element by his mobile phone, and subsequently he presses the button "In transit". Together with the production status information the mobile application automatically updates the model server with data about time, date, user and current location of the GPS. His mobile phone has Internet access, and connects to the service provided by the model server.

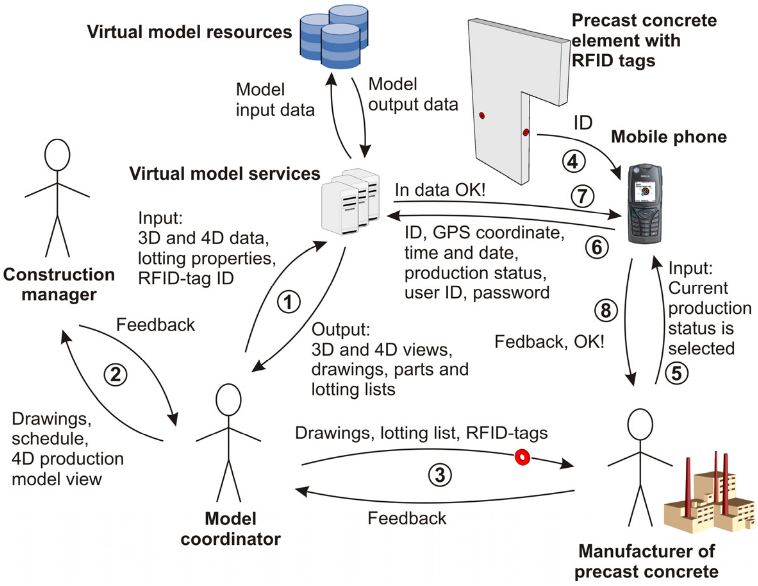

Figure 6 Rich picture illustrating future use of a digital link between virtual models and physical components in construction for model generation and precast element management. The numbered events refer to an execution sequence of the actions.

Construction site precast concrete element acceptance and inventory management: *When the precast elements arrive at the construction site, Jane uses the RFID enabled mobile phone to identify the elements. Prior to arrival, she has already received information about the elements installation time, date, storey and grid line from the virtual model service. While making the acceptance check, Jane writes comments on the phone, if any, and updates the model server with new element data about production status, location, time, date, and user. The acceptance checking also includes finish, transportation damages and measurements of window and door holes.*

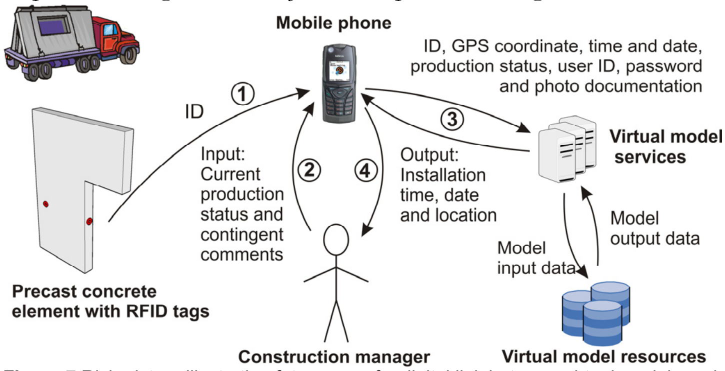

Figure 7 Rich picture illustrating future use of a digital link between virtual models and physical components in construction for precast concrete element acceptance and inventory management. The numbered events refer to an execution sequence of the actions

On site element location: *A continued update of the virtual model enables any user of the system to retrieve information about current production status, location, comments and direction of any of the precast concrete elements. Foreman Paul uses his mobile phone to retrieve information about where he can find the next element to be installed,* *and he reads the comment input during element acceptance at the construction site. In case the element is not in place at the construction site, he is notified where in the supply chain it is currently located.*

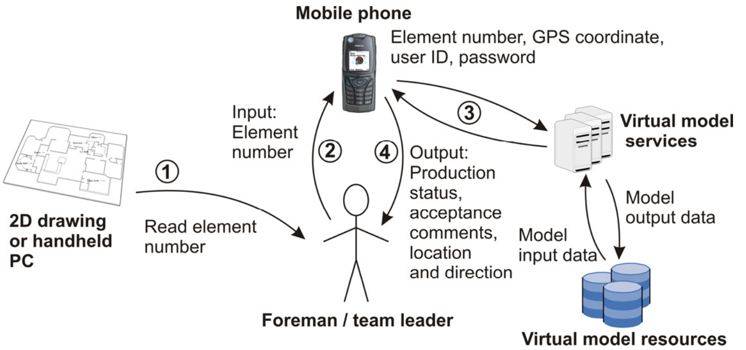

Figure 8 Rich picture illustrating future use of a digital link between virtual models and physical components in construction for on-site location of building elements. The numbered events refer to an execution sequence of the actions.

Task accomplished update: *When a precast concrete element is installed, Paul updates the virtual model with his mobile phone by reading the RFID-tag and selecting the "Task finished" button. He supplements the input with a photo for the quality assurance documentation. He now receives information about the next task, and the location of the elements to be installed.*

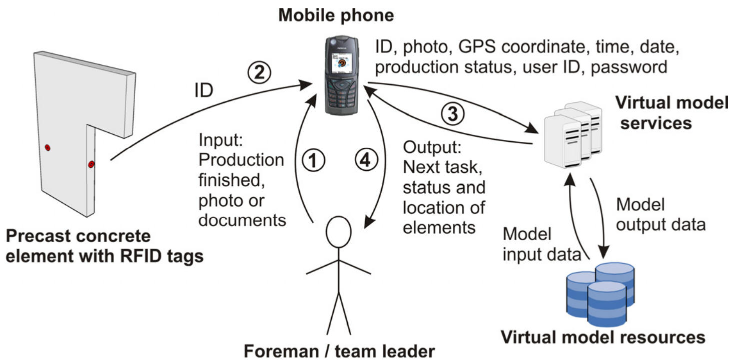

Figure 9 Rich picture illustrating future use of a digital link between virtual models and physical components in construction for on-going process update of the virtual model. The numbered events refer to an execution sequence of the actions.

Ongoing information retrieval: *During the construction process contractors, engineers, architects and the client can follow the progress of the project in their own offices by means of a virtual 4D model viewer. Furthermore for elements where they have subscribed to notification, they receive an e-mail, SMS or RSS feed (Really Simple Syndication (RSS 2.0), RDF Site Summary (RSS 1.0 and RSS 0.90), or Rich Site Summary (RSS 0.91)) whenever production status of the elements is changing. The structural engineer uses this option to get information about when he has to go to the construction site to do follow-up quality checks, and the construction manager is quickly informed when new elements arrive at the construction site.*

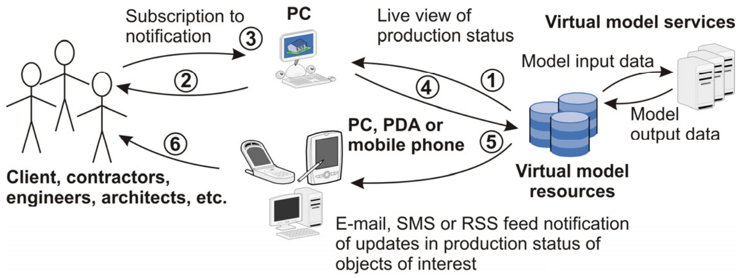

Figure 10 Rich picture illustrating future use of a digital link between virtual models and physical components in construction for on-going information retrieval. The numbered events refer to an execution sequence of the actions.

8 User Environment Model

The findings from the contextual inquiries, work modelling, consolidation, visioning, work-redesign and storyboards described in this paper are used to develop the user environment model presented below. An important prerequisite to enable the real-time project progress management, quality assurance and inventory management is to be able to view, edit, link, and organise the data stored in the virtual model resources. A high-level user environment model for a future ICT system supporting the users in this collaborative information management process is shown in Figure 12. The ICT system will enable the users to overview and easy access the electronic information produced and shared during construction projects. This ICT system will therefore be the backbone of managing the project progress, the quality assurance process and the inventory. There exist many useful ICT tools for use in design and construction of buildings, but there still is a need of providing the industry with better ICT systems supporting the general handling of information and resources.

The idea of an integrated interface for information access in construction is not new. In 1984, Christiansson (1984) wrote: "*Tomorrow's systems will contain project information which should be highly accessible to many persons during all the design phases of the project.*" and *"To meet this development it is very important to tackle the problem of structuring knowledge and making classifications which are universal enough to be used in integrated systems."* Today, some of the challenges of structuring knowledge within construction have been addressed with the development of the ontology for product and process models, Industry Foundation Classes (IFC), see Liebich et al., (2008). However, there are still challenges in the development and introduction of meta-ontologies and business process ontologies based on functional building systems (Sørensen et al. 2009), (Christiansson, 2007).

The user environment model in Figure 12 organises the user needs into focus areas. In Figure 11 an explanation of how to read the user environment model is given. For each focus area, (or page/window) in the new system a short description of its purpose is given. The description is supplemented by a short list of related functions, list of links to other focus areas, objects presented to the user, and special risk or constraints relevant to the subject. The main purpose of the user environment model is to form the basis of a future detailed system specification and use case descriptions in the UML (Unified Modelling Language) modelling of the system to be developed. The user environment model can also act as a checklist, allowing system designers to review the function in relevant context and to verify that all the functions are needed and that all needed functionality is available as well as point to artefacts needed to use the system.

Name of page, window or focus area
Purpose: Short description of the purpose

Functions
● Functions to be activated by the user
o Functions to be activated by the system

Links
> Pages or windows to which this user environment object can navigate to

Objects
■ Objects presented to the user

Risks/Constraints
Particular risks/constraints not giving the user the expected experience

Figure 11 Explanation to the elements in the user environment model in Figure 12.

Documents and drawings in paper or digital form are expected to be important to the construction industry for many years. Therefore as illustrated in Figure 12 the new system must provide the user with a combined overview of information stored in electronic document management (EDM) systems as well as in virtual model resources. While the use of virtual models becomes more and more daily practice, it is expected that there will be a transition of information stored in documents to information residing in the virtual model resources.

The system must also enable the user to view the content of the document and virtual model resources. This is illustrated with the "Work area" in Figure 12. "Work Area" is linked to the "Model Overview" as well as to "Quality assurance" and "Properties, location and status" providing the user with detailed information about the objects accessed in the "Work area". To enable a rational handling of information added to virtual models, it is important to give the user good functionalities and artefacts for grouping and linking of the virtual and physical objects. This is included in the model with the "Arrange" focus area. Much of the management of projects in construction concerns handling personal interaction. To support this in a digital manner, communication management is also an important focus area of the ICT system. The system must be individually configured to each user, as well as to the users' projects and technical services, which is illustrated with the "Services" and "Setup" focus areas. Finally the system must provide the users with sufficient feedback on interaction with the system.

How these overall requirements can be implemented in real ICT systems are illustrated in section 9 of the paper.

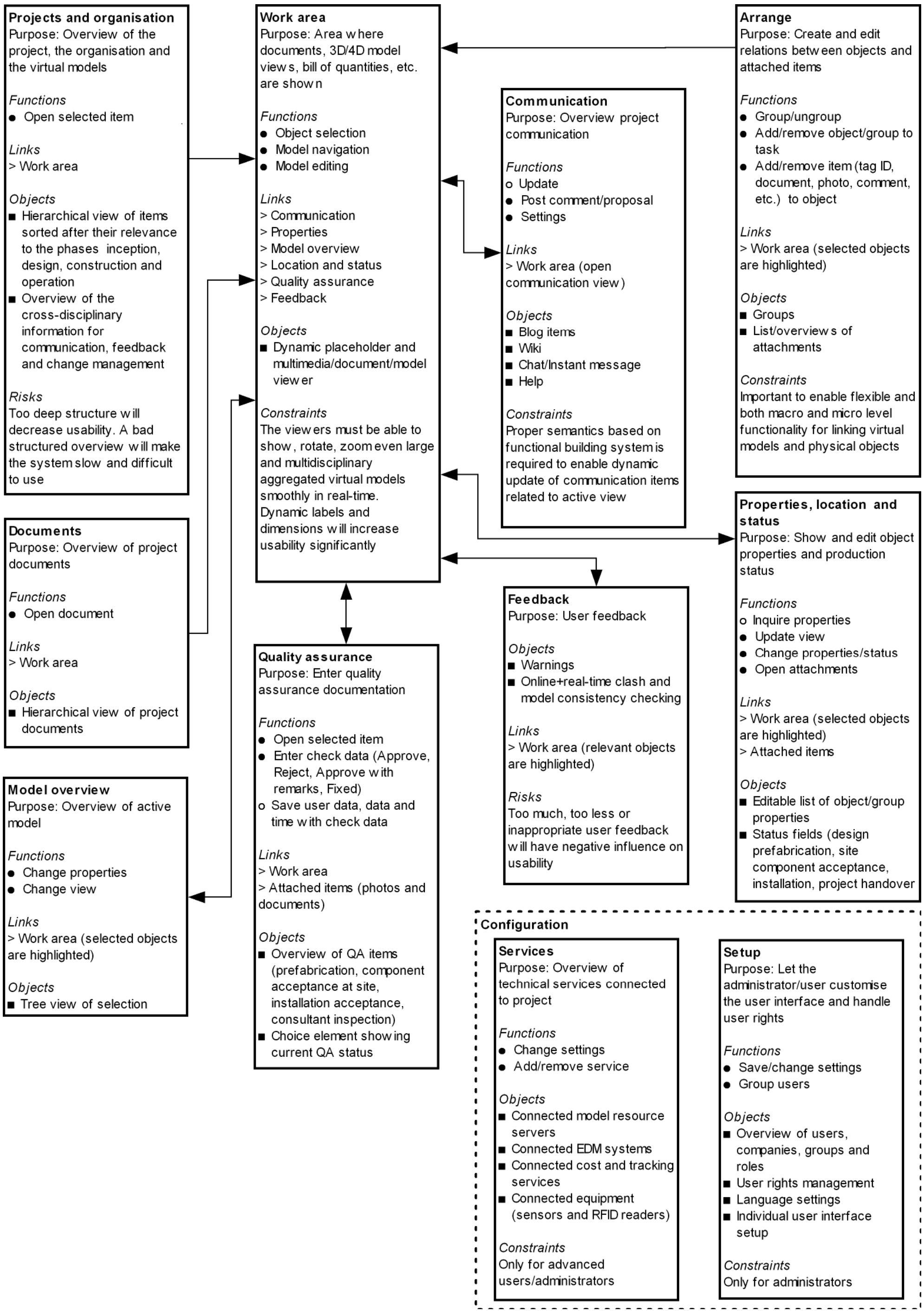

Figure 12 High level user environment model for a future ICT system supporting project progress management, quality assurance and inventory management in construction.

9 Mock-ups

A very important aspect in the development of future ICT systems for construction is usability (easy to learn and remember). Today, interfaces for information handling systems used in construction, such as electronic document management systems and model server managers, often suffer from badly designed user interfaces. High usability is a less important aspect in e.g. CAD or numerical simulation systems because they are mostly used by experts. However, in broadly used ICT systems usability is a very important subject to address, especially in the construction industry where the barriers concerning implementation of new ICT systems are often more human grounded than technical grounded. The user interfaces presented below are based on the human-needs-centred system development, presented in this paper, and are therefore expected to provide future system developers with a background for implementing a satisfactory user interface.

Going from paper-based or diagram-based prototypes (the user environment model in section 8 of the paper) to real applications often introduces constraints to the design. Constraints in screen sizes, graphical component dynamics and preferred use of standard user interface patterns to encourage high usability (Nielsen and Loranger, 2006) introduce compromises to be taken into the design. To exemplify how these limitations can be addressed, two prototype systems are presented in sections 9.1 and 9.2. These prototypes can act as a basis for future developments of interfaces to e.g. model server managers and mobile data capturing equipment.

Different use cases require different user interfaces. Firstly, a general ICT system for collaboration and information handling is presented in section 9.1. It is expected to be used on regular PC's and laptops. Secondly, a tool for on-site project progress management and quality assurance is presented in section 9.2. The use of virtual model resources stored in e.g. IFC model servers or in a virtual model authoring tool supporting construction management, such as Tekla Structures or the VICO software suite is common to both systems. The information resources are accessed through the Internet, and RFID tags are used in the systems to create a digital link between the virtual models and the physical components.

9.1 User Interface for a System for Virtual Collaboration in Construction (V2C)

Besides the user needs and requirements found during the Contextual Design process, the mock-up design has also been inspired by the popular integrated development environments (IDE) used in software engineering, such as Netbeans (http://www.netbeans.org), Eclipse (http://www.eclipse.org) and Visual Studio (http://msdn2.microsoft.com/vstudio). The IDE Netbeans is illustrated in Figure 13 (left), together with the developed prototype system named Virtual Collaboration in Construction (V2C). The user interface is developed using standard Java Swing Components (Java, 2008). This prototype illustrates how the requirements found through the Contextual Design process, and consolidated in the affinity diagram and user environment model, can be implemented in practice.

It is expected that a system implementation of the presented prototypes with focus on user needs and e.g. based on an open business model (Chesbrough, 2006) could be an important step towards a more comprehensive use of virtual models in construction.

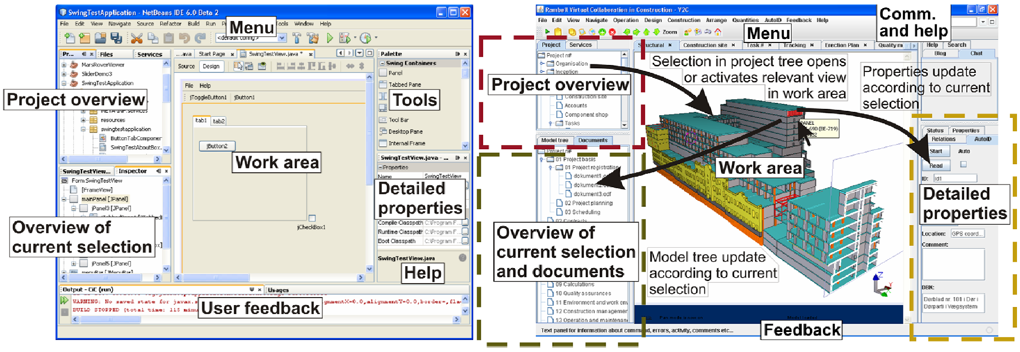

Figure 13 Left: Screen dump from the integrated development environment (IDE) Netbeans for software development. Right: Prototype of an ICT system for Virtual Collaboration in Construction (V2C).

In Figure 14 it is illustrated how V2C is expected to support the linking of virtual models with physical components in construction. Here, it is demonstrated how the actual location of a component selected in the physical model is shown on a map. In another window, the current production status of the building is illustrated as a 4D model view.

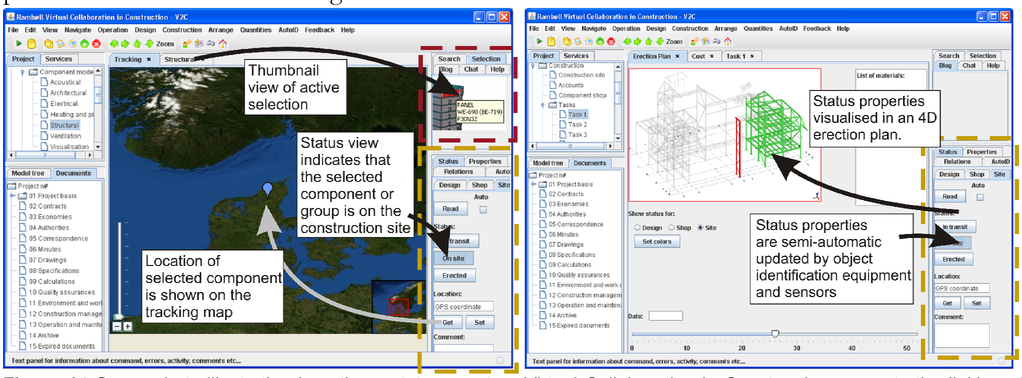

Figure 14 Screenshots illustrating how the prototype system Virtual Collaboration in Construction supports the linking of virtual models with physical components.

9.2 User Interface for a System for Project Progress Management and Quality Assurance

Automatic object identification sensors (RFID readers) are needed through the whole supply chain, to keep the virtual model resources updated with information about production status and component locations. The introduction of new ICT tools in construction has however proven to be a challenging task. The one exception that has gained wide acceptance is the mobile phone. Rugged computers, bar code readers or fixed RFID gate readers are often used for logistic optimisation in manufacturing companies, but they have not yet gained ground within construction. Therefore, the focus in the presented prototype developments is to develop new methods and applications that work with the traditional mobile phones rather than using the other tools dedicated for automatic identification. They are today available with embedded RFID reader (Sørensen et al., 2009)

The downside of using a traditional mobile phone as RFID-reader is the fact that the reading range is short (2-3 cm), and the possibilities are limited for developing rich multimedia applications for execution on a small display. Therefore, one of the key challenges is to find a practically usable method both for reading the RFID tags and accessing the virtual 3D and 4D model on mobile devices. Overcoming this challenge with the right system design will also be an important enabler for a wider introduction of the automatic object identification technology and supporting working processes within construction.

In Figure 15, screen dumps from a prototype application for project progress management and quality assurance are shown. The idea of the application is to demonstrate what a simple and easy to use mobile application could look like. Another important constraint is that the mobile application should be designed to run on traditional mobile phones with a 240x320 pixels display, which are commonly used today. The prototype is available in an interactive edition for execution on a mobile phone supporting Java 2 Micro Edition, the Connected, Limited Device Configuration and the Mobile Information Device Profile 2.0 (J2ME CLDC/MIDP 2.0) or in mobile phone emulator on a PC. The prototype is exemplified with that Java run-time environment because it is available on today's most popular compact mobile information devices, such as mobile phones and mainstream PDA's. A detailed user environment model was made, prior to the development of the interactive prototype illustrated in Figure 15, but it is left out of this paper.

During the prototype development it has been identified that by introducing the object registration in the quality assurance process, no additional work compared to daily working practice is required to keep the virtual models updated with production status information. However, in many organisations it would be necessary to formalise and change today's quality assurance process. It is with this prototype illustrated how the manual paper-based checking and project follow-up now can be done digitally by means of the RFID enabled mobile phones and virtual models.

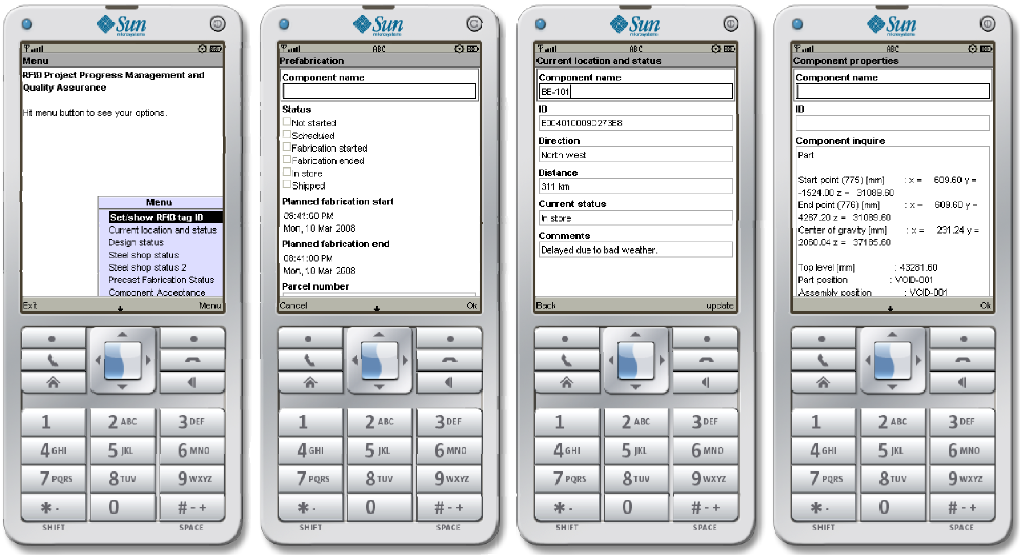

Figure 15 Screen dumps from a mobile phone based prototype application for project progress management and quality assurance. From left the screen dumps show 1) some of the menu, 2) input window used by the manufacturer of prefabricated components, 3) output from an inquiry of a component's current location and production status, and 4) output from a full component attributes inquiry.

9.3 Test With Users

The prototypes were development and tested through an iterative process in cooperation with future users (labourers and construction managers). Knowledge gathered from these tests is included in the affinity diagram in section 5 of the paper. Tests of using RFID technology in practice were conducted in connection with the building project described in section 4.2 of the paper. It included test of: 1) methods for embedding RFID tags in precast concrete elements, 2) readability and reliability of the RFID tags at the construction site, 3) setup requirements of the virtual model to support RFID, and 4) possibilities for use in practice. Some of the functionality of the prototype illustrated in Figure 15 was implemented in an operative application on a mobile phone with embedded NFC compatible RFID reader (Sørensen et al., 2009). The mobile phone had on-line GPRS-connection to a data capturing web application. RFID tags were embedded in the precast concrete elements and attached on the outside of the elements. It included most of the wall elements and several of the slabs, beams, and columns for the building project - more than 500 elements in total. The tests showed that the technology works in practice and quick response time can be achieved for the tags attached on the outside of the elements. For the RFID tags embedded in the precast concrete elements satisfactory readability was achieved for approximately 90% of the tags. A combination of the NFC compatible tags with tags with longer reading distances should therefore be considered for embedment in concrete. Another option would be to refine the method for embedding the RFID tags in the concrete. The tests are in the process of being further documented.

10 Future Extensions

Some aspects concerning project progress management, quality assurance and inventory management have not been covered in the prototypes described above. They have though not been forgotten. They have been given lower priority due to this early stage of the development. Only the core functionalities to fulfil the ambitious vision in section 7 of the paper have been included in the prototypes. As earlier mentioned, the vision is to "develop a simple and implementable system and supporting work processes for real time project progress management, quality assurance and inventory management." In this section of the paper the relevant future extensions of the system will shortly be outlined and discussed. They are important to be aware of in the implementation of the described prototypes to avoid putting restraints on systems, which in the near future will cause conflicts with the user needs.

Automation of the data collection: This prototype system is solely based on data capture from mobile phones because they are cheap, highly flexible, easy to carry, and already implemented in construction. One of the drawbacks of using the mobile phone for data capture is that it requires manual attention. Automatic readers on trucks, gates, etc., can avoid some of the manual work required for the data capture. However, it should be noticed that no extra work will be introduced by the described system. At all the stages where the system is going to be used for data capture, a manual and often paper-based quality assurance procedure is conducted today (shipping from manufacturer, acceptance control at the building site and documentation when installed), so the additional benefits from using fully automatic identification are expected to be rather limited.

Integration with other systems: The idea behind the use of a separate virtual model service (as illustrated in the figures in section 7 of the paper) for the data capture is to create a flexible solution that is easy to integrate into other systems, such as business enterprise resource planning systems (ERP), various CAD systems, room and equipment databases, production planning tools and operation and maintenance systems.

Integration through standardised data representations: The Industry Foundation Classes (IFC) data model, developed by IAI, is most likely the most important data representation form of virtual model data for the construction industry in the future. For that reason future extensions of the system should contain integration with IFC model servers through standardised data exchange. This will support improved inter-organisational use of the systems and a better scalability.

Visualisation, reporting and optimisation of the construction process based on the captured data: The prototype presented has some focus on visualisation and optimization, but many other possibilities will turn up when the system is a reality. There will for example be many possibilities for different kind of reports, such as lists of deviations between planned and realised construction.

Use of RFID tags with long reading distances and active tags with sensors: When designing new RFID based systems, it is very important to focus on the core business issues. In this case the core business problem is to develop a system that supports working methods enabling user-friendly information delivery and real time data capture of the project progress and quality assurance documentation. Therefore, the use of more advanced RFID tags and readers will not create significantly more value. The fully flexible mobile solution is much more important. When e.g. UHF EPC (Electronic Product Code, (EPCglobal, 2008)) readers are available for standard mobile phones, like the NFC (Near Field Communication) technology is today and current challenges concerning the use of UHF tags together with metals are solved, it should be considered to use these tags. It is also expected that dual or tri band (LF+HF+UHF) RFID tags would be useful for the construction industry because no single RFID technology meets all the requirements to RFID tags for use in the construction industry.

Legal aspects must be covered: A number of legal questions should be clarified such as: Who is the virtual model data owner, who is responsible for updating what kind of information in the virtual model and what can the data be used for?

Detailed check lists in the quality assurance: It should be considered to include more detailed check lists in the quality assurance (QA) process. It is, however, currently not done because it has been identified that the four options: 1) Approve, 2) Reject, 3) Approve with comments, and 4) Fixed, supplemented by the ability to add comments will cover most user needs. It also makes the system very flexible and it only requires the user to enter deviations, and it does not overtax him/her with unnecessary registration work.

Product data life cycle management: Comprehensive use of virtual models as illustrated with the prototypes in this paper introduces a need to consider and develop methods for accessing and re-using the data in the full life-time of the building.

Optimisation for other platforms: The presented prototypes have been developed for use on regular PC's and mobile phones. New display technologies and the introduction of ultra mobile low cost and rugged laptops such as the One Laptop per Child (OLPC) (OLPC, 2008) are expected to have a positive influence on the use of ICT at construction sites. Therefore future implementations should be able to take advantage of these technologies. In Figure 16 it is illustrated how a construction detail and a web site containing work instructions (in this case a Wiki) easily can be viewed on the OLPC even on a rainy day or a very sunny day. OLPC is water resistant and in contrast to most displays on common mobile phones and laptops it can be used in direct sunlight due to a reflective display. These features are important to be aware of when developing a future system supporting One Laptop per Workman (OLPW).

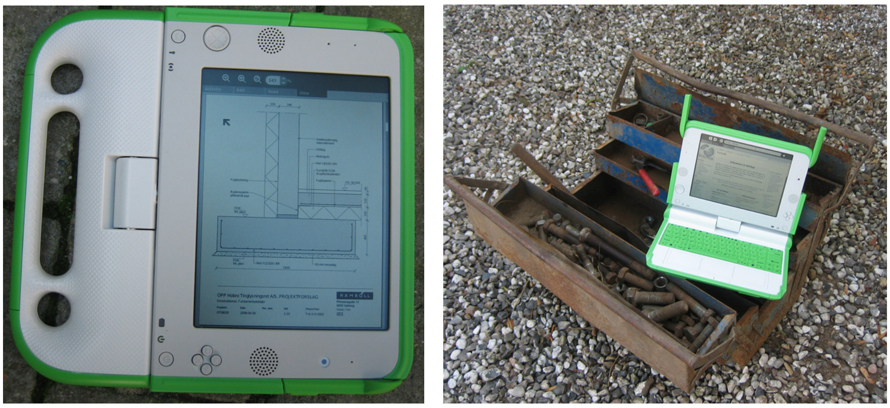

Figure 16 Illustration of how the OLPC can be used for displaying construction details and work instructions.

11 Conclusions

The initial idea behind the research presented in this paper was to identify and formalise user needs in relation to construction management by means of virtual models and RFID. The Contextual Design method was found useful in the research process, when developing ICT system prototypes (an early example) and as a framework for capturing the user needs.

Based on three case studies and involvement of more than 20 future users, an extensive list of future user needs was discovered. They are in the paper presented in an affinity diagram of challenges to be addressed, and as potential that can be utilised e.g. by new ICT systems. It was found useful to structure the affinity diagram of the captured observations according to their relevance to the overall strategy, organisation and working processes, technology and infrastructure, human resources, physical components, virtual models in construction management, quality assurance, and social and political aspects. For a successful future system development and implementation, a number of challenges to be addressed were identified such as 1) need to integrate interorganizational and conflicting working processes, 2) lack of interoperability and de facto standards, 3) need for better integration of the traditional paper document/drawing based working practice into modern virtual model based working paradigms, and 4) need for new competences at the middle management level or a project information officer (PIO) service function who would be responsible for implementing the technology at the construction site.

However, great potential has also been identified, e.g. 1) mobile phones can be an important key to introduce a wider introduction and use of RFID in construction, 2) a combination of automatic identification technology and lean construction principles can give new possibilities for process optimisation, 3) use of automatic identification can introduce a new object-oriented paradigm for quality assurance in construction, and 4) the combination of RFID and GPS technology can enable real-time tracking and location of machines and materials.

A prototype was developed of a simple and implementable system with supporting working processes for real-time project progress management, quality assurance and inventory management in order to provide further insight in how the potential and challenges can be addressed. By this prototype it is illustrated how today's manual and paper-based checking and project follow-up can be done digitally by means of the RFID enabled mobile phones and virtual models.

A prototype of a new collaboration tool for Virtual Collaboration in Construction (V2C) is also presented. It illustrates a possible user-interface to a collaboration tool that can support the link between virtual models and physical components in construction.

The prototypes presented in this paper are preliminary conceptual work that has to be implemented, and further it has to be validated by full-scale tests. The authors expect the prototypes can act as a basis for future developments of interfaces to e.g. model server managers, and development of mobile data capturing equipment. The research and development was done as a highly iterative and user involving process, and was based on a well-documented methodology (Contextual Design), which despite of lack of full scale tests, improves the validity of the findings.

12 Acknowledgements

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Paper III

RFID in Construction Operation and Maintenance – Contextual Analysis of User Needs

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RFID in Construction Operation and Maintenance – Contextual Analysis of User Needs

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Abstract: *As early as in 1995 it was stated that automatic identification of objects using RFID was a promising technology for the construction industry. However, 13 years later the applications of RFID in the construction industry are rare and mostly used in prototype projects or used for theft prevention and access control. Recently maintenance applications have been proposed to hold the trigger needed to launch RFID more widely in the construction sector. Therefore the purpose of the research presented in this paper is to identify the actual user needs for automatic identification in construction operation and maintenance. Research results from a contextual design process are presented and supplemented with practical experiences from implementing an RFID-supported operation and maintenance system. The greatest obstacles for successful implementation of RFID-based O&M systems have been found in structuring working processes and information rather than in making the hardware work.*

1 Introduction

Radio Frequency Identification (RFID) denotes any identification system in which electronic devices occur that use radio waves or pulsating magnetic fields to communicate with identification units fastened to objects. The most referenced components in RFID systems are tags, readers and middleware. Tags are identification units attached to the objects to be localised. The RFID reader is via an antenna used for scanning the data content of the tags. The middleware is the software component which ties the RFID reader together with the other software components (e.g. an operation and maintenance system) in an IT system and, if necessary, also filters the data before it is relayed.

As early as in 1995 it was stated that automatic identification of objects using RFID was a promising technology for the construction industry (Jaselskis et al., 1995). However, 13 years later the applications of RFID in the construction industry are rare and mostly used in prototype projects or used for theft prevention and access control (Erabuild, 2006). A number of recently published papers describe various examples of tested RFID implementations in construction: 1) Automating the task of tracking the delivery and receipt of fabricated pipe spools is described in Song et al (2006), 2) On-site tool tracking is described in Goodrum et al. (2006), 3) Project progress management with virtual models is described in Chin et al. (2005), 4) Tracking and locating components in a precast storage is described in Ergen et al. (2007). Ontologies relevant for linking virtual models with physical objects in construction using RFID are described in Sørensen et al. (2008). In all the papers it is concluded that RFID technology can be brought to function effectively even in the harsh construction environment.

Recently maintenance applications have been proposed to hold the trigger needed to launch RFID more widely in the construction sector (Erabuild, 2006). Therefore the purpose of the research presented in this paper is to identify the actual user needs for automatic identification in construction operation and maintenance. It is important for both research and development of new IT systems in operation and maintenance (O&M).

In order to identify the user needs contextual inquiries have been carried out on an infrastructure enterprise operating in Denmark and at a Danish municipality operating public buildings (the enterprises preferred to keep their names anonymous). The infrastructure enterprise and the municipality are currently implementing IT supported document and job management for their facility operation and maintenance. They have decided to use the operation and maintenance systems Rambyg (Rambyg, 2008) and SMART (SMART, 2008) developed by Ramboll.

Rambyg and SMART are applicable for use in the building industry and the infrastructure industry respectively. Rambyg is a web based system with an overall building model description based on the SfB classification system. Rambyg distinguishes itself e.g. by supporting IFC-file import of building models for easier creation of the operation and maintenance model. SMART is a Java application deployable to PC's, Personal Digital Assistants (PDA´s) and smart phones and its hierarchical structure is customised for each client.

Many papers describe case studies and research about IT in operation and maintenance. In Cardellino and Finch (2006) an overview of recent innovation projects within the domain is given, Roberti (2008) proposes RFID as a technology to manage and document mandatory maintenance, in Yu et al. (2000) a framework for developing interoperable O&M systems based on and as an extension to the Industry Foundation Classes (IFC) is presented. In COMIT (2004) a pilot implementation of an administration system for maintenance tasks and timesheets by use of PDA's is presented.

This paper presents the research results from a contextual design process supplemented with practical experiences from implementing an RFID-supported operation and maintenance system. The case used in the implementation is operation and maintenance of a small part of the infrastructures associated with a railway north of Copenhagen, Denmark. Experiences from this implementation show that the RFID technology is fully functional for operational use in the construction sector. The greatest obstacles for successful implementation of RFID-based O&M systems have been found in structuring working processes and information rather than in making the hardware work. The mobile system's usability is also a critical factor for success. Limited current possibilities for access to and reuse of product and process models from design and construction in operation and management are also significant obstacles for a wider introduction of RFID in construction.

Although the demand for RFID in construction is presently limited, it has been possible to identify a number of user needs that can be fulfilled with the use of RFID in combination with mobile computing. The conclusions based on the contextual analysis and the case study include identified user needs for: on-site navigation in the IT-system, subscription to information services from e.g. building component manufacturers, easier update of maintenance information and registration of inspection history.

2 Research Method

A contextual design of a prototype IT-system has been conducted to identify user needs in relation to automatic object identification in construction operation and maintenance. Contextual design is a method developed by Beyer and Holtzblatt (2000) to handle the collection and understanding of data from field studies to design of software based products. The method is user centred and the following techniques are used in the method:

Contextual Inquiry: Interviews and observations of future users in their actual working environment are carried out to get an understanding of the business problems the system must support. It ensures capture of the real business practice and daily activities and not just self-reported issues and company politics.

Modelling: Drawn models representing the user's work practice allows the developer and end user to attain a common understanding and share their findings. It includes work flow models, sequential models of tasks, cultural models and models of the physical environment and the used artefacts.

Consolidation: All the individual findings from interviews, brainstorming and work modelling are grouped in hierarchies and consolidated to show common work patterns.

Work redesign and visioning: Based on reviews of the models a vision for how the new system will support and streamline the working practice is sketched.

Storyboarding: A sketched and written story is created including sketches of future user environment and narrative descriptions of how it all will work in practice. The story will function as the common understanding between end users and developers about how the system will work and which functionality it will have.

User environment design: Based on the storyboard a single model of the user environment's functionality and organisation is created.

Mockup and test with users: Paper based mockups of the user interface are designed and evaluated by user tests. The level of detail of these mockups is increased through the development process starting with very simple sketches.

The above presented process is iterative and incremental which means that findings from one step in the process will lead to updates to both the preceding and following steps in the process. The design is initiated from rough sketches, notes and simple models which are detailed through iterations in the research and development process.

Compared to other methods from social science (see e.g. Alveson and Sköldborg (2000) for an overview) used to study human behavior and actions, contextual design offers a complete and easy to-use framework. It is well organised and provides modeling tools to formalise the unstructured connections in work processes with the needs in relation to software development. The work models developed from contextual inquiries provide a basis for a common understanding between software developers and end users.

In this research project the contextual design process is supplemented with reviews of available literature within the field and trail tests of software and hardware to be used in the final system and for the development. Also demonstration software applications are created and tested by future users.

It has been found rewarding to take the design of paper-based mockups of the user interface used in the contextual design method one step further by giving them some functionality and appearance like the real applications. Demonstration software applications with some functionality is therefore created and used for collecting user feedback and ideas. It is important to let the users know that it is only a demonstration application being presented; otherwise they might expect the development process to be in a late state where their input does not matter any more. There is also a risk that they might be disappointed if the final release of the application has a different appearance or functionality due to findings later in the system development process.

Introduction of new IT tools in construction has proven to be a challenging task. For that reason practical implementation tests of RFID technology and a pilot test are conducted. It shall lead to an increased knowledge about how the technology can support the operation and maintenance process and lead to new improved working processes.

The contextual inquiry has been done as informal interviewing and work observations of future users with different roles in relation to operation and maintenance. Also visits to sites where the system is going to be used have been done. The contextual design and inquiry has focussed on use of object identification in both building and infrastructure operation and maintenance. The results from the two industries are presented jointly in this paper because of the major similarities in the identified user needs and working processes. Approximately 10 future users have been involved in the inquiry process. Their identified needs are supplemented with input from discussions with colleagues, software developers and other researchers to form the presented consolidated work models. In Beyer and Holtzblatt (2000) it is stated that interview of 10-20 users are enough to collect most of the user needs. More interviews will not result in significantly more identified needs.

As mentioned before the contextual inquiries have been carried out on an infrastructure enterprise operating in Denmark and at a municipality operating public buildings. Both the railway enterprise and the municipality use IT based O&M systems. The focus of the inquiries is therefore to identify how automatic object identification by RFID can give additional benefits for users of O&M systems.

The users involved in the inquiry are consultants, building service personnel and managers at the end user. The interviewed person's roles in the case study are the following: 1) The consultants do the initial building registration and job management setup of the operation and maintenance systems for use by their clients (in this case the municipality and the railway enterprise). 2) The service personnel use the O&M systems for planning, retrieving and updating information about operation and maintenance tasks. 3) The managers are responsible for implementing the systems and use the O&M systems to retrieve information for making financial decisions and keep an overview of their organisations budgets and upcoming tasks.

3 Results

The results from the contextual inquiry and design include consolidated work models, affinity diagrams, a vision for a new system, story board, user environment models and paper prototypes of the new system. In this paper an affinity diagram, a consolidated work flow model, a cultural model and experiences from prototype implementations are presented.

3.1 Affinity Diagrams

In the contextual design method affinity diagrams are used to organise the individual notes captured during interviews and observations into a hierarchy of common issues. The hierarchy is built bottom up by raising a structure from the content of the notes. A number of future user needs and comments have been collected based on exiting system usage. It can be divided into the five categories presented in Table 1. To keep the broad understanding of the users' needs no distinction is made in the presentation between what in reality is possible or financially desirable to implement.

Table 1 Affinity diagram (shortened edition)

On site O&M system use	Improve navigation, tablet PC's have been tried without success, RFID tags can link physical objects with digital models, equipment must be robust, RFID tags will be hidden in the building component.
Experience gathering	Maintenance condition can be difficult to assess, personal judgements can be very different, guidance from the building component manufacturer should underlie the judgement, history of registrations should be archived.
Real time information update	It is time consuming to keep the O&M system updated, Quantity measurement is time consuming, control option to check whether registrations of a given building part are carried out on site and not just from the office.
New services and funct.	Documentation of the age of the building components, digital information from manufacturer, post-qualifying education, digital publication of the tender material, link to services containing gathered experiences.
General features	Encapsulation of the digital building objects to units, re-use of digital building model from design, equip only building components with RFID tags if they demand maintenance, log for changes in data, context dependent user interface.

3.2 Work Flow Model

Work flow models are used to define and illustrate how work is spread out on people, how they coordinate work and which artifacts (formalised messages) and placeholders (information containers, meeting places etc.) they use to assist the communication. Usually one work flow model is created per person/role interviewed. However, in the consolidated workflow model presented in Figure 1 several users are included to give a broader overview. Each person or user role is shown in the bubbles annotated with their responsibilities listed below their job title. The rectangles in the model work flow model show the artifacts and placeholders used for information transfer between the people.

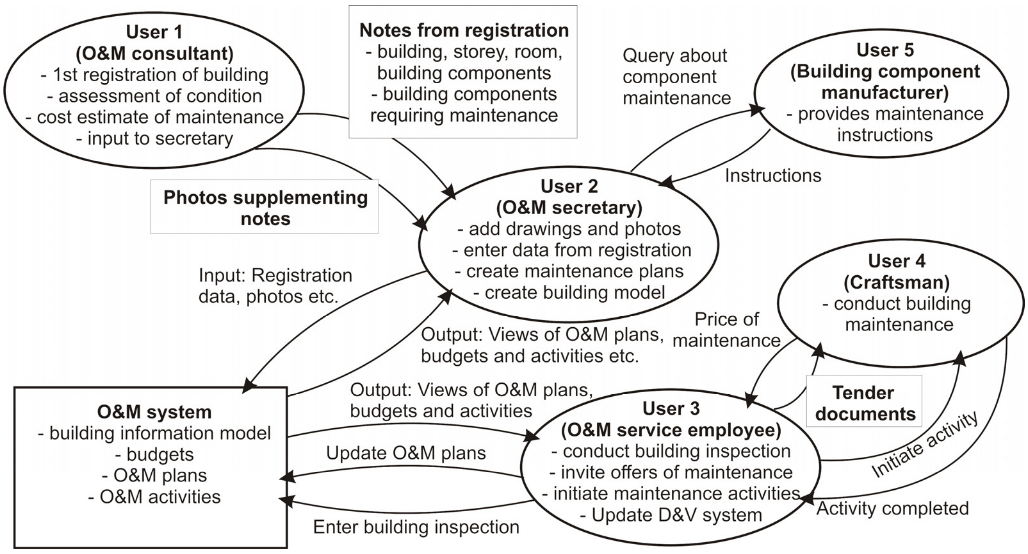

Figure 1 Work flow illustration for activities concerning operation and maintenance. Bubbles illustrate roles and rectangles illustrate artifacts (formalised messages) supporting the information transfer.

It is found that especially working processes involving the secretary role can be optimised by use of RFID and mobile IT equipment such as PDA´s, smart phones or tablet PC's. RFID tagged building components can enable easier on-site access and real time update of the O&M system.

3.3 Cultural Model

Cultural models are used to illustrate, concretise and capture the invisible and pervasive cultural context that influences the system or product to be developed. The authors' interception of the interviewees' behaviour, their informal answers and unwritten values is presented in Figure 2. Cultural models are relevant in any system development because cultural aspects can have significant influence on people's choices and thereby the success ratio of the new system. The introduction of RFID in operation and maintenance may introduce many potential conflicts, as illustrated in Figure 2 with the zigzags. In the implementation it will lead to conflicts about who should pay for adding RFID tags to components and what must the detailed registration of people's behaviour be used for? Also public attitude about the RFID technology, which can be hard to tackle, can have major influence on its success.

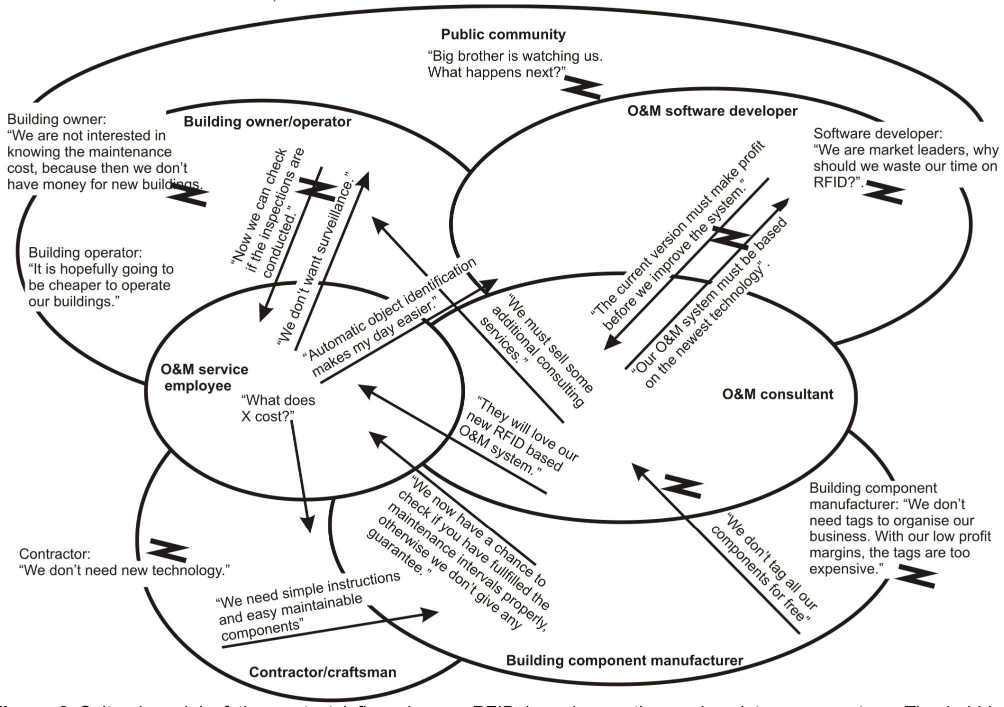

Figure 2 Cultural model of the context influencing an RFID based operation and maintenance system. The bubbles illustrate users with overlapping interests and the arrows illustrate cultural influence. Zigzags indicate conflicts.

3.4 Lessons Learned from Prototype Implementation

As described above needs have successfully been captured and they have been used as basis for a pilot implementation. It is developed as an extension to the existing mobile edition of the O&M system SMART (SMART, 2008). The first edition of the system is currently implemented and will be tested with users during the autumn 2008. An example of the user interface for a Java application for rugged PDA's with attached RFID reader is shown in Figure 3.

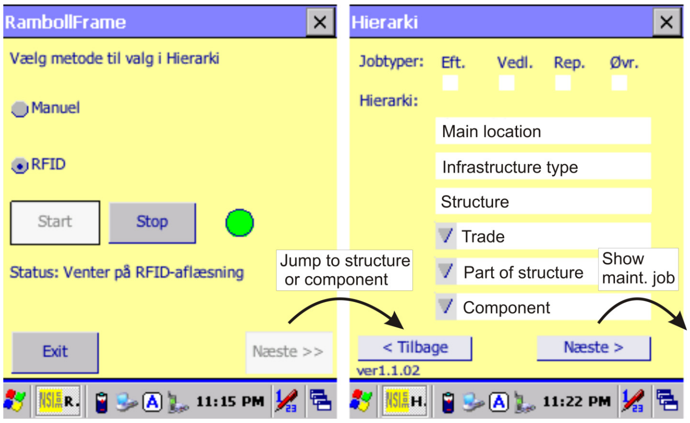

Figure 3 Example of user interface for SMART mobile edition.

The PDA has access to the O&M database through use of GPRS. By use of RFID technology and the PDA the users have quick on-site access to information (check lists, maintenance jobs etc.) stored in the O&M database and it is also automatically documented that components are inspected regularly. It was decided to use ISO 15963 tags (13.56 MHz) due to the wide availability of supporting hand held readers and good all-round properties (price, readability near metal, size). See Sørensen et al. (2008) for a discussion about selection of RFID tags for use in construction.

It has been found: 1) That the hardware is working in practice but it is yet not plug and play technology. Software drivers had to be developed by the system developers for the Java application. 2) It is difficult to assess which RFID standard to use for tags and readers. The lack of a de-facto RFID standard in construction is introducing a risk of basing the system development on standards that will be outdated in a few years. 3) Structuring information and working processes for digitalising the O&M procedures is a much more extensive task than implementing the RFID technology.

4 Conclusion

This paper describes a contextual development and needs capture for automatic object identification by RFID technology in operation and maintenance (O&M). The conclusions are: 1) A number of needs can be identified such as easier on-site information access, increased focus on documentation, education of users and re-use of knowledge across organisations by new services. The needs can form as basis for more detailed requirements specifications. 2) The introduction of RFID in operation and maintenance may introduce many potential cultural conflicts about e.g. cost, unwanted surveillance, public attitude which can influence the success for a wider use of this technology. 3) Demand from the property owners is needed to gain the benefits from implementing the technology. 4) The technology works in practice. The obstacles for using RFID in O&M is found in information structuring, need for de-facto technology standards and lack in the use of general ontologies for storing and accessing the information resources.

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Paper IV

ERP Application of Real-Time VDC-Enabled Last Planner System for Plan Reliability Improvement

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ERP Application of Real-Time VDC-Enabled Last Planner System for Planning Reliability Improvement

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Abstract: *The Last Planner System (LPS) has since its introduction in 1994 become a widely used method of AEC practitioners for improvement of planning reliability and tracking and monitoring of project progress. However, the observations presented in this paper indicate that the last planners and coordinators are in need of a new system that integrates the existing LPS with Virtual Design and Construction (VDC), Enterprise Resource Planning (ERP) systems, and automatic object identification by means of Radio Frequency Identification (RFID) technology. This is because current practice of the LPS implementations is guesswork-driven, textual report-generated, hand-updated, and even interpersonal trust-oriented, resulting in less accurate and reliable plans. This research introduces a prototype development of the VREL (VDC + RFID + ERP + LPS) integration to generate a real-time updated cost + physical % complete based weekly work plan and look ahead plan with product progress visualization based on programming intelligence. VREL allows LPS users to enable real-time information generating/sharing, more accurate and reliable planning, immediate proactive action execution, machine-to-machine process, and clear progress understanding by product visualization.*

1 Introduction

The main objective of the Last Planner System (LPS) of Production Control (Ballard, 2000) is to enhance planning reliability by utilizing three main techniques: 1) look ahead and weekly work planning, 2) make-ready process, and 3) reliable commitment of labor resources. When it comes to P-O-P models (Product, Organization, and Process), however, these techniques intend to improve mechanisms that control organization and process while a digital representation of the product aspect is of less importance. Our observations indicate that the last planners and coordinators are in need of the product aspect since current practice of the LPS implementations is guesswork-driven, textual report-generated, hand-updated, and even interpersonal trust-based, resulting in less accurate and reliable plans. Thus this paper introduces a prototype system that improves planning reliability of the LPS by providing a product aspect from Virtual Design and Construction (VDC) models.

Another issue in the LPS is a factor that no compelling, automation-oriented use of earned value exists. One of the reasons is that LPS users are not fully using ERP (Enterprise Resource Planning) solutions for both 1) aggregation and analysis of business information and 2) aggregation and analysis of building product information with the business process information. Although ERP has been widely used by AEC practitioners for the purpose of reporting, history storing, and communicating (Shi and Halpin, 2003), LPS users apply disparate accounting, scheduling, human resource planning, and job costing solutions. They monitor and track the number of the planned activities based on Complete/Non-Complete records which do not provide information about how much of the amount (e.g. Linear Foot, Square Foot, or Cubic Yard) of the planned activities are complete. In the field, however, they measure quantity complete on a weekly basis, which is input into the ERP system to generate a cost progress report, the most widely used key factor of project progress management (Navon, 2005). This paper intends to switch current metric, PPC (Percentage of Plan Complete), a key metric of the LPS, which is a defect rate and a product of the quality management mentality (Ballard, 2000), to quantity-complete generated by a cost-loaded PPC. Automatic quantity extraction of VDC software and mapping of unit costs stored in the ERP system to the quantities extracted can enable this.

There have been research and real construction projects utilizing RFID (Radio Frequency IDentification) for the purpose of project progress monitoring and quality assurance (Jaselskis, 1995; Chin et. al, 2005; Sorensen et al., 2009). This emerging innovation has potential to help LPS become a more robust solution in its adoption in the industry by increasing the update frequency of the look ahead and weekly work plans from weekly-updated to real-time updated. This RFID-supported LPS will enable last planners to receive real-time information of predecessors' progress. As a result immediate proactive actions against predecessors' delay or defect can be taking and the nature of PPC will thereby be improved.

This research introduces a prototype development of VREL (VDC + RFID + ERP + LPS) integration to generate a real-time updated cost + physical % complete based weekly work plan and look ahead plan with product progress visualization based on programming intelligence. VREL allows LPS users to enable: 1) real-time information generating/sharing, 2) more accurate and reliable planning, 3) immediate proactive action execution, 4) machine-to-machine process, and 5) clear progress understanding by product visualization.

The research tasks include observations of current LPS practice to document LPS users' needs, test of the proposed VREL through theoretical exploration to discover what values can be gained, and interview-based validation with last planners, coordinators, software developers, and theorists. This is done to identify how the VREL can have an advantage over the current LPS.

The contributions of this report are to theoretically and practically improve the plan reliability by integrating current LPS with other innovative tools, VDC, RFID, and ERP, and develop basis of guidelines of the VREL implementation in real AEC projects.

2 Observed Problem

The LPS has since its introduction (Ballard, 1994) become a widely used method for planning and monitoring of activity progress. Across the world, the method is being used by AEC practitioners to enhance planning reliability. However, Ballard et al. (2007) have observed some barriers in executing LPS such as 1) time-consuming, 2) limited success in getting participation of the subcontractors, 3) subcontractor tradesmen who are suspicious of the system and concerned over results, 4) lack of experience to recognize gaming of the system, and 5) difficulty to define measurable quantities for some activities. In addition to these defined observations, this paper presents another five observed problems in executing LPS, which are basis of the VREL development.

1) Lack of product aspect: Last planners and coordinators are in need of product models to enable visualized communication and collaboration in order to overcome LPS shortcomings. The system is guesswork-based, textual report-generated, hand-updated, and interpersonal trust-based. In addition to this, in the field, last planners use less reliable tools, on-screen takeoff or even measuring tape, to measure quantity complete. With use of an automatic quantity extraction function of the VDC software, the quantity measurement will be improved.

2) Lack of quantity- and cost-driven aspect: Even though LPS aims at planning reliability improvement, LPS is simply based on the number of the scheduled activity-complete events and ironically generates different outcomes from what the last planners are actually using for monitoring and tracking their work progress in the field. For example, last week a drywall contractor was planned to complete one activity. This activity consisted of layout work of three walls: a 10LF (Linear Foot) wall, a 20LF wall, and a 30LF wall, and the contractor failed to complete the 30LF drywall layout. As shown in Figure 1, this week's LPS shows 67% of PPC based on a successful completion of 2 out of 3. However, in reality the contractor's PPC should be 50% (30LF out of 60LF) that will give a more reliable and realistic outcome, and this outcome will be compared to cost progress reports that the contractor focuses on when monitoring and tracking their work progress. Thus it is proposed that LPS can be improved by switching current schedule-activity-complete based PPC to quantity-complete generated cost progress PPC and this is definitely doable by a quantity extraction in the VDC software.

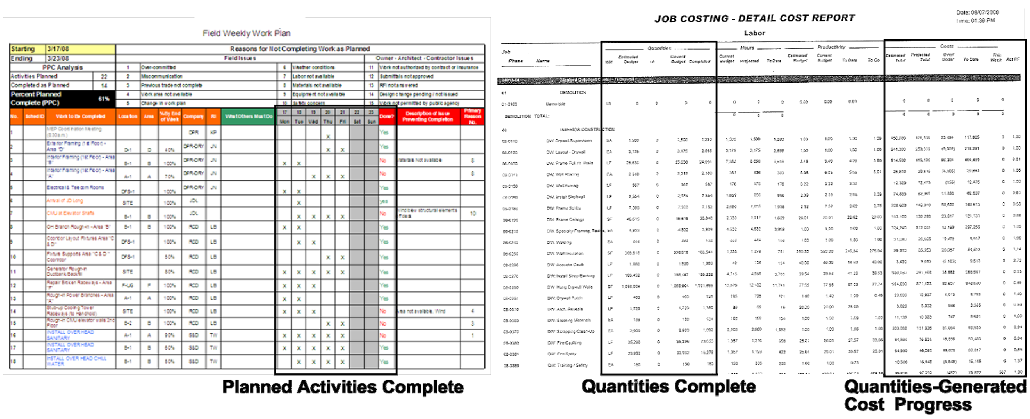

Figure 1 Figure 1. Current LPS (left) measures the number of planned activities complete or non-complete through PPC, which is not in accordance with most widely used metric of project progress management, cost progress report (right). Tables courtesy of DPR Construction, Inc.

3) Lack of cost impact analysis: It has been observed that once PPC is not 100% achieved, all the proactive remedies are: 1) put in more resources to make up for the delays in the following week and 2) delay following schedule activities which could negatively impact the critical path. In order to measure cost impact on non-complete works and remedy selection, accounting, work hours, and unit costs of materials, laborers, and equipment should be easily accessible and even checkable in the PPC through machine-to-machine interface between LPS and ERP system, which will enable the cost-loaded PPC. However, from one of the Ballard et al. (2007) case studies it was learned that it might be an idea to remove cost information from the weekly work plans to improve PPC and work flow reliability. This is contradictory to our experience and observations.

4) Lack of immediate action: Another observation is that last planners and coordinators come to Monday's weekly meeting to announce their PPC of the previous week and plan this week's to-do activity items. This recurring weekly meeting practice generates insufficient communication between the parties. If there is a delay on the critical path of the schedule happened by one contractor, for example, should announcement of this delay still wait until next Monday's meeting? Should the LPS coordinator place several calls or send emails to all the last planners and set up an in-person meeting or web-conference? It is observed that the LPS coordinator generally spends four hours per week for detecting/exploring critical delay issues, selecting appropriate last planners for reporting and placing calls/emails, and setting up a problem solving meeting. A combination of real-time update in VDC models and automatic object identification by means of RFID can enable an immediate warning sign distribution of delayed events (e.g. automatically created messages in the form of emails, SMS messages, or RSS feeds (Really Simple Syndication, RSS 2.0)). A color-coded VDC model can be web-published to a project site so that appropriate last planners can see nature and impact of the failure event on a real-time basis from anywhere, which will dramatically reduce coordination efforts.

5) Lack of automatic features: It is observed that current LPS is spreadsheet-formatted or web-based, which necessitates an extensive manual entry of data. Thus this is naturally error-prone and time-consuming. Recent innovation in mobile technology such as tablet PC, PDA, and mobile phones, however, enables automatic data capturing and transferring with higher accuracy and time efficiency.

3 Re-design of LPS Work Process

Figure 2 illustrates current LPS based on the five observations described above.

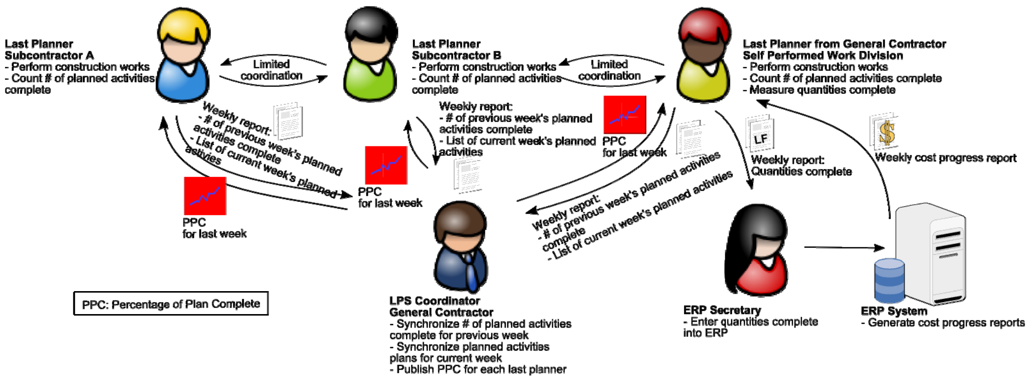

Figure 2 Current work process where LPS is based on hand-updated, non-cost-associated, textual report-generated, and interpersonal trust-based.

The workflow illustrated above can be mostly automated and machine-to-machine interfaced and thereby be more reliable by integrating VDC models, RFID technology, ERP systems, and LPS (VREL). The improved workflow is illustrated in Figure 3 where mobile RFID device is introduced to real-timely capture supply chain status. The status is then sent to the VREL system that will generate real-time updated cost + physical % complete based weekly work plans and look ahead plans with color-coded 4D model views.

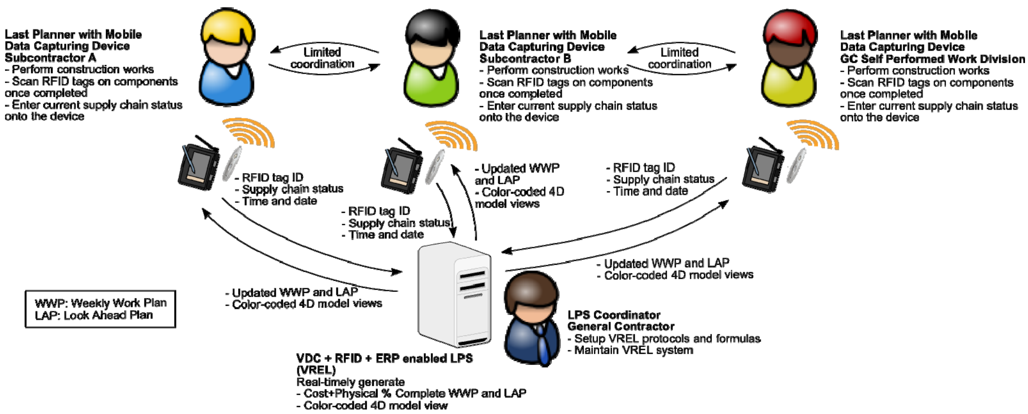

Figure 3 Proposed new work process where the VREL system 1) maps RFID tag IDs to model object IDs, 2) extracts quantities complete, 3) publishes color-coded 4D model views, 4) triggers the ERP system to calculate cost progress, and 5) generates updated real-time updated cost + physical % complete based weekly work plans and look ahead plans.

4 VREL Prototype Development

Current LPS is being widely used for monitoring and tracking project progress. Without use of earned value, however, the capacity of the LPS is limited to a simple reporting tool of what has been done and what needs to be done. The ERP system stores unit costs which can be mapped to planned activities of the LPS and can generate cost-loaded outcomes from the LPS. With formula parameters embedded, VDC will help the LPS generate accurate quantities complete for each planned activity complete and color-coded 4D model views. RFID-supported LPS will increase frequency of update on the weekly work plan and look ahead plan and send immediate warning signs regarding critical delay issues to appropriate last planners to initiate immediate proactive actions. Figure 4 shows how VREL works.

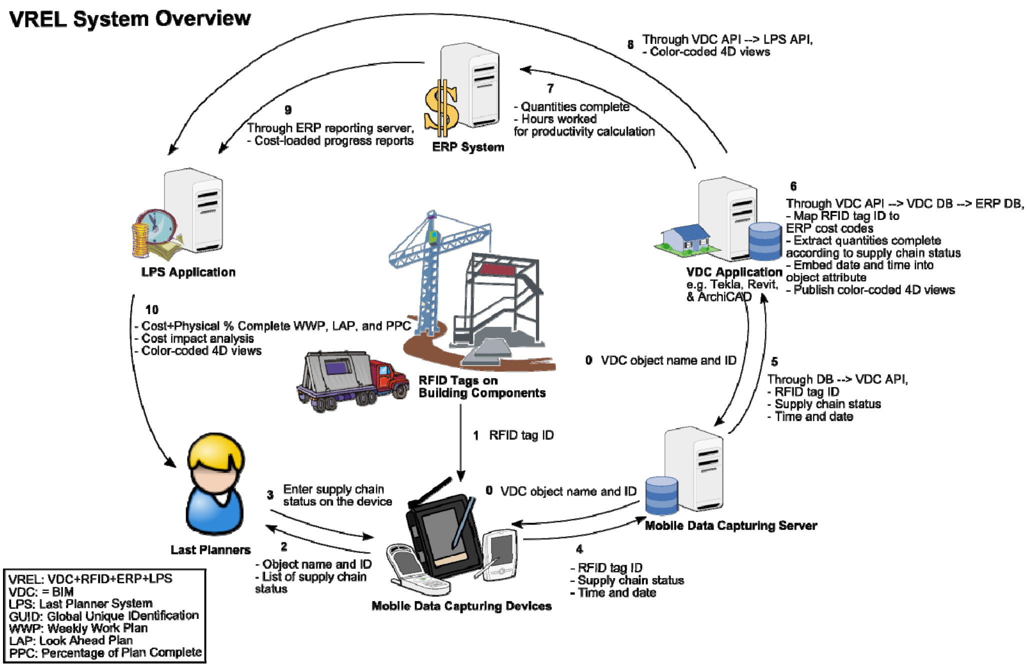

Figure 4 Overview illustrating how the VREL prototype system is used to create cost-loaded weekly work plans, look ahead plans, and PPC and how the system performs cost impact analysis.

The events in Figure 4 are:

0) Preparation: VDC model object names and IDs are loaded from the model into mobile data capturing devices.

1) A RFID tag attached to (or embedded in) a building component is read by a mobile device (mobile phone, PDA or tablet PC) on each supply chain status change of the component.

2) Last planners are presented with object name and ID and a list of supply chain status of the component.

3) Last planners enter the status of the component into the device by manual clicking.

4) The status entered is synchronized with the data capturing web server.

5) The data capturing web server functions as a middle tier between the mobile device and VDC model and is synchronized with the VDC model.

6) An algorithm in the VDC model authoring tool calculates the determining quantities according to the status of the component. The quantities are rearranged according to cost codes provided from the ERP system.

7) In the ERP system the quantities are loaded with unit costs.

8) Color-coded 4D view on each status of the component is web-published by the VDC model and viewed real-time by the last planners from anywhere.

9) The ERP generates cost progress reports which will be used as parallel comparison to cost-loaded weekly work plan WWP, look ahead plan (LAP), and PPC.
10) The LPS application generates cost + physical % complete based WWP, LAP, and PPC. The plans will be viewed along with the color-coded 4D views. If the LPS application notices any last planner that is behind in its cost and schedule responsibilities through comparison of as-built with as-planned, real-time notifications including cost impacts and 4D views will be emailed or posted to appropriate last planners for their immediate proactive action execution.

Figures 5, 6, and 7 show proposed conceptual prototypes and examples of each main components of the VREL: mobile RFID device, VDC model, and ERP system. The authors created the prototypes and used them to communicate with the interviewees for validation.

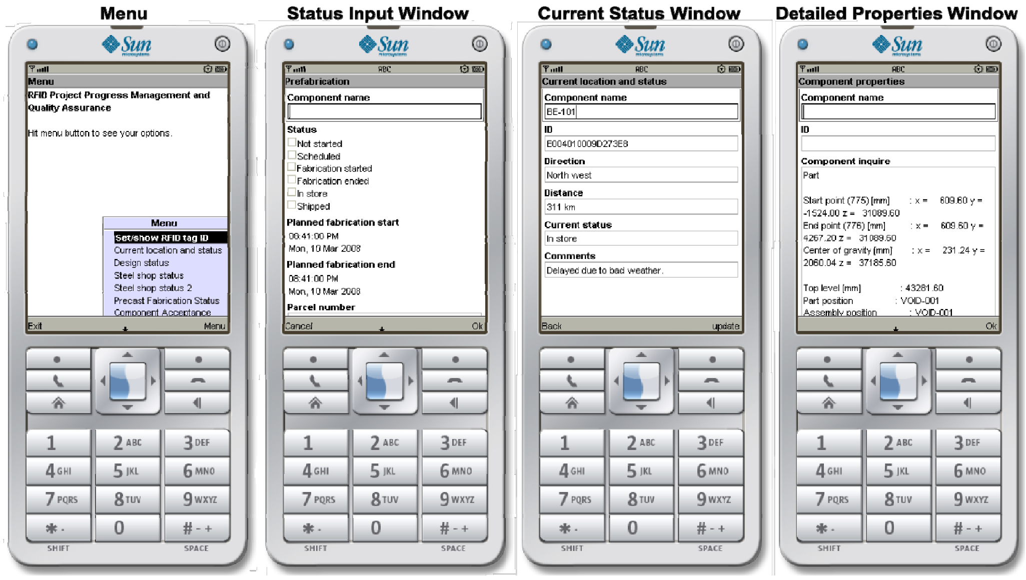

Figure 5 Prototype of the mobile RFID data capturing device in the VREL consists of login window, status clicking boxes, and object properties.

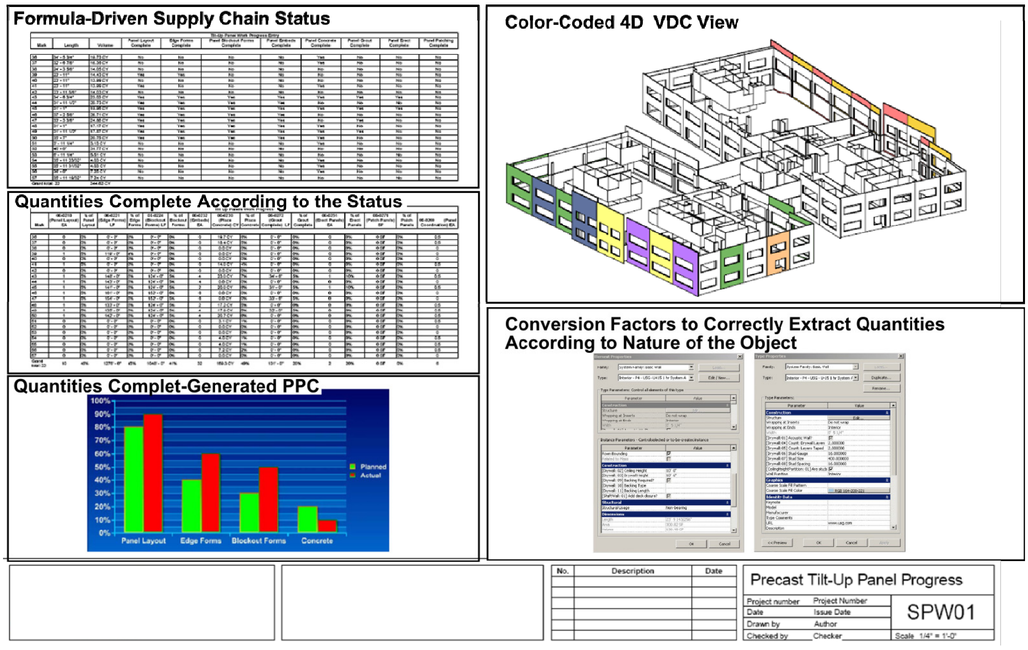

Figure 6 Prototype of the VDC in the VREL consists of quantity-complete extraction, quantity-complete generated PPC, and color-coded 4D views.

Phase	Planned Activities	Takeoff Quantity	Total Amount	Total Cost/Unit	Location
	SUBSTRUCTURE	**SF**	**7,059,685**	**/SF**	
04.03000	Slab on Grade	sf	820,086	/sf	
	Layout	51,475.91 sf	18,247	0.35 /sf	
	Base Rock - Class II	635.51 cy	35,140	55.29 /cy	
	Sand - (SPW)	317.75 cy	31,929	100.49 /cy	
	15 mil Vapor Barrier - (SPW)	51,475.91 sf	29,498	0.57 /sf	
	Edge Forms - 6"	2,004.80 lf	24,897	12.42 /lf	
	Pour Protection at B.O.Wall	1,002.40 lf	726	0.72 /lf	
	Install Grade Lines at B.O.Wall	1,002.40 lf	1,263	1.26 /lf	
	Slab Concrete 3000 PSI	1,048.58 cy	176,752	168.56 /cy	
	Finish Concrete - (SPW)	51,475.91 sf	56,624	1.10 /sf	
	Finish Concrete	51,475.91 sf	50,426	0.98 /sf	
	Concrete Pump	1,048.58 cy	20,185	19.25 /cy	
	Laser Screed - SPW	51,475.91 sf	10,421	0.20 /sf	
	Misc Equipments (Lights)	51,475.91 sf	6,730	0.13 /sf	
	Form Column Blockouts	1.00 ea	171	170.70 /ea	
	Pour Column Blockouts	1.00 ea	48	48.24 /ea	

Figure 7 Example of the ERP system export in the VREL consists of unit costs and progress costs calculation according to planned activities complete. Tables courtesy of DPR Construction, Inc.

5 Validation of the VREL System

This paper uses a validation approach through interviews with potential users and developers of the proposed VREL system. Guidelines for the VREL implementation in a real project as well as possible future system refinement and development will be documented in the authors' ongoing research.

1) Interview with LPS Coordinator: "From a management perspective, it is often exceptionally difficult to integrate cost management, project management, and procurement processes and ensure all are being performed at a high level (especially when construction is in full swing). This tool looks appealing because it could automate the compilation of information in all of these areas. It would also expose any party that is behind in the responsibilities in an objective and clear manner, which will help motivate completion. Best of all though, it will enable a manager to view all aspects of the project as a whole and make decisions that weigh all factors; cost, schedule, and quality."

2) Interview with Last Planner: "The most important benefit of the VREL is that the information is always current and links inventory directly to schedule. However, there is always the challenge of introducing new technology into the field. After the users learn the system, there are other questions that arise. How will waste be managed? How does the software track going 'over inventory' or reusing products? What if productivity is not directly linked to inventory?"

3) Interview with VDC Modeler: "Thanks to VDC software in the market, we do have capabilities of publishing a color-coded 4D model views with bill of material table showing how much of the amount of the planned activities that are complete. Attributes for converting LF, SF, and CY of modeled objects to appropriate quantity forms aligned with planned activities can be easily created and embedded once rational intelligence from estimators can be merged into models. One challenge I see now is that as Tekla Structure offers a synchronization tool of RFID scanned status into Tekla models, there should be another synchronization tool between quantities extracted from VDC models and model-based unit costs assemblies in the ERP system. Without this tool, we still need to go to another manual process, manually entering into the ERP system."

4) Interview with Mobile Device Developer: "We could save at least 20-30% on our software implementation time if the VDC model had a Web Service (W3C definition of an interoperable machine-machine interaction over the Internet) interface for integration rather than the proprietary API (Application Programming Interface)."

5) Interview with Academic Scholar: "To improve the inter-organizational information exchange illustrated with the prototypes further research and development on meta ontology is needed."

6 Conclusion

The observations on current LPS system indicate needs for improvement: cost-loaded LPS, electronic generating/sharing through ERP, update frequency increase from weekly to real time, and visualization-based planning. Through the proposed VREL development, a more accurate and reliable planning method is presented and the method is validated by potential VREL users and developers. The VREL system presents an improvement over the current LPS system not only because it is real time, but also because it is based on cost + physical % complete. Although the need for a more reliable planning method has been identified and a new VREL system has been proposed, there are also many challenges to be addressed in the system development and implementation. The system must be highly interoperable to integrate well with existing VDC and ERP applications and have good usability to be easy to implement in practice and there is a need for a significant business driver to make the solution.

The authors' ongoing research, which will be published in the near future, will include guideline development of the VREL implementation in real AEC projects and document benefits and challenges.

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Paper V

A Method for Updating Production Status in Computer Based Four Dimensional Models

Patent application No PA 2009 00801 submitted to Danish Patent and Trade Office, July 2009

A Method for Updating Production Status in Computer Based Four Dimensional Models

Kristian Birch Sørensen

Abstract: *A method for updating production status in four dimensional (4D) computer based models of facilities such as buildings, plants and infrastructures, compromising the steps of: (a) providing a list of components in a 4D model of the same type as the actual component, (b) ranking components in the list, (c) switching identification code of the highest ranked component in the list and the actual component, (d) updating status of component. The embodiment ensures, that the right component in a 4D model is updated, even if multiple components are identical and not managed individually. The embodiment saves time and effort required in construction management compared to traditional methods for keeping the 4D models updated.*

1 Background - Field

This application relates to computer based models used in planning and management of construction projects, specifically to a method for updating the models with production status.

2 Background – Prior Art

One of the most efficient technologies and work processes to increase the productivity in the construction industry is Virtual Design and Construction (VDC) also called Building Information Modelling (BIM). VDC is the process of creating and using computer based models for design and construction of building and infrastructure projects. VDC models are often 3 dimensional (3D) and include aspects as:

- Components or objects with an intelligent digital representation,
- Components that include data that describe how they behave,
- Consistent and non-redundant data
- Coordinated data.

VDC models are further described by Eastman et al. (2008). VDC models can be created by authoring tools or CAD software (Computer Aided Design) in all phases of the construction process from design, through procurement, manufacturing, assembly, operation, and maintenance. Often VDC models are reused from one phase or discipline in the construction process to another, but in many cases new VDC models are created to support specific requirements.

When data added to the VDC model are used for planning and monitoring the progress of the project, the VDC model often is called a four dimensional (4D) model (3D+time). As defined by Fischer (2001): "*4D Models link components in 3D CAD models with activities from the design, procurement, and construction schedules. The resulting 4D production model of a project allows project stakeholders to view the* *planned construction of a facility over time on the screen and 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."*

Research projects have since the beginning of the 1990s proven the high economical potential in using 4D models in construction, see further description by Koo and Fischer (1998). However, some of the drawbacks of 4D models are that comprehensive time and effort is required to create and continues update the 4D production model during the construction period. Automatic object identification by means of bar-codes, RFID (Radio Frequency Identification) and similar identification technologies is useful for reducing the time end effort needed to continuous update the 4D model. This prior art method is discussed by Chin et al. (2005). In addition, automatic identification technologies also provide improved methods for quality assurance compared to current practice. A digital link between the 4D model and the physical components can be created by adding identification units (RFID tags) to physical construction components. Subsequently, the unique identification (ID) number from the tag is added to the attributes of the objects in the 4D model representing the physical component. This link is then used to keep the 4D model updated with production status information throughout the whole construction period and through the whole supply chain. It is done by scanning or reading the objects' ID at different stages e.g. when they are fabricated, shipped, delivered, installed and checked. It is done either fully automatic by portal RFID scanners or scanners attached to lifting and transportation equipment or semi-automatic by scanners embedded in handheld computers, personal digital assistants (PDA's) or mobile phones.

The ability to monitor and plan projects' progress becomes more and more necessary as the demand increases on the construction industry to improve productivity. Therefore the use of the above mentioned technologies and methods are expected to increase significantly in the near future and replace manually 4D model update.

In practice many identical components such as doors, windows, wall elements, ventilation ducts, pumps etc. are used in the construction of a building. In the prefabrication and delivery of these components to the construction site these identical components are handled by type and not on individual basis. A prefabricated wall component is for example named and handled in the supply chain by the type name "WE 101" and not by a unique name "WE 101-07" (type name + serial number). The components can be given a unique ID tag to enable progress monitoring with the 4D model, but if they are not handled as unique components in the supply chain it results in a wrongly updated 4D model. This problem can be avoided by planning the components delivery to the construction site uniquely. However, this prior art method is not advisable because it leads to time-consuming micro management of the components.

3 Detailed Description

In accordance with one embodiment of the present invention, there is provided a method (computer implementable algorithm) for updating production status in 4D models used for planning and managing the construction of facilities such as buildings, plants, and transportation infrastructures. The said method automates the handling of unique components and save the user time in production management.

The said invention is illustrated in b 3 and described in detail after a description of an ICT-system (Information and Communication Technology system) in which the said invention can be used.

The said invention can be implemented in 4D model software applications and used in the process of updating the 4D model with information about changes in the components production status e.g. at delivery to the construction site or installation. A typical user scenario and ICT-system for this real-time project progress monitoring is illustrated in Figure 1. The numbers in Figure 1 refer to a sequence of execution of the communication between the devices and servers.

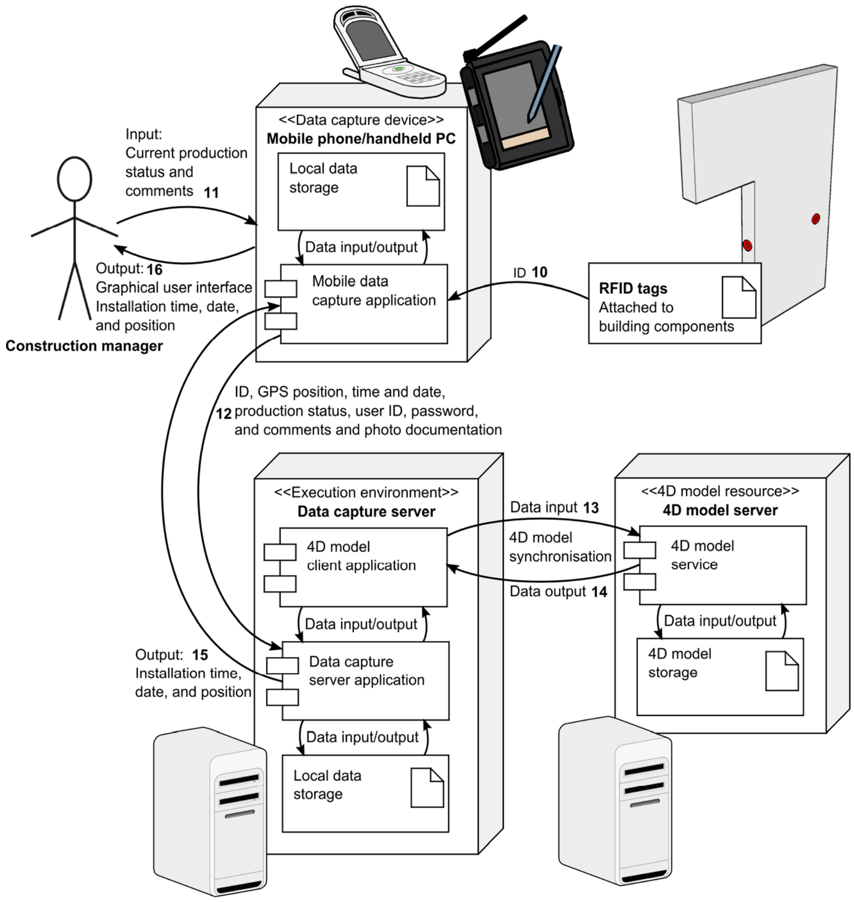

Figure 1 An example of a typical system for project progress monitoring using 4D models and automatic identification technology.

The components in the said system illustrated in Figure 1 are RFID tags, data capture devices, a data capture server and a 4D model server. Tags, also termed transponders, are identification units that are attached to the components to be identified. The data capture device or RFID reader is the component used for scanning the data contents (a unique ID number) of the tag. The RFID reader is often embedded in a mobile phone, PDA (Personal Digital Assistant) or portable/handheld computer but can also be stationary e.g. at the portal to the construction site.

In Figure 1 this component is named the data capture device. However, the RFID reader can also be self-contained and attached to a computer by wire or wireless by WLAN (Wireless Local Area Network) or WPAN (Wireless Personal Area Network, e.g. Bluetooth). The data capture device contains a data capture application that activates the RFID reader, receives the signal from the hardware and translates it into the ID number or string used to link the physical component with the 4D model objects, and if necessary, also filters the data before it is relayed. The data capture application furthermore provides a user interface for the manual system interaction and make use of local temporary data storage. The data capture device can by advantage also contain a global positioning system (GPS).

The data capture server receives data from the data capture device and is responsible for updating the 4D model with this data. The data capture application also makes use of temporary data storage and can provide a user interface for system setup (not shown in Figure 1). The data capture server also runs a 4D model client application used for the communication/synchronisation with the 4D model server. Examples of existing 4D client/server applications (4D model authoring tools) are Tekla Structures, Autodesk Navisworks™ and Vico Software's Virtual Construction™ software suite. The 4D model server provides the data storage and enables shared access to the data from multiple users, however, for simplicity only one user is shown in Figure 1.

The said invention can be implemented in 4D client application software or in a data capture server application. The method is in the following described in detail using the flow chart in Figure 3. However, the prior art of updating 4D models is first introduced using the flow chart in Figure 2, and it comprises of the steps:

(17+18) When a component is installed at is final location in the facility being build the user (e.g. the construction manager or team leader) activates his tag reader device (a mobile phone, PDA, or handheld computer with an RFID reader or bar code reader embedded) and scans the ID tag. (19) An input window is shown on the device and (20) the user enters the production status of the current component and comments. (21) The process flow is then split in two parallel processes. (22) If the component is known (data about the component is already available on the data capture device from a previous scanning) the input window is updated with the component name to quickly let the user know which component is scanned. (23) In the parallel process the data capture server application search for the component, (24) and again the process is split in two parallel processes. (22) If the component is already known by the data capture server application, information is returned to the data capture application to enable a quick update of the user interface. (25) In a parallel process the synchronisation between the data capture server application and the 4D model is initialised. (26) The first step in this synchronisation/model update is to update the 4D model client application. (27+28) Secondly, the client model is synchronised with the model server. (29) The data capture server application is updated with the new production status, (22) and the user interface is updated. (30) Feedback about the component status update is shown to the user. (31) If the update is successful the next task (component to be installed) is shown to the user, otherwise an error-message is shown and the user can try again.

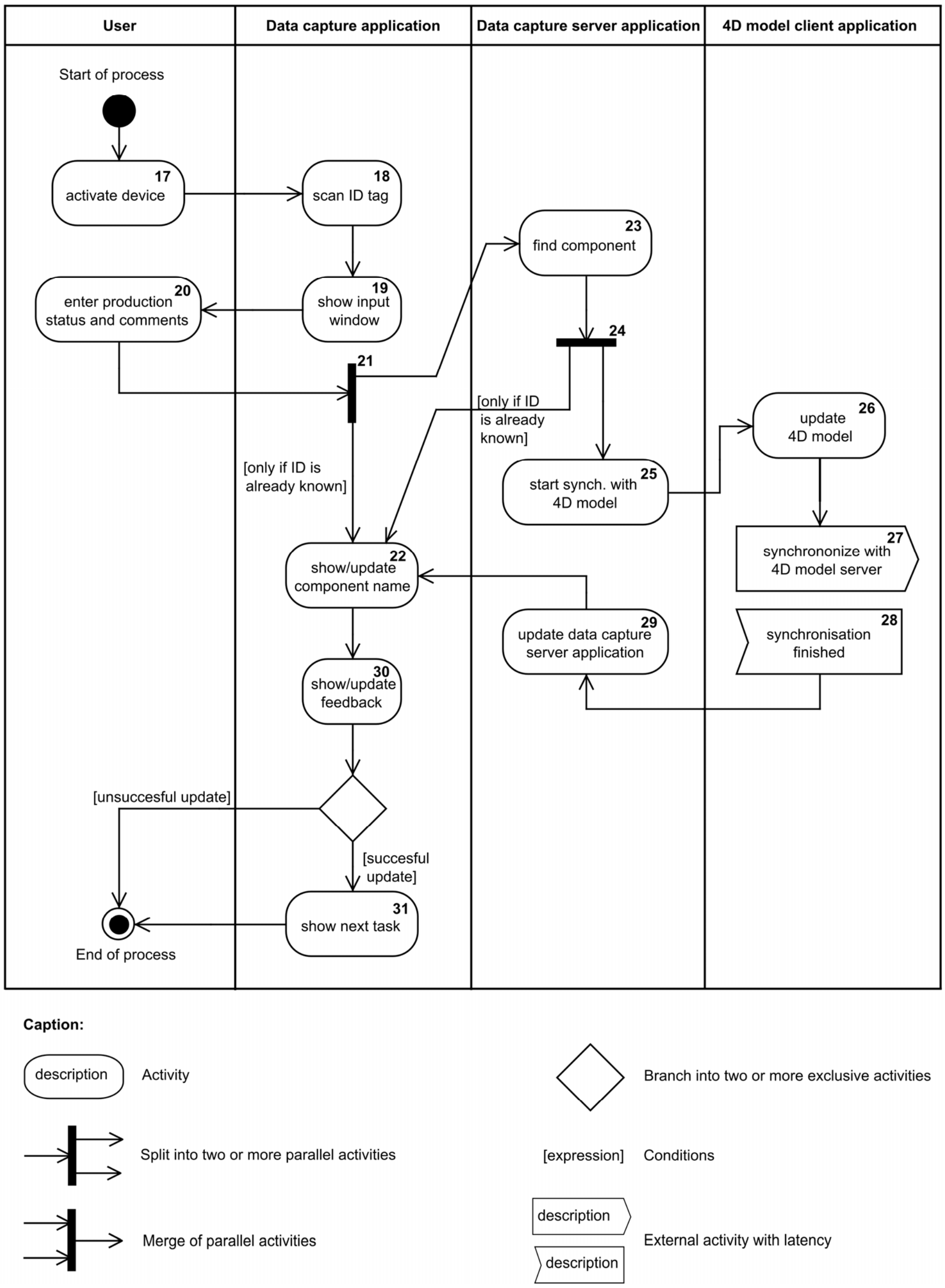

Figure 2 A typical flow of activities in the prior art method for updating the 4D model with input from automatic identification devices.

The said invention is a sub-process in updating 4D models and is in the present embodiment supposed to replace the steps (26-28) in Figure 2. The method is shown in Figure 3 and comprises of the steps:

(32) The first step is to identify if the component is unique. (33) If the component is unique no further action is needed and the 4D model can be updated, (34+35) and synchronised with the model server.

(36) If the component is non-unique all components in the model of the same type as the scanned component are listed. Components in the model where the production status attribute is already set to "installed" are omitted in the list. (37+38) Depending on the data available about the components in the list, they are ranked according to either the distance between their actual installation position and their planned installation position or according to their planned installation date and time. If position data as well as installation date and time data is available a combination of the two ranking lists can be used to increase the reliability of the method. (39) If the scanned component's ID is equal to the ID of the component with highest rank on the ranking list no further action is needed and the 4D model can be updated (33), and (34+35) synchronised with the model server. (40) If the scanned component's ID is not equal to the ID of highest ranked component, the ID of these two components in the 4D model are switched. This switch ensures that the right component in the 4D model is updated without requiring manual micro management of the non-unique components in the 4D model. (33) The right component in the 4D model was identified and its production status attribute is updated and the final step in this sub-process is (34+35) to synchronise with the 4D model server.

The remaining steps in the 4D model update are similar to prior art and described above from step 29 and in Figure 2.

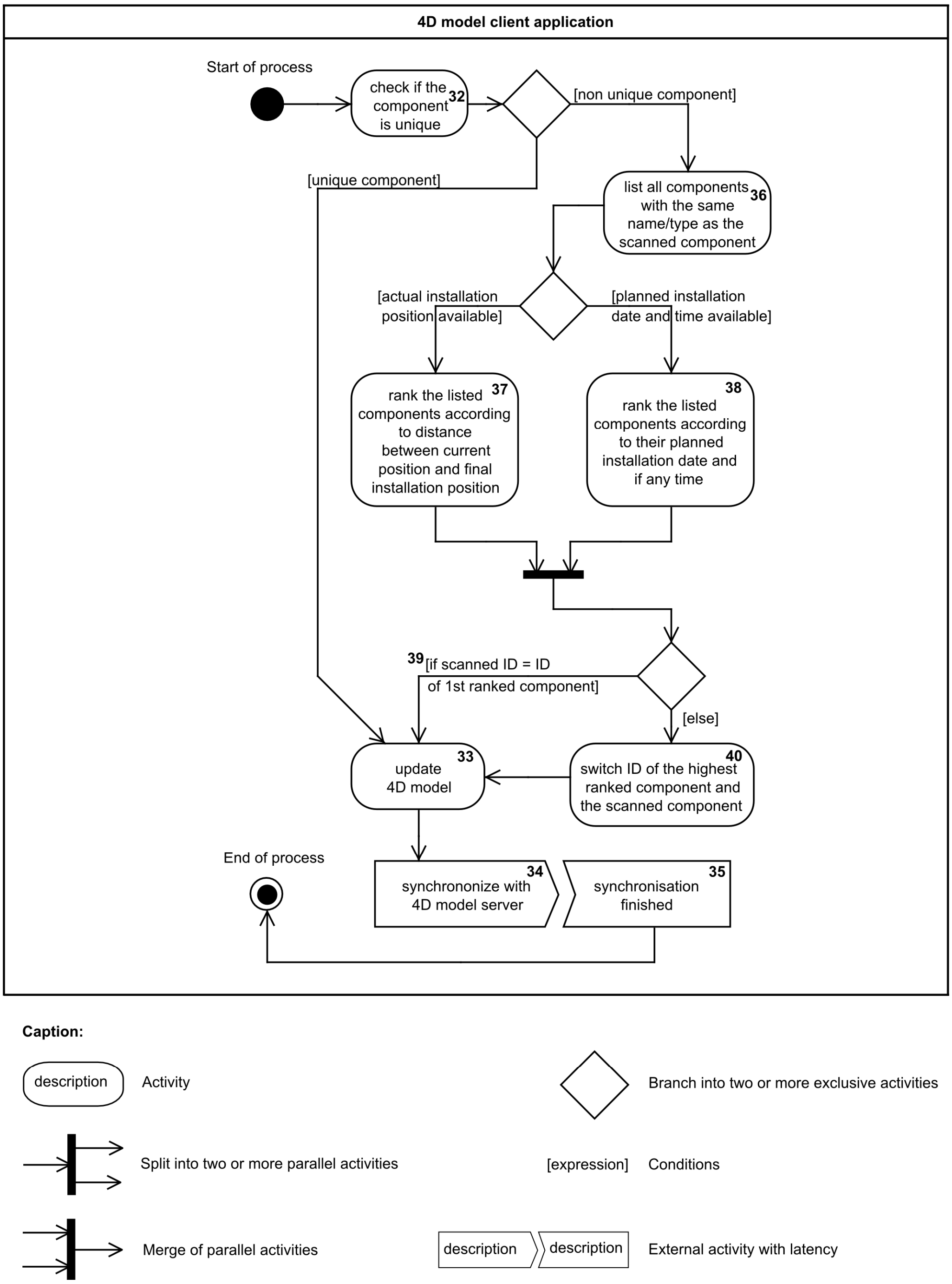

Figure 3 The flow of activities in a preferred embodiment of the present invention.

The present method can also be used in processes where the component identification is done automatically by e.g. a tag reader constructed as a portal scanner or a scanner attached to lifting and transportation equipment. In this case the manual input in steps (17-20) should be omitted.

3.1 Advantages

From the description above, a number of advantages of some embodiments of the method for updating production status in 4D models become evident:

(a) The said invention enables a correct update of the 4D model, as illustrated in Figure 4. A similarly updated model where the prior art method was used is shown in Figure 5. It is illustrated how the model in Figure 4 reflects the current status of the construction project where Figure 5 illustrates an almost random and wrong update of the model.

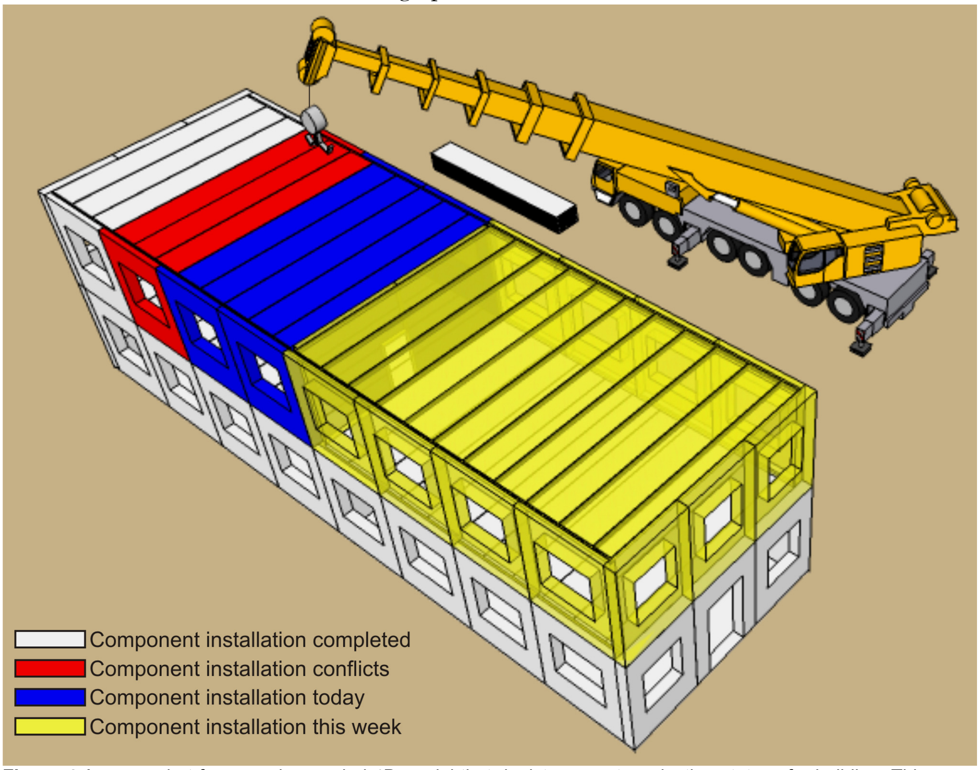

Figure 4 A screenshot from a colour-coded 4D model that depicts current production status of a building. This screenshot shows a correctly updated 4D model where one embodiment of the present invention was used for updating the model with input from automatic identification devices.

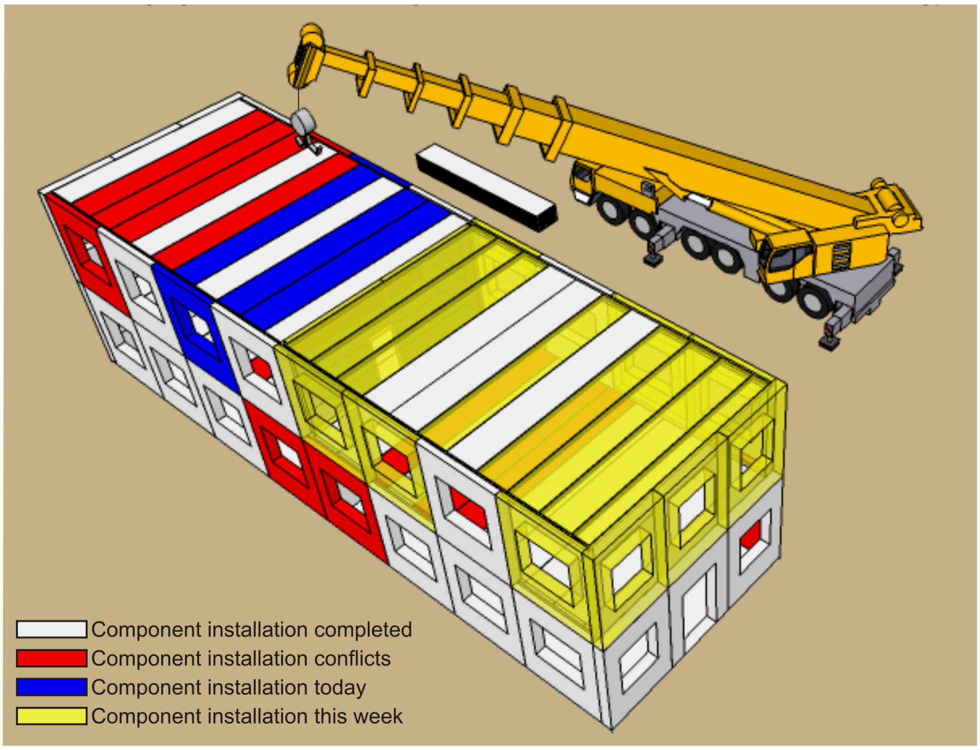

Figure 5 A screenshot from a colour-coded 4D model that depicts current production status of a building. This screenshot shows a model where a prior art method was used for updating the model with input from automatic identification devices.

(b) The update is done without the need of micro-management of each component in the 4D model. This is handled by the said invention and saves time for the 4D model user in the production management.

(c) Depending on the data available for the components the method can be based on installation date and time as well as on position data.

(d) The method is important to achieve benefits from using automatic object identification in construction management by means of RFID and barcode technology.

4 Conclusion, Ramification, and Scope

Accordingly, the reader will see that the embodiment provide a reliable and time-saving method for updating production status in 4D models used for construction management of buildings. The embodiment ensures, that the right component in the 4D model is updated, even if multiple components are identical and not managed individually. It permits the construction manager, 4D model coordinator or any other user of the system implementing the embodiment to have focus on management of the processes and let the ICT system handle the details of specific components.

In addition to the illustrated example with precast concrete elements the method will also be applicable to any other component installation or handling of components in construction processes such as installation of heating, ventilation or air-condition equipment as well as steel and timber structures.

Although the description above contains many specificities, these should not be construed as limitations on the scope of the embodiments but as merely providing illustrations of some of the presently preferred embodiments. For example the embodiment will also be applicable in other industries such as in construction of airplanes, and ships. The embodiment can also be implemented in the data capture server application rather than in 4D model client application and in cases where more than one identification tag is used to identify each component.

Thus the scope of the embodiments should be determined by the appended claims and their legal equivalents, rather than by the examples given.

5 Claims

I claim:

1. A method for updating component status in four dimensional models, comprising:

(a) providing a list of components in said four dimensional model of the same type as the said component,

(b) ranking components in said list

(c) switching identification code of the highest ranked component in said list and said component,

(d) updating status of said component,

whereby it is ensured, that the right component in said four dimensional model is updated, even if multiple components are identical and not managed individually.

2. The method of claim 1 wherein components in said list are ranked according to their planned installation date and time.

3. The method of claim 1 wherein components in said list are ranked according to the distance between their actual installation position and their planned installation position.

4. The method of claim 1 wherein components in said list are ranked according to the distance between their actual installation position as well as their planned installation position.

5. The method of claim 1 wherein components in said list are ranked according to their planned delivery to the construction site.

6. The method of claim 1 wherein components in said list are ranked according to their planned shipping date and time from the manufacturer.

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Paper VI

Evaluation and Guidelines for Implementation of ICT Systems Supporting RFID in Construction

Submitted to Journal of Information Technology in Construction, August 2009

Evaluation and Guidelines for Implementation of ICT Systems Supporting RFID in Construction

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[2]Aalborg University, Department of Civil Engineering

Abstract: *The evaluations presented in this paper demonstrate usefulness and potential of combining virtual models and automatic identification technologies in construction. Real-world applications of two prototype systems for operation and maintenance, and construction management are used in the evaluations. The evaluations reveal that the technology is ready for implementation in construction and can enable a new object-oriented quality assurance process, facilitate on-site information access, and improve project and operation management procedures. These conclusions are based on practical technology experiments and the authors' observations, interviews, and questionnaires of future users of the applications.*

On the other hand, the evaluations also show that a lot of work is still required before the potential can be realised in form of improved quality, cost and reliability of the construction projects where the technology is adapted. The main barriers for future implementation of the technology are identified to be: Lack of resources for innovation projects in construction and reluctance to change among manufactures and mid-level managers/project managers. However, labourers are more willing to try the new technology and expected future benefits by using it. A challenge for the future is therefore to guide the managers in construction, through the practical implementation of the technology. For that reason an implementation framework for the forthcoming technology change process is presented in this paper. It is also argued that reuse of the virtual models and radio frequency identification (RFID) tags from the design and construction in operation of the building and use of traditional consumer equipment such as the NFC (Near Field Communication) compatible mobile phones, are crucial aspects to lower the cost of the technology implementation and increase the chance of success with the implementation.

1 Introduction

Automatic object identification by means of radio frequency identification (RFID) is in several research projects proposed as a key technology to enhance data capture and information management in construction (Jaselskis, 1995; Sacks et al., 2003; Chin et al., 2008). In two of the authors' previous articles (Sørensen et al. 2008; Sørensen et al., 2009b) it was argued that the greatest potential of the technology in construction is in operation and maintenance, project progress management, quality management, and on-site information retrieval. These articles, respectively, describe information and communication technology (ICT) system prototype development and user needs capture related to operation and maintenance, and construction management. As a follow-up on the previous work, evaluations through real-world applications of the developed prototypes are described in this paper.

The first system is a mobile operation and maintenance system for infrastructure constructions supported by RFID (SMART Mobile RFID), and the second system is a prototype of a virtual building model based system for construction management supported by mobile phones and RFID (Mobile Manager). The two systems are at different stages in their development, and they are therefore evaluated differently. Smart Mobile RFID developed by Ramboll Informatik has been released in its first version and is currently used in practice by a contractor for document management, maintenance and operation reporting of infrastructures related to railways. It is evaluated by observing the users in action and by informal interviews about user interface satisfaction.

Mobile Manager is in its early development. The focus of this evaluation is therefore to test if the technology and processes are useful in construction practice, explore the barriers, assess cost, and test functionalities and usability of the mobile user interface.

The introduction of automatic object identification by means of RFID in construction induces a multi-facetted change process. During the evaluations a need for guidelines for construction managers was identified in order to enable this implementation. Existing guidelines such as Chin et al. (2008) or Kotter (1996) were found either too technology oriented or too social/organisational oriented to be practical and useable in construction. A practical framework supporting the integration of people, technology, resources, processes and organisations is therefore described in Section 5 of this paper. The framework is driven by user and business needs, and applies an iterative and incremental process to support continuous learning and improvement.

2 Evaluation Methodology

Evaluations are important to check if the systems and processes under development meet the users' needs and check if they are able to use it, identify errors and validate design decisions etc. Tognazzini (2000) argues that: *"Iterative design, with its repeating cycle of design and testing, is the only validated methodology in existence that will consistently produce successful results. If you don't have user-testing as an integral part of your design process you are going to throw buckets of money down the drain."* The systems under development have therefore been through several evaluations as described in this paper.

A number of paradigms and techniques exist for system and process evaluation; for an overview and discussion see e.g. Preece et al. (2002). The authors have focused on qualitative methods because they are particularly helpful for evaluating complex systems involving several tasks embedded in other activities that include multiple users (Preece et al., 2002). Methods supporting forward thinking and provide useful inputs to the future development has also been preferred over methods that focus on documenting the past.

The DECIDE (Determine-Explore-Choose-IDentify-Evaluate) framework (Preece et al., 2002) has been used to structure and direct the prototype evaluations and is described further below:

Determine the overall goals addressed in the evaluation: The overall goal is to evaluate the functionalities, usefulness and practical applicability of the systems SMART Mobile RFID and Mobile Manager. This is done in order to identify if a digital link between virtual and physical objects provides benefits for building owners and contractors in operation and maintenance, and construction management. Lessons learned should be captured in a usable form for future development and user needs that did not come out during the prototype development stage must also be captured.

Explore the specific questions to be answered: The following questions will be answered through the evaluation: Does the technology work in practice and is it ready for implementation in construction? Can the benefits be demonstrated in operation and maintenance already? Do the designed methods designed for quality management and project progress management make sense for construction managers as well as labourers? The questions are further detailed for the two cases described in Sections 3 and 4 of the paper.

Choose the evaluation paradigm and techniques to answer the questions: The paradigms "Quick and dirty" where designers informally get feedback from users to confirm the ideas, and field studies are mainly used for the evaluation. They are supplemented with usability testing (Nielsen and Loranger, 2006) based on user satisfaction questionnaires and interviews to elicit users' opinions (Preece, 2002). Predictive evaluation based on heuristics was also used to predict usability problems.

Case 1, described in Section 3 of the paper, was used for the evaluation of SMART RFID Mobile. A combination of workshops, observations, and informal interviews of the users and developers in their working environment were used for this evaluation. The questions used in some of the interviews were based on a questionnaire for evaluating computer usability satisfaction, efficiency, and ease of use developed by Lewis (1995). System developers and current users were involved in the evaluation.

Case 2, described in Section 4 of this paper, was used for the evaluation of Mobile Manager. The evaluation was done by observations in the field, practical experiments with the technology and as semi-structured interviews of future users after presentations of interactive prototypes. The evaluation period was about 5-7 months and the future users involved in the evaluation included manufacturers, construction managers, labourers, CAD technicians, and consulting engineers.

In order to reach a broader group of the respondents, the observations and interviews are supplemented with a web-based questionnaire where the prototype is explained on a web-site using storytelling, video clips and screen shots from the prototype. A group of approximately 10 lead users in Denmark responded to the questionnaire. The questions used in this evaluation are based on a combination of questionnaires developed by Lund (2001) and Davis (1989) for measuring usability and for evaluating perceived usefulness, and perceived ease of use of information technology.

Identify the practical issues that must be addressed: Running research project evaluations and construction projects in combination is a major challenge. It requires good timing to do the field experiments because the construction project has a tight schedule and a fixed budget, so minimal disturbance of the construction team is required to avoid conflicts. It is also difficult to motivate the future users to give feedback because of the busy and short-sighted working environment in the construction industry. As described in Sections 3 and 4, the evaluation is split in two cases and several objectives to overcome these challenges. The practical issues also include setup of the practical experiments, finding relevant future users, making a realistic presentation of the system and arranging meetings in the field.

Decide how to deal with the ethical issues: The first author is in the field studies and interviews a participating observer (insider) with strong relations to organisations involved. It can be seen as an objection against the validity of the data, but on the other hand it is also an advantage because future users in construction are more likely to express their true opinions to people they can relate to. It is also an advantage in relation to overcoming the previously mentioned practical issues of doing experiments in ongoing construction projects. The authors' only interest is to elicit reliable knowledge in order to be successful with the future development, while the ethical issues of conducting the evaluation as an insider are assessed to have minor influence on the collected data. The involved users also felt free to comment on prototypes and questionnaires.

During the field studies, labourers often expected the first author to be a representative of the Danish Working Environment Service, but after a short explanation about the evaluation the labourers accepted the observer and kept on their normal working practice. Resistance against change of working practice and use of ICT is another issue that might influence the results negatively.

Evaluate, interpret and present the data: Results from the evaluation are presented in the following Sections 3 and 4 of the paper. The findings are condensed in a short summary explaining each objective and the most important lessons learned to respectively be reused and improved in future implementations. As argued by Aagard (2009), this is an effective and reusable way to collect the evaluation results.

3 Evaluation of SMART Mobile RFID

In this case the company Ramboll was hired by a facility owner to prepare outsourcing of operation and maintenance activities and deliver a digital job management and document handling system.

Ramboll's IT-system SMART was chosen to support the job management and document handling. SMART is a Java application deployable to PCs, Personal Digital Assistants (PDAs) and smart phones and its hierarchical structure of construction and mechanical installation compoenents is customised for each client. The interest for RFID technology arose because the facility owner also wanted an efficient way to document that the contractors did the inspections on-site and within the right time frame. RFID was chosen rather than e.g. barcodes because of the technology's superior durability in a potentially harsh environment. It was therefore decided to extend the PDA (Person Digital Assistant) and smart phone edition of SMART, called SMART

Mobile, with functionalities for automatic identification of facilities, components, and users by means of RFID. The first author of this paper was involved in the requirements specification for RFID support and system evaluation. It was decided to use ISO 15963 tags (13.56 MHz) because of good availability of supporting handheld readers and good all-round properties (price, readability near metal, size). Rugged RFID tags and PDAs with an RFID reader, as illustrated in Figure 1, are used for the system implementation and the tags are placed at the entrance to each facility (in this case a pump station) and at components needing service and inspection (pumps, structures, instruments, valves, wells etc.).

Figure 1 Illustration of rugged RFID tags placed at the entrance to the facility and the PDA with RFID reader used for the implementation of SMART Mobile RFID.

The PDA has on-site and full-time access to the O&M database through GPRS. The automatic component identification by means of RFID enables the users to have quick on-site access to relevant information at the specific location (check lists, maintenance jobs etc.) stored in the O&M database, and it is also automatically documented that components are inspected regularly. The inspection is still done by a person, but all information is now stored digitally. Illustrated in Figure 2 is an example of the data entering routines the O&M contractor are required to fulfil when doing service or inspection.

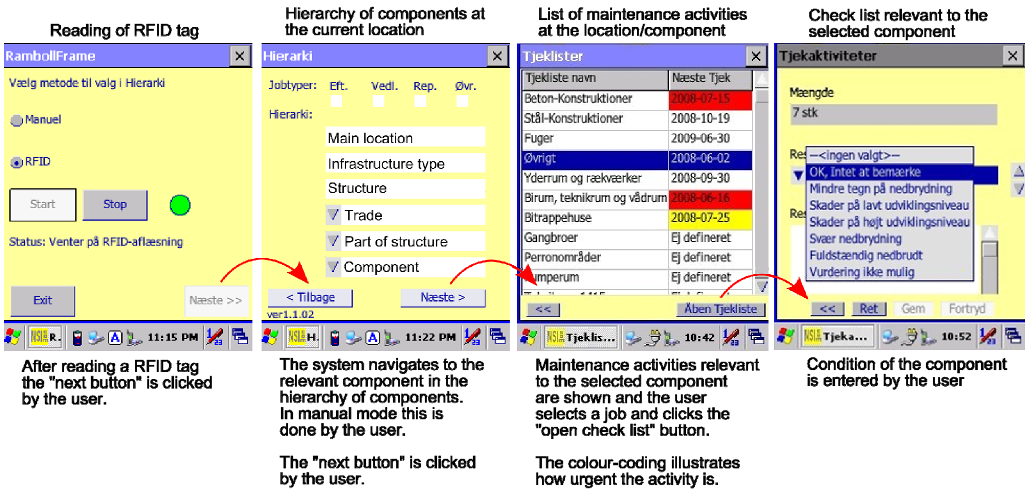

Figure 2 Four screen dumps from the system SMART Mobile RFID to illustrate how the user activates the RFID reader, selects components and maintenance activities, and enter maintenance condition information.

3.1 Most Important Lessons Learned to Reuse in Future Implementations

To introduce the users to the new system a training workshop was conducted. It was a rewarding workshop not only for the users but also for the developers because the users' immediate comments, questions and suggestion for improvement to the new system were collected. Following, the users were observed and interviewed in their working environment.

The hardware was found to work in practice and ready for implementation in construction. Several rugged PDAs (International Protection Rating 54 or 65 and drop resistant from 1.5m) exist with a RFID reader embedded or attached. The PDAs with RFID reader mounted at the bottom was found awkward to use in practice while a top mounted reader is preferred. Systems where the PDA and RFID reader are two separate devices were as well assessed to be awkward in practice.

A reading distance of the RFID tags of 3-5 cm could be reached with the PDA's even when the tags were mounted on metal, and this was found sufficient by the users. The Polytag shown in Figure 1 was selected because of the good readability when used on steel structures and mechanical installations.

The users found the system useful and easy to use and perceived it as an improved method for documenting their on-site inspections. The facility owner is also satisfied with the more consistent documentation, the digital working practice provides. This observation was stated by one of the software developers: *"They used to have as many methods for documentation as employees in the organisation."*

The tags attached to the physical components can be linked to the information in SMART in several ways. A tag on a component can point to a job list for a particular trade (electrical, mechanical, structural), to a job type for the component (inspection, maintenance, repair) or just directly to the component. The last approach of using the RFID tag solely as a virtual-physical component link was found the most flexible. The retrieval of trade or person dependent work instructions and checklists etc. should then be handled by the O&M system, either automatic or by manually letting the user select the relevant trade. The same tag can thereby be used for several purposes and trades. This approach is also recommended for other systems e.g. for project progress management or quality management.

3.2 Most Important Lessons Learned for Improvement of Future Implementations

Despite the good availability of hardware, the technology is not yet plug and play. Software drivers had to be developed by the system developers for the Java application deployed to the PDA. Only proprietary .net drivers were delivered with the RFID reader embedded in the PDA. This also results in needs for recoding the system when changing the PDA.

It was difficult to assess which RFID standard to use for tags and readers. The ISO 15963 standard was, as previously mentioned, chosen because of good availability of supporting handheld readers and good all-round properties (price, readability near metal, size). From a cost perspective, changing to Near Field Communication (NFC/ISO 14443) compatible tags and readers should be considered when they become more available for traditional consumer mobile phones; see Section 4 where such mobile phones are used in the evaluation.

Structuring information and working processes for digitalising the O&M procedures is a much more extensive task than implementing the RFID technology. This task took at least 50% extra time than first estimated (according to the project schedule). A new (proprietary) data model specific to the facility owner's needs had to be developed and implemented.

Several minor and more severe usability issues were identified during the evaluations and they are currently being corrected before the wider deployment of the system. E.g. from the training workshop a list 20 issues relating presentation of checklists on the PDA, use of the on-screen keyboard, colour-coding of data fields, and how to link components and data in the system etc. were collected. The following observations and interviews gave supplementary details about these issues and it was also identified that the screen is impossible to read in direct sunlight and new search features would be appreciated by the users.

Based on practical experiments it was found useful to do the first registration of RFID tags and locations/components on-site rather than prepare and label the tags for a specific location/component at the office. It is much more flexible, and changes in the setup of the data structure can thereby be made on-site. To increase the start-up speed of SMART Mobile, it would be useful with a faster (3G) Internet connection on the PDA. It is currently using GPRS, but rugged PDAs with RFID and 3G Internet connection are currently being tested.

The system will often be used in pump stations three stories below surface of the earth without possibilities for mobile Internet connection. As a consequence SMART Mobile's concept based on constant connection to the server must be redesigned to support automatic synchronisation whenever an Internet connection is available.

The weight of the PDA of approximately 600g was considered to be acceptable, but a bigger screen is desired. Another request from the users was the ability to combine the use of the PDA with a netbook (small, light and inexpensive laptop) e.g. placed in the service car.

4 Evaluation of Mobile Manager

As described in Sørensen et al. (2009b), the prototype of Mobile Manager was developed in a Contextual Design process where the inquiry was done in the construction management process in three different cases. One of the cases concerning management of precast concrete element manufacturing and installation was also used for the prototype and technology evaluation described in this paper. The case used in the evaluation, was a traditional two-storey Danish office building of 3700 m^2 including a basement. It was a public-private partnership project, where MT Hojgaard was the general contractor, Ramboll was consultant on all engineering services, and the architectural firm was the company Cubo. The carcass of the building was prefabricated of concrete elements. This is a very common construction method in Denmark.

Mobile Manager is a prototype of a system for project progress management and quality management. The system is deployable to traditional mobile phones with an ISO 14443 / NFC compatible RFID reader embedded; see Sørensen et al. (2009a) for a discussion of RFID standards relevant to the construction industry. The mobile phone is connected to a Java web server application (M_Solution) through GPRS/EDGE or HSPA (3G) mobile broadband and used for automatic identification and data capture. By synchronising the database, used by the web server for data capturing with the virtual model server (Tekla Structures), the mobile phone can be used to real-time update the virtual model. Tekla Structures is a 3D/4D modelling application for structures and M_Solution is a multi-purpose and configurable data capture server with possibilities for connecting different clients such as mobile phones and PCs. The combined system is useful in construction for e.g. real-time inventory management, quality management, project progress management, and on-site information retrieval such as of work instructions and check of compliance with the schedule. Popularly speaking, a digital link is created between the virtual model and the physical building shown in Figure 3.

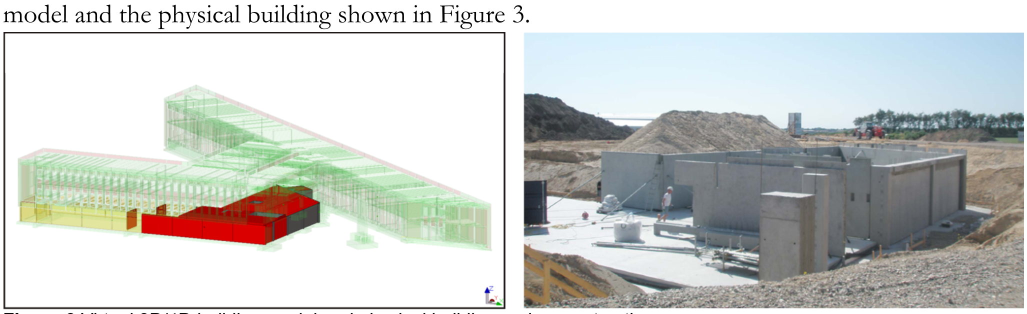

Figure 3 Virtual 3D/4D building model and physical building under construction.

The Mobile Manager and the process of using it can to some extent look similar to other RFID and virtual model based systems for construction management such as RFID+4D PMS (Chin et al., 2008). At least three important features distinguish the Mobile Manager solution from the other systems: 1) The virtual 3D model is the back-bone for the whole process from design, through construction to operation. Construction and shop drawings are created on basis of the virtual 3D model, not the other way around. 2) Mobile phones with real-time access to the server are used rather than PDAs and tablet PCs because they are widely used in construction. 3) RFID tags are not recycled but left on the components for reuse in location based services, quality inspection and operation and maintenance.

The scenario and system architecture evaluated is shown in Figure 4. It is illustrated how the construction manager uses mobile equipment to automatically identify and capture data when building components arrive at the construction site and at installation; see further description of user scenarios in Sorensen et al. (2009b).

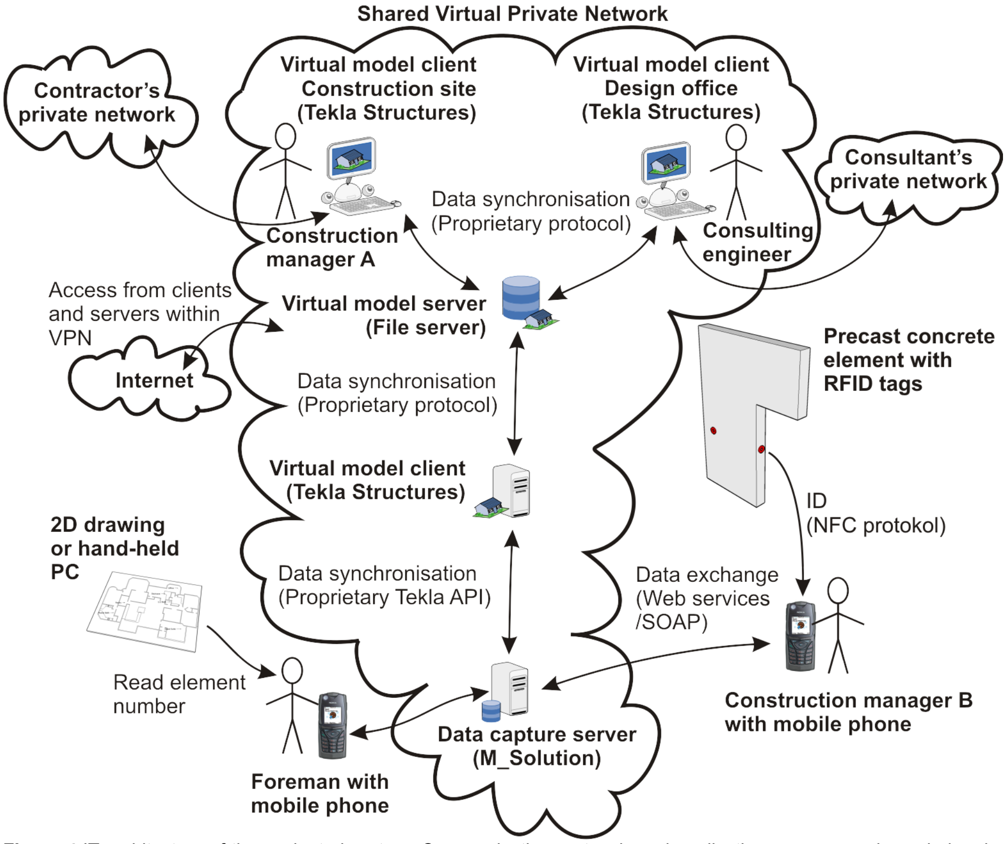

Figure 4 IT architecture of the evaluated system. Communication protocols and application names are shown in brackets. The clouds illustrate different networks.

It is complicated and often impossible to run ICT development projects parallel with construction projects. In construction projects decisions are often made late, the schedule is short and the budget is tight which also influenced this ICT development and evaluation. To initiate the scenario a number of prerequisites are necessary: The virtual models of the building must be available and sused both in design and construction, the users must have the competences to take advantage of the models, and the technology must be working and have a proper user environment etc. It was decided to divide the evaluation into intermediate testable system domains. The system domains evaluated within the time-frame of the construction project are selected to enable test of central aspects of the whole system and listed below:

1. Implementation of daily virtual 3D model use at the construction site
2. 4D model for planning
3. Test of input of production status in 3D/4D virtual model
4. Placement and readability of RFID tags embedded in concrete elements
5. Usability of user interface of mobile equipment
6. Use of RFID tags as a physical hyperlink to information in the virtual 3D model
7. Real time project progress management based on RFID, vitual model and a mobile application
8. Analysis of the actual work flow after the construction project is completed based on real life and accurate production data

The synchronisation using the proprietary Tekla API between the virtual 3D model server and the data capture server was not ready for use in production during the construction project, and it was therefore not possible to evaluate item 7 and 8. In the following sections, a summary of results from the six evaluated system domains is given by first briefly introducing the evaluated objective and then explaining the most important lessons learned to be reused and improved in future implementations.

4.1 Implementation of Daily Virtual 3D Model Use at the Construction Site

3D models were created prior to construction and used for 2D drawing extraction. The structural models were created with Tekla Structures and MEP (Mechanical/Electrical/Plumbing) models were created with MagiCad. The architect used 2D drafting in AutoCAD. Aggregated models were created in Solibri Model Checker and Navisworks on basis of IFC and DWG file export/import, see Figure 5. The use of separate discipline and aggregate models is a working principle proposed by the national Danish development project called Digital Construction and described further in bips (2007). This principle limits the possibilities of software vendor lock-in and enables each discipline to use their preferred applications. With more than 150 accomplished projects in Ramboll Denmark based on these working methods and tools, it is widely used and tested and was therefore not evaluated further in this case.

The construction site shed was equipped with computer equipment for accessing the design team's models at Ramboll's file server through a secure VPN Internet connection (Virtual Private Network). As illustrated in Figure 5 (right) the shed was also equipped with a projector and wireless Internet connection for the handheld equipment.

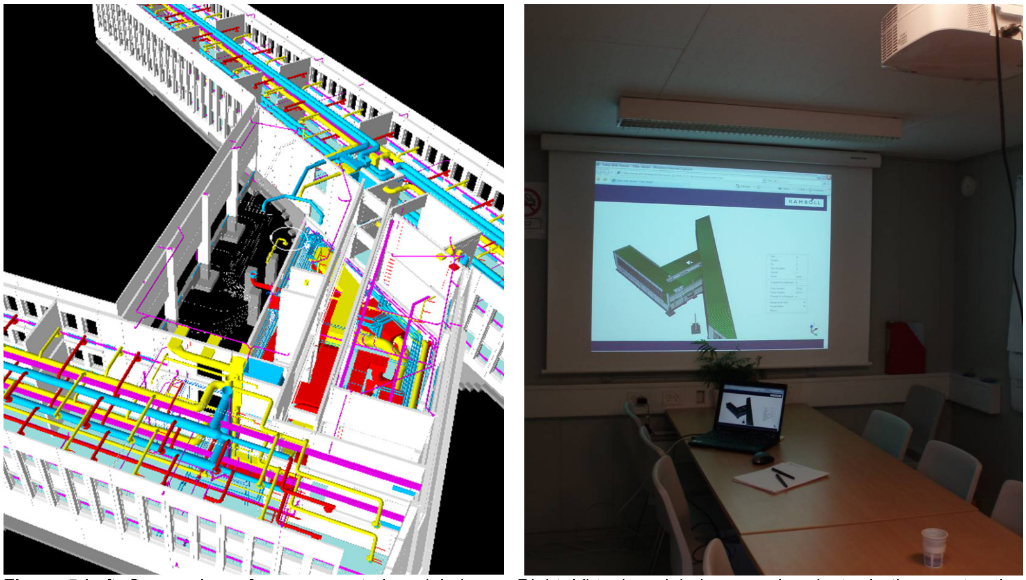

Figure 5 Left: Screen dump from aggregated model viewer. Right: Virtual model viewer and projector in the construction site shed.

4.1.1 Most Important Lessons Learned to be Reused in Future Implementations

Several people (typically engineers and construction managers) involved in workshops during the system development (supported by online questionnaires) have commented that it would be hard for the craftsman or the unskilled worker to use the virtual models or the mobile equipment. A comment from a civil engineer in a workshop expressed it this way: *"Watch out not to loose John the plumber, when introducing all this new technology"*.

However, based on observations and informal discussions at the construction site, the labourers were found very keen to use virtual models and mobile technology for quality assurance. They often need some assistance using the new equipment or show some reluctance using the mouse and keyboard, but they definitely don't act against the changes. They rather look forward to the further implementation and see great benefits in the improved overview the virtual model gives in their daily work, as illustrated in Figure 6.

Figure 6 Welding of pipes directly from a virtual 3D model viewer. Image courtesy of Ramboll Denmark and Brondum.

This observation is contradictory to Davis (2004) where no difference in resistance to change was identified for different professions. However, it underpins the observations of Gottlieb et al. (2009) that the workers are ready to use new technology in their working processes, but the middle management level (construction manager) is a "crushing anti-program" for use of virtual models. As argued by Gottlieb et al. (2009) this is because "The manager also inserts a divide between knowledgeable and ignorant actors in order to uphold his own image of a social order in which the contractors retain their dominant position in the construction process, rather than having to conform to the requirements of the model…".

4.1.2 Most Important Lessons Learned for Improvement of Future Implementations

Several system functionalities to be improved were identified during the evaluation. Clash detections between virtual models were done sporadically and only visually during the design of the building while several design errors needed correction at the construction site, e.g. modifications of precast concrete elements and drilling of missing holes for pipes. Later examinations showed that a more formalised clash detection procedure (e.g. using Solibri Model Checker) could have eliminated these errors.

The system setup illustrated in Figure 4, where the contractors have direct access to the virtual models stored on the consultants file server through VPN caused some trouble. However, the technical solution was a minor problem. The hurdles were more organisational and interpersonal trust-oriented because of the security risks involved in sharing networks between two companies.

Simplifications of the user-environment to the virtual 3D model viewers and new features are needed to make them really useful directly in the construction process, as illustrated in Fig 6. The virtual 3D model viewers need automatic and dynamic dimension lines and a game-console like user-environment. Today even experienced users can have difficulties navigating in a virtual 3D model viewer.

4.2 4D Model for Planning

At the time of the evaluation a new construction management module in Tekla Stuctures was under development, and it was beyond the resources and scope of this evaluation to bring in another application for construction management supporting 4D (link between virtual 3D model and schedule). Sequencing and colour-coded model views based on production status attributes on the objects in the virtual model were already implemented in Tekla, and it was therefore decided to evaluate the possibilities for user-defined configuration to digitalise current working practice. In Figure 7 the colour-coded virtual model used for sequencing is showed together with the traditional colour-coded drawings. There are no de-facto standards today for setting up colour-coding schemes in 4D modelling, and in this project the resources only sufficed to doing a preliminary setup as described in section 4.2.1; see also e.g. Gao and Fischer (2008) or Staub-French and Khanzode (2007) for other research projects about this topic.

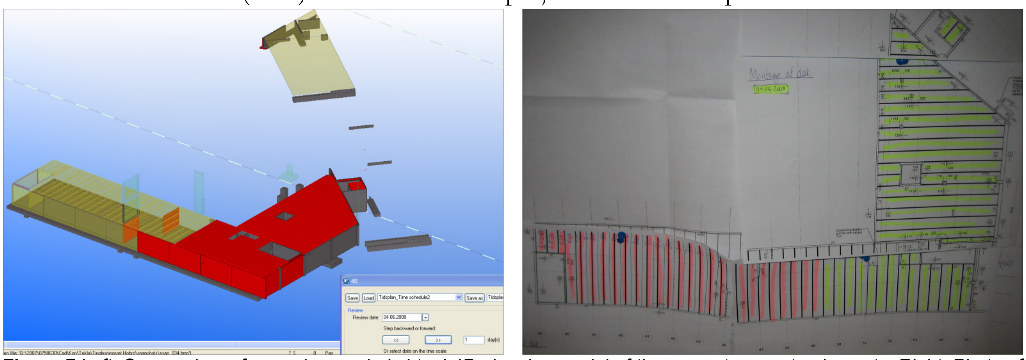

Figure 7 Left: Screen dump from colour-coded virtual 4D planning model of the precast concrete elements. Right: Photo of traditional A3-sized drawings stitched together and manually colour-coded for planning purposes of the precast concrete elements.

4.2.1 Most Important Lessons Learned to Reuse in Future Implementations

The possibilities of setting up user-defined attributes were very flexible, and it was found useful to set up different object representations for different phases and analyses. Figure 7 shows the construction site schedule follow-up view where grey objects are already installed, red objects will be installed the present week, and transparent yellow shows the following three week's work. In Table 1 the colour-coding schemes developed for the project are presented. This was done to initialise a standardisation of 4D model views in construction management. The schemes can be used both with discipline models and aggregated models.

Table 1 Colour-coding schemes with user defined attributes/filter values for 4D modelling and analysis; see also Figure 8.

4D model views defined in the project						
	Design status	**Prefabrica-tion status**	**Component overview**	**Quality manage-ment**	**Construc-tion site schedule**	**Follow-up**
Gray	Sketched	Not started			Finished	Finished and OK
Green	Detailed	Scheduled	In transit	Approved	Erection after 4 or more weeks	Ahead schedule
Yellow	Checked	In production	On site	Approved with comments	Erection in 1-3 weeks	On schedule
Red	Ready for production	Shipped	Installed	Fixed	Erection this week	Behind schedule
Black		Returned	Returned	Rejected	Problems	Problems

The construction site schedule view was found useful in practice but the other views will require further verification. Transparent colours can advantageously tone down components that are currently of less importance such as the components to be erected next week or later. Further national or international standardisation of the views would be useful to enable easy recognition of project status for new project participants and across projects.

4.2.2 Most Important Lessons Learned for Improvement of Future Implementations

A link between the virtual 3D model and the project's schedule, and an automatic synchronisation of the data in the virtual 3D model and the schedule is essential to gain benefits from 4D in construction planning. The evaluated sequencing functionalities did add some additional overview to the project's erection, but in this project it did not counterbalance the additional work required to prepare the sequencing model compared to the traditional paper and fluorescent marker method. More advanced project management features (e.g. dynamic link to schedule, line of balance planning methods, and improved interface for project progress management) than those available in Tekla Structures 14 will be required to gain further benefits.

During the evaluation period of this objective from May to August 2008, one of the two construction managers on the project had time reserved (7 hours a week) to update the 4D model. However, it turned out to be problematic for the construction manager to combine being in charge of running parts of the construction project and also implement new technology and working methods. In future implementations it is therefore proposed to divide the traditional construction management and 4D modelling/updating between two persons/teams with the different competences and focus areas. The 4D modelling is a new task to be taken care of by a project information officer (Froese, T. & Han, 2008; Sørensen et al., 2009), and it is recommended to build up a new service in this area to ensure a proper implementation.

In this project the 4D planning was based on the design models and they were not available for the construction managers in adequate time for use in construction management. To avoid such a crucial dependency for the construction managers, it would be useful to create construction models for the management that are decoupled from the design models to enable flexibility in the work processes. The design and construction models should however be dynamically linked/synchronised to avoid unnecessary duplication of work.

4.3 Test of Input of Production Status and QA Documentation in 3D/4D Virtual Models

In this evaluation the possibilities of using the combination of the virtual model and a data capture service were evaluated. The property sets of the objects in the virtual model were customized to hold the production status and quality assurance data, as illustrated in Figure 8. Similarly, the data capture server's checklists were customised to hold the same data. Figure 9 shows a screen shot of the web interface to the data capture application taken during setup of the checklist for prefabrication. When activating the RFID reader in the mobile phone the deployed Java application for data capture automatically started and downloaded the checklists from the server. The use of these checklists was evaluated at the construction site but the synchronisation between the virtual model and the data capture application was not fully implemented due to lack of resources.

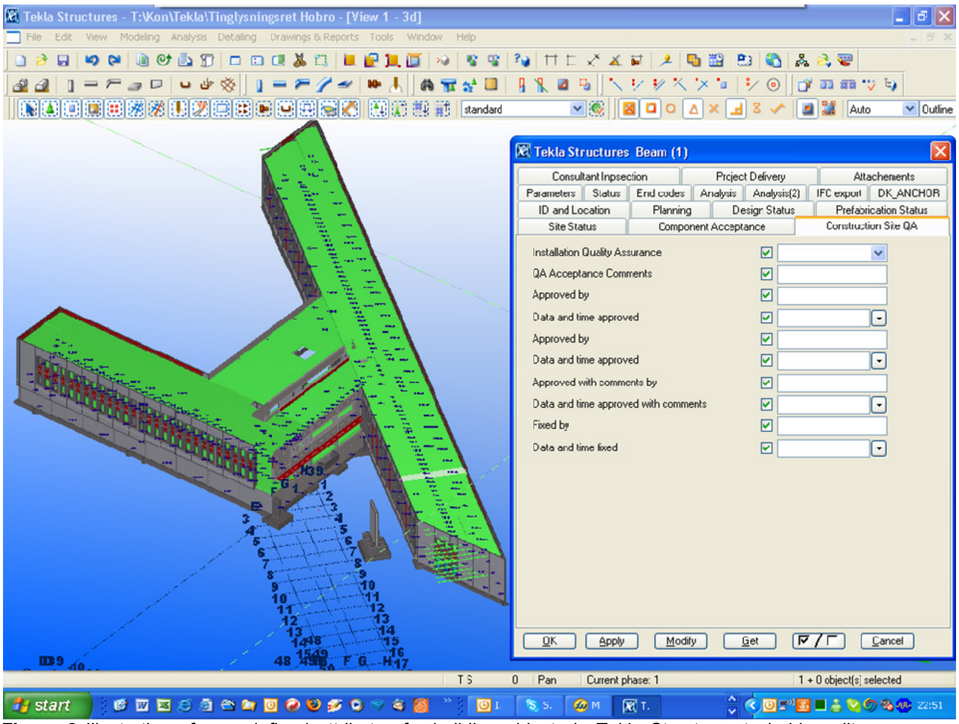

Figure 8 Illustration of user defined attributes for building objects in Tekla Structures to hold quality management and production status information.

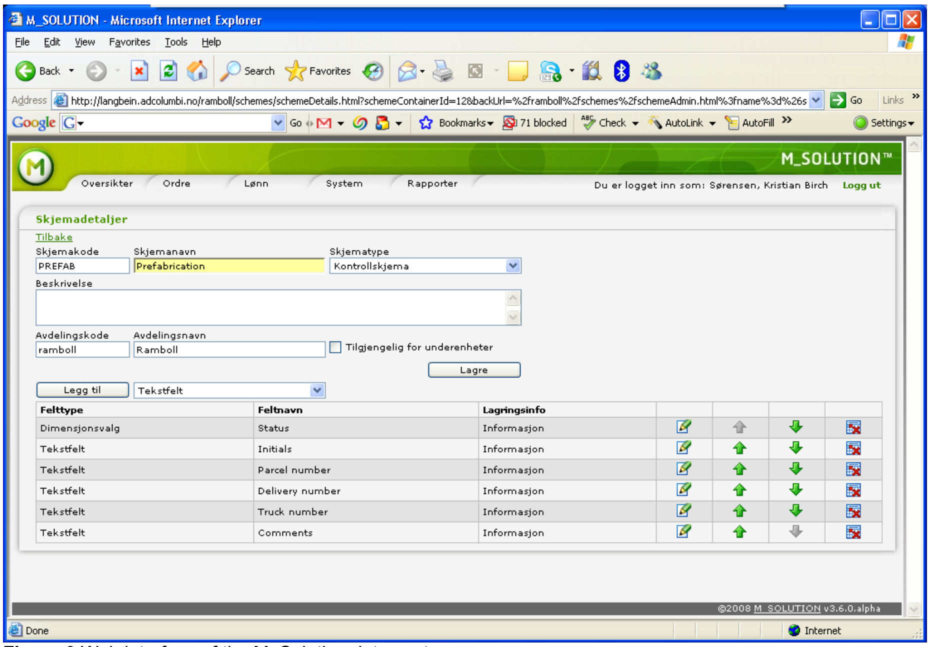

Figure 9 Web interface of the M_Solution data capture server.

4.3.1 Most Important Lessons Learned to Reuse in Future Implementations

The uses of a data capture service (M_Solution platform) to link between the virtual model server and the data capture equipment proved to be a good choice. The data capture service was quick and efficient for real-time data capture and introduces some flexibility in the system because it can be connected or synchronised with a large variety of other systems such IFC model servers, facility management systems, quality management systems, ERP systems etc.

4.3.2 Most Important Lessons Learned for Improvement of Future Implementations

Implementations of the synchronisation between the data capture service and the virtual model server turned out to be much more time-consuming than the ICT-developers first expected. As explained previously the full synchronisation between the virtual model and the data capture service was therefore not implemented. The data capture service (M_Solution platform) is Java based and the proprietary API (Application Programming Interface) to the virtual model (Tekla Structures) is .Net based which also complicated this development. A direct database connection (e.g. ODBC/JDBC based), use of ETL frameworks (Extraction, Transformation, and Loading) or the ability to use common ontology based Web service interfaces are important future developments to better facilitate this integration.

Photo documentation is today an important part of the quality assurance process in construction. The used virtual building model server did not support handling and storage of photos while further development is required to include this feature. Another option would be to store the photos in a separate fileserver or "Flicker-like" photo sharing system and include links to them in the object attributes in the virtual model.

Additional work is also required on report setup based on the data captured in the virtual building model, to enable communication of intent and consistency of action as required for fulfilment of DS/EN ISO 9000 (Dansk Standard, 2006). This quality management standard is today implemented by many companies in the construction industry.

4.4 Placement and Readability of RFID Tags Embedded in Concrete Elements

Today, LF tags (see Sørensen et al., 2009a for an RFID technology introduction) are used in practice for identification of precast concrete elements at the Danish manufacturer Fårup Beton Industri and other research projects have done successful experiments on readability of UHF tags embedded in concrete. However, one of the important findings during the prototype design was the need for full compatibility with traditional consumer mobile phone technology. Therefore it was decided to evaluate the usefulness of ISO 14443 RFID tags compatible with the NFC (Near Field Communication) standard, which is already implemented by several mobile phone manufactures.

Another reason for using the ISO 14443 tags with short reading distance (0-10 cm) is to minimize the risk of unintended reading of the tags and violation of privacy. It is today a requirement stated in a recommendation by the Commission of the European Communities (2009): *"Because of its potential to be both ubiquitous and practically invisible, particular attention to privacy and data protection issues is required in the deployment of RFID"*

4.4.1 Most Important Lessons Learned to Reused in Future Implementations

The short reading distance (a few centimetres with a mobile phone) makes demands on the placement of the tags in the building components: They must be placed at the surface of the building component and if invisible be placed at the exact same location every time so it is easy for the user to find.

In this evaluation precast concrete elements were used as an example and it was found useful to attach the RFID-tags with a "distance piece" to the reinforcement in concrete beams, columns and slabs, see Figure 10 pictures D and E. The "distance pieces" are used in the concrete production to ensure the right coverage of concrete around the reinforcement bars and are therefore widely available.

For precast concrete walls it was found sufficient to place the tags at the top of the wet concrete just before glazing because they are often produced horizontally with the inside surface upwards in the mould.

Several respondents to the questionnaires have expressed a desired need for applications being implemented on traditional mobile phone rather than rugged PDAs. This feedback also underpin the fact that despite the traditional mobile phones are not rugged and does not have a big screen they are already widely used in construction and must therefore be supported to get success with the system implementation.

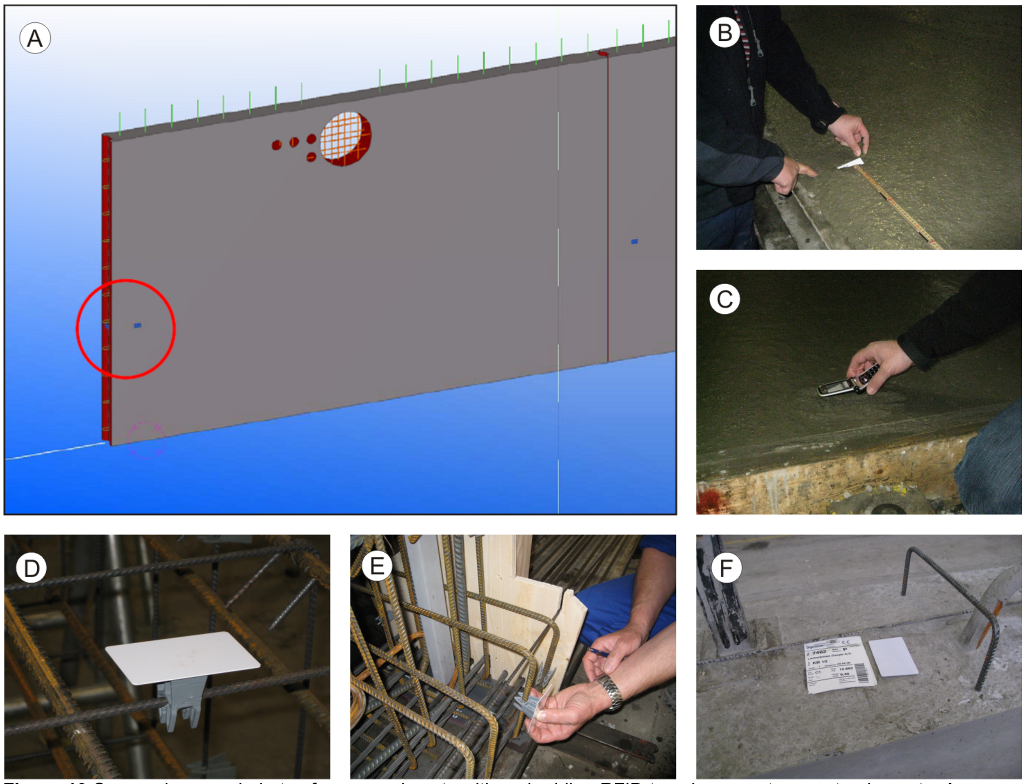

Figure 10 Screen dump and photos from experiments with embedding RFID tags in precast concrete elements. A: screen dump of a 3D object in the virtual model with RFID tags embedded and attached. B: Embedment of RFID tag in precast concrete wall. C: Test of RFID tag readability in wet concrete. D: RFID tag fixed to precast column reinforcement with distance piece and ready for casting. E: Fixing of RFID tag to concrete reinforcement. F: RFID tag attached to a precast concrete element next to the existing label.

To make sure the RFID tags were embedded correctly in the building components, it was found necessary to treat them as any other embedded part in the building components. Therefore they were also included in the structural engineer's shop drawings and virtual models, as shown in Fig 11. This drawing is automatically generated on basis of the precast element shown in the virtual model screen dump in Figure 10 picture A.

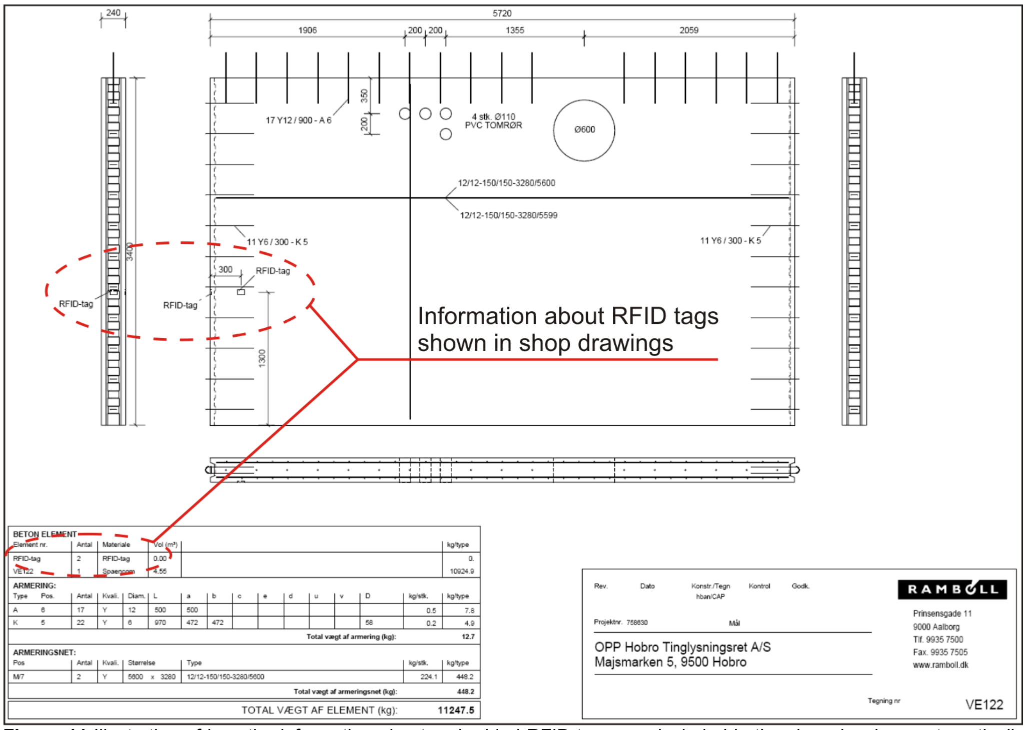

Figure 11 Illustration of how the information about embedded RFID-tags was included in the shop drawings automatically generated from the virtual 3D model.

To be able to find the invisible embedded RFID tags, it is necessary to standardise the placement of the tags. In Figure 12 it is shown how this can be done on some of the larger components in a building. In general, the tags were placed 1 m above finished floor or 1 m above the supporting structure. At least two RFID tags are needed when using passive tags on/in larger components such as the bearing structures, doors, windows etc. One tag should be placed at the end of the element next to the existing label and used during transportation and storage, and the other tags should be placed in a location readable after installation. Tags must therefore be placed on the underside of the slabs because of levelling concrete and flooring is put on top of the bearing concrete slabs. For doors and windows and their frames, it was found logical to place one tag near the handle and another at the top.

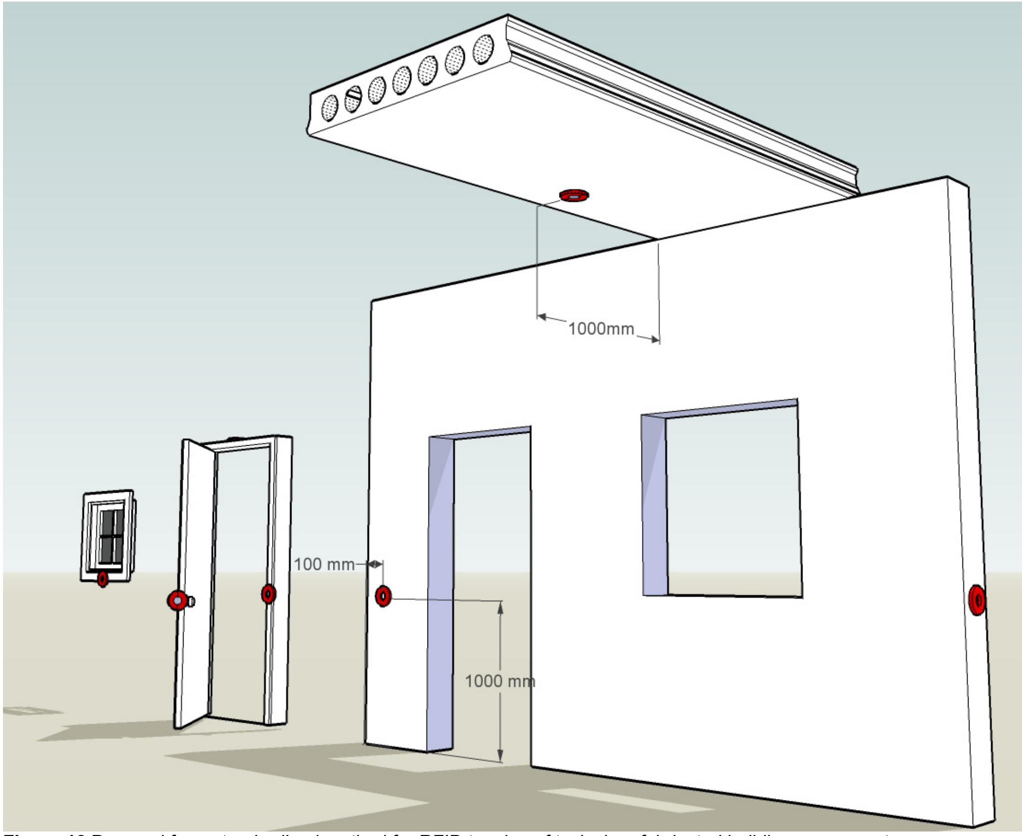

Figure 12 Proposal for a standardised method for RFID tagging of typical prefabricated building components.

4.4.2 Most Important Lessons Learned for Improvement of Future Implementations

It was found that the cost of embedding the RFID tag in the concrete was higher than the tag itself. The price to embed any small part as a RFID tag in a precast concrete element is approximately 1 EURO in Denmark. The cost of the smart card sized ISO 14443 PVC tags used in this evaluation was ~0.7 EURO when bought in low quantities. In future implementations focus should therefore be on bringing down the embedment cost of the RFID tags. This can be done e.g. by refining the prototype of the RFID tag fixture shown in Figure 10 picture D or include it as an automatic operation handled by the robots used in modern precast concrete element fabrication plants.

Approximately 85% out of the 500 RFID tags embedded in precast concrete elements for this evaluation could be read after the components where installed in the building. All the tags where tested before the embedment so the reasons for the 15 % none-readable RFID tags should be found in errors in embedment (wrong location or depth) and omission of the tags. All the tags attached to the surface of the elements could be read and only very few fell off during transportation and installation. To improve the reading distance and readability of the embedded tags, it is recommended to use a combination of HF and UHF tags in future systems. Thereby the support of mobile technology as well as fixed readers with long (several meters) reading distance can be achieved even with the passive RFID tags.

The main barriers for future implementation were found to be with the manufacturers. They claimed to see very few benefits in the technology. Therefore if the general contractor or building owner wants the benefits of using RFID technology in production and operation management, it must be specified and priced in the tendering process.

4.5 Usability of User Interface for Mobile Equipment

A prototype of an application for mobile phones was developed to support the project progress management and quality assurance documentation. The usability (easy to learn and remember) of this prototype was evaluated at the construction site, during interviews and in questionnaires. Figure 13 shows some screen dumps of the application and use of it in practice at the construction site.

Figure 13 Left: Examples of user interface for Mobile Manager. Right: Photo from evaluation of Mobile Manager.

4.5.1 Most Important Lessons Learned to Reused in Future Implementations

The idea of focussing on traditional mobile phone technology proved to be right also from a usability perspective. The practical usability experiments showed that it can easily be used for simple data collection needed to update production status in a virtual model and for quality inspection. Similar feedback was received in the questionnaires with comments from respondents like: "*It is cool to make use of a mobile phone that everybody is carrying at the construction site to collect data*" and "*The functionalities are limited, but it is clear and easy*".

4.5.2 Most Important Lessons Learned for Improvement of Future Implementations

The first author's observations at the construction site and informal interviews of workers lead to contradictory conclusions when compared to the feedback received from engineers and managers in workshops and questionnaires. The engineers and managers see the major barriers in motivating the workers to use the new technology and to questions about future barriers they gave comments like: *"Workmen must use it? – it's always a challenge"* and *"The major barrier is to educate foremen, gaffers etc. and change their attitude against the use of IT at the construction site"*.

However, during the informal interviews of the workmen, they claimed to find it easy to use the mobile application for data collection. It was also observed that the unskilled workers that stayed overnight in campers at the construction site had laptops and HSPA/3G Internet connection for private communication with their families. Future effort should therefore be focussed on changing the attitude about use of IT among construction managers rather than among the workmen. This observation also illustrates the importance of observing users in the real working environment rather than just relying on questionnaires, interviews and their immediate self-expressed needs as stated by e.g. Beyer and Holtzblatt (2000) and Kelley (2001).

4.6 Use of RFID Tags as a Physical Hyperlink to Information in the Virtual 3D Model

RFID tagging of building components enable real-time and component specific information extraction of e.g. work instructions and virtual 3D model views. It was the objective of this evaluation to asses how it can be done technically and for what it is useful. In Figure 14 (left) it is illustrated how a laptop with an attached RFID reader is used to read the tag embedded in a precast wall element. The screen dump in Figure 14 (right) shows the application running on the laptop and how it is used to support the physical hyperlink from the building component to a virtual 3D model view and the html-document associated with the component. The screen dump is from the prototype application IFC Document Associator under development at Aalborg University.

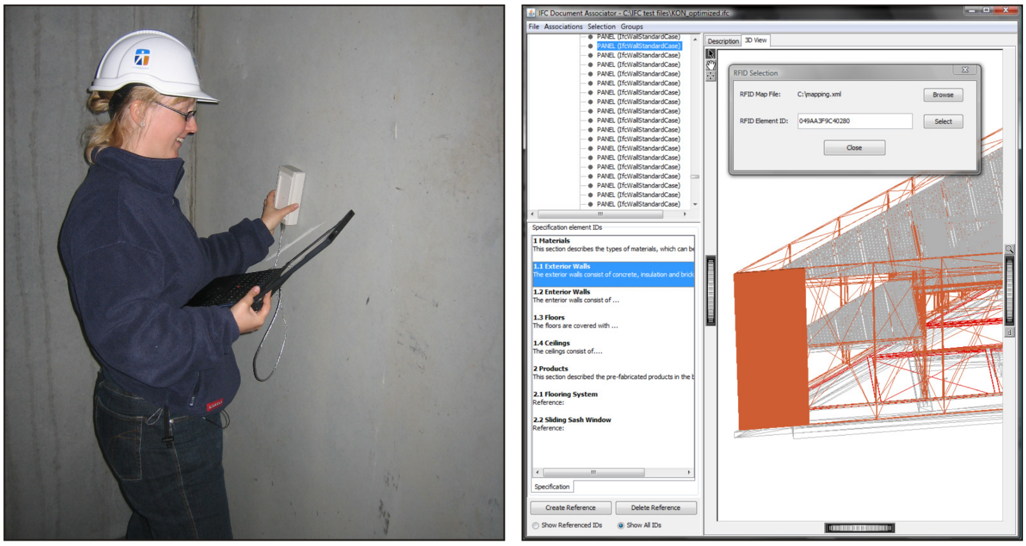

Figure 14 Left: RFID tag embedded in precast concrete wall and used as a physical hyperlink with the RFID reader connected to the laptop. Right: Screen dump from the prototype application IFC Document Associator under development at Aalborg University demonstrating the physical hyperlink used to retrieve work instructions and virtual 3D model views of relevant components.

4.6.1 Most Important Lessons Learned to Reuse in Future Implementations

Two different approaches to implement the physical hyperlink to the information in the 3D model were evaluated. First a small add-on application to Tekla Structures was developed based on the .net API provided by Tekla. The application automatically highlights and zooms in on the component scanned by the RFID reader. The second approach was an IFC application called IFC Document Associator developed almost from scratch. It is based on a Java IFC API from Eurostep (2009) and a Java class library to handle 3D graphics called Jun (2009). Both approaches were feasible but by developing the IFC application from scratch, a simpler information handling system could be build not requiring the user to have 3D CAD competences in order to view the work instructions. Functionalities to quickly associate documents and RFID IDs with the building objects and groups of objects were implemented in the IFC application. However, it would be beneficial to use the RFID tags modelled in the virtual 3D model directly, but this will require IFC support of these attributes in the authoring tools, see Sørensen et al. (2009a) for more information about how RFID can be supported by IFC.

4.6.2 Most Important Lessons Learned for Improvement of Future Implementations

This evaluation showed the potential in using IFC models as a backbone in applications providing a link between the physical components and related resources. The application is a proof of concept rather than a tool useful for the industry. To become useful future implementations of the tool should e.g. support Internet based synchronisation with existing authoring tools and data capture servers, change management, extraction of information about surrounded or related objects to the one scanned, and standardised and reusable collections of work instructions. Viewer performance issues when automatically zooming in on the specific components were identified with large virtual 3D models in both applications.

During the evaluation it was realised that the work instructions should be available before the components arrive at the construction site. Therefore it is not enough to use the physical hyperlink as the only way to access the needed information, however it is effective for reducing latency etc. during quality inspections, problem solving and installation of complex structures and mechanical installations. Systems that automatically push relevant work instructions to the contractors' mobile devices at the right time would be a useful combination with the RFID based information pull technology.

5 Future Implementation

The evaluations showed usefulness and potential in using virtual models and automatic identification technologies for process optimisation and information management in construction. It was demonstrated how the technology can enable a new object-oriented quality assurance process, facilitate quick on-site information access, and improve project and operation management procedures by utilising real-time virtual building model update. On the other hand, the evaluations also showed that a lot of work is still required before the potential can be realised in form of improved quality, lower cost and higher reliability of the construction project's completion where the technology is adapted. The contextual design methodology proved to enable the capture of future user needs and facilitated the development of prototype systems to fulfil these needs. A challenge for the future development and implementation is now to design or find a framework or method that deals with the critical success factor of integrating people, technology, processes and organisation. A large number of generic and specific models and frameworks exist that could serve as a template for this implementation framework. Depending on the profession domain various approaches are used.

From a business perspective the implementation framework must address the aspect normally included in a business plan for a new product or service such as: mission, human resources, company and customer benefits, financial plan, supply chain management, and marketing among others (Quick MBA, 2009). From a social science perspective the implementation framework must address the aspects and relationships between: structures, actors, tasks, technology, and the surrounding environment. This is described in e.g. Leavitt's model for organisational change and extended by Nielsen and Ry (2002) to also include vision and goals, rewards, organisational culture and physical structure. Cameron and Green (2004) present in their book a broad overview of models, tools and techniques useful for organisational change, including Kotter's (1996) "*eight-stage process of creating major change*" widely used in change management consulting. For business process improvement frameworks such as Six Sigma (McCarty et al., 2005) and Total Quality Management (TQM) are widely used. The key methods of Six Sigma are Define-Measure-Analyze-Improve-Control (DMAIC) and Define-Measure-Analyse-Design-Verify. In software engineering the Rational Unified Process (RUP) and the supporting Unified Modelling Language (UML) is widely used in the development and implementation of large and complex ICT systems and is a result of more than 25 years of best practice (Jacobson et al., 2005). From a technical perspective an implementation framework must also include software and hardware user manuals, building requirements specifications, CAD design and collaboration manuals, and interfaces between the ICT-systems. Yoon et al. (2006) and Chin et al. (2008) describe an application strategy of RFID and 4D CAD for structural steel works in high-rise buildings but only deal with technical and information management related issues.

To enable the selection of a suitable model for the implementation framework under development a set of requirements were identified. The model must be:

- Driven by user and business needs
- Apply an iterative and incremental process
- Integrate people, technology, resources, processes and organisations
- Practical to use for managers in construction
- Support continuous improvement

None of the above mentioned models and frameworks for change management supports all the mentioned requirements. Similar challenges were identified by the Software Engineering Institute (SEI) at Carnegie Mellon University. Therefore they developed the five phase IDEAL Model (Initiating, Diagnosing, Establishing, Acting, Learning) to guide the life cycle of major change efforts (Gremba and Myers, 1997; Levine, 1999; Levine, 2000). The model originates from software process improvement initiatives and is based on the fundamental consideration that *"learning is the fuel for technology change management"*. The model fulfils the requirements above, and an adaptation of the model to guide the implementation of virtual models and RFID for project and quality management in construction is described in the following sections of the paper. The adaptation is based on the authors' experiences from implementation of ICT systems in construction and the two cases described earlier in this paper. The theoretical description is for each phase supplemented with experiences from case studies. The IDEAL model is illustrated in Fig 15.

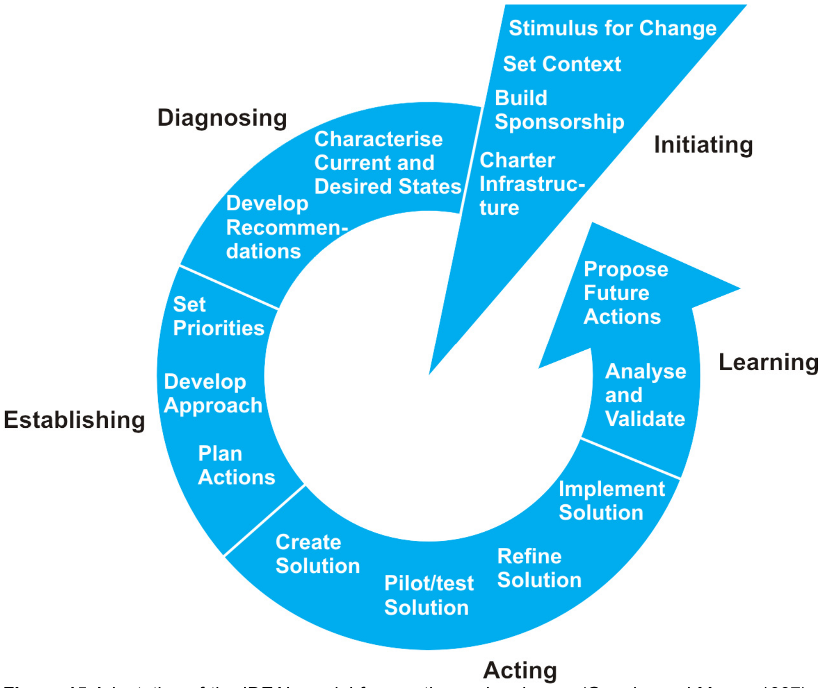

Figure 15 Adaptation of the IDEAL model for creating major change (Gremba and Myers, 1997). Adapted with permission from Carnegie Mellon University.

5.1 The Initiating Phase

Stimulus for change: The first activity is to identify and initiate the stimulus for change. However, this is easy to recognize in the construction industry because several research projects have documented severe challenges for the construction industry to reduce construction errors and reliability of schedules and budgets in construction. Apelgren et. al. (2005) estimated the direct and indirect costs of defects to be 8% of the production cost in a typical Danish construction project. Based on several years of data collection from 258 mega infrastructure projects in 20 countries Flyvbjerg (2007), estimated that *"for rail, average cost overrun is 44.7 percent measured in constant prices. For bridges and tunnels, the equivalent figure is 33.8 percent, and for roads 20.4 percent."*

Despite the good statistical basis of the general challenges in construction, it will in most organisations be necessary to find stimulus from self-performed benchmarking to ensure the right anchoring in the organisation. This activity also includes "establishing a sense of urgency", which, as argued by Kotter (1996), is crucial to gain the needed cooperation and common acceptance.

Set Context: Based on the recognised reasons for initiating the change process specific visions, objectives and goals must be formulated according to the overall business strategy of the organisation. According to Kotter (1996) visions serve three important purposes in a change process: 1) clarify the general direction for change, 2) motivate people to take action in the right direction, and 3) help coordinate the actions of different people. In one of the authors' previous research publications the contextual design methodology was used to develop the following vision for the system (Sørensen et al., 2009b): *"…a vision of developing a simple and implementable system with supporting work processes for real-time project progress management, quality assurance and inventory management. The system must be flexible and give the user access to virtual model information anywhere, at anytime, and about any component modelled in the system."*

This vision serves as a guideline in the ICT-system implementation, and in the formulation of SMART (Specific, Measurable, Attainable, Relevant and Time-bound) goals and objectives.

Build Sponsorship: The often chaotic process of driving the implementation of virtual modelling and automatic object identification requires sponsorship from persons in the organisations' top management. This is needed to ensure the commitment of essential resources and demonstrate the urgency to the rest of the organisation. The sponsors must be personally engaged in the change process and find change management champions with a mix of competences in information technology, the building process and leadership to drive the implementation.

Charter Infrastructure: The infrastructure will depend much on the size of the organisation and the projects involved in the change process. In all regards it is recommended to start small and develop the infrastructure over several projects. For the first project implementation, the infrastructure could be a small team of engineers and technicians skilled in virtual modelling, construction management and computer science. Temporary involvement of IT helpdesk, CAD-support, and network administrators will also be required. At larger construction sites the establishment of a "Genius Bar" with trained people who can take care of everything from troubleshooting to repairs of the new technology (Apple, 2009) will be crucial for success. The infrastructure also includes written agreements that describe expectations and responsibilities of the involved parties.

5.2 The Diagnosing Phase

Characterise Current and Desired States: In the diagnosing phase, current working practices are analysed and the destination of the change process is sketched. To guide this activity the first parts of the contextual design methodology (Beyer and Holtzblatt, 2000) can by advantage be used. This involves finding and understanding the organisations' needs by doing contextual inquiry, work modelling, consolidation of work models, work-redesign, and finally presentation of the desired state using storyboards, see Sørensen et al. (2009b) for further introduction on the use of this methodology in construction technology development.

Develop Recommendations: The diagnosing phase also includes describing how to move from the current state to the desired stated. The recommendations should be made by experienced people in the field in order to obtain acceptance easier among key managers and sponsors. A fall back strategy should also be developed in this phase.

5.3 The Establishing Phase

Set Priorities: Time, money and resources are commonly used priorities in most change processes and in relation to the virtual modelling and RFID tools there are several others as well. It is also relevant to set prioritisation criteria of aspects such as existing competences in the organisation, ambition level, usability, flexibility, specialist requirements, support from supplier and vendor, interoperability, data reuse across disciplines and tools, reuse of data from design to construction, quality assurance and documentation, operation cost and effort, performance to handle large amounts of data especially in large projects, reuse of virtual model for simulations, training effort, other related functionalities, and ad-hoc data extraction. External factors and overall organisational strategies can also be relevant to prioritise.

Too often virtual modelling tools and other information technologies are selected on basis of good offers from sales representatives, management assumptions or personal reasons, and too primitive product evaluations in stead of the organisation needs. The prioritisation criteria are the basic tools to avoid such mistakes.

Develop Approach: The combination of the increased understanding of the current and desired working practice achieved in the diagnosing phase is combined with a set of priorities to develop a strategy of how to realize the goals. Non-technical challenges such as the managers' resistance against change, organisational culture, and market potential must also be addressed in the strategy. Because of the RFID technology's lack of de facto standardisation in construction formation of a coalition to develop this among leading consultants, contractors and IT suppliers in Northern and Western Europe, North America and Asia should also be considered.

Plan Actions: Finally a specific action plan is developed. It must describe the resources needed, intermediate aims, milestones, schedules, results to be delivered, risk analysis, and measurable goals to be used in the learning phase for analysis and validation. Kunz and Fischer (2009) suggest that *"each project should set, track and manage against a small (2 – 3) set of explicit objectives of each type of: Controllable factors, process performance parameters and project outcome objectives*". They also propose at least 29 specific objectives in the three categories that can be used for inspiration. An example of a set of controllable factors, process performance parameters and project outcome objectives to strive after to prove the value of this new process and technology could be: 1) More than 90% of all actual coordination activity among project participants is planned (weekly), explicit, informed, public and tracked, 2) More than 95% of all construction activities are started and completed within one day of their planned start and finish dates, usually based on a 2-3 week look ahead schedule, 3) cost reduction of more than 20% for similar or improved function, quality and schedule.

5.4 The Acting Phase

Create Solution: The acting phase requires the most effort of the phases in the implementation and is highly iterative. First a "best guess" solution of the system to support the user needs is created on the basis of the priorities and recommendations previously prepared.

For example in relation to 3D/4D modelling implementation advice on potential and barriers can be found in several research projects such as Gao and Fischer (2008). They have collected data from 15 projects and on this background they describe an implementation and impact measurement framework. This framework can be used as a checklist for solution creation and consists of seven aspects to be addressed during the 3D/4D model implementation: 1) Model use, 2) Timing of model use, 3) Stakeholder involvement, 4) Data (scope, structure, level of detail and exchange), 5) Tools (functionality and interoperability), 6) Workflow and 7) Effort and cost. BIM Handbook (Eastman et al., 2008) and 3D Working Method 2006 (bips, 2007) are other important resources for information about the 3D/4D implementation. In addition to the comprehensive guidelines given in these reports and books the authors propose to use a three step approach to implement the technology:

1) Create and use 3D models in design and construction from the early sketches to the detailed design. Use the 3D models for creating construction basis such as drawings, bill of materials, constructability analysis, computer-aided manufacturing data, visualisations, and simulations of statics, indoor environment, and energy performance. Use the 3D models at the design offices as well as at the construction site and for all disciplines. Create aggregated discipline models and use them for coordination. Establish interorganizational model sharing servers.

2) Establish links between the 3D models and the projects' schedule, estimation, and knowledge capturing databases. Use the 3D/4D models for planning, procurement, project progress management, as-built documentation, and quality assurance during the whole project and transfer it to the building owner when the finished project is delivered. Continuously update the model on a weekly or daily basis.

3) Automate the data capturing in order to reduce the time and effort required to update the 3D/4D models. RFID technology can with advantage be used to create the digital link between the virtual models and the physical components to enable the automated data capture.

Pilot/Test Solution: Pilot implementations are important to gather knowledge about how the solution (new system) works in practice. A part of the complete project selected for the first implementation can helpfully serve as a pilot to test the developed solution. It is important not only to pilot test the technical solution but also to include the infrastructure, the people and the process.

Refine Solution: Depending on the lessons learned from the pilot solution refinements must be made. It will often require several iterations to develop an effective, efficient and useable solution. Implementation of non-working ICT systems is a common source to frustrations and conflicts in change processes.

Implement Solution: In construction a project-by-project roll-out is advisable because it will reduce the risk of financial failure and generate reusable knowledge from one project to the next. The three steps proposed above can be implemented on three successive projects.

5.5 The Learning Phase

Analyse and Validate: The learning phase is important to encourage knowledge transfer between projects. During the first iterations, at least lessons learned reports and change logs should be made. As part of the maturation of the implementation more detailed performance measurements, analysis and data collection should be made. The measurements are important to validate and visualise the return of investment for the sponsors. Generation of visible short term wins are also important to recognise and reward the people who made the wins possible (Kotter, 1996). The use of the virtual building models and automatic building parts identification offer many possibilities to develop a comprehensive and structured knowledge base with well-documented and reusable information about construction projects quality, cost and erection schedule.

Propose Future Actions: The learning phase finalise the IDEAL change management cycle and end up by proposing future actions for the next iteration in the process starting with the diagnosing phase. In case of major changes in the organisation a new initialising phase will also be relevant.

5.5.1 The Cases in the Context of IDEAL

The IDEAL model was adapted because of a need for guidance in the forthcoming technology implementation. In this section it is briefly exemplified how the case 2 performed in the context of the IDEAL methodology.

During the **initialising** phase of Case 2 workshops were held to create a stimulus for change among participants in the building project. The context was investigated and it was found relevant to focus on project progress management and quality management. The project started in a very busy period for the Danish construction industry (winter/spring 2008) and it therefore turned out to be difficult engage the management team and make them feel ownership of the prototype development. It resulted in difficulties to allocate enough resources for e.g. 4D modelling and on-site follow-up.

The **diagnosing** phase had the most focus in the research project. Therefore a clear understanding of the current and the desired state was developed and documented in research papers (Sørensen et al. 2009a; Sørensen et al. 2009b). Storytelling and scenarios were successfully used to develop a common understanding of the challenges among developers, researcher and future system users.

The **establishing** phase in Case 2 consisted of planning and prioritising the experiments and evaluations. Prior to this project the ICT tools used in the design and construction of the project were selected on basis of a list of prioritisation criteria lists similar to those listed in Section 5.3.

The **acting** phase of the research project described in Case 2 served as a pilot implementation of the complete system. Important aspect concerning data collection, usability and project progress management etc. were tested in a small scale. These experiments gave important input to the future implementation, despite a fully operational system was not implemented.

Learning was another important focus area of the research project and this paper is an essential part of systemisation and communication of the captured knowledge. According to the IDEAL methodology future implementations should have increased focus on the initialising phase to ensure commitment and ownership among important stakeholders. To generate the “short term wins” and visualise financial benefits future implementations should include detailed performance measurements of the technologies impact on e.g. the explicit planned activities, reliability of plans, and construction errors.

6 Conclusions

In this paper evaluation of two prototype systems supporting RFID in construction was described. The systems support infrastructure operation and maintenance and construction management, respectively. In the first prototype system ISO 15963 compatible RFID technology was used because of good all-round properties such as availability, price, readability and size. In the second prototype NFC / ISO 14443 compatible mobile phones were used because they are available in some traditional (low-cost) consumer mobile phones today.

The evaluations show that mobile technology and passive RFID technology is an efficient and practically implementable way to introduce digital links between virtual models and physical components in construction. It is useful for on-site inspection work and documentation, real-time project progress management, and quality assurance. According to the authors' observations, interviews, questionnaires and technology experiments the future users perceive benefits of the more reliable planning and follow-up the technology enable. They also find it beneficial to use the combination of automatic identification and virtual models to improve current practice of quality management by making this process digital and object oriented.

Reuse of the virtual models and RFID tags from design and construction to operation of the building and use of traditional consumer equipment such as the NFC compatible mobile phones were found as crucial aspects to lower the cost of the technology implementation and increase the chance of success in an appearing change process.

However, several major barriers were also identified: 1) Lack of resources for innovation projects in construction limited the prototype development and thereby also practical implementation of the construction management solution. 2) Cross company network sharing is introducing security and inter-personal trust conflicts. 3) Reuse of virtual models from design directly in construction management is important to avoid unnecessary duplication of work. On the other hand the models should be decoupled enough to allow flexibility in the construction phase work process so delays in the design do not affect the possibilities for planning the construction. 4) Manufactures and mid-level managers/project managers were found to be the most reluctant to change. However, labourers were more willing to try the new technology and expected future benefits of using it.

To overcome these barriers several suggestions to guide the implementation are provided in this paper. First of all a proven methodology to drive the change process should be used. During this research project the authors considered different options and ended up describing how the IDEAL model for change management (Gremba and Myers, 1997) can be adapted to guide the implementation of virtual models supported by RFID in construction management. Only parts of the described implementation framework were used in the development so far, and it requires further research is required to document the effects and economical benefits in construction practice of the framework and the technologies.

Although the IDEAL model was adapted to use for implementation of virtual models and automatic identification technology, it is a general approach that can be used to support many information technology change implementations in construction.

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Part 3

Appendices

Appendix A

Linking Virtual Models with Physical Components in Construction – Analysis of Business Perspectives

Business report accepted in fulfilment of the industrial part of this Industrial PhD project,
Danish Ministry of Science, Technology and Innovation, November 2007.

Linking Virtual Models with Physical Components in Construction – Analysis of Business Perspectives

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Abstract: *This appendix describes and analyses business perspectives in relation to the establishment of a digital link between virtual models and physical components in construction. More than 25 promising new products and services are presented and their business perspectives are assessed according to their potential value for contractors and property owners in the construction industry.*

This appendix is written as a self-contained report. Therefore if the reader is familiar with the Introduction, Summaries and Conclusions part of this thesis the Section 1.1.2 can be skipped when reading this appendix.

1 Introduction

The current report is part of an Industrial PhD study that focuses on the cross disciplinary use of virtual models by linking the models with physical objects in the construction process. The study has a threefold focal point consisting of; firstly, an analysis of business processes in the industry, secondly, an analysis of supporting technologies and, thirdly, an analysis of business opportunities in relation to the study area.

Besides the educational aspects of this Industrial PhD study, the purpose is to bring new knowledge to Ramboll, which will enable the company to achieve a central position in information handling in the construction industry and thereby make the company the preferred cooperation partner for the project owners as well as for the contractors and the architects.

This report describes and analyses new business areas in relation to the PhD study and the purpose of the report is to provide the management group in Ramboll with input for the development of new business strategies within the areas studied in the Industrial PhD.

A short introduction to the entire Industrial PhD is given in this Section followed by an introduction to Ramboll; the company where the author is employed. In Section 2 the methods used in this business analysis are introduced, and in Section 3 a large number of business perspectives are listed. Their potential is analysed in the following Sections 4 and 5, and the final conclusion on the business analysis is given in Section 6.

1.1 Introduction to the Industrial PhD Study

The Industrial PhD study concerns improving knowledge and information sharing in the construction process by an enhanced use of virtual 3D models with automatic object identification.

Virtual modelling and virtual models are not new inventions; hence the terms have been used in many contexts and also under different names. In construction practice and research names like object oriented model, information model, 3D model, building information model (BIM) and virtual building model are often used interchangeably.

In this report the word virtual model will be used for a digital object oriented model of a physical object (a person, a building part, a room, a house, a city or a planet etc.). The term virtual model is used rather than BIM in this report to reflect that the subjects discussed are not only applicable to buildings, but generally applicable in the building and construction industry. The virtual model often, but not necessarily, contains a geometrical 3D representation of the objects it models.

Virtual 3D models have in recent years proven their worth in practice relating to building design. Today it is the current practice in Ramboll to create a virtual 3D model of the complete project before it is carried out. The immediate advantages of this are great and the author's own experiences have shown that the new working methods introduce fewer errors, better production basis, improved clarity and enhanced communication methods etc.

However, there is still much unutilised potential in the virtual models, especially in the construction and operation phases. A part of that potential forms the idea behind this Industrial PhD study. It is formulated in the hypothesis below:

Hypothesis: It is expected that a digital link between the virtual 3D models and the real objects in the construction process can improve the information and knowledge handling from design to construction and operation. When this link is introduced during the design phase by the consultants, it can improve not only the designers' overview of the project, but also the contractors and the end users' overview. This will also lead to improved resource and logistic management both in construction and operation.

1.1.1 Intermediate Objectives

The work in the entire Industrial PhD study is split in several intermediate objectives, as listed below. This structure serves as a connecting thread in the work towards verification or rejection of the hypothesis. The intermediate objectives are organised in three primary objectives: development of concept, demonstration of concept and generalisation of concept, as shown in Table 1. The intermediate objectives are used as a way to categorise the work to be done through the Industrial PhD study, but the order of the objectives does not strictly form a linear timeline of the project because it is a highly iterative process.

In the third intermediate objective, “Analysis of business perspectives”, which is the objective considered in this report, it is analysed how Ramboll, or anyone else who wants to bring the research into practice, can benefit from it.

Table 1 Intermediate objectives of the entire Industrial PhD study.

Development of concept	
1	State of the art analysis of process and product modelling and automatic identification
2	Contextual analysis of processes in the construction industry to identify user needs
3	Analysis of business perspectives and ontologies
4	Analysis of enabling technologies and ontologies
5	Development of conceptual models and IT architecture of business services and resources to support current and future needs
Demonstration of concept	
6	Evaluation of process and conceptual models
7	Development of demonstration applications
8	Field tests of the technologies and applications
Generalisation of concept	
9	Further examination of ontologies and development of new ontologies

The creation of a digital relationship between the physical reality and the time dependent virtual 3D model gives many opportunities to develop further applications which can analyse the building process, visualise time management, do automatic quality assurance etc. The documents prepared by the consultant in the form of e.g. bidding lists and descriptions are also obvious to link with both the virtual, the physical model and the suppliers’ component databases containing instructions for installation and maintenance. Accordingly, reuse and effective utilisation can also be attained from the information created and used throughout the whole lifetime of the building process. The digital link will also provide basis for an automatic update of as-built documentation.

In Section 3, the ideas are specified in concrete business perspectives and further analysed in the following chapters.

1.1.2 Background and Supporting Technologies

Before the wide introduction of personal computers in 1982, 3D modelling of buildings could only be done on very expensive work stations attached to mini computers with software like BDS, Intergraph, Medusa and Computervision. Object oriented design tools usable in the construction industry were introduced in the middle of the 1980s, but their spread was limited due to many restrictions in the designer’s work.

In recent years, focus has increased on the use of 3D object oriented design in the construction industry; including Ramboll to a large degree. This is mainly because the 3D CAD tools used in the design have now matured enough to be used in practice without introducing any extra costs compared to traditional 2D design tools. Rather, the new smarter design tools such as Tekla Structures and ArchiCAD yield time savings when they are used properly. The 3D object oriented

CAD tools were first introduced in the design and shop drawing production for steel structures but are widely used today within both architectural and engineering design.

The PDES/STEP[1] standardisation process and later IFC (Industry Foundation Classes) is today's foundation of the possibilities in 3D object oriented design and is very important in future information handling in the construction industry.

To encourage the use of digital working methods in the construction industry, the Danish government initiated the project "The Digital Construction", in Danish called "Det Digitale Byggeri" (DDB), in 2002. The project ran from 2003 to 2006, and the focal point of DDB was the vision of an object oriented working method, where all the project data is associated with the 3D virtual model that gradually develops through the life-cycle of the building. The visible results of DDB are a statutory order on requirements for the use of information and communication technology in construction ("BEK nr. 1365 af 11/12/2006"). It includes 10 formal requirements that have been mandatory since 1 January, 2007, on all governmental construction projects and projects with government subsidies of more than 50 %. The requirements deal with four subjects; 1) use of a web based electronic document management system for information exchange, 2) use of 3D object oriented models and delivery in IFC-format, 3) digital tendering based on standardised documents and use of a web based IT-system, 4) delivery of digital material for facility management (FM) in either IFC, XML or directly in the project owner's FM system. The 10 requirements are supplemented with instructions on implementation, working methods and agreements to fulfil these requirements. Similar initiatives have been launched in other Scandinavian countries and in the USA, where The National Institute of Building Standards (NIBS) has set up a committee to formulate the National Building Information Model Standard (NBIMS). The first version of an NBIM Standard defining a framework for the project, principles and methods was published in March 2007. Common for DDB and NBIMS is that they focus on implementation and practical adaptation of digital working processes rather than development of new technologies.

The governmental projects in Denmark only represent about 2% of the annually constructed gross area, and therefore the impacts of the requirements are rather limited. Nevertheless, the process of preparing the requirements and supporting standards for working methods has had a positive influence on the overall use of IT in the Danish architectural and engineering industry. Hence, today virtual models are widely used in the sector.

The Internet and WWW, as we know it today, dates back to 1992 and is now facing some comprehensive paradigm shifts that will introduce new applications. First of all, the introduction of XML cleared the way for separating the storage and the access medium for digital information on the Internet. The following introduction of Semantic Web from 2000 with its supporting standards formed the basis of efficient future handling of information associated with meta data and data stored in information containers distributed globally on the Internet.

[1] STandard for the Exchange of Product model data or ISO 10303, an International Standard for the computer-interpretable representation and exchange of industrial product data

Another paradigm shift is the introduction of IPv6. The internet protocol (IP) specifies a hierarchical addressing system that enables unique identification of all units connected to the Internet. The present version 4 of IP is from the 1970s and consists of a 32 bit address, which will not continue to be sufficient for all units connected to the Internet. IPv6 uses 128 bit addressing which gives 4 millions unique addresses per square metre, which should be sufficient for supporting the growth of the Internet for at least the next 50-100 years.

These paradigm shifts form the potential for an Internet of things. It means a network where all physical objects such as humans, clothes, machines, building components etc. have a unique identification, and where information about them can be structured and used rationally by humans and machines. There will be great potential in using the next generation of the Internet in interaction with virtual models in the construction industry.

Several interesting technologies exist which can be used to create a digital link between the virtual models and the physical objects such as GPS, photo and video recognition, bar codes, RFID etc. The RFID-technology (Radio Frequency Identification) has in other businesses proved its usability for automatic identification of objects. Therefore it is also expected to be applicable in the construction industry to link virtual models with physical components. Already in 1995 it was stated that *"RFID technology is a promising technology for the construction industry that can be integrated into systems that can track materials, identify vehicles, and assist with cost controls"* (Jaselskis et al., 2005). Still, 12 years later the applications of RFID in the construction industry are very rare and only on pilot level as discovered by Erabuild (2006).

1.2 Introduction to Ramboll Denmark

Ramboll Denmark is part of the Ramboll Group which is a leading Nordic provider of knowledge services, with more than 8000 employees and activities all over the world. The company operates in a broad international context with a strong presence in Northern Europe, India, Russia and the Middle East and from close to 200 offices worldwide.

Today's Ramboll is a result of merging several companies mainly in Scandinavia and the UK. In 2004, the Danish firm Rambøll, Hannemann & Højlund merged with the Swedish Company Scandiaconsult to become the largest consultative engineering company in Northern Europe named the Ramboll Group. Recently the Ramboll Group merged with the British company Whitbybird and more companies in Norway.

The Ramboll Group provides engineering, consultancy, product development and operation services within the areas of:

- Building
- Water and Environment
- Infrastructure
- Telecommunication
- Industry
- Management
- Energy

- IT

Ramboll's core values are (www.ramboll.com):

- **Trust** - Honesty and integrity, openness and cooperation
- **Quality** - Quality and value for the customer
- **Innovation** - Development, improvement, exploitation and sharing of knowledge
- **Commitment** - Responsibility, focus, initiative and high motivation
- **Empowerment** - Decentralisation and delegation of authority

Together with the holistic enterprise model shown in Figure 1, these core values form the basis for the working practice throughout the whole Ramboll Group. The Ramboll Group is a holistic company where holistic cooperation between employees, customers and the surrounding environment aims to optimise the overall commercial result for all partners.

In brief, a holistic management principle is characterised by (Bligaard, 1997):

- A holistic value based management principle where focus is on all the company's values.
- Bringing the human in the centre through the establishment of cooperation based on mutual personal responsibility and authority – a partnership.
- Is based on motivation through well defined goals and frameworks for the employees rather than control and sanctions.
- Respects individual self-independence and liberty to fulfil the framework of daily work.
- Strives for continuous improvement through iterative planning, completion and result measurement of resources and values.

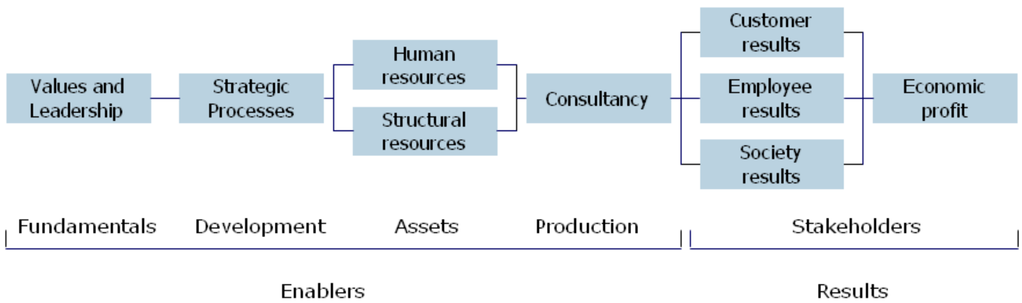

Figure 1 Ramboll's holistic enterprise model.

1.2.1 Vision 2015

This Industrial PhD study concerns future business perspectives for Ramboll, and therefore it is important to evaluate the findings against Ramboll Denmark's Vision 2015. In Vision 2015 the managing group of Ramboll Denmark has marked out future directions for Ramboll's development towards 2015. The Vision was introduced in 2005 and is today well known among both managers and employees in Ramboll.

The ambitions of the Vision are:

Confidential

Main points of the Vision 2015 are:

Confidential

The findings in this business report are evaluated against Vision 2015 in Section 4 and 6.

2 Methods Used in the Business Analysis

Strategic planning is an important performance driver in all industrial settings, and it enhances both economic performance and organisational innovation (Andersen, 2000). Furthermore, it is widely used in Ramboll as illustrated with the Ramboll Vision 2015 in chapter 1.2.1. A new vision or mission for Ramboll's strategy within IT in construction and within research and development is under development. For this reason the purpose of this report is, as mentioned earlier, to provide the management group in Ramboll with input to the development of business strategies within the areas studied in the Industrial PhD. The report should not be seen as a complete business plan because subjects such as economics are only considered on a qualitative level.

Various methods traditionally used in strategic planning have been used to develop, describe and analyse the business perspectives (Hill, C.W.L & Jones, G.R., 2001). These methods are combined with methods used in portfolio management to maximise the value and select the right balance in new product developments (Cooper, 2006). Portfolio management and its supporting tools are useful to select the right research and development projects and avoid the "spray-and-pray method" (Rostrup-Nielsen, 1997). Yet this method is the most commonly used method in the construction industry today, including Ramboll, for selecting research and development projects.

The methods used in this PhD study are illustrated in Figure 2 and described in the following sections.

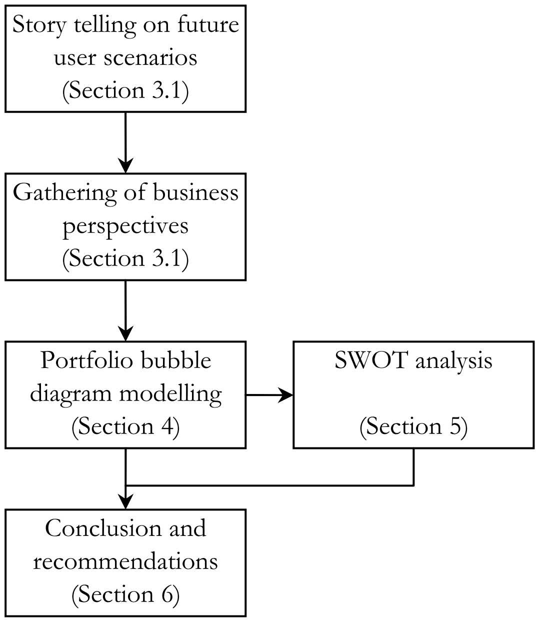

Figure 2 Methods used for the analysis of business perspectives.

2.1 Story Telling

To introduce the reader to the business perspectives, story telling has been used in Section 3 to describe future user scenarios of how innovations from the Industrial PhD study can be developed into practical applications. Story telling is an effective technique, in scientific communication as well and especially when communicating science to none-scientists. By turning a scientific discussion or description into a story, the abstract can be made concrete, and what the author wants to say is turned into what the audience prefers to hear.

A good story often contains:

- Characters with whom one can identify.
- Driving forces behind the characters' behaviour which appeal to the public or the specific reader's interest.
- Description of the setting where the story takes place.
- A specific time period.
- The action that organises the story.
- An authentic happy ending.
- No unnecessary details.

Story telling is used in this report to make the reader interested in the rather complex subject discussed throughout the report and makes it more understandable. It is because that *"The human mind seems to be specially made for creating stories, which represent the most natural way to receive information. The mental images created by stories are precious cognitive references since they organize our experiences and make them coherent."* (Carrada, 2006)

In Section 3, it is by three introductory stories exemplified how the knowledge gathered and developed through the Industrial PhD study can be used in practice. After this introduction a list follows. It contains a large number of new products and consulting services gathered from brainstorming, supervision meetings, discussions with colleagues and managers and also from working with the technology in practice. By having the three introductory stories in mind, it should be easier for the reader to understand the subsequent gross list of business ideas and to shape his own conceptions of their practical application.

2.2 Portfolio Management

Portfolio management is a dynamic decision process whereby a business' list of new product research and development projects is constantly revised and evaluated in order to make "Go"/"Kill" decisions on the projects. There are four common denominators for the goals with portfolio management (Cooper, 2006):

- **Value maximisation:** The goal is to maximise the value of the project portfolio.
- **Balance:** The right balance between size, risk and product categories is an important goal in order to optimise the investment portfolio.
- **Strategic direction:** The goal is to ensure that the projects reflect the company strategy.
- **Right number of projects:** To properly allocate scarce resources, the goal with portfolio management is to balance between required resources for the "Go" projects and the available resources.

The right balance of projects includes both projects with high, medium and low expected value as well projects with high, medium and low probability of success. Diversity in the project portfolio ensures the highest possibility for success both short-term and long-term. Of course projects with both a low expected value and low probability for success should be closed as soon as possible or never initiated.

To benefit from portfolio management, it is important to have a good company strategy, otherwise it makes no sense that the projects reflect the strategy. Because all research and development projects with portfolio management are evaluated against the company strategy. It introduces the risk that if a wrong strategy has been chosen, wrong decisions in relation to research and development projects will also be made. There is also a risk of neglecting excellent projects, because they do not match the company strategy. Despite the risks the alternative, the "spray-and-pray" method, is seen as a worse method for assessing research and development projects.

When selecting the number of projects, it is sensible to have more projects than resources. It is then made possible to close projects where the combination of probability for success and expected value changes to below the set threshold without influencing the activity in the company. The number of projects should, however, only require slightly more resources than available. Otherwise the working day for research and development employees would be too stressful.

In this Industrial PhD study, portfolio management methods are used to produce a model of the business perspectives presented in Section 3 and thereby visualise the balance of the perspectives in value and risk. In this way it is possible to use the diagrams to select the most prospective products for further analysis.

2.3 SWOT Analysis

SWOT analysis is one of many analytical frameworks commonly used in strategic planning. It is more like a heuristic list than an actual method and has been selected for use in this project because of its clarity and its widespread acceptance in practice. SWOT analysis is used to scan internal and external factors influencing the product or firm. Internal factors are classified as Strengths and Weaknesses and external factors as Opportunities and Threats. Often SWOT analysis is combined with a PEST analysis. The acronym PEST stands for a ”Political, Economic, Social and Technological” analysis and describes a framework of macro environmental factors used in environmental scanning. In this analysis, it was found sufficient and relevant to include the PEST factors in the opportunities and threats in the SWOT analysis.

One of the prospective products described in Section 3 which is representative for most of the listed products is chosen as subject for the SWOT analysis.

Finally, the main findings from the analyses are collected in the conclusion and recommendations (Section 6).

3 Business Perspectives

There is a need to improve the knowledge and information handling in the construction industry. It is expected that linking the virtual 3D models created during design with the physical objects in the construction process can facilitate this improvement. But it requires further development of today's IT platforms for knowledge and information sharing. These new platforms must introduce new and more user friendly tools to access and use the virtual models, besides from introducing new working processes. These goals for new IT tools and working processes to improve knowledge and information handling are the basis for the business perspectives formulated in this chapter.

3.1 User Scenarios for Linking Virtual Models with Physical Components

To exemplify and introduce how the new and improved working processes are seen, three future user scenarios are described below.

3.1.1 Scenario 1 - Design and Quality Management

John is an experienced civil engineer and is working as a building manager on a new 10,000 square metre residential building. He is employed by a consulting engineer and hired by the client to monitor the progress in the project. It is his responsibility that the client gets a high quality building within the specified budget and within the agreed time frame.

For the design of the building, the consulting engineer has collected the client and their user needs in their new client specification database (requirement model), and they have designed the building using 3D virtual models. For this reason they were able to do automatic weekly model check ups to demonstrate that the designed virtual model was being constructed within the timeframe, statically safe, consistent with the requirement model, contained the needed equipment and looked like the architect intended. This method makes John's job easy, he just needs to ensure that the new building is built exactly like the virtual model and to report any changes. In practice he does sample inspections on the site where he uses his handheld computer supplied with an RFID reader. Thereby he can easily retrieve the building part specifications from the virtual model and also visually compare the 3D model on the screen with the actually built construction. Any discrepancies between the virtual model and the real construction is reported, photographed and stored in the virtual model linked to the right object and used in the weekly model check-up which is done also during the construction phase.

The scenario is illustrated in Figure 3.

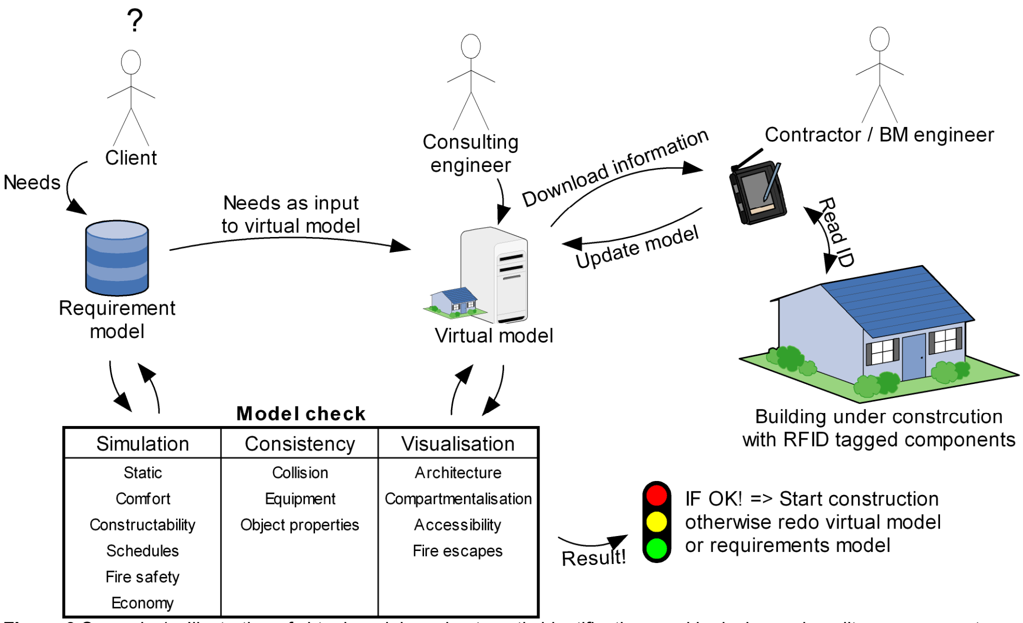

Figure 3 Scenario 1 - Illustration of virtual models and automatic identification used in design and quality management.

3.1.2 Scenario 2 - On-site Mounting of Construction Components

George is a labourer and works with mounting of precast concrete panels on residential buildings. When the concrete panels are delivered, he checks the panels for transport damages, and by reading the ID stored in the embedded RFID tag, he gets easy access to the digital production card on his handheld computer and reports any damages. On the production card he notices that the panel is delivered in time while the work crew is ready to mount it immediately. On the 3D model viewer he now finds the location of the panel and supplementary information about the sizes of bracing to be used. After the mounting and grouting is done, George takes a few photos for documentation and clicks the "finalise" button on the production card.

On his way home from today's work, George mentions that the two 4D models on the big screen in the workmen's site hut are displaying exactly the same state of the building which means that they keep pace with the time schedule.

The scenario is illustrated in Figure 4.

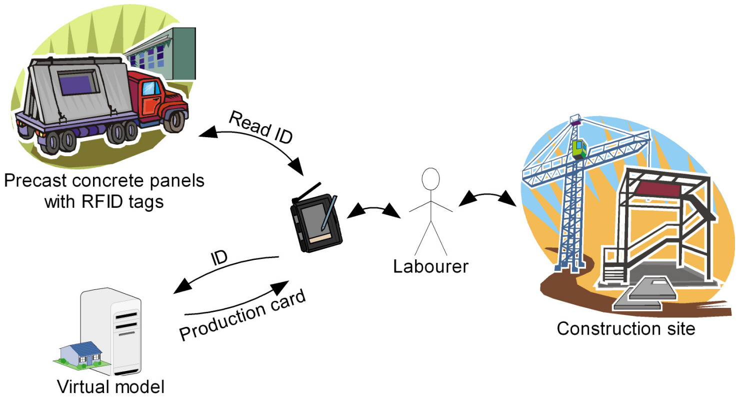

Figure 4 Scenario 2 - Illustration of how virtual models and automatic identification are used in construction.

3.1.3 Scenario 3 - Operation and Facility Management

Peter is a caretaker at a large elementary school and he is doing his yearly inspection of the school's maintenance condition. He is equipped with his most important tool, a handheld computer in the hard case edition which resists the daily use. His handheld computer is supplied with a broadband Internet connection and access to the school's web-based facility management system.

Peter has now arrived at the windows in the southern façade on the first floor of the main building, where he retrieves information about the windows. This he does via the facility management system by moving the handheld computer near the window handles where the electronic ID tag is embedded. On the computer screen he now sees that the windows are 17 years old and were previously painted 5 years ago. Yet he is in doubt if it is worth spending money on painting the windows, or if he should let them change in 5-7 years. For this reason he enters data to the computer by selecting one out of five windows illustrating levels of wear. The most recent maintenance instructions from the window supplier are now sent to Peter, and in addition he receives a cost calculation from the price service to which he subscribes. Based on this information, Peter can now conclude that it is more cost-effective to initiate the maintenance activity for the windows than to exchange the windows. Because the system does not contain any framework agreement on painting, he chooses to have private tender material sent automatically by e-mail to the painting contractors registered in the system.

On his way out of the building, Peter is automatically notified that the newly installed toilets on the ground floor are not yet in the facility management system. He moves the handheld computer near the toilets and the system recognizes that the IDs of the toilets are unknown. Therefore he starts the procedure for registering new objects. By reading the ID tag on the door frame, Peter gets quick access to the right place in the facility management model to add the toilet data. Because Peter is logged on the facility management system as caretaker, he automatically receives maintenance instructions from the supplier, which he accepts to save in the system. He also accepts receiving a message every time the supplier updates the instructions. Earlier the same day the plumber has received mounting instructions by using the same ID tags.

Services and resources needed for the scenario described above are illustrated in Figure 5 together with some of the users of the services and resources. The services and resources are briefly described below the figure.

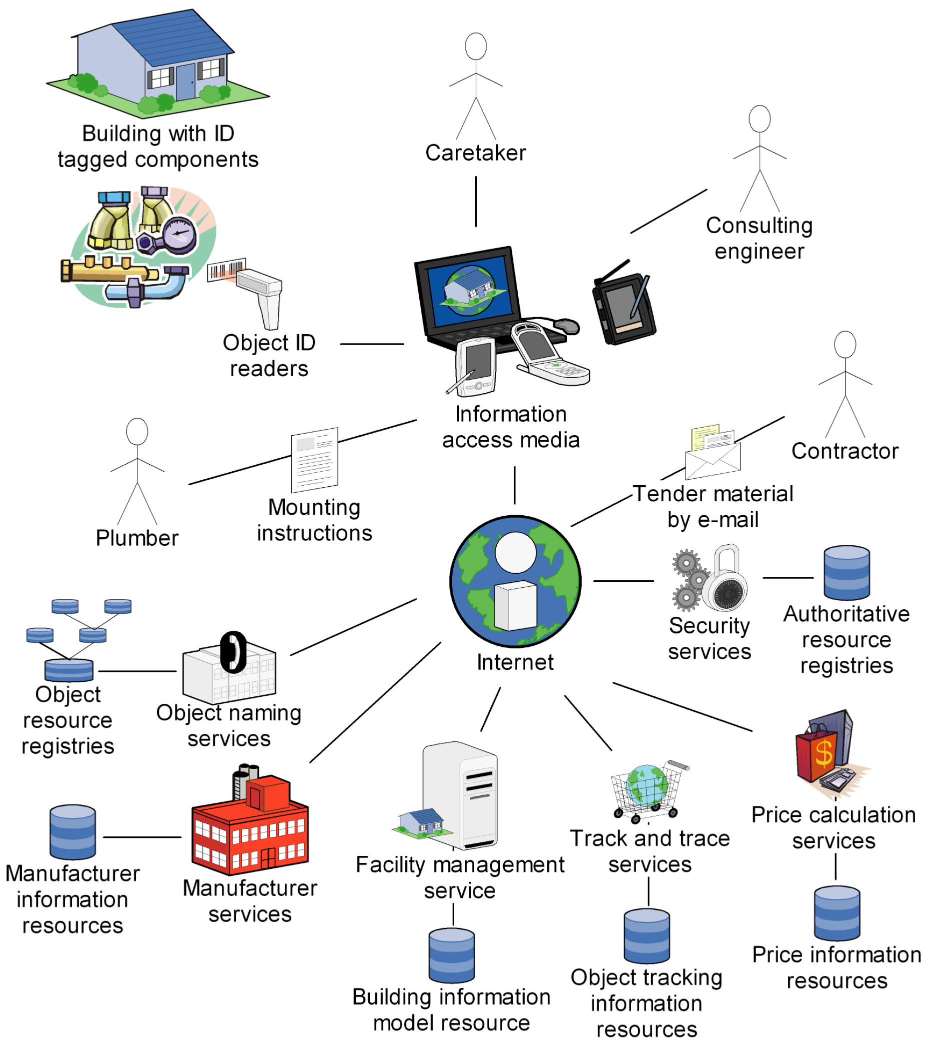

Figure 5 Scenario 3 - Illustration of automatic identification used in facility management.

Description of business services and resources in Figure 5:

Object naming services (ONS): Services that provide information about where information services concerning a given object are located on the Internet. The connected registries contain databases that link unique object IDs with URI (Uniform Resource Identifier) for services delivering information about the objects. ONSs are organised in hierarchies which enable global distribution of object information.

Manufacturer services: Services delivering information from the manufacturer knowledge resources about objects.

Facility management service: Service or application used by the caretaker, consulting engineer and plumber to access, manipulate and store information in the building information model.

Track and trace services: Services that record and provide track and trace information about location and status of objects in the entire construction supply chain and building life cycle. The track and trace information is stored in the object tracking information resource.

Price calculation services: Services providing information about price estimates or quotes from contractors. In the price information resources, actual prices are dynamically stored to provide users with up to date information for cost estimates.

Description of technical services in Figure 5:

Web services: The supporting IT system that enables interoperable machine to machine interaction over a network (the Internet).

Security services: Services used to authorise users by means of registries of digital signatures.

Technical services for equipment: Services to enable interoperable access to ID reader equipment which enable them to operate effectively together and with the business services.

3.2 Ideas for New Products and Services

During this research project many ideas of new business areas have arisen. In the sections below, the promising prospects of these ideas are introduced in two categories: 1) new products to support working processes in the construction industry and 2) new consulting services. In the following chapters 4 and 5, the business ideas are analysed more comprehensively, and in the conclusion recommendations are summarised.

3.2.1 New Products

1. Virtual Model Platform: The first and most important module to build in the system is the information model which will work as the backbone of all the other applications. There are different solutions to how this platform can be developed. Either a system can be built from scratch which will require the largest amount of development costs but also give Ramboll the total ownership of the product.

Another option is to base the platform on an existing model server solution. Octaga for instance, which Ramboll already collaborate with in the Rambyg system provides such a solution.

2. Long-time virtual model archive: The increased use of virtual models will set new demands for storing information in the future. For instance, the municipalities will, within few years, face problems in their building application processing when it comes to archiving methods for drawings and virtual models. Today, they have neither the competences nor the technologies to handle and store virtual models in a rational way. This will lead to both a need for new IT solutions and consultancy services in information handling.

3. Automatic identification in facility management: Today, Ramboll provide different tools for facility management, and their object oriented structures make it easy to provide costumers with improved usability and facilitate model access by automatic object identification. New needs for better documentation of inspections on infrastructure constructions have already given Ramboll the first contract on developing SMART (a Ramboll developed facility and document management system) to an RFID based facility management system. Experiences from this project about how, when and by whom the identification is made will be valuable in the development of the above and below described applications.

4. On-site model viewer for contractors: The implementation of virtual models has increased the efficiency in the design process, but the same has not been observed in the construction phase of the projects. One of the major problems concerns the methods of knowledge transfer. Today the design team hands over the project material to the contractor in the form of paper-based drawings and specifications or in similar locked formats. This practice constrains the inherent dynamics and intelligence of the virtual 3D models created during the design phase. As a consequence hereof, there is a need and business opportunity in on-site model viewers specifically designed for contractors to use. These model viewers can provide the contractors with the right information in the right place. Automatic object identification by RFID can significantly improve the usability of such applications.

5. Automatic identification in quality management: Automatic object identification will both enable the inspector to get quick on-site access to the information needed, for instance with visualisation in a 3D model viewer on an ultra mobile PC, but it will also provide a structured way of storing the information gathered on site in the form of memos and photos linked to the objects in the model.

6. 4D and 5D modelling and visualisation supported by automatic object identification: The first software applications supporting both 4D and 5D (popular names for time and economic management, respectively, using 3D virtual models) have recently been introduced, but the number of applications is very limited. Thus, there will be potential for products of this kind. When using 4D and 5D models, it is time-consuming to keep the models updated but automatic object identification can automate this work.

7. Feedback: Automatic on-site object identification will enhance the opportunities for easy feedback from the contractors to the designers. A structured collection of feedback knowledge is valuable in designing better buildings. Today much knowledge is only available as tacit knowledge. Therefore it is difficult for others than the owner to benefit from it. In a proliferating company like Ramboll the ability to share knowledge in a smooth way is very important to maintain a profitable business.

8. Supply Chain management: Identification of products from fabrication to installation will enable a reuse of information from business to business.

9. Track and trace: Today all major postal services offer web based track and trace information to great gratitude for the receivers of the packages. Individual object tagging with RFID on construction components will enable the same features and give the contractors important information to be used in their daily planning and daily work with components.

10. Computer aided construction: Much of the previous research and development on ICT (Information and Communication Technology) in construction has focused on Computer Aided Design tools (CAD). New tools focusing on processes on the construction sites will be of great benefit for the industry. A collection of the above mentioned applications will be valuable on the construction sites and can be collected in a Computer Aided Construction (CAC) application.

11. Temperature, moisture, acceleration, movement, cracks and deflection registration: It will be valuable to determine the maintenance condition of construction components and conditions during fabrication, transportation and mounting etc. by extending the automatic identification with sensor technology.

12. "Amazon" for the construction industry: A well structured and smooth running information handling system will bring Ramboll in the position of becoming an information aggregator similar to some of the world's best earning companies like Google and Amazon. A more structured information handling process in the construction industry will facilitate new web based trading of products in the construction industry.

13. Hyperlink to virtual communities: Virtual communities are growing and automatic identification can be used to link the virtual communities with the real world.

14. Automatic identification in final buildings: For instance, in the tourist and entertainment industry there will be potential in using automatic identification to link the buildings and its components with web based services.

15. Logistic optimisation applications: Automatic object identification can be used to optimise the logistics in construction.

16. Deconstruction: Structured product information about manufacturer, fabrication year, materials etc. will be valuable in the deconstruction and recycling of environmental resources.

17. Patient and equipment management in hospitals: An ID tag reader on all doors and tags on all patients, furniture and equipment will give possibilities for exact track and trace in hospitals.

18. Navigation in buildings in emergency situations: Large buildings like hospitals, schools, high-rise buildings etc. can in an emergency situation, like a fire, be very difficult to navigate in for the rescue team. By tagging rooms, doors etc. the virtual model can be used for navigation.

19. Automatic quality management by intelligent building parts: Active and intelligent tags will be able to identify if the building parts are installed next to the right object and positioned correctly.

20. Identification of drawings and specifications: A combination of smart label printers with traditional plotters and printers will enable electronic identification of paper drawings and documents.

21. Identification of user patterns in buildings: When designing new buildings, user patterns in for example existing office buildings are studied to give the new building an optimised layout. Automatic identification and tracking of users will improve this process and thereby the design. It also offers an option to test if the design matches the user pattern, and it gives support for a dynamically changing building.

3.2.2 Foundation for the Business Ideas

On the basis of the findings in the Industrial PhD study, there will be opportunities for developing numerous new IT products, which can support the building process. The overall idea for this reason could be to develop a new multi purpose IT platform with a number of modules, which are aimed towards different markets but share the same underlying IT backbone. It will introduce a large degree of reuse between the applications but also allow support for properties for proprietary reasons. The platform must be highly scalable and be based on long living standards.

In other words, the foundation for all the applications listed in the section above could be a Ramboll Virtual Model Platform, and the glue between the virtual models and the physical components is RFID or similar technology. A rich picture of IT architecture for this distributed information and knowledge handling system supported by RFID is shown in Figure 6. This figure illustrates how the services and resources (also shown on the rich picture in Figure 5) can be combined with an information model platform and electronic document management for both in-house and on-site use.

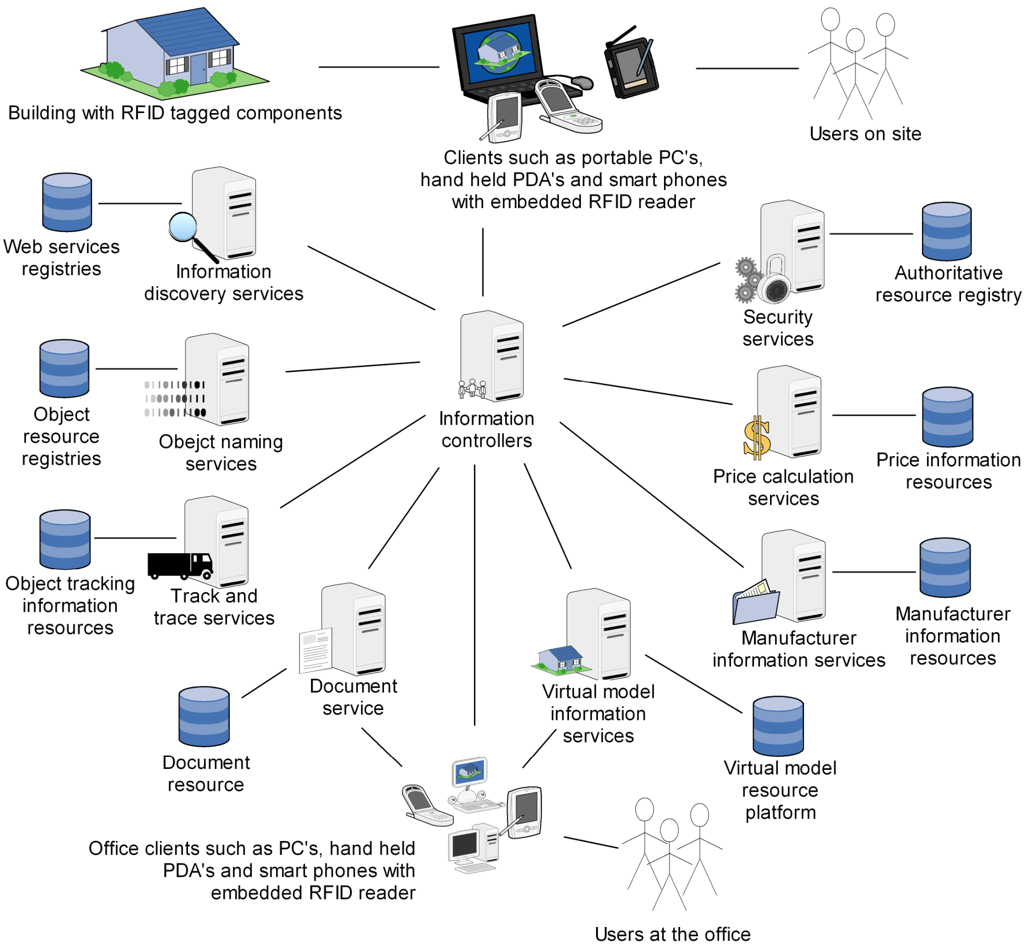

Figure 6 Illustration of IT architecture for a knowledge handling system supported by RFID.

3.2.3 New Consulting Services

I. Innovative design and construction process: Successful projects are created through a continuous innovative digital design and construction process where the whole construction life cycle is supported by intelligent and context sensitive information handling and sharing. Modern ICT tools are used from the generation of the first project ideas to the final building is handed over to the user.

II. Client and contractor advisory services: There is a general lack of knowledge within IT in the building and construction industry. For this reason there is a potential for new consulting assignments in this area to help clients and contractors to develop and introduce new technologies.

III. Virtual model coordination: Model coordination is a new discipline in the design process. Project managers of today have limited skills in this area and will, as a consequence, need support in the future to be able to take advantage of the virtual models.

IV. On-site technology support: In relation to the introduction of new technology in the construction industry, there will also be a need for consultancy in how to use and set up the technology and how to gain the full benefit from using it.

V. IT consultancy in developing and introducing RFID systems for production lines and on construction sites: Together with the introduction of RFID in construction, a complimentary need will arise for consulting in the use and implementation of the technology.

VI 4D and 5D modelling and visualisation: Together with the introduction of 4D and 5D modelling and visualisation in the construction industry, consulting in implementing the technology on the construction sites will become necessary.

4 Analysis of Portfolio

The portfolio bubble diagrams in Figure 7 to Figure 12 are the author's qualitative assessment of the values versus the risks (probability for success) of the business perspectives presented in Section 3. The sizes of the bubbles illustrate an estimate of the resources needed to accomplish the development of the projects. The new consulting services presented in Section 3 are based on knowledge accumulation within IT in construction rather than a concrete development, and therefore they are presented in a separate bubble diagram in Figure 10.

The two most significant costumer groups for the products listed in Section 3 are property owners and contractors. For this reason two bubble diagrams have been made, one for each customer group. It is not possible to make a clear distinction between which of the prospective products has value for the contractors and which for the property owners, because in most cases there will be a common interest and thereby common value. Nevertheless, a loose grouping is done to simplify the overview within each costumer group. It is done by showing products with only direct value to the property owner and contractor respectively in Figure 7 and Figure 8. In the figures, value for Ramboll's costumers is seen as possibilities for reduction in cost and time consumption, increased user experience and easier management both in construction and operation.

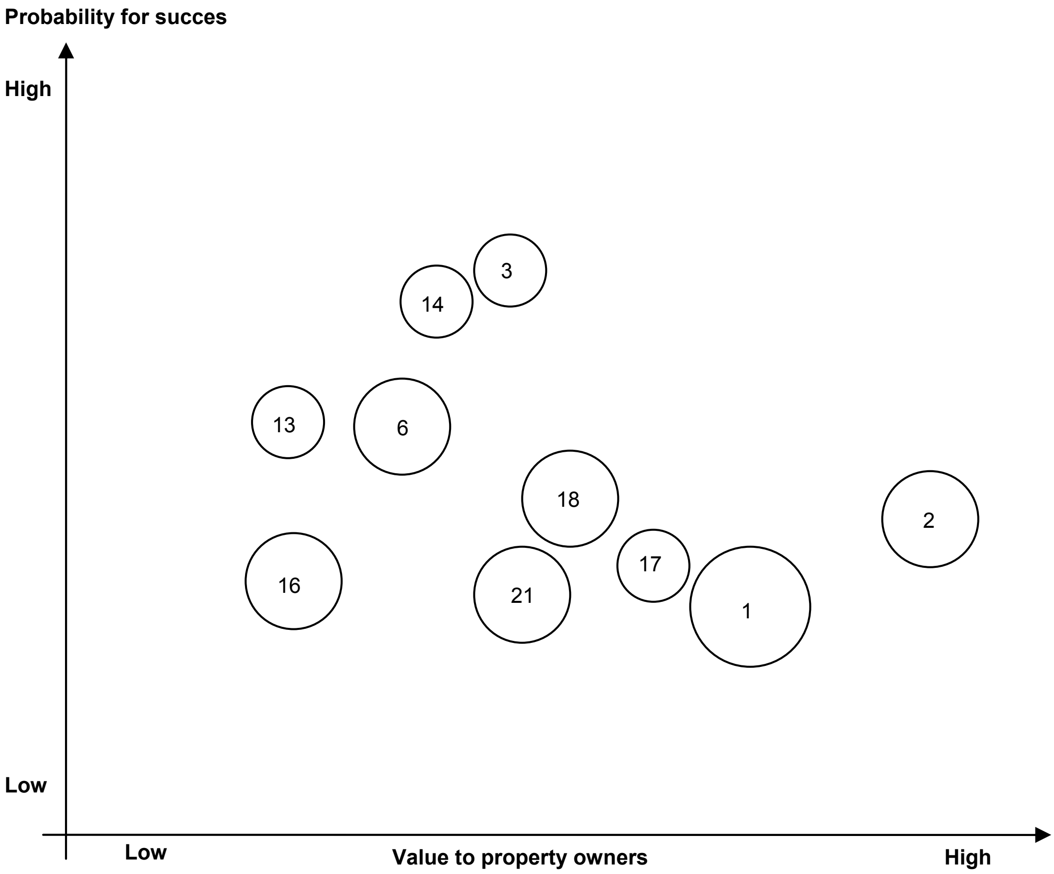

Figure 7 Risk-Reward bubble diagram for prospective products aimed at property owners. The numbers refer to the business perspectives in Section 3. The sizes of the bubbles illustrate an estimate of the resources needed to accomplish the development of the projects.

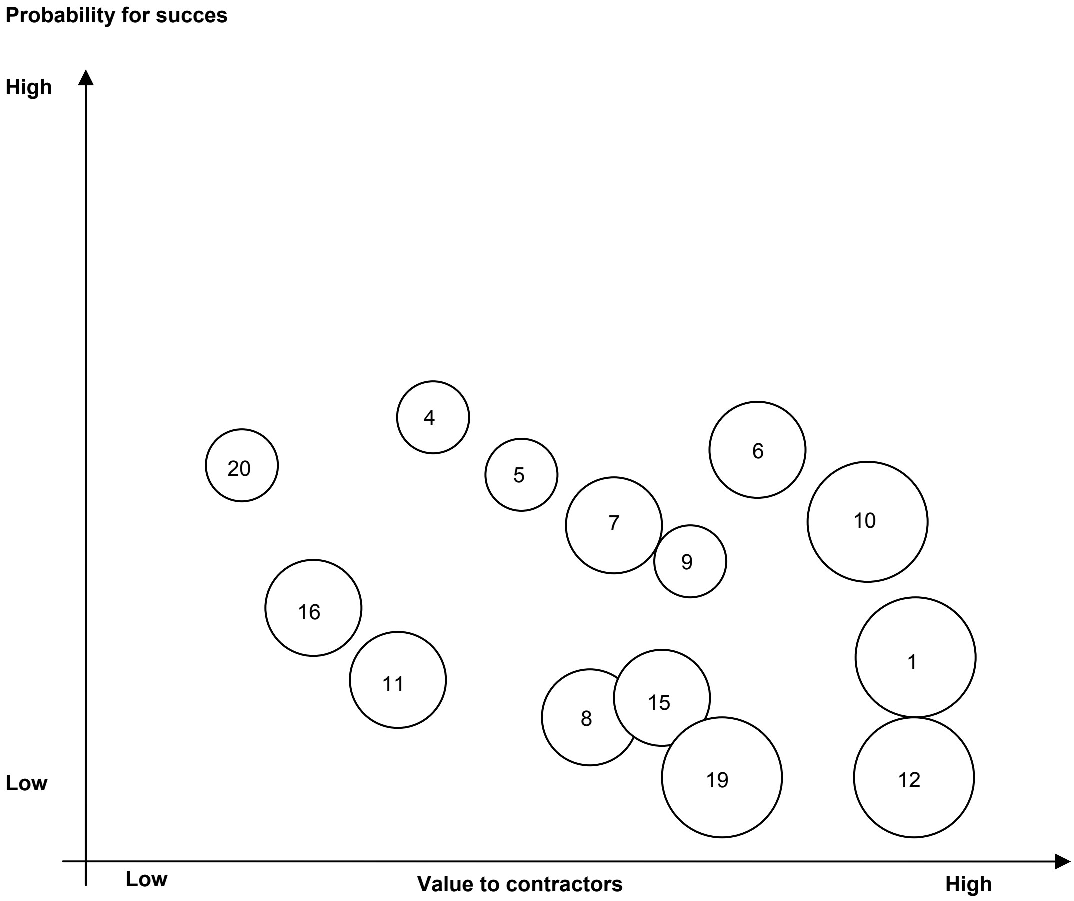

Figure 8 Risk-Reward bubble diagram for prospective products aimed at contractors. The numbers refer to the business perspectives in Section 3. The sizes of the bubbles illustrate an estimate of the resources needed to accomplish the development of the project.

The value of the prospective products to Ramboll is seen as a combination of the values to the property owners and contractors. This combination is illustrated in Figure 8.

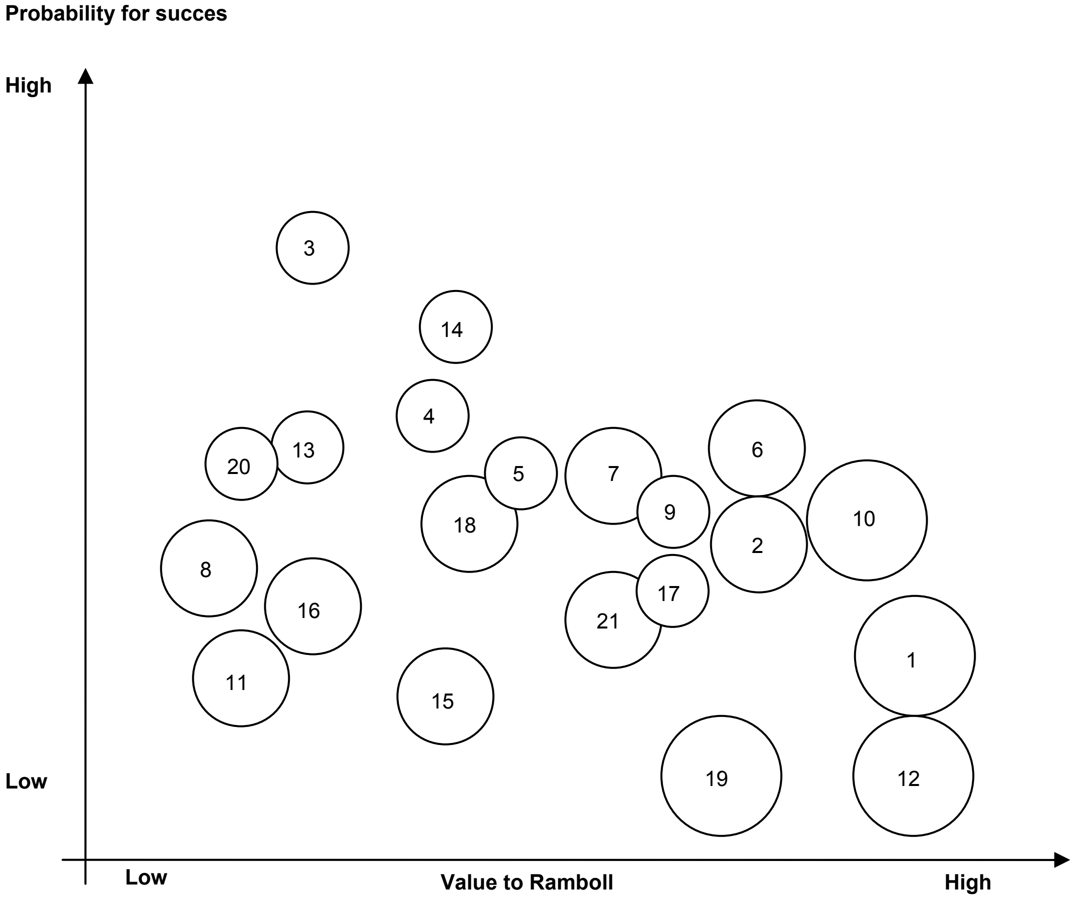

Figure 9 Risk-Reward bubble diagram. The numbers refer to the business perspectives in chapter 3. The sizes of the bubbles illustrate an estimate of the resources needed to accomplish the development of the projects.

It would be useful for Ramboll to include the company's other research and development projects in the portfolio bubble diagram to show and select the right overall balance in the projects. However, this was not possible to accomplish during this Industrial PhD study.

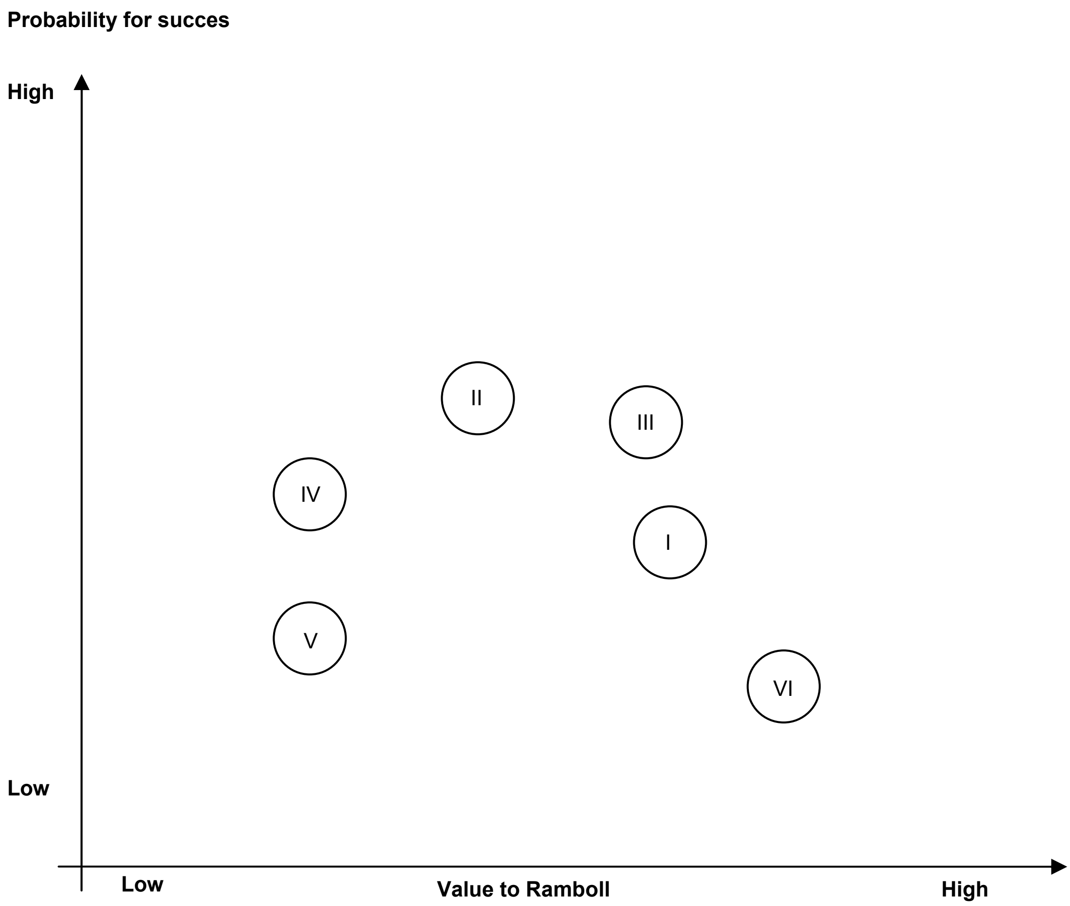

Figure 10 Risk-Reward bubble diagram. The numbers refer to the prospective consulting services listed in Section 3.

All the consulting services in Figure 3 are plotted with the same size because they are business perspectives as a result of knowledge acquired through the employees rather than as a result of a specific development.

4.1 Results and Recommendations from the Portfolio Analysis

In Figure 11 and Figure 12 the author's recommendations are illustrated for future development of products and services related to linking virtual models with physical objects.

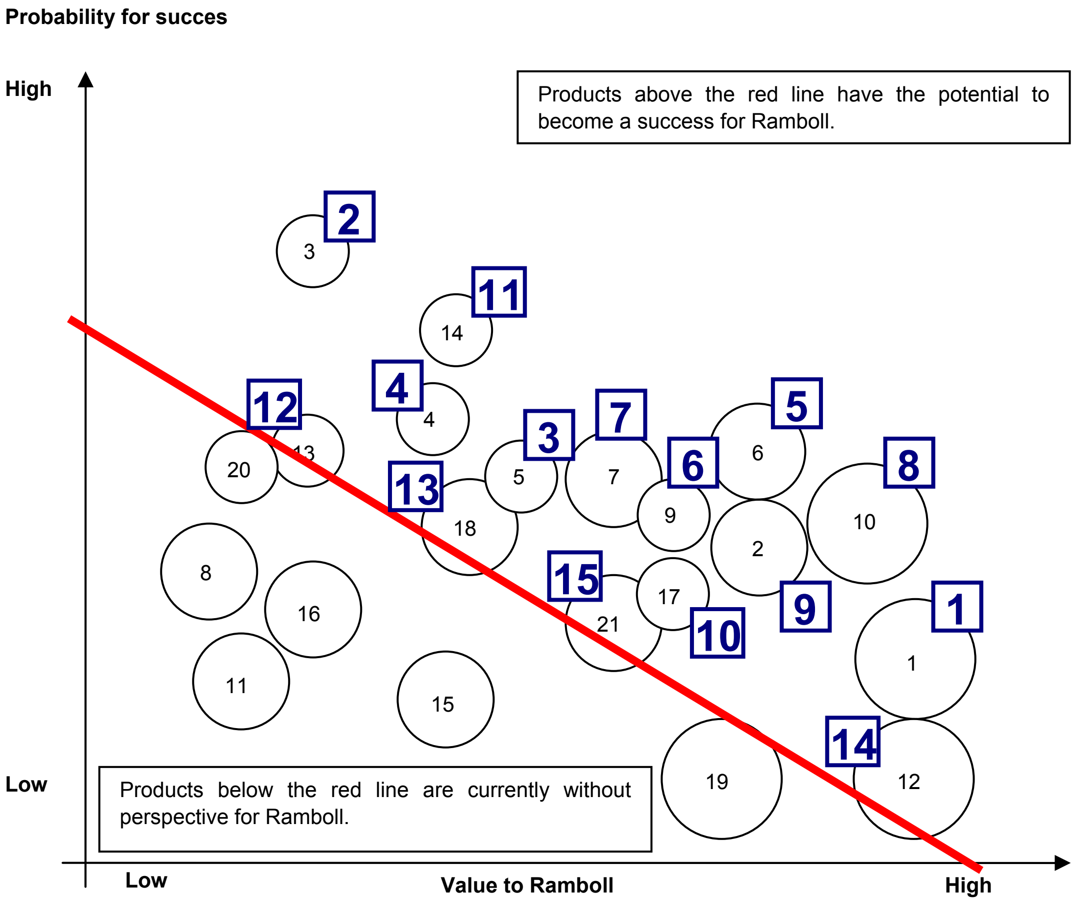

Figure 11 Risk-Reward bubble diagram. The numbers in black refer to the prospective products listed in chapter 3. The red line separates the promising products from the products without perspective to Ramboll. The blue boxes and numbers indicate a recommended order for future product development.

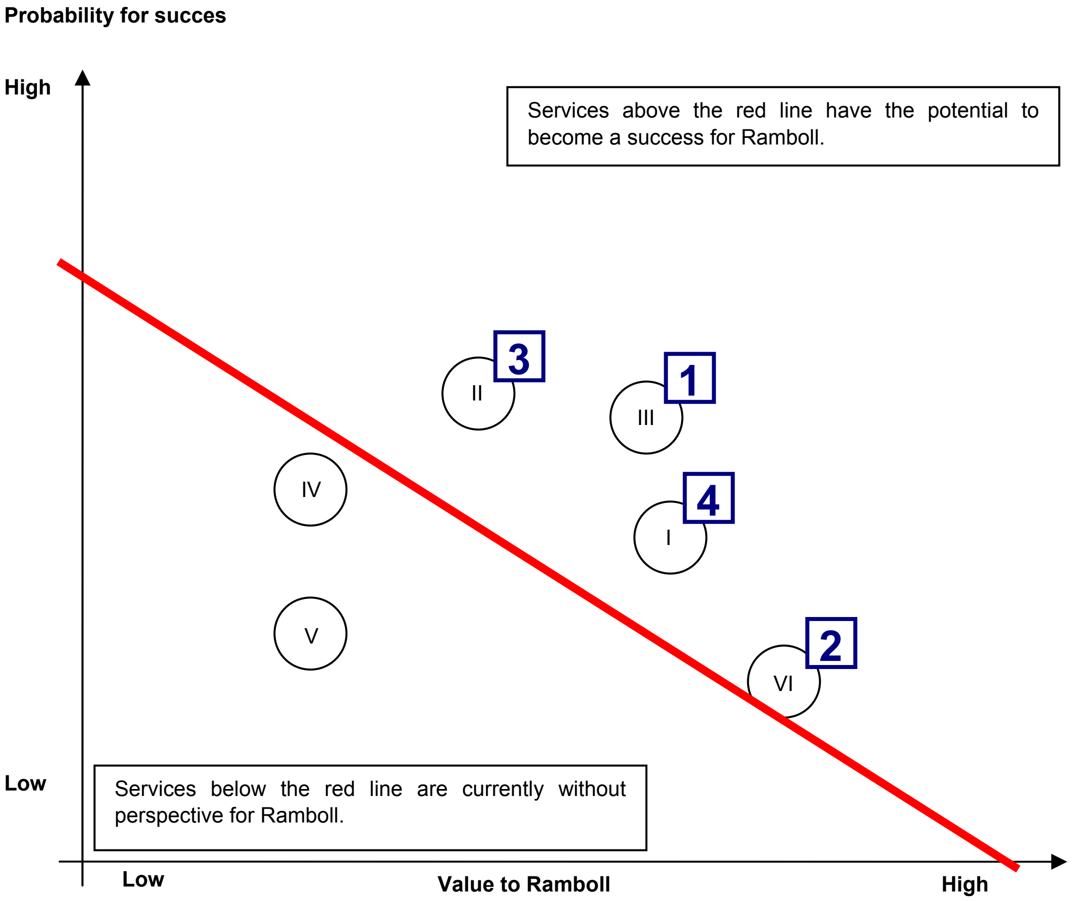

Figure 12 Risk-Reward bubble diagram. The numbers in black refer to the prospective consulting services listed in Section 3. The red line separates the promising services from the services without perspective to Ramboll. The blue boxes and numbers indicate a recommended order for future product development.

In Figure 11 and Figure 12 the recommended order of product development and introduction of new services is given to reflect diversity in the product development. By initiating product developments in the given order, there will soon be a good combination of prospective products and services with both a short and long-range perspective. That will increase the probability for success. The greatest possibilities for cost reduction and rationalisation in construction are expected to be in structuring and easing the access to information. The development of new business ontologies and an increased use of ontologies already accepted internationally will enable this structuring and reuse of information to greatly benefit the whole industry. Yet, it is also one of the most complicated hurdles to overcome for the industry.

Before the development of the products is initiated, it is also important to match the resources for the development with the actual capacity in Ramboll. It has not been included in these recommendations.

With new technological developments and changes in the knowledge within Ramboll the portfolio diagrams in Figure 7 to Figure 12 can change radically. The diagrams must therefore not been seen as a definitive assessment but as an overview of the current situation.

According to Ramboll's Vision 2015 described in section 1.2.1, it is Ramboll's ambition to become the indisputable leading consultancy company in Denmark and be known and recognised as a company with a strong development-oriented business culture skilled within client and marketing oriented creative innovation. The products and services recommended in Figure 11 and Figure 12 highly support this strategy. None of these products and services can currently or in the near future be delivered by Ramboll's competitors. In order to be recognised as a company with the ability to be innovative, the products to the right in Figure 11 will especially be of significant interest. Most of Ramboll's current product and service enhancements can be characterised as improvements rather than radical innovations.

5 SWOT Analysis of Computer Aided Construction Supported by Automatic Identification

From the products mentioned in Section 3 the tool named Computer Aided Construction (CAC) supported by automatic identification using RFID (number 10) has been selected for further analysis. CAC is a collection of several of the applications listed, while the findings in the SWOT analysis listed in the tables below are expected to be representative for most of the listed products.

SWOT analysis **Internal factors influencing the product or firm**	
Strengths	**Weaknesses**
▪ Ramboll is currently in the front within digital object oriented design in construction. ▪ Relatively cheap equipment. ▪ Many providers of RFID-equipment. ▪ Flexible, since tags used in one phase of construction can be reused in other phases. ▪ RFID tags can be made very robust. ▪ Automatic identification is very compatible with the object oriented design process under implementation in the industry. ▪ RFID is already widely used in large production companies and in logistics. ▪ It is possible to start on minor projects and scale up when the organisation and industry is ready. ▪ Reuse of data from design to construction and operation.	▪ Many ISO and upcoming ISO standards available. There is a risk of basing current implementation on standards that will not gain acceptance in the future. ▪ Dedicated tags developed for use in construction are not available. ▪ A good IT infrastructure is needed to gain benefits from implementing RFID. ▪ The experiences on using IT tools on construction sites are very limited, at least in Denmark and within Ramboll. ▪ Experiences using RFID in construction is very limited. ▪ Missing interoperability between currently used ICT systems. ▪ Very limited demand from our costumers as to improving current problems by use of new

▪ Less time-consuming than today's working processes.	technology. ▪ Our clients accept the current situation because of lack of competences and powerlessness. ▪ Many resources are required for training of employees in new technologies and working processes. ▪ Ramboll developed IT tools are currently difficult to sell internally in the company due to methods for settlement between departments.

SWOT analysis **External factors influencing the product or firm**	
Opportunities	**Threats**
▪ Only few ICT tools exist to support the contractors' working processes on the construction site. ▪ Improved control of the construction project. ▪ Improved control of resources. ▪ Easier handling of changes. ▪ Opportunities for simulations and model check-ups based on automatic object identification leading to real time management. ▪ Architect, engineer and contractor will all do their work based on the same data. ▪ New opportunities for visualisation. ▪ New ICT products will facilitate more industrialised working processes in construction. ▪ Integration with Enterprise resource planning. ▪ Unique tracing of objects and appurtenant data and information through the whole building life cycle. ▪ Increased governmental focus on documentation. ▪ Increased focus on financially failed mega projects. ▪ Lean and Just-In-Time is currently in focus for contractors. ▪ Automatic up-date of as built documentation. ▪ A rapid development in smart building	▪ The construction industry consists of many small companies and only few large industrialised companies. ▪ The product manufacturer must install RFID tags without necessarily gaining benefits from it. ▪ The organisation of the construction industry is inflexible and the current static division of tasks between client, consultant and contractor is not supportive for the introduction of new developments. ▪ Only few believe in a "life" after the current project. ▪ The national research programme "The Digital Construction", or "Det Digitale Byggeri" in Danish, has focused on adapting new technologies to old working processes rather than on breaking down radical barriers. ▪ Public ICT infrastructure is not trendy as it has low priority for politicians setting the order of business in the construction industry. ▪ The contractors are not too willing to adapt new technology. ▪ Lack of standards and acceptance for current developed standards. ▪ The ICT pull from the industry is very limited. ▪ The contractors might start implementing the virtual models and RFID themselves.

products is expected.	▪ Conflicts are daily practice on construction projects. ▪ User perception of increased surveillance.

To contribute to the development of a strategy that takes the above presented SWOT profile into account, the TOWS matrix below was developed. Strengths and opportunities are combined to identify how to pursue the opportunities that fit the company's strengths. Weaknesses and opportunities are combined to identify how to overcome weaknesses to pursue opportunities. Strengths and threats are combined to illustrate ways that Ramboll can use its strengths to reduce its vulnerability to external threats. Weaknesses and threats are combined to establish a defensive plan to prevent Ramboll's weaknesses from making it highly susceptible to external threats. The TOWS matrix is thereby the author's collection of strategic recommendations for doing business in the area of linking virtual models with physical objects in construction.

TOWS matrix	**Strengths**	**Weaknesses**
Opportunities	▪ Use experience from 3D to move forward to 4D and 5D. ▪ Think in integration across tools and platforms. ▪ Develop tools that support lean construction or similar. ▪ Start implementing RFID in areas where we already have experience and products such as facility management. ▪ New products must be highly scaleable. ▪ Prove that 3D, 4D and 5D will give financial security in construction projects. ▪ Become the driver for RFID in construction. ▪ Use the virtual model as the information carrier throughout the whole construction process. ▪ Use automatic identification in combination with the virtual models to ensure traceability. ▪ Visualise the construction process and current project status to improve client experience. ▪ Strive for reuse of data between	▪ Use the strong position to force software suppliers to support interoperability based on international standards such as IFC and ODF. ▪ Use experience from 3D to show that the use of new technology introduces fewer errors in construction. ▪ A well implemented innovative construction process is the way to become the indisputably leading consultancy company in Denmark; yet it requires training in ICT at all levels, from top management to ordinary employees. ▪ Set the standards for the improved construction process - do not expect our costumers to demand it. ▪ Prove to costumers that the new technologies can increase quality, user experience and operation management – do not keep it a Ramboll secret. ▪ Introduce a shared license policy for internally developed products similar to the one used for externally

	disciplines and phases in construction. ▪ Keep the virtual model updated through the whole building process and use it for as-built documentation. ▪ Introduce virtual models to support information from smart building products.	purchased software products. ▪ Contribute to and get involved in the development of new RFID tags to better support special needs in the construction industry. ▪ Introduce a new business area for innovation in construction.
Threats	▪ Look for new ways to organise the projects and partnerships. ▪ Take responsibility for the project completion. ▪ Look for long-time partnerships with contractors, architects and manufacturers; it is costly for us to train not only ourselves but also our partners on each new project. ▪ Avoid conflict seeking partners. ▪ Train department and project managers to think in a longer range than only the current project. ▪ Use our experience with 3D to improve on-site constructability. ▪ When developing applications for use in construction have focus on keeping the user-interface simple and easy to use. ▪ Prove the value of automatic identification in all stages of construction. ▪ Contribute to the development of business ontologies.	▪ Base developments on international standards rather than on only Danish standards. ▪ Develop the products in many steps and look for benefits for costumers in each step. ▪ Make products that are immediately useful to the users. ▪ Establish relationships and innovate with costumers in the construction industry who want to make a difference. ▪ Construct a robust, flexible and scaleable IT backbone. ▪ Accept that not all innovations lead to success and learn to benefit from the failures. ▪ Dedicate time and resources to innovation. ▪ Base the developments on an open innovation business model. (Chesbrough, 2003) ▪ Find partners with experience in RFID technology. ▪ Introduce better methods for selecting the right innovation projects as described in Section 2. ▪ Use iterative development methods with frequent user evaluation.

6 Conclusion and Recommendations

As outlined throughout this report, linking virtual models with physical components in construction introduces plenty of business potential. It is therefore a question of choosing the right prospective future products and services to focus on rather than deciding if it is a prospective business.

The greatest possibilities for cost reduction and rationalisation in construction are expected to be in structuring and easing the access to information. The development of new business ontologies and an increased use of ontologies already accepted internationally will enable this structuring and reuse of information to greatly benefit the whole industry. Yet, it is also one of the most complicated hurdles to overcome for the industry.

Much of the previous research and development within IT in construction has focused on the design process. It is expected that future financial benefits and improvements can be found in moving the virtual models from the design offices to the construction sites. With Ramboll's strong position in the use of ICT in construction, the company can contribute to these improvements even though the current representation on the construction sites as consulting engineers is limited to follow-up meetings and quality assurance tasks.

If Ramboll want to make a difference and improve the construction industry, IT and innovation in construction should not be seen as a separated discipline but as an integrated design and construction process. Ramboll must be the drivers in the introduction of a computer aided construction process.

The process from demonstrating the use of technologies in practice on selected projects to the implementation in the whole company is demanding. But it is with the full implementation Ramboll can make a great difference for the industry and costumers. Competences to implement 3D, 4D and 5D models on construction sites must therefore be built up in the entire company.

6.1 Iterations Towards an Innovative Construction Process

The combination of innovation, system development and introduction of new technology in the construction industry is a highly iterative process that requires work in many fields. To be successful in this process, it is important to focus on other disciplines than the common ones for system development. Besides analysis, design, implementation and test it is also important to focus on strategy, partnerships, communication, context, users, evaluation etc. This is illustrated in Figure 13 with a model of an innovative development process in construction. The model has been developed with inspiration from Jacobson (2005), Kotter and Cohen (2002), Beyer and Holtzblatt (1998) and from own experiences with implementing IT in construction. For Ramboll to fulfil its Vision 2015 to be "known and recognised as a company with a strong development-oriented business culture with ability for client and marketing oriented creative innovation", it is necessary to start working with a more targeted method for innovation as the one illustrated in Figure 13.

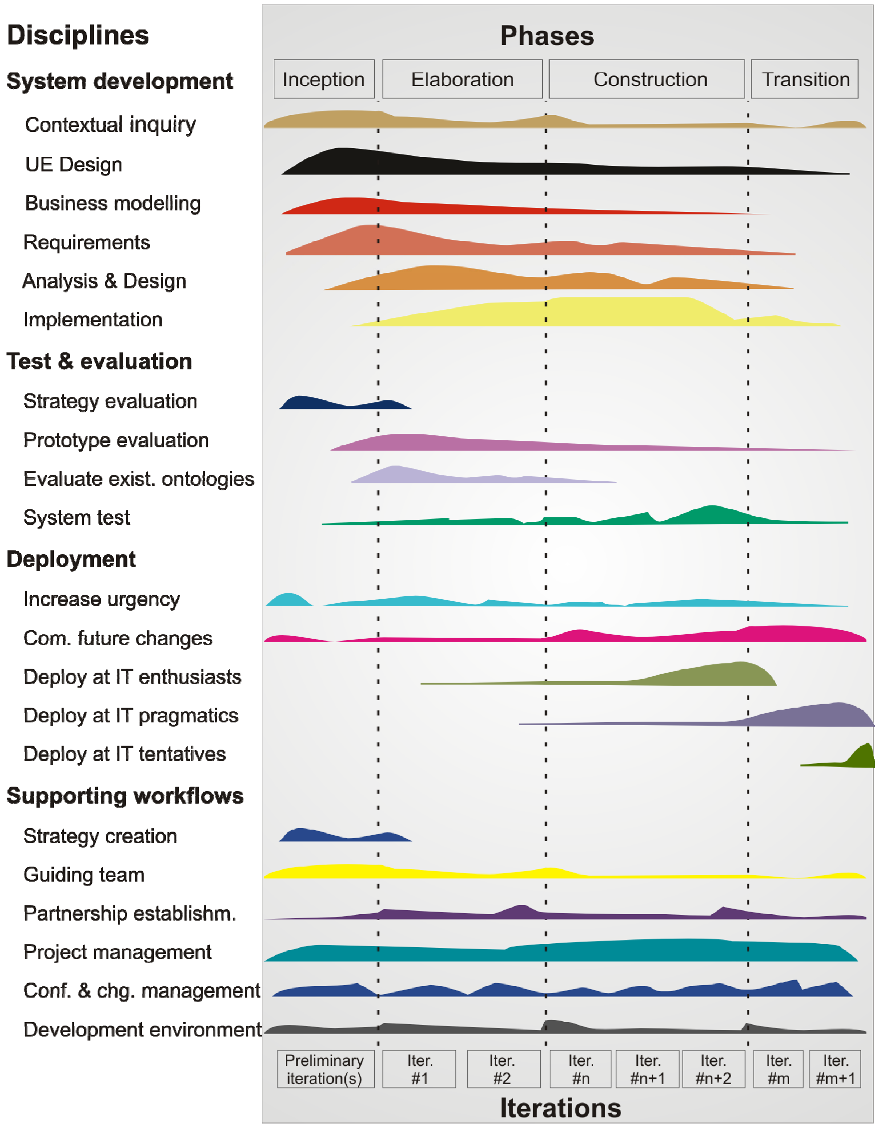

Figure 13 Model of an innovative development process for ICT in construction.

An improved use of ICT and an improved process for innovation can bring Ramboll in a position where the company as leaders on the construction projects is a guarantee for project completion within the agreed time, budget and without errors. The quality of Ramboll's projects will be raised and the company can reuse data from one phase in construction to the next. All this will be of great value to Ramboll's customers.

Finally, ten recommendations towards linking virtual models with physical components in construction shall be summarised:

- Formulate a vision for IT in construction.
- Do developments with a long-range perspective but get experience with small development projects first, such as automatic identification in facility management, model viewers or quality management (business idea numbers 3, 4 and 5 in Section 3.2.1).
- The information models are more important and more complex than the technology to link them with the physical components.
- Keep focus on user needs and involve them in the innovation process.
- Establish partnerships with manufacturers, retailers and contractors about tagging of objects.
- Increase the general ICT competence level in Ramboll.
- Communicate improvements already experienced from the use of new technology and new methods to convert the construction industry's view on ICT.
- Look for business opportunities in open innovation.
- Develop an open business model where third parties can use and contribute to our systems. Thereby Ramboll can become the preferred information aggregator for the industry.
- Base developments on internationally accepted ontologies and contribute to the development of such.

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Appendix B

System Specification of an ICT system to Support Project Progress Management and Quality Management

System Specification of an ICT system to Support Project Progress Management and Quality Management

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Abstract: *In this appendix a specification is described of an Information and Communication Technology (ICT) system to support project progress management and quality management. The system is deployable to mobile phones and use Radio Frequency Identification (RFID) and virtual 3D models for component identificaon, data capturing and data storeage.*

This appendix is written as a self-contained memo. Therefore if the reader is familiar with the content of Paper I and Paper VI of this thesis the Sections 1.1, 1.2, 1.6, 2.4, 2.5, 2.6, and 8 can be skipped when reading this appendix.

1 Introduction

This appendix presents a development of a new ICT-system to support project progress management and quality management by means of mobile technology and Radio Frequency Identification (RFID).

To obtain a more extensive understanding of how RFID can support working processes and knowledge handling in construction, a prototype system and supporting working methods are developed and tested in practice. This appendix describes the vision for an ICT-system, its requirements, bindings, future usage, future users and how a prototype of the system is evaluated in practice.

The first prototype experiments were conducted during the spring and summer of 2008. The next step towards a proof of concept and further implementation has not yet been scheduled.

1.1 Background

Lack of quality and too many defects are well-known problems in the construction industry. Many research projects have focused on identifying the causes and cost of the defects in construction.

The purpose of the research presented in this appendix is to form a background for a future information and communication technology (ICT) system developed to address these challenges. This is done by capturing user needs and prototype (an early example) development in relation to construction management, virtual models, and automatic object identification by means of radio frequency identification (RFID) technology.

In Josephson and Hammarlund (1999) an overview of several studies of defects in building projects from 1969-1992 is given. In this overview the cost of defects occurring during production is stated to be 2-6 % of the cost of production. The cost of defects occurring during the maintenance phase is stated to be 3–5 % of the production cost. No figures are given regarding the briefing and design phase due to a limited number of studies on these phases in the construction process. Josephson and Hammarlund (1999) also present results from an extensive study on causes of defects where seven building projects was monitored during six months. No single reason for defects can be given, and Josephson and Hammarlund's analysis shows that on average 32 % of the defect cost derive from the early phases, i.e. in relation to client influence and design. Approximately 45 % of the defect cost derives from the site in relation to the site management, and the workers and subcontractors' activities. Approximately 20% of the defect costs derive from materials and machines. The causes of defects are difficult to identify, but it is stated that on average 50% of the defects are caused by lack of motivation. However, only a few of these are intentional. 29% of the defect costs are caused by lack of knowledge, and 12% of the defect costs are caused by a lack of information. A small part is due to lack of communication, stress and calculated risks. Josephson and Hammarlund's results show that the causes of the defects can be found in: 1) Key persons in the client organisation were often replaced, 2) client's long decision time, 3) user involvement in the late stages, 4) time pressure, 5) changing project organisations, 6) cost pressure, 7) lack of support for site managers from their main offices, 8) lack of activities aimed at motivating workers on site.

Findings from the Danish research project "Snublesten i byggeriet" (Stumble stones in construction), and a case study on a 3500 m2 residential building conservatively estimate the direct and indirect costs of defects to be 8% of the production cost (Apelgren et. al, 2005). In this project the most frequent causes are stated to be: 1) Deficiencies in communication and cooperation, 2) mistakes and weaknesses in the design, 3) deficiencies in production planning and preparation, 4) insufficient project information handover meetings, 5) mistakes by contractors due to lack of competences and few resources allocated to instruction and control.

The Danish Government has in the project "Digital Construction" (DC) promoted the enhanced use of modern information and communication technology (ICT) to facilitate increased productivity through better coordination between the different phases of the building project (NAEC, 2005). The project ran from 2003 to 2006, and the focal point of DC was the vision of an object-based working method, where all project data are linked to a virtual 3D model that gradually develops through the life cycle of the construction. The visible results of DC are a statutory about requirements for the use of information and communication technology in construction (NAEC, 2006) supplemented by recommendations for new working methods (bips, 2007).

The main aspects of the working methods described by bips (2007) are practised in Ramboll Denmark today. It concerns the use of building information modelling (BIM) in the design phase, collecting discipline models to aggregated models, consistency check, etc. The immediate advantages are great, and the author's experiences using this new working method in practice show that it; 1) introduces fewer errors, 2) gives a better production basis, and 3) improves clarity and enhances communication methods compared to traditional 2D drafting methods. Other researchers have recently reported similar productivity gains using virtual modelling compared to traditional drafting (Sacks and Barak, 2008; Woksepp, 2007).

No single method can solve all the challenges indicated above. However, the use of modern ICT in the design phase has proven to address some of the challenges. Therefore, it is expected that improved use of similar technologies in the construction phase may reduce defects and increase quality in construction by improving knowledge and information handling, project transparency, project and quality management methods as well as knowledge capturing in general. It is expected that a better link (both in digital terms and working process relevance) between the virtual models and the physical components in construction will be an important future development to achieve the benefits from using virtual models in construction. Such a digital link can be created by means of radio frequency identification technology (RFID). See Sørensen et al. (2009) for an introduction to this technology, its application in construction, and an overview of related ontologies.

1.2 RFID in Construction

RFID stands for Radio Frequency Identification and denotes any identification system in which electronic devices occur that use radio waves or pulsating magnetic fields to communicate with identification units fastened to objects. In the 1970s and 1980s RFID was introduced in the industrial sector primarily to keep track of railway wagons and auto chassis in production lines in the USA. Since then it has spread to other areas such as identification of animals, clothing in laundries, billeting systems, admittance control etc. From the beginning of this century there has been an increasing focus on the employment of RFID. This is, among other things, because of recommendations from the U.S. Department of Defence and the U.S. Food and Drug Administration about using the technology. Furthermore, the world's largest retail chain, the Wal-Mart Stores, Inc., has required its largest suppliers to use RFID on all their product pallets and larger units since 2005. The supply of RFID equipment has gradually increased, and there is now a higher degree of standardisation in the area than earlier.

The most referenced components in RFID systems are tags, readers and middleware. Tags, also termed transponders, are identification units that are attached to the objects to be localised. The interrogator, the transceiver or the RFID reader, as they are often called, is the component which via the antenna is used for scanning the data contents of the tag. The middleware is the software component, which ties the RFID reader together with the other software components in an IT system and, if necessary, also filters the data before it is relayed. RFID is a technique whose applications are far from finally developed and new areas appear in a still increasing pace. (Glover and Bhatt 2006).

As early as in 1995 it was stated that automatic identification of objects using RFID technology, was a promising technology for the construction industry (Jaselskis et al. 1995). However, 13 years later the applications of RFID in the construction industry are rare and mostly used in prototype projects or for theft and access control but not in interorganisational applications (Erabuild 2006).

The reason for this should be found in the lack of widely used ontologies and the shortcomings of virtual product and process model applications used in the construction industry rather than in shortcomings of the RFID systems hardware. The true benefits and complexity of automatic identification systems do not arise from the hardware itself, but from possibilities to get information in the right place, at the right time, in a usable form.

A number of recently published research papers describe various examples of RFID implementations tested in construction: 1) Automating the task of tracking the delivery and receipt of fabricated pipe spools described in Song et al. (2006), 2) inspection and management in concrete test lab described in Wang (2008), 3) on-site tool tracking described in Goodrum et al. (2006), 4) project progress management with virtual models described in Chin et al. (2005) and 5) tracking and locating components in a precast storage described in Ergen (2007). In all the papers it is concluded that RFID technology can be bought to function efficiently even in the harsh construction environment.

1.3 Vision

The vision is to develop a simple, implementable and inexpensive system and working processes to support real time project progress management, quality assurance and inventory management. The system must be flexible and give the user access to virtual model information anywhere at anytime and about any component modelled in the system.

Pilot-testing of the system will lead to an increased awareness of benefits and obstacles for using modern ICT in construction and lead to development and validation of ontologies in the system domain.

Typical use-cases of the system will be:

- Construction planning
- On-site inventory management
- Quality management such as
    - Continuous follow-up
    - Registration of component flow
    - Documentation of quality and project progress
    - Check of compliance with schedule
- Construction Process optimization
- Retrieving work instructions from a virtual model
- Real time visualisation of current project stage
- Visualisation of differences in actual and planned installation order and schedule
- On-site and office component information retrieval and notification

1.4 Goals of the Development and Test

The short term benefits of the development project will be:

- Extension of a virtual 3D and 4D tool to support RFID in construction
- New mobile application to support RFID in construction

- Increased possibilities for track and trace of building components through the whole construction process
- Contractors, clients and consultants will be able to follow the exact progress of the construction from their own office computer
- Digitalisation of the contractors' working processes
- Exact and real time data capturing of actual construction progress for later studies to improve working methods by means of management methods as e.g. lean construction and lean Six Sigma.
- Improved digital quality assurance
- Possibilities for user subscription to notification by SMS, e-mail or RSS feed about status updates on building components
- Possibilities for theft and counterfeiting protection

The long term benefits of the development project will be:

- Increased understanding of the prospectus and obstacles in using RFID, mobile technology and GPS in construction
- A practical foundation for creating future ontologies (e.g. an extension to IFC), technologies and products for automatic identification in construction
- Possibilities for reuse of embedded tags in quality assurance, operation and maintenance
- Knowledge about new disciplines in construction. Virtual model coordination and supervision will be an important new discipline for gaining benefits from the new technologies
- Basis for developing new tools and working methods to optimize and improve quality in the construction process

1.5 Organisation

Experiment 1

The first experiments were conducted in an informal collaboration between Aalborg University, Dansk Industri Optimering, M_Solution and Ramboll Denmark. Tekla Structures was used as backbone for the developed system and Tekla delivered support on integration with the back bone. Ramboll and MT Højgaard conducted the practical tests of the prototypes, collected future user needs and developed new work methods.

Experiment 2 - Proof of Concept

The organisation to develop a proof of concept of the system has not yet been established.

1.6 Method

The method used to develop the system description presented in this memo is to a large extent inspired by the contextual design method. Contextual design is a method developed by Beyer and Holtzblatt (2000) to handle the collection and understanding of data from field studies in relation to designing software based products. The method is user centred and the following techniques are used in the method:

Contextual Inquiry: Interviews and observations of future users in their actual working environment are carried out in order to get an understanding of the business problems the system must support. It ensures capturing of real business practice and daily activities and not just self-reported issues and company politics.

Modelling: Drawn models representing the user's work practice allow the developer to attain a common understanding along with the end user and share their findings. It includes e.g. workflow models, sequential models of tasks and models of the physical environment and the used artefacts.

Consolidation: All the individual findings from interviews, brainstorming and work modelling are grouped in hierarchies and consolidated to show common work patterns.

Work redesign and visioning: Based on reviews of the models, a vision is sketched that outlines how the new concept will support and streamline the working practice.

Storyboarding: A sketched and written story is created including sketches of future user environment, automation assumptions and narrative descriptions of how it all will work in practice. The story will function as the common understanding between end users and developers concerning how the system or concept will work and which functionality it will have.

User environment design: Based on the storyboard, a single model of the user environment's functionality and organisation is created.

Mockup and test with users: Paper based mockups of the user interface are designed and evaluated by user tests. The level of detail of these mockups is increased through the development process starting with very simple sketches.

The above presented process is iterative and incremental which means that findings from one step in the process will lead to updates in both the preceding and following steps of the process. The design is initiated from rough sketches, notes and simple models which are detailed through iterations in the research and development process.

Compared to other methods from social science (see e.g. Alvesson and Sköldberg (2000) for an overview) used to study human behaviour and actions, contextual design offers a complete and easy-to-use framework. It is well organised and provides modeling tools to formalise the unstructured connections in work processes with the needs in relation to software development. The work models developed from contextual inquiries provide a basis for a common understanding between software developers and end users.

In this research and development project the contextual design process is supplemented with reviews of available literature within the field and trail tests of software and hardware to be used in the final system and for the development. Also demonstration software applications are created and tested by future users.

It was found rewarding to take the design of paper-based mockups of the user interface used in the contextual design method one step further by giving them some functionality and appearance like the real applications. Demonstration software applications with some functionality are therefore created and used to collect user feedback and ideas.

Introduction of new IT tools in construction has proven to be a challenging task. For that reason practical implementation tests of RFID technology and a pilot test are conducted. It will lead to an increased knowledge of how the technology can support the construction process and lead to new improved working methods.

The contextual inquiry has been carried out with informal interviewing and work observations of future users with different roles in relation to construction. Also visits to sites have been paid where the system is going to be used. More than ten future users have been involved in the inquiry process. Their identified needs are supplemented with input from discussions with colleagues, software developers and other researchers to form this memo. In Beyer and Holtzblatt (2000) it is stated that interviews of 10-20 users are enough to collect most of the user needs. More interviews will not result in significantly more identified needs.

The users involved in the inquiry are consultants, construction managers and sub contractors. The interviewees' roles in the case study are the following: 1) the consultants do engineering design of structures and installations, 2) the construction managers are responsible for the building erection and construction planning, 3) the sub-contractors manufacture, deliver and install prefabricated concrete elements in the building.

2 System Description

2.1 Overall Functionality – Experiment 1

A prototype of an ICT-system will be developed and tested in practice. By use of RFID-technology in combination with mobile technology and GPS, the ICT-system can keep a virtual 4D model semi-automatically updated throughout a building's construction process. The virtual 4D model is an extension of a virtual 3D model. Aside from a virtual object-oriented 3D representation of the building, it also includes data about time for planned fabrication and installation of each component or task linked to the schedule of the project.

The 3D and 4D CAD tool Tekla Structures will be customised with object properties supporting input from the mobile device. Physical building components will automatically be identified by means of Radio Frequency Identification (RFID). It will create a digital link between the physical components and their digital representation in the virtual 3D model. A mobile application is developed on the basis of an existing system from M_Solution. This system is specialised in mobile data capture and will be extended to support synchronisation with the Tekla model server. The mobile application will, through Web access over GPRS/EDGE, retrieve and update data in the virtual 3D and 4D model. The virtual 3D and 4D model is placed on a server with Internet connection supporting cross company collaboration. A scenario explaining the system in use is presented in section 2.3.

Introduction of new IT tools in construction has proven to be a challenging task. The one exception that has gained wide acceptance is mobile phones. Rugged computers, barcode readers or permanent RFID gate readers are often used for logistic optimisation in manufacturing companies but have gained no ground in construction. Therefore the focus is to develop new methods and applications working with the mobile phones rather than using the other tools dedicated for automatic identification.

The downside of using a traditional mobile phone as RFID-reader is that the reading range is very short and the possibilities are limited to developing rich multimedia applications for execution on a small display. Therefore one of the key challenges in the project will be to find a practical usable method for reading the RFID tags and accessing the virtual 3D and 4D model. But overcoming this challenge with the right system design will also be an important enabler for a wider introduction of the technology and work processes within construction.

2.2 Overall Functionality - Experiment 2 - Proof of Concept

The proof of concept system will in overall functionality be similar to the system described in Experiment 1. Based on the experiences from this development other supporting systems should however be considered.

The specific components for the proof of concept system are not yet decided.

2.3 Users and Their Characteristics

In general the system can be used by anyone involved in a construction project. However, the primary target user is the construction site management, the craftsmen and the consultant's site inspection. Therefore the system must be useable for people with limited or basic ICT competences. Secondary users will be the design team supporting the contractor using the 4D model and for model coordination. Also the client will be a secondary user interested in following the project progress.

2.4 Workflow

A future potential user scenario is presented below to outline how the new prototype is intended to be used. An important part of the tests described in Section 6 is to verify whether this scenario is appropriate for further implementation and development of the system.

The scenario is illustrated in Figure 1 to Figure 5 and described with the following fictive protagonists:

- John, the virtual model coordinator
- Jane, the construction manager
- Michael, the precast concrete manufacturer
- Paul, the foreman

Step 1: Model generation and precast element lotting management: *John is model coordinator of the design and construction of a new office building. His task is to secure a smooth information flow between all parties in the project. During the design of the building John is responsible for the 3D and 4D modelling and works in close collaboration with the general contractor's construction manager, Jane, and project manager, Michael, who is from the manufacturer of precast concrete. John is also responsible for adding the IDs from the RFID tags to the objects in the virtual model stored on the model server.*

When the concrete elements are ready for shipping, Michael is responsible for updating the 4D production status information on the model server. He does that by reading the RFID tag embedded in each concrete element by his mobile phone, and subsequently presses the button "In transit". Together with the production status information, the mobile application automatically updates the model server with data about time, date, user and current location of the GPS. His mobile phone has Internet access, and connects to the service provided by the model server.

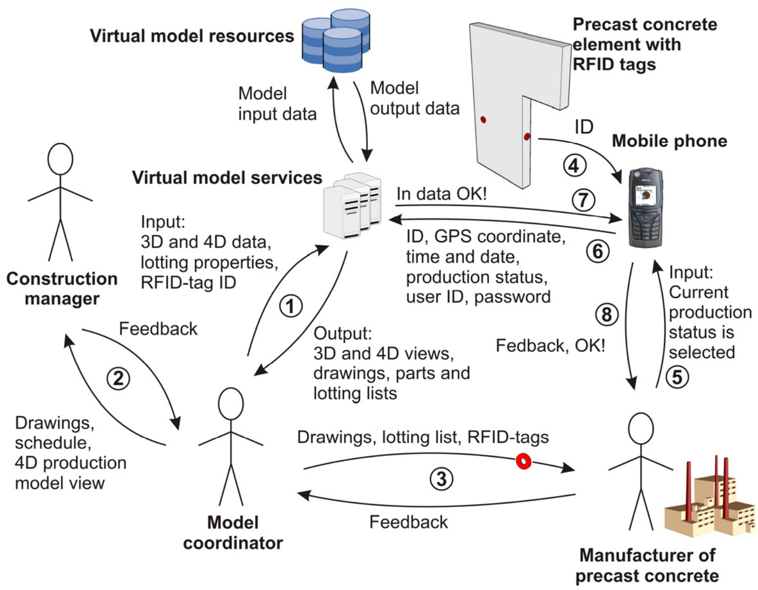

Figure 1 Rich picture illustrating future use of a digital link between virtual models and physical components in construction for model generation and precast element management. The numbered events refer to an execution sequence of the actions. 1/5

Step 2: Construction site precast element acceptance and inventory management: When the precast elements arrive at the construction site, Jane uses the RFID enabled mobile phone to identify the elements. Prior to arrival, she has already received information about installation time, date, storey and grid line of the elements from the virtual model service. While making the acceptance check, Jane writes comments on the phone, if any, and updates the model server with new element data about production status, location, time, date, and user. The acceptance checking also includes finish, transportation damages and measurements of window and door holes.

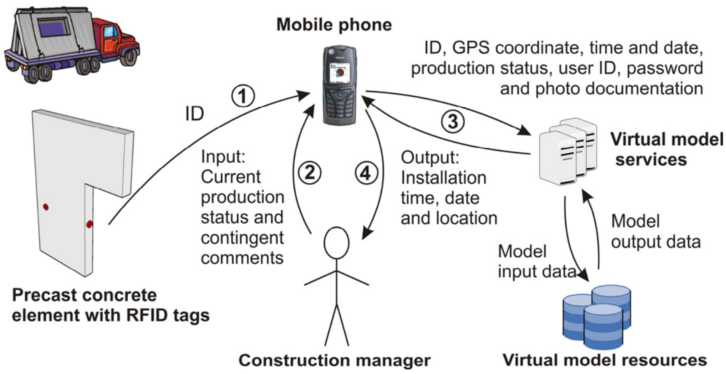

Figure 2 Rich picture illustrating future use of a digital link between virtual models and physical components in construction for precast concrete element acceptance and inventory management. The numbered events refer to an execution sequence of the actions. 2/5

Step 3: On-site element location: *A continued update of the virtual model enables any user of the system to retrieve information about current production status, location, comments and direction of any of the precast concrete elements. Foreman Paul uses his mobile phone to retrieve information about where he can find the next element to be installed, and he reads the comment input during element acceptance at the construction site. In case the element is not in place at the construction site, he is notified where in the supply chain it is currently located.*

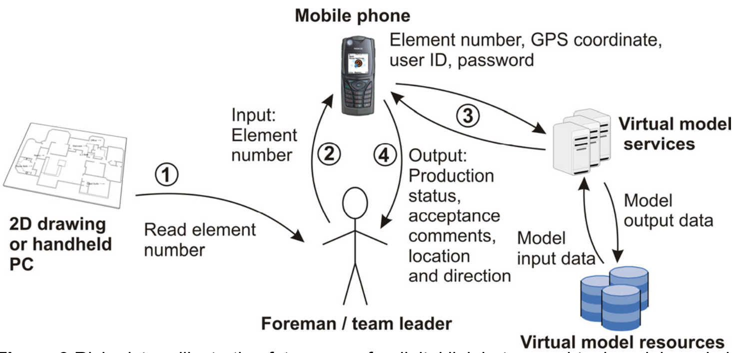

Figure 3 Rich picture illustrating future use of a digital link between virtual models and physical components in construction for on-site location of building elements. The numbered events refer to an execution sequence of the actions. 3/5

Step 4: Task accomplished update: *When a precast concrete element is installed, Paul updates the virtual model with his mobile phone by reading the RFID tag and selecting the "Task finished" button. He supplements the input with a photo for the quality assurance documentation. He now receives information about the next task, and the location of the elements to be installed.*

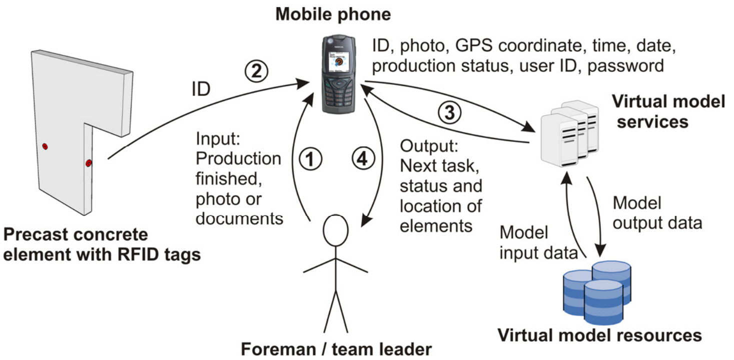

Figure 4 Rich picture illustrating future use of a digital link between virtual models and physical components in construction for on-going process update of the virtual model. The numbered events refer to an execution sequence of the actions. 4/5

On-going information retrieval: *During the construction process, contractors, engineers, architects and the client can follow the progress of the project in their own offices by means of a virtual 4D model viewer. Furthermore for elements where they have subscribed to notification, they receive an e-mail, SMS or RSS feed (Really Simple Syndication (RSS 2.0), RDF Site Summary (RSS 1.0 and RSS 0.90), or Rich Site Summary (RSS 0.91)) whenever production status of the elements is changing. The structural engineer uses this option to get information about when he has to go to the construction site to do follow-up quality checks, and the construction manager is quickly informed when new elements arrive at the construction site.*

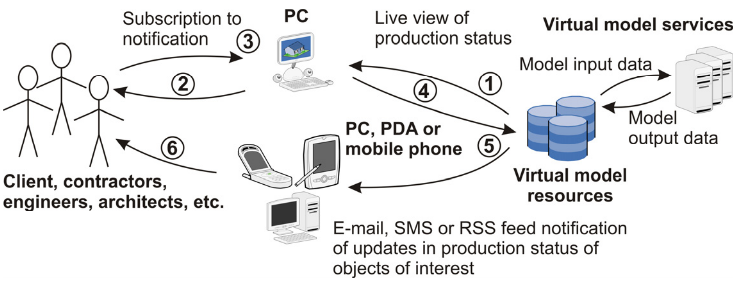

Figure 5 Rich picture illustrating future use of a digital link between virtual models and physical components in construction for on-going information retrieval. The numbered events refer to an execution sequence of the actions. 5/5

2.5 Cultural Aspects

In Figure 6 results from a previous analysis of the cultural aspects in the use of RFID technology in operation and maintenance is presented. Similar potential conflicts can be expected in processes concerning project progress management and quality assurance. Cultural models, as shown in Figure 6, are used to illustrate, concretise and capture the invisible and pervasive cultural context that influences the system or product to be developed. The author's interception of the interviewees' behaviour, their informal answers and unwritten values is presented in the model. Cultural models are relevant in any system development because cultural aspects can have significant influence on people's choices and thereby the success ratio of the new system. The introduction of RFID within construction may introduce many potential conflicts, as illustrated in Figure 6 with the zigzags. In the implementation it will lead to conflicts about who should pay for adding RFID tags to components and what must the detailed registration of people's behaviour be used for? Also public attitude about the RFID technology, which can be hard to handle, can have major influence on the success of the technology.

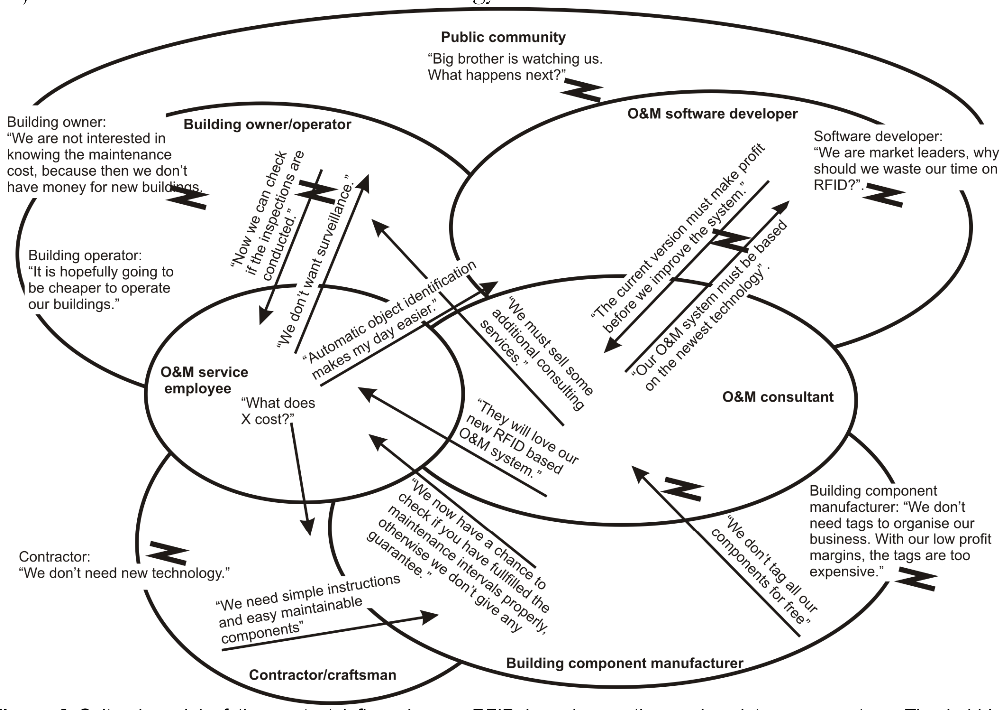

Figure 6 Cultural model of the context influencing an RFID based operation and maintenance system. The bubbles illustrate users with overlapping interests and the arrows illustrate cultural influence. The zigzags indicate conflicts. Similar potential conflicts can be expected in processes concerning project progress management and quality assurance.

2.6 Physical Environment

Physical models are used to illustrate the physical environment in which the future system is going to be used. It thereby illustrates the physical bindings on the system. In this case, the system under development is not only going to work in a single physical environment, but in different contexts. Therefore the physical model shown in Figure 7 illustrates a generic model of a construction site. The most important constraints illustrated in Figure 7 are that a construction site consists of a number of highly distributed physical and virtual spaces. The links between the spaces consist of access roads and supply chains for network, electricity, water and sewer system. These spaces are often moved ad hoc during the construction phase, and the ICT system must therefore be very flexible to support these changes.

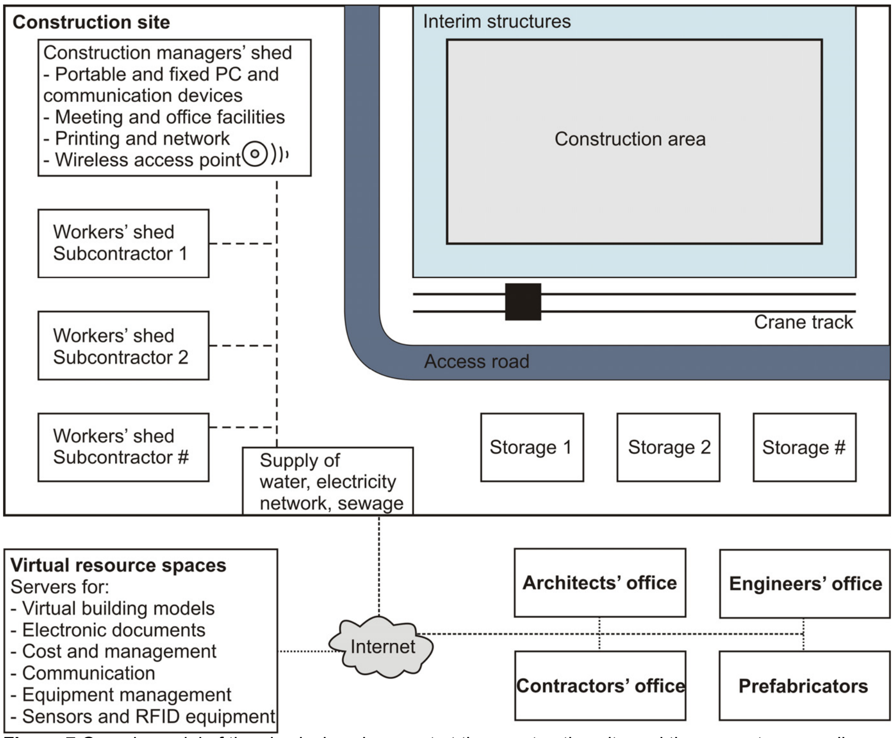

Figure 7 Generic model of the physical environment at the construction site and the nearest surroundings.

2.7 User Environment Design

Results from the user environment design process can be found in the Enclosure. A user environment for a mobile application to conduct project progress management and quality assurance is presented.

Diagrams showing the content on each page or window in the user environment are presented in Enclosure A. An explanation to the diagrams is also given in this Enclosure. The flow between each page or window is visualised in Enclosure B. Enclosure C presents a paper demo of the mobile application. The paper demo is developed for inspiration and can be subject to changes during implementation. The paper demo is also available in an interactive edition for execution on a mobile phone supporting Java 2 Micro Edition, the Connected, Limited Device Configuration and the Mobile Information Device Profile 2.0 (J2ME CLDC/MIDP 2.0) or an emulator. It is the Java runtime environment for today's (2008) most popular compact mobile information devices, such as mobile phones and mainstream PDAs.

2.8 Bindings on Design and Implementation

The mobile application for Experiment 1 must be designed to run on a mobile phone with a 240x320 pixels display. Simplicity and ease of use are important factors for the design of the mobile application. Deployment to other tools such as PDAs and ultra mobile PCs should also be considered.

2.9 Other Conditions and Dependencies

No special requirements on this subject in this prototype implementation.

3 External Interface Requirements

3.1 User Environment

N/A

3.2 Hardware Interfaces

N/A

3.3 Software Interfaces

The .net application programming interface (API) to be used for synchronisation with the Tekla model server is described in the files: "Tekla.Structures.DotNet.chm", "Tekla.Structures.Drawing.chm", "Tekla.Structures.Model.chm" and "Tekla.Structures.Plugins.chm"

Further Input from information service developers is needed on this subject

3.3.1 Communication Protocols and Interfaces

N/A

4 Functional Requirements to the Mobile Application

ID	Description	Critical	Important	Optional	Nice to have
1.0	**Login** - Identify user either by entering user name and PIN code or reading identity card.	X			
2.0	**Menu** - A menu for easy navigation in the program is required. Consider using a hierarchical menu.	X			
3.0	**Show and set RFID tag ID –** It must be possible to show RFID tag ID from the mobile application.	X			

3.1	Possibility to add an RFID to virtual model on site.		X		
4.0	**Location and status** – By entering a component name it should be possible to retrieve information about its current production status.	X			
4.1	Capture of GPS location has been identified as an important functional requirement for the future users.		X		
4.2	The mobile application must calculate distance and direction to component location.		X		
4.3	Positioning based on Google Mobile Maps can be used as an alternative to GPS. It is expected to be detailed enough in many cases. See: http://www.google.com/mobile/gmm/mylocation/index.html		X		
5.0	**Component history** – View history of a given component's production progress			X	
6.0	**Component properties** – Inquiry of component properties.		X		
7.0	**Setup** – Individual customisation of the mobile application. It is preferably done from a central server.		X		
7.1	Support for multiple projects and multiple servers		X		
7.2	Multi language support. It is important for the Danish contractors that the application supports Danish. Yet the international market for the mobile application is assessed to be much larger than the Danish. Therefore the application should at least support English.		X		
8.0	**Associated documents and photos** – Possibility to associate documents and photos with components.				X
8.1	As an alternative or in addition to the possibility of associating photos and documents with components, linking to a web site and opening the site in a browser on the mobile phone would be very useful.	X			
9.0	**Design status** – Set and show design status for any component.			X	
10.0	**Prefabrication status** - Set and show prefabrication status for any component by reading its RFID tag.	X			
11.0	**Component acceptance** – Register a component at arrival to the construction site by reading its RFID tag.	X			
12.0	**Site quality assurance** – Register a component when installed by reading its RFID tag.	X			
13.0	**Feedback** – Appropriate feedback must be given to user when updating information about a component.	X			
14.0	**Consultant inspection** – possibility to use the application for site inspection				X

15.0	**Manual status update –** If it is not possible to enter real time data, then it should be possible to enter data manually at any time. It can be done either from a separate window, from the production status windows used for real time data update or from a web site accessed from a PC.	X			
15.1	It should be easy for the user to distinguish between editable fields and fixed fields. E.g. by use of colours.		X		
15.2	In windows showing user initials, date, time, GPS location etc. the current date should be entered automatically by the application. Possibilities to edit the data should be given. However, it should be registered if the user changes the automatically entered values.	X			
18.0	**Visualisation** - Graphical presentation of the component's placement in the virtual 3D model on the mobile application would be a nice future feature.				X
19.0	**Deployment** - The mobile application should also be deployable to PDAs and ultra mobile PCs. The Virtual Model Service (M_Solution server) and Virtual Model Resource (Tekla Structures) are deployed on different servers and connected through e.g. VPN.		X		
20.0	**User rights management** - It must be possible to individually set the users' right to view and edit different object properties.		X		
21.0	**Synchronisation –** Virtual Model Service database and Virtual Model Resource are synchronising when information is retrieved from a mobile client and with a specific interval (e.g. 1 time per hour).		X		
22.0	**Project delivery –** possibility to use the application in the project delivery process.		X		

5 Other Non-functional Requirements

5.1 Performance Requirements

It is important that the user gets immediate response when entering data in the mobile application.

5.2 Security Requirements

No special requirements on this subject in this prototype implementation.

5.3 Software Quality Attributes

The following attributes should be characteristic for the mobile application:

- Simple
- Flexible
- Easy to use
- Good-looking
- Motivating for the user. It should be easier to do project progress management by this mobile application than traditional paper based methods.

5.4 Project Documentation

Experiences from the prototype testing will be added to this memo in Section 10.

5.5 User Documentation

No special requirements regarding this subject in this prototype implementation.

5.6 Test Requirements

Application must be tested before delivery. Se also Section 6 for planned test in construction practice.

5.7 Installation Requirements

No special requirements on this subject in the prototype implementation.

6 Evaluation Plan - Pilot Tests in Construction Practice

6.1 Test of Proof of Concept

Not scheduled.

6.2 Experiment 1

The prototype is tested on the construction of a new registration court in Hobro, Denmark. It is a public-private partnering project where MT Højgaard is the general contractor, Rambøll is consultant on all engineering services and the architect is Cubo. The building is app. 3500 m2 distributed on two storages and a basement. The carcase is, as is common practice in Denmark, fabricated of precast concrete elements. The working processes concerning precast concrete element design, fabrication and erection will form the basis for the testing. It is expected that if we can develop a method and supporting services for this complex multi-disciplinary task, it can be applied to any work process in construction.

The planned tests are listed below and are described further in the document "Evaluation plan and status for RFID in construction" dated 2008-04-29:

1. Implementation of daily 3D model use on the construction site
2. 4D model for planning
3. Test of input of production status in 3D/4D model
4. 4D model for planning and process optimisation
5. Placement and readability of RFID tags in concrete elements
6. Test of user environment
7. Use of RFID tag as a quick link to information in the 3D model on the construction site
8. Real time project progress management based on RFID, Tekla model and a mobile application
9. Analysis of the actual work flow after the construction project is completed based on real life and accurate production data

7 Schedule

System Development Project 2

Not scheduled.

System Development Project 1

February 2008: Project start-up

- February 2008 – April 2008: System analysis and design
- April 2008 – May 2008: Implementation of mobile application and modifications to Tekla
- April 2008: Development of method for mounting and embedding RFID tags in precast concrete elements
- May 2008: Test of software components by developers
- May 2008 – June 2008: Intermediate tests in practice described in Section 6
- July-August 2008: Real life test of prototype

Construction Project

- January 2008 – April 2008: Conceptual design and authority acceptance
- February 2008 – May 2008: Modelling of the virtual building in 3D and 4D
- March 2008 – June 2008: Detailed design
- April 2008 – April 2009: Erection
- March 2008 – May 2008: Detailed design of precast concrete elements at manufacturer
- May 2008 – July 2008: Production of precast concrete elements
- May 2008 – August 2008: Mounting of concrete elements

8 Future Extensions

Some aspects concerning project progress management, quality assurance and inventory management have not been covered in the prototypes described above. They have not been forgotten though. They are given a lower priority due to this early stage of the development. Only the core functionalities to fulfil the ambitious vision in Section 1.3 of the appendix are included in the prototypes. As mentioned earlier, the vision is to "develop a simple and implementable system and supporting work processes for real time project progress management, quality assurance and inventory management". In this section of the paper the relevant future extensions of the system will shortly be outlined and discussed. They are important to be aware of in the implementation of the described prototypes to avoid putting restraints on systems, which in the near future will cause conflicts with the user needs.

Automation of the data collection: This prototype system is solely based on data capturing from mobile phones because they are cheap, highly flexible, easy to carry, and already implemented in construction. One of the drawbacks of using the mobile phone for data capturing is that it requires manual attention. Automatic readers on trucks, gates, etc., can avoid some of the manual work required for the data capture. However, it should be noticed that no extra work will be introduced of the described system. At all the stages where the system is going to be used for data capturing, a manual and often paper-based quality assurance procedure is conducted today (shipping from manufacturer, acceptance control at the building site and documentation when installed), so the additional benefits from using fully automatic identification are expected to be rather limited.

Integration with other systems: The idea behind the use of a separate virtual model service (as illustrated in the figures in Section 2.4 of this appendix) for the data capture is to create a flexible solution that is easy to integrate into other systems, such as business enterprise resource planning systems (ERP), various CAD systems, room and equipment databases, production planning tools and operation and maintenance systems.

Integration through standardised data representations: The Industry Foundation Classes (IFC) data model, developed by IAI, is most likely the most important data representation form of virtual model data for the construction industry in the future. For that reason future extensions of the system should contain integration with IFC model servers through standardised data exchange. This will support improved inter-organisational use of the systems and a better scalability.

Visualisation, reporting and optimisation of the construction process based on the captured data: The prototype presented has some focus on visualisation and optimization, but many other possibilities will turn up when the system is a reality. There will, for example, be many possibilities for different kind of reports, such as lists of deviations between planned and realised construction.

Use of RFID tags with long reading distances and active tags with sensors: When designing new RFID based systems, it is very important to focus on the core business issues. In this case the core business problem is to develop a system that supports working methods enabling user-friendly information delivery and real time data capturing of the project progress and quality assurance documentation. Therefore, the use of more advanced RFID tags and readers will not create significantly more value. The fully flexible mobile solution is much more important. When e.g. UHF EPC (Electronic Product Code, (EPCglobal, 2008)) readers are available for standard mobile phones, like the NFC (Near Field Communication) technology is today and current challenges concerning the use of UHF tags together with metals are solved, it should be considered using these tags. It is also expected that dual or tri band (LF+HF+UHF) RFID tags would be useful for the construction industry because no single RFID technology meets all the requirements of RFID tags for use in the construction industry.

Legal aspects must be covered: A number of legal questions should be clarified such as: Who is the virtual model data owner, who is responsible for updating what kind of information in the virtual model and what can the data be used for?

Detailed check lists in the quality assurance: It should be considered to include more detailed checklists in the quality assurance (QA) process. It is, however, currently not done because it has been identified that the four options: 1) Approve, 2) Reject, 3) Approve with comments, and 4) Fixed, supplemented by the ability to add comments will cover most user needs. It also makes the system very flexible and it only requires the user to enter deviations, and it does not overtax him/her with unnecessary registration work.

Product data life cycle management: Comprehensive use of virtual models as illustrated with the prototypes in this paper introduces a need to consider and develop methods for accessing and re-using the data in the full lifetime of the building.

Optimisation for other platforms: The presented prototypes have been developed for use on regular PCs and mobile phones. New display technologies and the introduction of ultra mobile low cost and rugged laptops such as the One Laptop per Child (OLPC) (OLPC, 2008) are expected to have a positive influence on the use of ICT at construction sites. Therefore future implementations should be able to take advantage of these technologies. In figure 16 it is illustrated how a construction detail and a web site containing work instructions (in this case a Wiki) easily can be viewed on the OLPC even on a rainy day or a very sunny day. OLPC is water resistant and in contrast to most displays on common mobile phones and laptops, it can be used in direct sunlight due to a reflective display. These features are important to be aware of when developing a future system supporting One Laptop per Workman (OLPW).

9 Cost Estimation

N/A

10 Lessons Learnt

See Paper VI.

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Enclosure A – User Environment Diagrams

Name of page, window or focus area
Purpose: Short description of the purpose

Functions
● Functions to be activated by the user
○ Functions to be activated by the system

Links
> Pages or windows to which this user environment object can navigate to

Objects
■ Objects presented to the user

Risks/Constraints
Particular risks/constraints not giving the user the expected experience

Explanation to user environment diagram.

Login
Purpose: Identify user and project

Functions
- ● Identify user by reading identity card or entering initials and pin code
- ● Select or enter project ID
- ● Login
- o Log user name, location, date and time

Links
> Menu

Objects
- ■ Input fields
- ■ List of recent projects

Risks
Useful feedback must be given if user input is not correct

Menu
Purpose: Give the user an overview of available functionalities

Functions
- ● Go to selected menu item

Links
> Set/show RFID tag ID
> Current location and status
> Design status
> Prefabrication status
> General prefab status
> Component acceptance
> Site quality assurance
> Consultant inspection
> Project delivery
> Manual status update
> Component history
> Object properties
> Setup

Objects
- ■ Menu

Risks
A badly structured menu will make the system slow and difficult to use

Show and set RFID tag ID
Purpose: Show the unique identification through actual RFID reading and let the user add or remove ID from virtual model.

Functions
- ● Add ID to component
- ● Remove ID
- ● Update
- ● Cancel
- o Read ID and get information about associated object(s)
- o Log any changes, user name, location, date, time, read ID and associated object(s)

Links
> Feed back window
> Go back to menu

Objects
- ■ Editable text box with component name
- ■ List of IDs associated with the entered component name
- ■ Editable text box for comments
- ■ Text box with DBK classification code associated with object in clear text

Risks
Response time must be satisfactory

Location and status
Purpose: Give information about current status and location by entering component name

Functions
- ● Update view
- ● View associated documents and photos
- o Get current location

Links
> Photos and documents window
> Google Mobile Map or similar
> Go back to menu

Objects
- ■ Editable text box with component name
- ■ Text box with RFID
- ■ Text box showing direction to component
- ■ Text box showing distance to component
- ■ Text box showing current status
- ■ Text box showing comments added to component
- ■ Text box showing component location
- ■ Text box showing component destination

Risks
Response time must be satisfactory

Component history
Purpose: Give an overview of component production progress

Functions
- ● Update view
- o Read RFID tag => get data

Links
> Photos and documents
> Feed back window
> Go back to menu

Objects
- ■ Editable text box with component name
- ■ Editable text box with RFID
- ■ Text box listing changes to component (component log). One line per registration showing, time and date, user initial, production status, location

Risks
Response time must be satisfactory

Component properties
Purpose: List all component properties

Functions
- ● Update view
- o Read RFID tag => get data
- o Update

Links
> Photos and documents
> Feed back window
> Go back to menu

Objects
- ■ Editable text box with component name
- ■ Editable text box with RFID
- ■ Text box showing component inquiry

Risks
Response time must be satisfactory

Setup
Purpose: Let the user customise the user interface, change project, language and server

Functions
- ● Save settings

Links
> Go back to menu

Objects
- ■ Editable text box with unique project ID
- ■ List of servers
- ■ Choice element for language (minimum english and danish)
- ■ Choice element for menu setup

Risks
Response time must be satisfactory

Associated documents, photos and web sites
Purpose: Add and view documents and photos associated with component

Functions
- ● View item
- ● Add document or photo
- ● Take photo
- ● OK, back to previous window
- o Read RFID tag => get data

Links
> Document and photo browser window
> Web browser
> File browser
> Camera utility
> Previous window

Objects
- ■ Component name
- ■ List of documents, photos and links sorted after subject, file name, type, date or creator

Risks
Inappropriate user feed back

Design status
Purpose: Set and show design status for any component

Functions
- ● Modify
- o Log any changes, user name, location, date, time, and associated object(s)

Links
> Photos and documents
> Feed back window
> Go back to menu

Objects
- ■ Editable text box with component name
- ■ Choice element showing current status (sketched, detailed, checked, ready for production, as build). Status can be changed by moving check mark
- ■ Date and time field associated with current status
- ■ Text box showing initials for user who set current status
- ■ Editable text box for comments

Risks
Response time must be satisfactory

Prefabrication status
Purpose: Set and show prefabrication status

Functions
- ● Modify
- o Read RFID tag => get data
- o Log any changes, user name, location, date, time, and associated object(s)
- o Update/set status

Links
> Photos and documents
> Feed back window
> Go back to menu

Objects
- ■ Text box with component name
- ■ Choice element showing current status (Not started, Production scheduled, Detailed for production, Fabrication started, Fabrication ended, In store, Shipped). Status can be changed by moving check mark
- ■ Date and time field associated with current status
- ■ Text box showing initials for user who set current status
- ■ All status fields are supplemented with matching fields for planned time and date.
- ■ Editable text box for parcel number
- ■ Editable text box for delivery number
- ■ Editable text box for truck number
- ■ Editable text box for comments

Risks
This window might hold too much information

Component acceptance
Purpose: Register component at arrival to construction site

Functions
- ● Modify
- o Read RFID tag => get data
- o Log any changes, user name, location, date, time, and associated object(s)
- o Update/set status to on-site

Links
> Photos and documents
> Feed back window
> Go back to menu

Objects
- ■ Text box with component name
- ■ Choice element showing current status (Approve, Reject, Approve with remarks, Fixed)
- ■ Date and time field associated with current status
- ■ Text box showing initials for user who set current status
- ■ Editable text box for comments

Risks
Response time must be satisfactory

Site quality assurance
Purpose: Register component when installed and document quality

Functions
- ● Modify
- o Read RFID tag => get data
- o Log any changes, user name, location, date, time, and associated object(s)
- o Update/set status to be installed

Links
> Photos and documents
> Feed back window
> Go back to menu

Objects
- ■ Text box with component name
- ■ Choice element showing current status (Approve, Reject, Approve with remarks, Fixed)
- ■ Date and time field associated with current status
- ■ Text box showing initials for user who set current status
- ■ Editable text box for comments

Risks
Response time must be satisfactory

Update feedback
Purpose: Give user feedback when any status field is updated

Functions
- ● OK, back to previous window

Links
> Previous window

Objects
- ■ Text box with component name
- ■ Text box displaying successful or failed status update
- ■ Date and time field showing planned installation date and time
- ■ Text box showing installation position
- ■ Text box showing next task
- ■ Text box showing comments added to component

Risks
Inappropriate user feed back

Consultant inspection
Purpose: Quality inspection by consultant

Functions
- Modify
  - o Read RFID tag => get data
  - o Log any changes, user name, location, date, time, and associated object(s)
  - o Update

Links
> Photos and documents
> Feed back window
> Go back to menu

Objects
- ■ Text box with component name
- ■ Choice element showing current status (Approve, Reject, Approve with remarks, Fixed)
- ■ Date and time field associated with current status
- ■ Text box showing initials for user who sets current status
- ■ Editable text box for comments

Risks
Response time must be satisfactory

Project delivery
Purpose: Comment on component quality at project delivery

Functions
- Modify
  - o Read RFID tag => get data
  - o Log any changes, user name, location, date, time, and associated object(s)
  - o Update/ set status to be delivered

Links
> Photos and documents
> Feed back window
> Go back to menu

Objects
- ■ Text box with component name
- ■ Choice element showing current status (Approve, Reject, Approve with remarks, Fixed)
- ■ Date and time field associated with current status
- ■ Text box showing initials for user who set currents status
- ■ Editable text box for comments

Risks
Response time must be satisfactory

Manual status update
Purpose: If it was not possible to enter registration real-time this page can be used

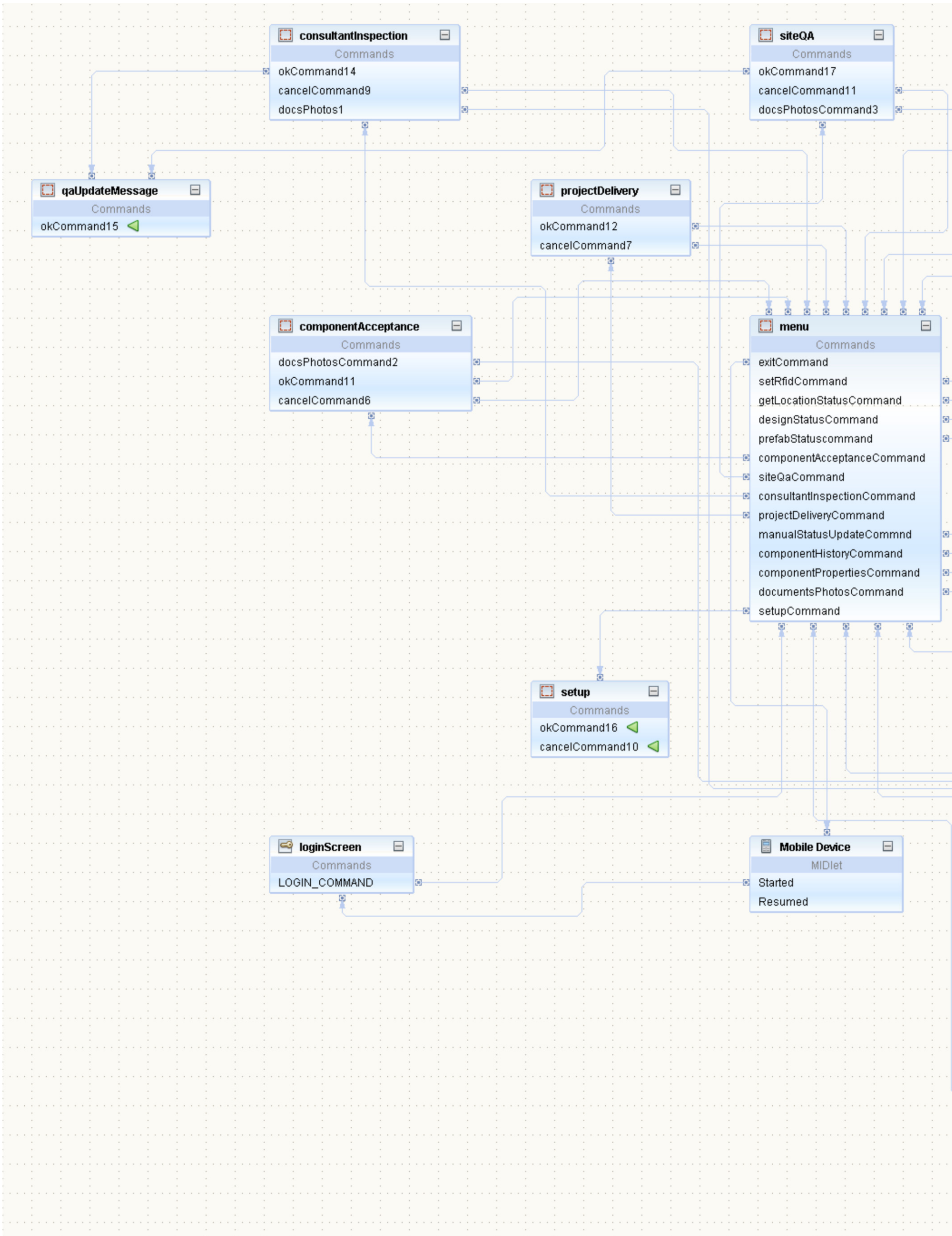
Functions
- Modify
  - o Read RFID tag => get data
  - o Log any changes, user name, location, date, time, and associated object(s)
  - o Update/set status

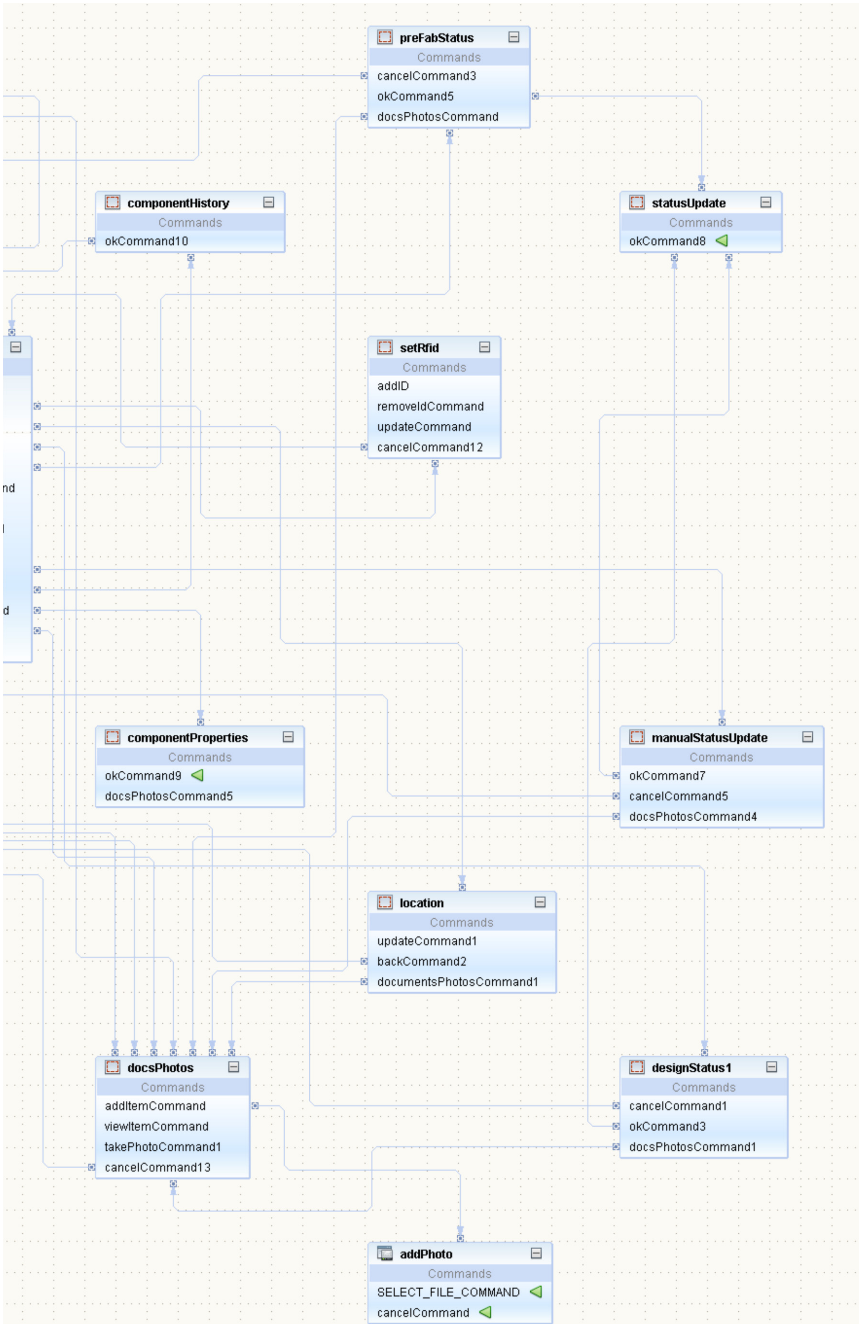
Links
> Photos and documents
> Feed back window
> Go back to menu

Objects
- ■ Editable text box with component name
- ■ Editable text box with RFID
- ■ Choice element showing current status (Not started, Production scheduled, Detailed for production, Fabrication started, Fabrication ended, In store, Shipped, Ordered, on-site, installed, delivered) . Status can be changed by moving check mark
- ■ Date and time field associated with current status
- ■ Text box showing initials for user who sets current status
- ■ All status fields are supplemented with matching fields for planned time and date.
- ■ Editable text box for parcel number
- ■ Editable text box for delivery number
- ■ Editable text box for truck number
- ■ Editable text box for comments

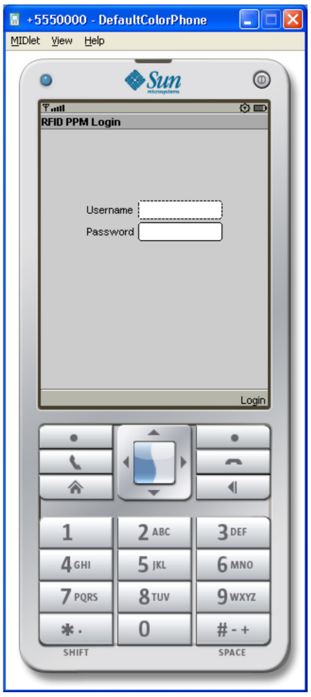
Risks
Component not in database

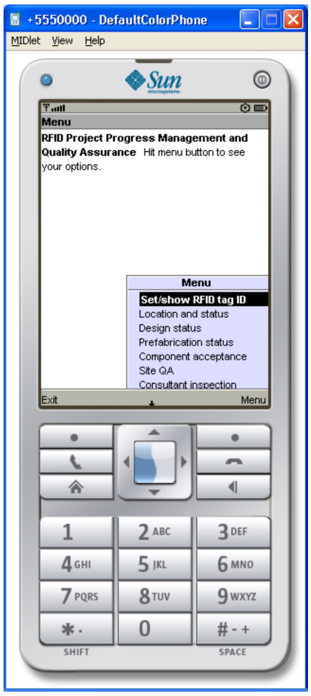
Enclosure B - Flow Diagram of User Environment

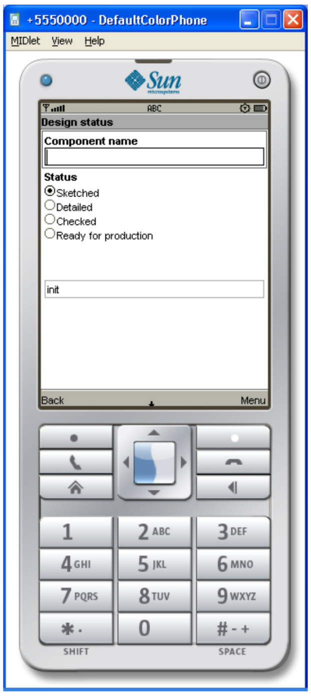


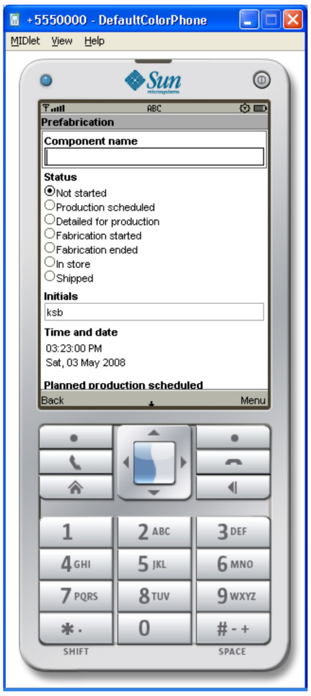

preFabStatus
Commands
cancelCommand3
okCommand5
docsPhotosCommand
componentHistory
Commands
okCommand10
statusUpdate
Commands
okCommand8
setRfid
Commands
addID
removeIdCommand
updateCommand
cancelCommand12
componentProperties
Commands
okCommand9
docsPhotosCommand5
manualStatusUpdate
Commands
okCommand7
cancelCommand5
docsPhotosCommand4
location
Commands
updateCommand1
backCommand2
documentsPhotosCommand1
docsPhotos
Commands
addItemCommand
viewItemCommand
takePhotoCommand1
cancelCommand13
designStatus1
Commands
cancelCommand1
okCommand3
docsPhotosCommand1
addPhoto
Commands
SELECT_FILE_COMMAND
cancelCommand

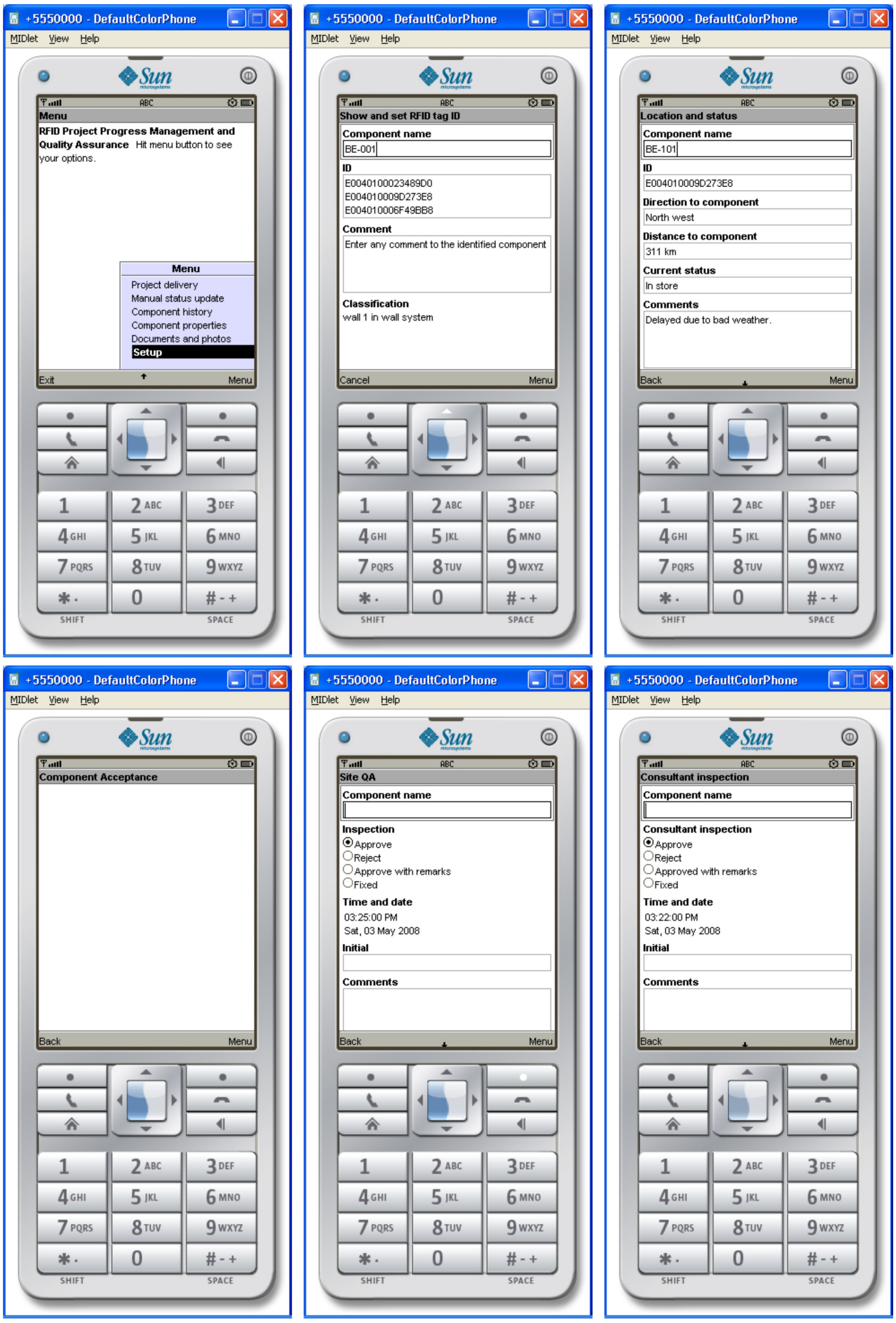
Enclosure C – Paper and Interactive Demo of User Environment



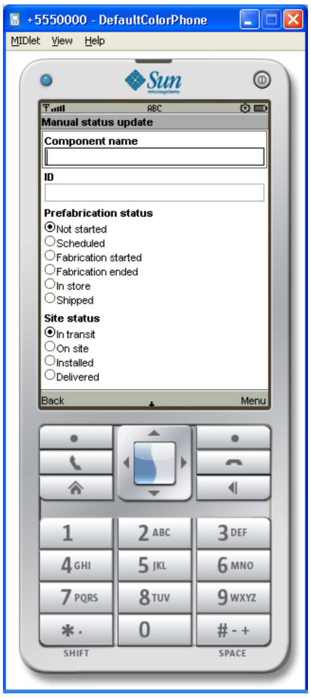


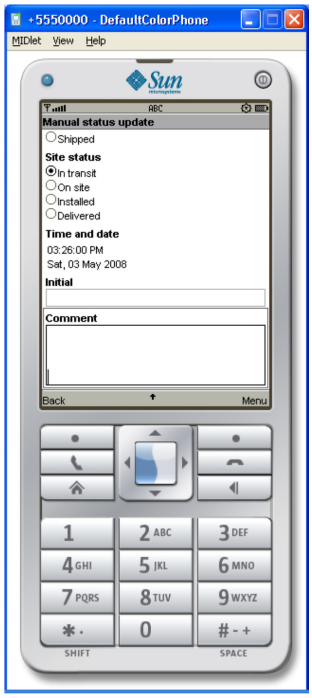


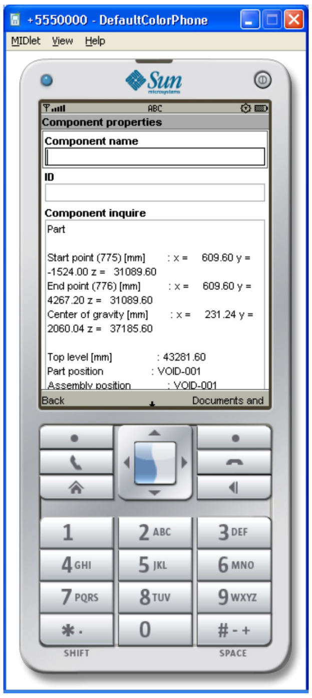


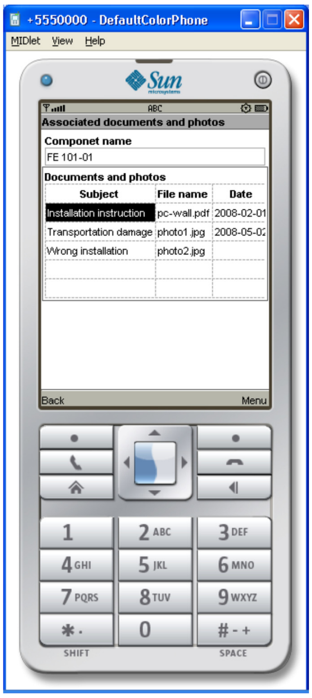

+5550000 - DefaultColorPhone
MIDlet View Help
Menu
RFID Project Progress Management and Quality Assurance Hit menu button to see your options.
Menu
Project delivery
Manual status update
Component history
Component properties
Documents and photos
Setup
Exit
Menu
Show and set RFID tag ID
Component name
BE-001
ID
E0040100023489D0
E004010009D273E8
E004010006F49BB8
Comment
Enter any comment to the identified component
Classification
wall 1 in wall system
Cancel
Menu
Location and status
Component name
BE-101
ID
E004010009D273E8
Direction to component
North west
Distance to component
311 km
Current status
In store
Comments
Delayed due to bad weather.
Back
Menu
Component Acceptance
Back
Menu
Site QA
Component name
Inspection
Approve
Reject
Approve with remarks
Fixed
Time and date
03:25:00 PM
Sat, 03 May 2008
Initial
Comments
Back
Menu
Consultant inspection
Component name
Consultant inspection
Approve
Reject
Approved with remarks
Fixed
Time and date
03:22:00 PM
Sat, 03 May 2008
Initial
Comments
Back
Menu

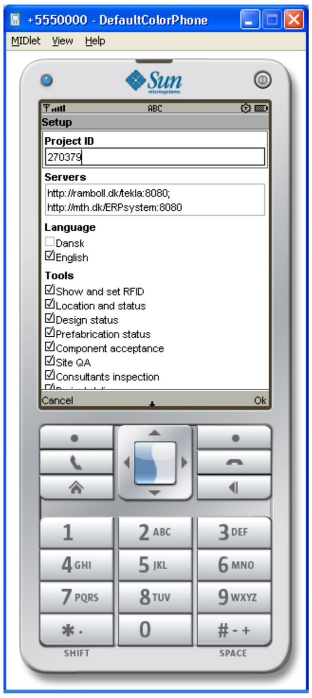

+5550000 - DefaultColorPhone
MIDlet View Help
Project delivery
Back
Ok


+5550000 - DefaultColorPhone
MIDlet View Help
Manual status update
Component name
ID
Prefabrication status
Not started
Scheduled
Fabrication started
Fabrication ended
In store
Shipped
Site status
In transit
On site
Installed
Delivered
Back
Menu


+5550000 - DefaultColorPhone
MIDlet View Help
Manual status update
Shipped
Site status
In transit
On site
Installed
Delivered
Time and date
03:26:00 PM
Sat, 03 May 2008
Initial
Comment
Back
Menu


+5550000 - DefaultColorPhone
MIDlet View Help
Component properties
Component name
ID
Component inquire
Part
Start point (775) [mm] : x = 609.60 y = -1524.00 z = 31089.60
End point (776) [mm] : x = 609.60 y = 4267.20 z = 31089.60
Center of gravity [mm] : x = 231.24 y = 2060.04 z = 37185.60
Top level [mm] : 43281.60
Part position : VOID-001
Assembly position : VOID-001
Back
Documents and


+5550000 - DefaultColorPhone
MIDlet View Help
Associated documents and photos
Component name
FE 101-01
Documents and photos
Subject | File name | Date
Installation instruction | pc-wall.pdf | 2008-02-01
Transportation damage | photo1.jpg | 2008-05-02
Wrong installation | photo2.jpg
Back
Menu


+5550000 - DefaultColorPhone
MIDlet View Help
Setup
Project ID
270379
Servers
http://ramboll.dk/tekla:8080;
http://mth.dk/ERPsystem:8080
Language
Dansk
English
Tools
Show and set RFID
Location and status
Design status
Prefabrication status
Component acceptance
Site QA
Consultants inspection
Cancel
Ok

Enclosure D – List of Data Fields

Description	Tekla name	Type	Comment
Show and set RFID tag ID			
Component name	RamName	String	
ID	RamRFID	String	User defined attribute (UD) Each component can contain several ID's separated by blank space.
Comment	comment	String	UD
Classification code	RamDBK	String	UD
Location and status			
Component name	RamName	String	
ID	RamRFID	String	UD
Direction to component	Must be calculated based on: RamLatitude, RamLongitude, RamAltitude and current location from GPS.		
Distance to component	Must be calculated based on: RamLatitude, RamLongitude and RamAltitude and current location from GPS.		
Component location	RamLatitude, RamLongitude, RamAltitude	Number, Number, Number	Decimal degrees UD
Component destination	RamPlannedLatitude, RamPlannedLongitude, RamPlannedAltitude	Number, Number, Number	Decimal degrees UD
Current status	Value of latest updated of RamDesignStatus, RamPrefabStatus, RamSiteStatus	String	
Comment	comment	String	
Component properties			
Component name	RamName	String	
ID	RamRFID	String	UD
Component inquire	Function named inquire in Tekla shows all component properties	String	
Associated documents, photos and web sites			
Component name	RamName	String	

Document and photos	RamAttDoc, RamAttDocPaths, RamAttDocCreators, RamAttDocDate, RamAttPhotos, RamAttPhotosPaths, RamAttPhotosCreators, RamAttPhotosDate	Table	UD
Links	RamAttLinks, RamAttLinksPaths, RamAttLinksCreators, RamAttLinksDate	Table	UD
Design status			
Component name	RamName	String	
Status	RamDesignStatus value{Sketched, Detailed, Checked, Ready, As_built}	String	UD
Design Comment	RamDesignComment	String	UD
Initial	RamSketchedBy, RamDetailedBy, RamCheckedBy, RamReadyBy, RamAsBuiltBy	String	UD
Time and date	RamSketchedDateTime, RamDetailedDateTime, RamCheckedDateTime, RamReadyDateTime, RamAsBuiltDateTime	Date+Time	UD
Prefabrication status			
Component name	RamName	String	
Status	RamPrefabStatus{Not_started, Scheduled, Detailed, Started, Completed, In_store, Shipped}	String	UD
Prefabrication comments	RamPrefabComment	String	UD
Parcel number	RamPrefabParcel	String	UD
Delivery number	RamPrefabDelivery	String	UD
Truck number	RamPrefabTruck	String	UD
Initial	RamPrefabSchBy, RamPrefabDetailedBy, RamPrefabStartedBy, RamPrefabEndBy, RamPrefabInStoreBy, RamPrefabShippedBy	String	UD
Time and date	RamPrefabSchDnT, RamPrefabDetDnT, RamPrefabStartedDnT, RamPrefabEndDnT, RamPrefabInStoreDnT, RamPrefabShippedDnT	String	UD
Component acceptance			
Component name	RamName	String	
Component	RamCompAcceptance{Approve, Reject,	String	When = Approve,

Acceptance	Approve_with_comments, Fixed}		Approve_with_comments or Fixed set RamSiteStatus = On_site UD
Comments	RamAcceptanceComment	String	UD
Initial	RamCompAppBy, RamCompRejBy, RamCompAppWComBy, RamCompFixedBy	String	UD
Time and date	RamCompAppDnT, RamCompRejDnT, RamCompAppWComDnT, RamCompFixedDnT	Date and time	UD
Site quality assurance			
Component name	RamName	String	
Inspection	RamSiteQA{Approve, Reject, Approve_with_comments, Fixed}	String	UD
Comments	RamSiteQAComment	String	UD
Initial	RamSiteQAAppBy, RamSiteQARejBy, RamSiteQAAppWComBy, RamSiteQAFixedBy	String	UD
Time and date	RamSiteQAAppDnT, RamSiteQARejDnT, RamSiteQAAppWComDnT, RamSiteQAFixedDnT	Date and time	UD
Consultant inspection			
Component name	RamName	String	
Consul Inspection	RamConsInsp{Approve, Reject, Approve_with_comments, Fixed}	String	UD
Comments	RamConsInspCom	String	UD
Initial	RamConsInspAppBy, RamConsInspRejBy, RamConsInspAppWComBy, RamConsInspFixedBy	String	UD
Time and date	RamConsInspAppDnT, RamConsInspRejDnT, RamConsInspAppWComDnT, RamConsInspFixedDnT	Date and time	UD
Project delivery			
Component name	RamName	String	
Project Delivery	RamProjDel{Approve, Reject, Approve_with_comments, Fixed}		When = Approve, Approve_with_comments or Fixed set RamSiteStatus = Project_delivered
Comments	RamProjDelCom		
Initial	RamProjDelAppBy, RamProjDelRejBy,		

	RamProjDelAppWComBy, RamProjDelFixedBy		
Time and date	RamProjDelAppDnT, RamProjDelRejDnT, RamProjDelAppWComDnT, RamProjDelFixedDnT		

The objects in Tekla Structures has been extended to hold the above described attributes. See also the file Obejcts.inp describing user defined attributes in the Tekla Structures project. To avoid problems from e.g. typos, for implementation use attribute names from the Objects.inp.

Notice that attributes using date and time has been changed to a date attribute only, because of a bug in Tekla version 13 and 14. This bug will hopefully be fixed in version Tekla 14.1.

Enclosure E – Revisions

Version 5

- Minor revision.

Version 4

- Updated to include proof of concept.

Version 3

- Enclosure D - User defined attribute names in Tekla has been updated due to a limitation of maximum 20 characters in attribute names.

Version 2

- Section 1.2 about previous research results on RFID in construction has been added.
- Section 4 - Functional requirements. Item 8.1 concerning link to web site added to the list updated.
- Section 4 - Functional requirements. Item 3.0 Set ID is be changed to important. Show ID is still a critical function.
- Section 4 - Functional requirements. Item 4.0. Only the status information is a critical requirement. Location is changed to important.
- Section 4 - Functional requirements. Item 4.3. Positioning based on Google Mobile Maps has been proposed as an alternative to GPS.
- Section 4 – Functional requirements. Item 22.0. Project delivery has been added.
- Item 15. Manual entering of data can be done from the web site. It is not critical to be able to do this from the mobile application. Any automatically entered field can be changed by the user.
- Section 8 containing future extensions have been added.
- Enclosure A – Location and status is updated. Does now include component location, destination and link to e.g. Google Mobile Map.
- Enclosure A - Associated documents, photos and web sites is updated to include links to web sites.
- Enclosure A – Design status. As build added as a new design status.
- Enclosure A – Manual status update. The site status value "In transit" is changed to "Ordered".
- Enclosure D containing list of data fields has been added.

Appendix C

Virtual Physical Link (VPL)

Ontology to Support Virtual Models Linked with Physical Components

Virtual Physical Link (VPL)

Ontology to Support Virtual Models Linked with Physical Components

Kristian Birch Sørensen

Ramboll Denmark

Abstract: *This appendix is a supplement to Paper I and Paper II and demonstrates how an ontology to support virtual models linked with physical components in construction can be developed. Ontology development methods, tools and recommendations are described and demonstrated by initialising the development of the ontology: "Virtual Physical Link".*

It is also the author's expectation that this appendix will inspire researchers and developers in the development of future ontologies for the construction industry (e.g. classification systems) to have focus on modern information and communication technology (ICT) usage rather than looking backwards for solutions to support outdated information handling methods.

1 Introduction

Development and use of commonly accepted ontoloiges, "… *explicit specification of a conceptualization"* (Gruber, 1993), are important to enable reuse of information in construction, share common understanding of the structure of information among people or ICT systems, make assumptions explicit, and analyse knowledge (Noy & McGuinness, 2001).

In Paper I and Paper II the author identified a need for new ontology development to enable a link between virtual models and physical components in construction. However, it is beyond the resources of this research project to develop a full-fledged ontology for this comprehensive purpose. Therefore, this appendix will present the early first steps, methods and ideas towards the development of such an ontology named: "Virtual Physical Link" (VPL).

Various terminologies, languages and tools can be used for ontology development and implementation. There is not a single best approach because it depends on the intended use of the ontology and competences of the developers. When the ontology is implemented as a hierarchical classification system, it is common to use documents or spreadsheets with tables of relevant terms. The main advantage of this approach is that experienced practitioners can read the tables immediately and contribute to the development. Some of the disadvantages are that the spreadsheet and document based authoring tools often lack automation in use and in evaluation of the consistency, correctness and redundancy of the ontology.

Support and use of Industry Foundation Classes (IFC) is critical, in connection with virtual building models ontology development. IFC is described in the EXPRESS language for product models and graphical tools exist (such as EDMvisualExpress) that can assist the ontology developer in the ontology development and validation. This is a major advantage compared to the spreadsheet and document based method. However, one of the main challenges with this approach is the transformation from EXPRESS to other programming languages, integrated development environments (IDE), ICT systems and relational databases.

Another possibility is to implement the ontology as Web Services described in the XML-based Web Services Description Language (WSDL) (Christensen et al., 2001). Graphical user-interfaces and parsers for XML and WSDL assisting the developer in quick code generation are widely implemented in modern IDEs such as Netbeans and Eclipse. From a business perspective this approach can be efficient, but a challenge is not to loose the full context and only focus on short-termed problems.

Ontologies are in relation to knowledge engineering and Semantic Web development often implemented in the languages RDF Schema (RDF-S) or the more expressive Web Ontology Language (OWL). Several graphical authoring tools exist that can assist the developer of Semantic Web ontologies. Protégé is one of them and was also chosen for the ontology development described in this appendix, see Horridge (2009) for a practical user guide. It supports visualisation, automatic taxonomy classification, consistency check, Java class generation, and database connection etc. A critical issue in relation to use of Semantic Web in the construction industry is the integration of IFC based virtual models. Various researchers have focused on transforming IFC into OWL such as El-Diraby et al. (2005) and Beetz et al. (2009). In another research project, a set of ontologies (SemanticSTEP) and derived Express schemas, that define the mapping between ISO 10303 (STEP) models and ontologies in OWL/RDF were developed (S-TEN, 2008). Converters were also developed in relation to the project that might be useful for a future IFC to OWL conversion. When developing generic applicable Semantic Web ontologies for the construction industry, a challenge is not being specific enough to support any business case.

For the ontology development described in this appendix it was chosen to use the OWL approach. The aim is to initialise an ontology development that can be used to define a basis for new ICT applications in construction supporting a digital link between virtual models and physical components. The appendix can also be used for inspiration to an ICT supported method for developing future classification systems for the construction industry.

2 Methodology

No single best methodology exists for ontology development, because there is no "correct" way to model a domain (Gasevic et al., 2006). Inspiration for the development process of ontologies can be found in software engineering and knowledge engineering. Based on literature studies and best practice in ontology development for the medical science domain Noy & McGuinness (2001) propose a methodology for ontology creation. This methodology was adapted for the work presented in this appendix and comprises the steps of:

1. Determine the domain and scope of the ontology

2. Consider reusing existing ontologies
3. Enumerate important terms in the ontology
4. Define the classes and the class hierarchy
5. Define the properties of classes – slots
6. Define the facets of the slots
7. Test by creating instances

The application of this methodology is described in the following sections.

3 Ontology Development

3.1 Domain and Scope of the Ontology

In Paper I and Paper II it was argued and illustrated by future working scenarios that there is a need for ontologies, and particularly business process ontologies, to support project progress management, work instruction delivery, quality inspection, inventory management, construction planning, procurement and facility management. Therefore, these fields of work will define the domain of the VPL ontology under development.

3.1.1 Competency Questions

One way to establish the scope of an ontology is to sketch a list of competency questions an ICT system based on the ontology should be able to answer (Grünninger and Fox, 1995). In relation to the construction industry, and in particular to the establishment of a digital link between the virtual models and physical components, the following are possible competency questions:

- Which working tasks are related to component XX and performed by person YY?
- What is the best choice of maintenance of component XX?
- How many bolts are needed to perform the installation of steel frame ZZ?
- Which one of our partner companies make the fewest errors in the installation of windows?
- How long time does the erecting of interior walls take in average and what is the standard deviation?
- Do we have enough materials in stock for next weeks planned activities?
- Is project KK running according to the schedule and which activities are not?

In order to answer these questions, classification of construction components and how they are related to working processes, persons and best practices is crucial for the ontology.

3.2 Consider Reusing Existing Ontologies

VPL is not a brand new ontology but mostly a combination of several other ontologies to fit a new domain. As a result of the evaluations, experiences and conclusions described in Paper I it is chosen to base VPL on the meta-ontology consisting of the upper classes: Business Process, Technical Service, Resource and Organisation. In addition, VPL draws on aspects from the ontology specifications of IFC (IAI, 2006), Dublin Core (DCMI, 2008), FOAF (Friend of a Friend) Vocabulary (FOAF, 2007), Physical Markup Language (PML) (Floerkemeier et al., 2003), OmniClass Table 32 (OCCS, 2006) and OWL-S, Semantic Markup for Web Services (Martin et al., 2004). To give a brief explanation these ontologies can be used to:

IFC: Resource ontology defining virtual building model related information.
Dublin Core: Resource ontology for document meta-data.
FOAF: Organisation ontology for social web-sites.
PML: Technical service ontology for automatic identification equipment and other sensors.
OmniClass Table 32: Business process ontology for services in construction.
OWL-S: Upper ontology for technical services and business processes.

3.3 Enumerate Important Terms in the Ontology

The VPL ontology is not developed from scratch, so the important terms are already enumerated in the existing ontologies described above. However, some translation or mapping between the terms in the ontologies will be needed. A Person e.g. in IFC as well as in FOAF inherits from Actor but that is the only parallel of the Actor definition in the two ontologies. In IFC the Actor is a class that enables selection between Person, Organisation or Person and Organisation. In FOAF the Actor is a super class from which the sub classes inherit common attributes such as age, e-mail address and IDs etc. Several similar challenges must be solved when integrating the six ontologies described in Section 3.2.

3.4 Define the Classes and the Class Hierarchy

In Figure 1 and Figure 2 the illustrations show how parts of the six ontologies described in Section 3.2 are used to define classes and class hierarchy within each of the four domains of the upper ontology in VPL. The figures show screen dumps from the class browser in Protégé with different classes expanded and collapsed in each view. For each entity in IFC a class is defined in VPL. The FOAF Dublin Core, and OWL-S ontologies are already described in RDF/OWL and are therefore used directly in VPL. PML is described in the six XML schemas:

- PmlCore.xsd
- Identifier.xsd
- RFIDReaderAndTags.xml
- RFIDReaderAndTagsWithMemory.xml
- RFIDReaderAndTagsWithSensor.xml
- SensorAndData.xml

For each element in the PML-XML schemas a class is defined in VPL. OmniClass Table 32 is a text based document defining names and hierarchy of working processes in construction. For each item in OmniClass Table 32 a class is defined in VPL. In addition a WorkPackage class is defined to contain the information of a business process. It is expected that for the execution works a more detailed specification will be required than the one currently available in OmniClass Table 32.

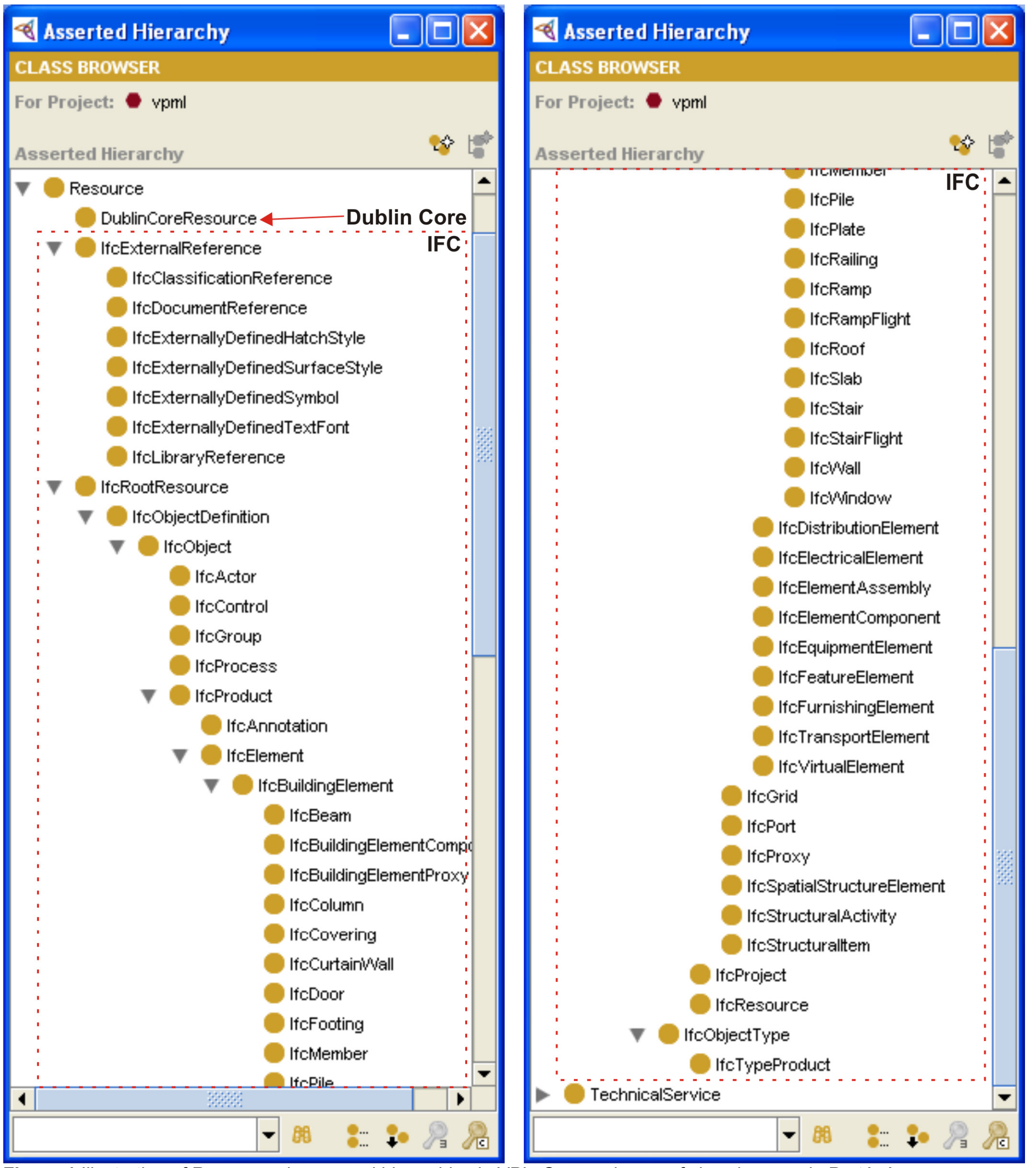


Figure 1 Illustration of Resource classes and hierarchies in VPL. Screen dumps of class browser in Protégé.

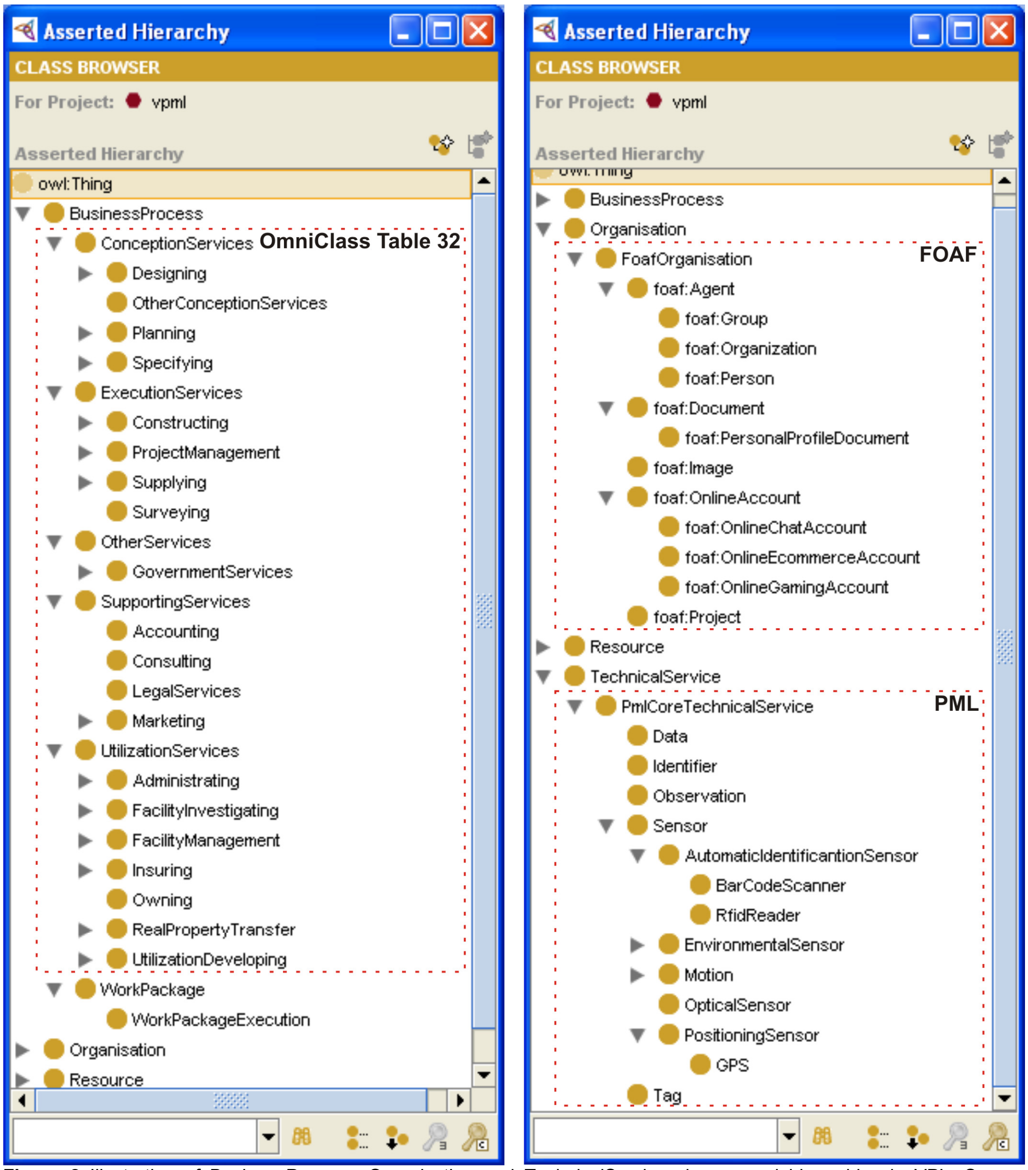


Figure 2 Illustration of BusinessProcess, Organisation and TechnicalService classes and hierarchies in VPL. Screen dumps of class browser in Protégé.

The OWL description of the IfcBeam class in VPL is shown below as an example of a class definition:

```
<owl:Class rdf:about="#IfcBeam">
  <owl:disjointWith rdf:resource="#IfcStairFlight"/>
  <owl:disjointWith rdf:resource="#IfcPlate"/>
```

```
  <owl:disjointWith rdf:resource="#IfcWindow"/>
  <owl:disjointWith rdf:resource="#IfcCurtainWall"/>
  <owl:disjointWith rdf:resource="#IfcDoor"/>
  <owl:disjointWith rdf:resource="#IfcRamp"/>
  <owl:disjointWith rdf:resource="#IfcBuildingElementComponent"/>
  <owl:disjointWith rdf:resource="#IfcFooting"/>
  <owl:disjointWith rdf:resource="#IfcRoof"/>
  <owl:disjointWith rdf:resource="#IfcMember"/>
  <owl:disjointWith rdf:resource="#IfcPile"/>
  <owl:disjointWith rdf:resource="#IfcColumn"/>
  <owl:disjointWith rdf:resource="#IfcCovering"/>
  <owl:disjointWith rdf:resource="#IfcRampFlight"/>
  <owl:disjointWith rdf:resource="#IfcStair"/>
  <owl:disjointWith rdf:resource="#IfcRailing"/>
  <owl:disjointWith rdf:resource="#IfcBuildingElementProxy"/>
  <owl:disjointWith rdf:resource="#IfcSlab"/>
  <rdfs:subClassOf>
    <owl:Class rdf:about="#IfcBuildingElement"/>
  </rdfs:subClassOf>
  <owl:disjointWith rdf:resource="#IfcWall"/>
</owl:Class>
```

3.5 Define the Properties of Classes – Slots

Properties of classes, also termed slots, describe the internal structure of the concepts. Object properties describe the relationship between the classes, and datatype properties are simple literals (e.g. an Integer, String, and others). In Figure 3, the screen dump from Protégé shows how the hasIdentifier property is used to define the relationship between instances of the Identifier class and several other classes such as the IfcClassificationReference, WorkPackage, Sensor, Tag etc. The IFC Entities (classes and subclasses) of IfcRelationship are in this "first try" implemented as object properties rather than classes, and define the relationship internally in the IFC data structure as well as the link to associated resources and processes. To recap from Paper I, the IfcRelAssociatesClassification relationship is used to link building components described in IFC with identification numbers of RFID tags. It is common to place a verb as prefix in object property names such as "has" or "is" but for the FOAF, IFC and Dublin Core ontologies the orginal names were kept.

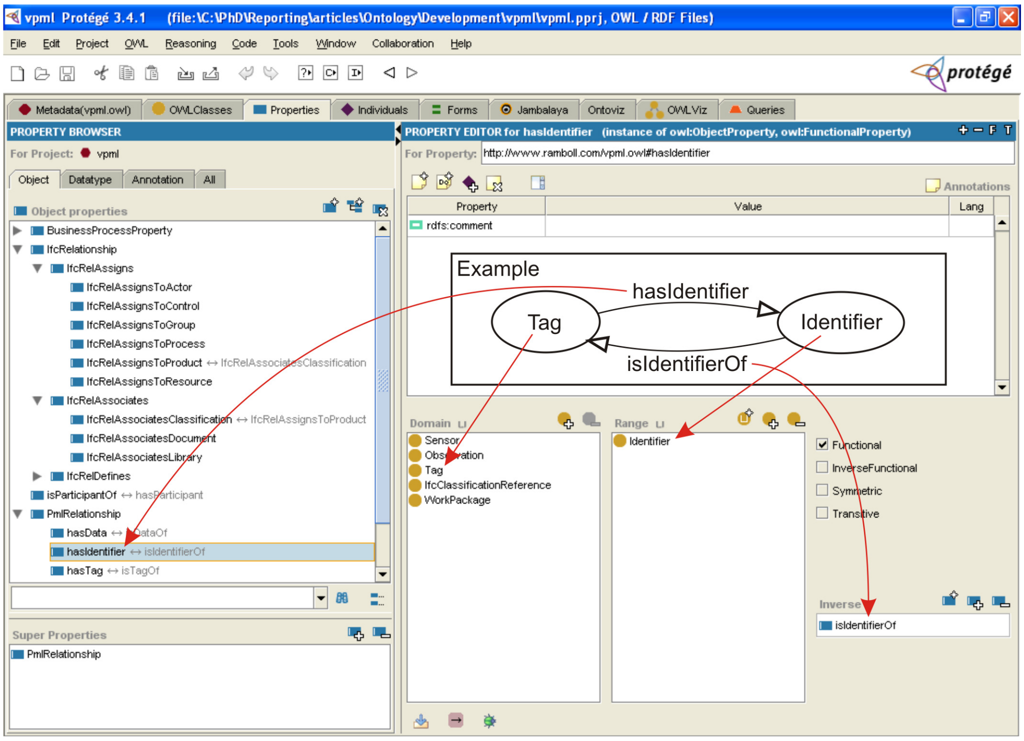


Figure 3 Illustration of object property definition in VPL. Screen dump of properties tab in Protégé.

The OWL description of the hasIdentifier in VPL is shown below as an example of a property definition:

```
<owl:FunctionalProperty rdf:ID="hasIdentifier">
  <owl:inverseOf>
    <owl:InverseFunctionalProperty rdf:ID="isIdentifierOf"/>
  </owl:inverseOf>
  <rdfs:subPropertyOf rdf:resource="#PmlRelationship"/>
  <rdfs:range rdf:resource="#Identifier"/>
  <rdfs:domain>
    <owl:Class>
      <owl:unionOf rdf:parseType="Collection">
        <owl:Class rdf:about="#Sensor"/>
        <owl:Class rdf:about="#Observation"/>
        <owl:Class rdf:about="#Tag"/>
        <owl:Class rdf:about="#IfcClassificationReference"/>
        <owl:Class rdf:about="#WorkPackage"/>
      </owl:unionOf>
    </owl:Class>
```

```
  </rdfs:domain>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
</owl:FunctionalProperty>
```

3.6 Define the Facets of the Slots

Facets of slots define restrictions of properties such as allowed values and other features properties can have. It was beyond the resources of this project to define facets of the slots.

3.7 Test by Creating Instances

Protégé enables the developer to populate the ontology with data (instances of classes). It actually makes Protégé the core of a complete knowledge management system, but it is probably mostly used for testing and evsaluation purposes. It is not recommended to make such a mix of class definitions and instances of classes in the same OWL-file but it can be useful for testing. In this development a small dataset was created for demonstration purposes. A part of these instances are shown in Table 1.

Table 1 Instances used for the evaluation of VPL.

Identifier			
Instance name	**hasID**	**isIdentifierOf**	
Identifier_12		IfcClassitionReference_14	
		WorkPackageExecution_17	
Identifier_14	"urn:epc:1:304:769"	Sensor_44	
Identifier_45	"urn:epc:1:304:768"	IfcClassificationReference_13	
Identifier_21	"urn:epc:1:304:770"	IfcClassificationReference_20	
Identifier_25	"urn:epc:1:304:771"	IfcClassificationReference_24	
Identifier_27	"urn:epc:1:304:772"	IfcClassificationReference_26	
Identifier_28		IfcClassitionReference_29	
		WorkPackageExecution_5	
Identifier_31	"urn:epc:2:102:356"	IfcClassificationReference_30	
Identifier_33	"urn:epc:2:102:911"	IfcClassificationReference_32	
Identifier_34		IfcClassificationReference_35	
		WorkPackageExecution_6	
Identifier_39	"urn:epc:3:007:996"	IfcClassificationReference_38	
Identifier_41	"urn:epc:3:007:997"	IfcClassificationReference_40	
Sensor			
Instance name	**has_Identifier**		
Sensor_44	Identifier_14		
Person			
Instance name	**firstName**	**isParticipantOf**	
Person_10	"Kristian"	WorkPackageExecution_6	
Person_11	"Michael"	WorkPackageExecution_17	
Person_18	"Peter"	WorkPackageExecution_17	
		WorkPackageExecution_5	
Person_7	"John"	WorkPackageExecution_5	
Person_8	"Jane"	WorkPackageExecution_6	
Person_9	"Paul"	WorkPackageExecution_6	
IfcBuildingElement			
Instance_Name	**hasName**	**hasDescription**	**IfcRelAssociatesClassification**
IfcDoor_12			IfcClassificationReference_13
			IfcClassificationReference_14
IfcDoor_16			IfcClassificationReference_20
			IfcClassificationReference_14

IfcDoor_17			IfcClassitionReference_24
			IfcClassificationReference_14
IfcDoor_19			IfcClassificationReference_26
			IfcClassificationReference_14
IfcWindow_22	"Window22"	"This is window 22"	IfcClassitionReference_29
			IfcClassificationReference_30
IfcWindow_23	"Window23"	"This is window 23"	IfcClassitionReference_29
			IfcClassificationReference_32
IfcWall_36	"Wall 36"		IfcClassificationReference_35
			IfcClassificationReference_38
IfcWall_37	"Wall 37"		IfcClassificationReference_35
			IfcClassificationReference_40
IfcClassificationReference			
Instance_Name	**hasIdentifier**	**IfcRelAssignsToProduct**	
IfcClassificationReference_13	Identifier_45	IfcDoor_12	
IfcClassificationReference_14	Identifier_12	IfcDoor_12	
		IfcDoor_16	
		IfcDoor_17	
		IfcDoor_19	
IfcClassitionReference_20	Identifier_21	IfcDoor_16	
IfcClassitionReference_24	Identifier_25	IfcDoor_17	
IfcClassificationReference_26	Identifier_27	IfcDoor_19	
IfcClassitionReference_29	Identifier_28	IfcWindow_22	
		IfcWindow_23	
IfcClassificationReference_30	Identifier_31	IfcWindow_22	
IfcClassificationReference_32	Identifier_33	IfcWindow_23	
IfcClassificationReference_35	Identifier_34	IfcWall_36	
		IfcWall_37	
IfcClassificationReference_38	Identifier_39	IfcWall_36	
IfcClassificationReference_40	Identifier_41	IfcWall_37	
WorkPackageExecution			
Instance_Name	**hasIdentifier**	**hasParticipant**	**hasMethod**
WorkPackageExecution_17	Identifier_12	Person_18	"Installation of doors 1st floor"
		Person_11	
WorkPackageExecution_5	Identifier_28	Person_18	"Installation of windows 1st floor"
		Person_7	
WorkPackageExecution_6	Identifier_34	Person_8	"Installation of prefab walls"
		Person_9	
		Person_10	

It requires some effort to immediately overview how the instances in Table 1 are related. This is better illustrated with Figure 4. The figure illustrates how the VPL ontology can be used to retrieve information about a work process when the craftsman "Peter" reads an RFID tag with his mobile phone. The RFID tag with the identification number "1:304:7682" in the EPC namespace is used to identify IfcDoor_12, with the related WorkPackageExecution_17, the method "Installation of doors 1st floor" and "Peter" as participant.

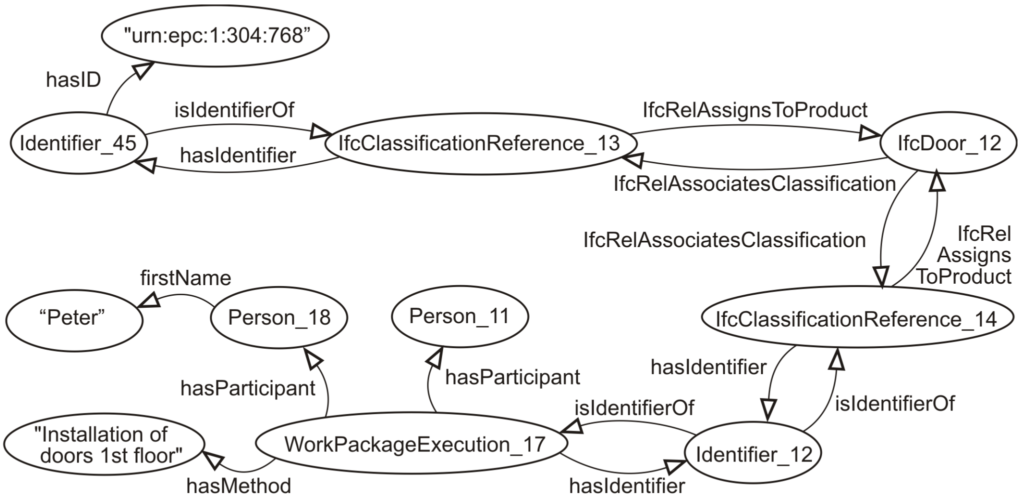


Figure 4 Illustration of how an ID of an RFID tag is related to a building component an instruction of a work method and a craftsman. Instance names are shown in the bubbles, object and datatype properties next to the arrow and string values in quotation marks (" ").

The OWL description of the IfcWall_36 in VPL is shown below as an example of an instance:

```
<IfcWall rdf:ID="IfcWall_36">
  <hasName rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Wall 36</hasName>
  <IfcRelAssociatesClassification rdf:resource="#IfcClassificationReference_35"/>
  <IfcRelAssociatesClassification>
    <IfcClassificationReference rdf:ID="IfcClassificationReference_38">
      <hasIdentifier>
        <Identifier rdf:ID="Identifier_39">
          <hasID rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
          >urn:epc:3:007:996</hasID>
          <isIdentifierOf rdf:resource="#IfcClassificationReference_38"/>
        </Identifier>
      </hasIdentifier>
      <IfcRelAssignsToProduct rdf:resource="#IfcWall_36"/>
    </IfcClassificationReference>
  </IfcRelAssociatesClassification>
</IfcWall>
```

3.7.1 Demonstration of Ontology Usage

A "quick and dirty" method for evaluating the ontology is to populate an ICT system based on the ontology with some instances and run queries to answer the competency questions listed in Section 3.1.1 of this appendix. In Protégé it can be done either with the query tool illustrated in Figure 5 or by executing SPARQL Queries (Prud'hommeaux et al., 2008). The query tool was primarily used in this project and a set of queries was defined to answer the competency question:

"Which working tasks are related to component XX and performed by person YY?" The queries described in Table 2 were defined to answer the question.

Table 2 Queries to answer the competency question: "Which working tasks are related to component urn:epc:1:304:7682 and performed by Peter?"

Query name	Class	Slot	Expression	Value/Query	Returns
Find Identifier	Identifier	hasID	contains	**"urn:epc:1:304:7682"**	Identifier_45
Find IfcClas.Ref. for Identifier	IfcClas.Ref.	hasIdentifier	contains	Find Identifier	IfcClas.Ref._13
Find Product	IfcProduct	IfcRelAssociatesClassification	contains	Find IfcClas.Ref. for Identifier	IfcDoor_12
Find Person	Foaf:Person	firstName	contains	**"Peter"**	Person_18
Find IfcClas.Ref. assigned to Product	IfcClas.Ref.	IfcRelAssignsToProduct	contains	Find Product	IfcClas.Ref._13 and IfcClas.Ref._14
Find Identifier of WorkPackage	Identifier	isIdentifierOf	contains	Find IfcClas. Ref. assigned to Product	Identifier_45 and Identifier_12
Find WorkPackage for Component and Person	WorkPackageExecution WorkPackageExecution	hasIdentifier hasParticipant	contains contains	Find Identifier of WorkPackage Find Person	**WorkPackageExecution_17**

A SPARQL expression equivalent to the first query in Table 2 can be written as:

```
PREFIX model: <http://www.ramboll.com/VPL.owl#>
SELECT ?Indentifier
From <http://www.ramboll.com/VPL.owl>
WHERE { ?Indentifier model:hasID  "urn:epc:1:304:768"}
```

The execution of the queries is illustrated in Figure 4.

Another possible usage of the VPL ontology is implementation in description logic based expert systems. This is supported in Protégé by means of the Semantic Web Rule Language (SWRL) or e.g. by translating the VPL ontology into Prolog, see Samuel et al. (2007).

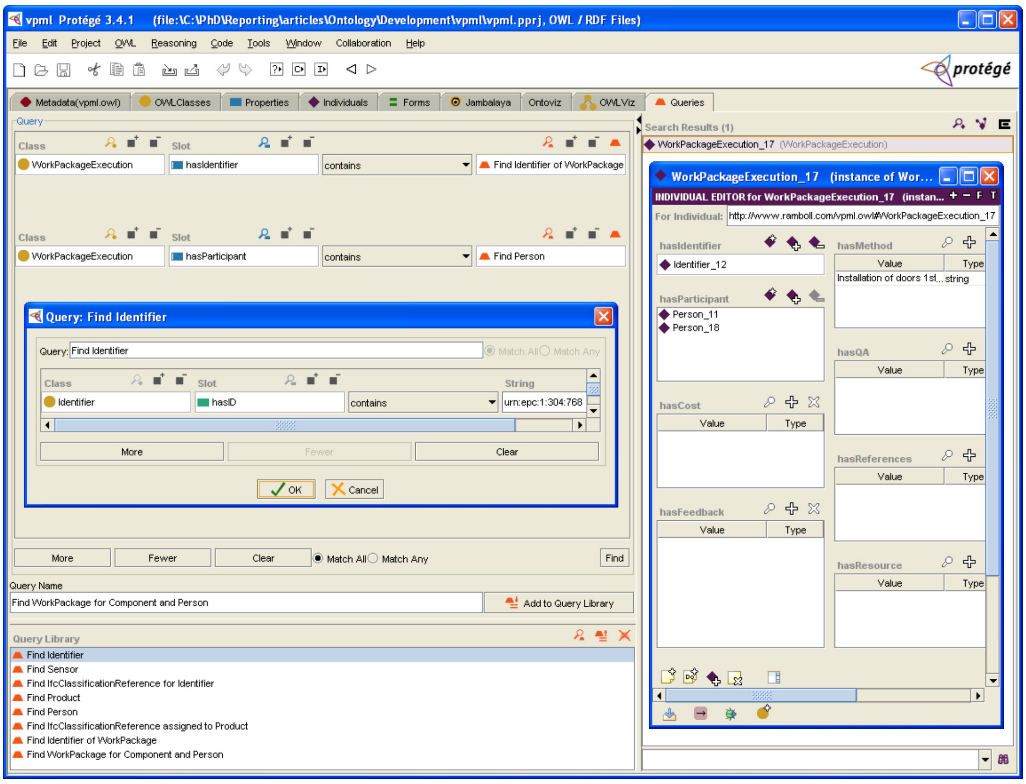


Figure 5 Illustration of queries in Protégé to answer the competency question: ”Which working tasks are related to component urn:epc:1:304:7682 and performed by Peter?”

4 Conclusion

ICT systems to support the scenarios described in Paper I and Paper II can be developed as proprietary solutions where the data capture services extract values from the virtual models on basis of the software providers APIs. This approach may lead to situations were users become locked to software providers or reuse of information across tools, and disciplines becomes infeasible. Methods, tools and recommendations on an ontology based approach to overcome these challenges were demonstrated in this paper. However, a significant amount of work is still required before a full-fledged Virtual Physical Markup Language ontology is developed and implemented in the construction industry.

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Appendix D

Other Publications

Other Publications

Abstract: *This appendix present a list of publications not included in this thesis, but to which the author has contributed during the Industrial PhD study. In addition lists of selected oral presentations and press coverage are given as well.*

1 Other Scientific Publications

Christiansson, P., Svidt, K., Sørensen, K.B. (2008). Future Intragrated Design Environments, Proceedings of CIB W78 25th International Conference on Information Technology : Improving the Management of Construction Projects Through IT Adoption. Universidad de Talca, Chile, 2008. pp. 176-188.

Christiansson, P. and Sørensen, K.B. (2007). Research project application. User involvement in the construction process. Programme for user driven innovation, Danish Agency and Construction Authority (Funding granted).

Christiansson, P., Sørensen, K.B, Rødtness, M., Abrahamsen, M., Riemnann, L. O., Alsdorf, M. (2008a). User Driven Innovation in the Building Process, Tsinghua Science & Technology, 2008-11-13, Qinghua Daxue Xuebao Bianjibu, 6 pp.

Christiansson, P., Sørensen, K.B, Rødtness, M., Abrahamsen, M., Riemnann, L. O., Alsdorf, M. (2008b). User Driven Innovation in the Building Process, Proceedings and Abstracts of the 12th International Conference on Computing in Civil and Building Engineering & 2008 International Conference of IT in Construction, Beijing, pp. 248-254.

Christiansson, P., Sørensen, K.B., Steffensen, K. G., Svidt, K. (2009). User driven innovative building design, Accepted for publication in proceedings of CIB W78 26th International Conference on Information Technology, Istanbul.

Jørgensen, K. A., Skauge, J., Christiansson, P., Svidt, K., Sørensen, K.B., Mitchell, J. (2008). Use of IFC Model Servers - Modelling Collaboration Possibilities in Practice, Aalborg University. Department of Production, 60 pp.

Gottlieb, S., Hundebøl, J., Jensen, J. S., Larsen, C. S., Sørensen, K.B. (2008). Shape shifting : The story of a 3D model in construction, Proceedings of the 5th Nordic Conference on Construction Economics and Organisation, Reykjavik.

Sørensen, K. B., Christiansson, P. Svidt, K., Jacobsen, K., Simoni, T. (2008a). Towards Linking Virtual Models with Physical Objects in Construction using RFID : Review of Ontologies, Proceedings of CIB W78 25th International Conference on Information Technology : Improving the Management of Construction Projects Through IT Adoption. Universidad de Talca, Chile, pp. 418-428

Sørensen, K.B., Christiansson, P. Svidt, K., Jacobsen, K., Simoni, T. (2008b). Radio Frequency Identification in Construction Operation and Maintenance : Contextual Analysis of User Needs, Proceedings and Abstracts of the 12th International Conference on Computing in Civil and Building Engineering & 2008 International Conference on Information Technology in Construction, Beijing, 6 pp.

2 Conference Presentations

September 2009. RFID anvendt på Tinglysningsretten i Hobro (English translation: RFID used at the Registration Court in Hobro), at the bips Conference, Nyborg Strand, Danmark.

September 2008. Digital byggestyring med 3D, 4D og RFID (English translation: Digital construction management with 3D, 4D and RFID), at the bips Conference, Nyborg Strand, Danmark.

October 2008. Radio Frequency Identification in Construction Operation and Maintenance : Contextual Analysis of User Needs, at the 12th International Conference on Computing in Civil and Building Engineering & 2008 International Conference on Information Technology in Construction, Beijing.

July 2008. Towards Linking Virtual Models with Physical Objects in Construction using RFID : Review of Ontologies, at the CIB W78 25th International Conference on Information Technology : Improving the Management of Construction Projects Through IT Adoption, Chile.

January 2007. It i byggeriet (English translation: IT in construction) at Day of Research, Aalborg University, Department of Civil Engineering

3 Other Selected Presentations and Teaching Activities

June 2009. PhD project presentation at BIM+Lean construction workshop, Tekla Finland.

April 2009. PhD project presentation at work shop about the Industrial PhD programme at Aalborg University, the Danish Ministry of Science, Technolgoy and Innovation.

March 2009. PhD project presentation at SBI's consulting forum, the Danish Building Research Institute (SBi).

January 2009. PhD project presentation at Stanford University, Center for Integrated Facility Engineering.

February 2008. PhD project presentation at seminar for future PhD students, Aalborg Univeristy.

January 2008. Virtual Collaboration in Construction, presentation at SmartHouseDK workshop.

November 2007. PhD project presentation at Univeristy of Toronto, the Centre for Information Systems in Infrastructure & Construction.

November 2007. PhD project presentation at University of British Columbia, Department of Civil Engineering.

May 2008. PhD project presentation at internal seminar for chief consultants, Ramboll Denmark.

August 2007. Lecture at AAU continued education, Aalborg University.

May 2007. PhD project presentation, Forum for RFID in construction, Danish Standard.

April 2007. Lecture for teachers and students about ICT in construction, University College, Vitus Bering Denmark.

December 2006. PhD project presentation at seminar about digital construction in practice, Ramboll Aalborg.

2006-2009. Lectures about ICT in construction and Virtual Models Linked with Physical Components in Construction at 4th and 7th semester at Aalborg University, Department of Civil Engineering.

2006-2009. Several project presentations at Ramboll's costumers such as local as well as international contractors.

4 Press Coverage

2009-07. Investering i fremtiden (English translation: Investment in the future), magazine article and web-site case story, AAU Matchmaking, 2 pp., author: AAU.

2009-05-04. Unge forskere står i kø til iværksætter-kurser (English translation: Young researchers queue for entrepreneurship course), Press release AAU, 2 pp., author: Carsten Nielsen, Aalborg Univsersity.

2009-04-03. Stanford har styrket troen på det digitale byggeri (English translation: Stanford has strengthen the believe in digital construction), newspaper article, Ingeniøren, Byggeri, p. 6., author: Tommy Brandi Krog.

2009-04-01. For folk med drive er en ErhversPhD en god måde at få afprøvet sine kompetancer indenfor både forskning og forretning (English translation: For people with drive an Industrial PhD is a good way to test your competences within both academia and business), article in union member magazine, Landinspektøren, pp. 43-44., author: Jesper Bernsdtorf.

2009-03-31. Dansk Byggeri skal bruge krisen til optimering (English translation: The Danish Construciton should use the crisis for optimization), newspaper article, Teknik Og Viden, 2 pp., author: Christina Terry, Outcom.

2009-03-26. Byggeri i den virtuelle verden (English translation: Buildings in the virtual world), marketing campaign, the Danish Ministry of Science, Technolgoy and Innovation (VTU), 2 pp., Author: VTU.

2009-03-02. Begrænset succes for ErhversPhD'er i Nordjylland (English translation: Limited success of the Industrial PhD programme in Northern Jutland), item on the radio news, DR-P4 Nordjyllands radio, presenter: Christina Ankerhus.

2008-10. BIM på byggepladsen i Hobro, (English translation: BIM at the construction site in Hobro), magazine article, bips nyt 3, 1 pp., author:bips.

2008-09-19. Rambøll afprøver RFID-chip på byggepladsen (English translation: Rambøll tests RFID tags at a construction site), newspaper article, Ingeniøren, Byggeri, 1 p., author: Tommy Brandi Krog.