

# Modelling and Simulation of Cast in Place Concrete Constructions Using N-Dimensions

*SBUF Project 11333 ITstomme - Final Report*

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**TECHNICAL REPORT**

**MODELLING AND SIMULATION OF CAST  
IN PLACE CONCRETE CONSTRUCTION  
USING N-DIMENSIONS**

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**Luleå 2005**

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## Preface

This report is the result of a research and development project on modelling and simulation of construction with cast in place concrete by using product modelling technology. The project is called ITstomme and was conducted in a two-year period from the end of June 2003 to July 2005. The ITstomme project was driven as a project within the eBygg centre for information technology in construction at Luleå University of Technology.

Product modelling poses challenges to cast in place concrete construction, but offers at the same time a number of opportunities. Within the ITstomme project a number of dimensions of product models are presented. These dimensions illustrate on the one hand the support for new and existing products and processes for cast in place concrete construction and on the other hand show the potential of product models beyond their common, but limited, use for 3D graphics.

Product models are now starting to be adapted in projects by JM and Betongindustri, which are two of the main participants in the ITstomme project. We hope that the developments and pilot implementation efforts from the ITstomme project can add to the value of product models in the business processes of both companies. In addition, we hope that the work in the ITstomme project forms a source of inspiration and a call for action for other actors in the construction industry.

During our work we had the opportunity to cooperate with many different, experienced and enthusiastic persons from Sweden and other countries. We thank these persons for their support and especially value the implementation efforts by the software developers at Enterprixe, Ceco and Concode-Intercopy.

Part of the research work has been performed by Rogier Jongeling while visiting the Center for Integrated Facility Engineering (CIFE) at Stanford University between March and July 2004. Professor Martin Fischer, Claudio Mourgues and Jonghoon Kim of CIFE are acknowledged for their time and input in this project.

We would like to express our gratitude to Svenska Byggbranschens Utvecklingsfond (SBUF) for funding this research and development project. We also thank the participating project members, Betongindustri, JM, Ceco, Enterprixe and the eBygg centre at Luleå University of Technology, for their contributions to the project.

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## **Abstract**

Product models have long been theoretical models within international research communities, but are now starting to be adapted in the construction industry. Product models are data models that can contain both product and process data, such as geometry and planning data. Their current use in construction is mainly limited to 3D graphics, but product models have many more than three dimensions. In this research project we developed and applied different dimensions of product models beyond their common, but limited, use in 3D. Development and implementation efforts in the project are mainly driven by the interests from a ready-mixed concrete supplier.

Product modelling systems imply an object oriented approach to cast in place concrete construction, which is not object oriented as a result of the nature of the product. Product models that are used in the design process differ from models that are used for production simulations. These, and other conditions, pose a number of challenges. However, product models offer also a number of opportunities to cast in place concrete construction. Products and processes can be simulated virtually for example, thereby facilitating the decision-making process regarding the application of new or existing technologies that can improve the construction process. Product models can also be used to link or integrate product data, such as material specifications, casting sequences, etc.

Based on these, mainly theoretically identified, possibilities and constraints, a number of dimensions of product models are developed and applied in practice to different case study projects.

The following model dimensions are explored in the project:

- Traditional 2D drawings and documents are partly generated from 3D models and hyperlinked to these models.
- Various types of 3D models from different disciplines are created by using file-based data transfers and a collaborative client-server environment.
- Multiple production plannings are linked to 3D models resulting in 4D models.
- 5D cost estimation is developed by linking different 3D models to cost estimation hierarchies.
- Model use and configuration of material parameters by a ready-mixed concrete supplier provides an additional dimension to the use of product models.

The different dimensions illustrate on the one hand the support for new and existing products and processes for cast in place concrete construction and show on the other hand the potential of product model use beyond 3D graphics. Advantages and possibilities can be identified for the ready-mixed concrete supplier in the different model dimensions and we believe that other actors in construction can do the same. When actors have identified benefits of product modelling for their own business process they might be more willing to participate in shared product model use in search of benefits for the project team as a whole.

**Keywords:** product model, cast in place concrete, design, construction simulation

## Abbreviations

ABC	Activity-Based Costing
ADT	Architectural DeskTop
AEC	Architecture Engineering Construction
BIM	Building Information Model
BoM	Bill of Materials
BSAB	Byggandets Samordning AB. Classification System used in the Swedish Construction
CAD	Computer Aided Design
CIFE	Center for Integrated Facility Engineering
CNC	Computer Numerical Control
CPM	Critical Path Method
EPX	Enterprixe
HVAC	Heating Ventilation Air-Conditioning
IAI	International Alliance for Interoperability
IFC	Industry Foundation Classes



IT	Information Technology
KPI	Key Performance Indicators
LCI	Lean Construction Institute
LoB	Line-of-Balance
PE	Project Explorer
PIO	Project Information Officer
SBUF	Svenska Byggbranschens UtvecklingsFond
SCC	Self-Compacting Concrete
SCM	Supply Chain Management
UDA	User-Defined Attribute
VBE	Virtual Building Environment
VIPP	Visualisering i Projektering och Produktion (SBUF project no 11693)
VRML	Virtual Reality Mark up Language
XML	eXtensible Mark up Language

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# 1 INTRODUCTION

## 1.1 Background

The cast in place concrete industry is increasingly interested in applying new processes and products to deliver value for its clients and to remain competitive compared to other construction methods and other types of materials. Thus, it is strived for the development of a more industrialized construction process using cast in place concrete. Efforts are made to improve the construction process on the one hand and the construction products on the other hand. These efforts are necessary to create conditions by which projects can be delivered on time, within budget and according to the requirements of the client.

The technical research and development that is aimed at establishing these conditions for the cast in place concrete industry can be grouped into five areas:

- Improved concrete qualities that are customized for specific and optimal use. For example, Self-Compacting Concrete (SCC) reduces work on site and adds to the quality of the structure. Concrete with reduced drying time can shorten the total construction time significantly.
- Minimized reinforcement activities utilizing fibre reinforced concrete and prefabricated reinforcement reduce on-site operations and increase the production rate of the work.
- Permanent formwork minimizes site logistics. Form elements are prefabricated in a factory under controlled conditions and erected on site.

- Weather independent construction processes, e.g. by building a structure inside a climate protective tent.
- Information Technology (IT) where different types of systems enable the regeneration, flow and access of information in and between different processes in the value chain of cast in place concrete construction.

These topics are not totally isolated from each other, but are interrelated areas and the benefits of the different technologies can be enhanced by applying them in different combinations. A practical prerequisite for the application of these technologies is that they can be applied in combination with other, existing, building systems and building processes that are part of the total construction process. As an example the application of permanent formwork systems can be given. Prefabricated permanent formwork elements for walls can contain openings for windows and doors or have these elements integrated in a factory. This requires coordination of different design disciplines, such as architects and structural engineers. It also requires detailed planning of logistics and erection on site due to the fact that prefabricated elements can demand a certain order of installation. From this example it becomes clear that the application of new technology demands a multi-disciplinary approach to design, planning and construction. However, the technical and organisational infrastructure for such a multi-disciplinary approach is currently not available or a common practice in construction projects.

A potential technology that can be part of this technical infrastructure is product modelling technology, which is discussed in Chapters 2 and 3. Product models are data models that can contain both product and process data, such as geometry, planning data, material specifications, etc. Product models for construction are nothing new and have been an area of research for many years. Much of the inspiration and experience for the application of product models comes from the manufacturing industry, which is far ahead of the construction industry in applying model-based design and production processes. Products and processes literally changed in the manufacturing industry partly as a result of the application product modelling (Olofsson 2004).

The construction industry has not come very far with the application of product models, with the exception of a few visionary and pioneering companies. Current application of product modelling in construction is often synonym to 3D modelling and 3D graphics, used in early stages of projects. There are

many reasons and explanations that can be given why the construction industry is still relying on a non-model-based information flow, e.g. 2D drawings. Many researchers state that the industry is fragmented and conservative. Professionals in the industry often agree with these statements, but note that research regarding product modelling has been too technical. These practitioners also experience that the application requires too many changes in today's processes, too much expertise to work with in practice, and without any clear and obvious advantages beyond the use of 3D graphics. These conditions result in prerequisites and challenges for the use of product models in construction, which are discussed in Chapter 10 'Challenges for Product Modelling in Practice'.

The challenges, but also the potential, for the use of product modelling for cast in place concrete are discussed in Chapter 4. This section is followed by a number of practical uses of product models for cast in place concrete structures according to the different dimensions of product models. These applications illustrate that product models can be applied in today's processes with minimal changes by using commercial and prototype software packages. The applications also illustrate the use of product models for cast in place concrete construction beyond 3D modelling and 3D graphics.

The application of product models to cast in place concrete construction is explored in a prestudy at Luleå University of Technology in which the current value chain from a contractor and concrete supplier are analyzed (Jongeling 2003). The main actors in the project are Betongindustri, a ready-mixed concrete supplier, and JM which is a residential project developer. In the prestudy it is shown that product modelling has the potential to improve the business process as well as the information management and cooperation in projects between Betongindustri and JM, by using product models beyond 3D graphics. As a result, both companies joined this project to study the application of product models with a broader scope and with application in real and virtual construction projects. Starting point for the application of product models is to support existing and new construction products and processes that contribute to the use of cast in place concrete and that suit the operations by contractors and material suppliers, such as JM and Betongindustri.



## **1.2 Objective**

The objective of this study is to support existing and new products and processes for cast in place concrete construction by developing and applying product modelling technology beyond 3D graphics.

The aim is to establish and analyze different model dimensions by the development and application of modelling tools to residential construction projects. This study does not address the structural design of concrete structures with product modelling systems, but focuses on the use of product models throughout a building process from the perspective of a contractor and a ready-mixed concrete supplier.

## **1.3 Method**

### **1.3.1 Model dimensions**

The implementation of the project is performed according to the nD modelling framework (Lee 2005) in which different dimensions of a product model are identified. This report is structured according to these model dimensions. The dimensions include:

- 2D drawings and documents in combination with 3D modelling
- 3D models of different design disciplines
- 4D modelling and simulation of alternative construction methods
- Cost estimation hierarchies are mapped to 3D models, providing a 5<sup>th</sup> dimension
- An example is given of a possible n<sup>th</sup> dimension of a product model by integrating input from a concrete supplier into 3D models.

### **1.3.2 Project phases – as planned**

When initiating the study in 2003 the plan was to approach the project in five phases:

1. A prestudy and overview of product modelling tools for cast in place concrete
2. Pilot study in which existing tools are applied to the construction project Hotellviken Marinan by JM

3. Evaluation and development work that form the basis for the next phase in which new tools are applied
4. Application of modelling tools in full scale in the next phase of the Hotellviken project by JM, called Ringvägen
5. Evaluation and reporting

### **1.3.3 Project phases – as implemented**

A number of factors resulted in a slightly different implementation of project phase two and four:

- The pilot study project Hotellviken Marinan was delayed due to a long process to obtain a building permit. Therefore a virtual project, with a similar type of construction as Hotellviken Marinan, was used as a test object in phase two of the project. This project was used as a basis for the development and application of 4D modelling tools while the building permit for Hotellviken Marinan was pending.
- When JM received the building permit in 2004 it was decided to treat Hotellviken Marinan as the full scale project in phase four of this project and to include the next phase of the project, Hotellviken Ringvägen, in the SBUF project no. 11693, called VIPP (Visualisering i Projektering och Produktion. SBUF project no. 11693).
- During the prestudy it became clear that the application of modelling tools connected to a model server by all consultants in full scale was not yet feasible, due to technical and organisational reasons. Parts of the 3D modelling work for Hotellviken Marinan were performed instead with stand alone tools by consultants and other parts of the modelling work were performed in a client-server environment by the project team of this project.
- The prestudy showed that there was a need to develop and use a model viewer in addition to the use of CAD systems to access and manipulate model data. Users at JM and Betongindustri are not used to CAD environments and model access by a light and user-friendly model viewer is preferred. The development of the model viewer required considerable effort and resources, and has delayed the actual application of the viewers in practice. However, model viewers have started to be adapted in both organisations and are now part of newly initiated research and development projects funded by the SBUF (LKAB MK3 project no. 11636 and VIPP project no. 11693).

- The process of making cost estimates based on product models appeared to be a challenging and time-consuming development process. The development of cost estimation tools, also-called 5D functionality, was successfully implemented in the model viewer. The 5D estimation has not been applied in full scale in the ITstomme project.
- A prototype program, called BiDry, has been developed for the calculation of the drying process of concrete slabs. With the final version of the program it will be possible to interact with product model data, such as material parameters, concrete volumes and thicknesses, etc.

### **1.3.4 To be implemented**

The following activities were originally planned for the ITstomme project, but have not been implemented yet. These activities will be implemented during autumn 2005 and spring 2006:

- 4D modelling and simulation will be performed in full scale by construction planners at JM itself and will be used to communicate and optimize the schedule for the Hotellviken Ringvägen project.
- 5D estimation will be evaluated in a future project by JM in full scale.
- A study will be made at JM and Betongindustri of the direct and indirect benefits and costs of model-based construction processes.
- The BiDry program for calculation of the drying process in concrete slabs will be developed as a stand-alone program, with the possibility to interact with product model data.

## **1.4 Organisation**

A publicly available project website has been established, which contains a short description of the project. The website can be found at: <http://construction.project.ltu.se/~ebygg>. A project intranet site has been established in addition to the public website for document management and project planning.

The issues addressed in the project are rather diverse and many of the implementing actors come from different organizations with varying backgrounds. The project is therefore decomposed in several project components. Every project component addresses a specific and manageable

topic of the overall project framework in each phase of the project. This led to the development of a project matrix to define and manage the various parts of the project. A schematic overview of this matrix is included in Appendix A.

## **1.5 Partners**

The main project participants are:

- Betongindustri (Curt Arne Carlsson, Mats Emborg, Thorbjörn Dorbell)
- JM (Martin Asp, Niclas Engdahl)
- Luleå University of Technology (Rogier Jongeling, Thomas Olofsson, Jan-Erik Johansson)
- Ceco (Daniel Thall, Anders Pettersson)
- Enterprixe (Jan-Olof Edgar, Pekka Karjalainen, Tapio Ristimäki)

During the research project Rogier Jongeling visited the Center for Integrated Facility Engineering (CIFE) at Stanford University (March 2004 – July 2004) where case study projects from this research project were used to perform studies of 4D modelling and 4D analyses. This research was performed together with Professor Martin Fischer and two of his PhD students; Claudio Mourgues and Jonghoon Kim.

## 1.6 Finances

The project was financed by the SBUF and Betongindustri. All the project participants contributed to this project with their own time. An overview of the funding and own contribution for this project is included in the table below.

Table 1: Funding and contribution for the ITstomme project (KSEK).

<i>Participants</i>	<i>Own contribution</i>	<i>Funding</i>
JM	200	
eBygg-LTU	150	
Betongindustri	250	260
Enterprixe-DDD Sweden	70	
Enterprixe Finland	70	
Heidelberg Zement Group	100	
SBUF		1040
<b>Total</b>	<b>840</b>	<b>1300</b>

## 1.7 This report

The definition and interpretation of product modelling are first discussed in this report. Secondly, the product modelling system used in this study is presented after which concrete supplier's motivation to study product modelling is discussed. Thirdly, different model dimensions of product modelling are presented, illustrated by examples from case study projects. For every model dimension a short abstract and introduction is given, followed by a more detailed description of the results and analyses of the application and development work. The chapters about model dimensions are followed by a discussion of the main challenges for the use of product models in construction. Finally, recommendations are given for further work with product modelling for cast in place concrete construction.

## 1.8 Project publications

This project has led to a number of publications that are part of the PhD work by Rogier Jongeling at Luleå University of Technology. The publications provide detailed descriptions of the research and development work performed for different parts of the project. This report summarizes and combines this work and for further reading about specific topics we recommend reading the publications (i.e. they can be denoted as project deliverables):

Jongeling, R., Olofsson, T., and Emborg, M. (2004) 'Product modelling for industrialized cast-in-place concrete structures.' In P. Brandon, Li, H., Shaffii, N., Shen, Q. (eds) *INCITE 2004 - International Conference on Information Technology in Design and Construction*, Langkawi, Malaysia, 103-110.

Jongeling, R., Olofsson, T., and Emborg, M. (2004) 'Modelling cast in place concrete construction alternatives with 4D CAD.' In A. Dikbas, Scherer, R. (eds) *ECPPM 2004 - eWork and eBusiness in Architecture, Engineering and Construction*, Istanbul, Turkey, 109-116.

Jongeling, R. (2004). 'IT-stomme - produktmodeller i stombyggnadsprocesser.' *Betong - Svenska Betongföreningens Tidskrift*, 4, 40-42

Jongeling R, Emborg M and Olofsson T (2005) 'nD modelling in the development of cast in place concrete structures', *ITcon Vol. 10, Special Issue From 3D to nD modelling*, 27-41, <http://www.itcon.org/2005/4>

Jongeling, R., Kim, J., Mourgues, C., Fischer, M., Olofsson T. (2005) 'Quantitative Analyses Using 4D Models – An Explorative Study', In Park (eds) *ICCEM 2005 - International Conference on Construction Engineering and Management*, Seoul, Korea, 830-835.

Jongeling, R., Kim, J., Mourgues, C., Fischer, M., Olofsson T. (2005) 'Analyses of Extracted 4D Model Contents', To be submitted to the *Journal of Automation in Construction*.

The following publications are the result of research that has been conducted in conjunction with this project:

Blokpoel, S. (2003). 'Cooperation and Product Modelling Systems - The Application of Product Modelling Systems in the Building Process.' 2003:17, Luleå University of Technology, Luleå, Sweden, pp. 126.

Blokpoel, S., Olofsson, T., and Jongeling, R. (2004) 'Cooperation and product modelling systems' In A. Dikbas, Scherer, R. (eds) *ECPPM 2004 - eWork and eBusiness in Architecture, Engineering and Construction*, Istanbul, Turkey, 423-429.

Carlsson, A., Helgesson, L. (2005). 'Modellering och representation av konstruktionsmoment med 4D-CAD relaterade till platsgjuten betong,' Diploma Work, Luleå University of Technology, Luleå, Sweden, pp. 124.

## 2 PRODUCT MODELLING

The development and use of computer-based models for the AEC (Architecture, Engineering and Construction) industry has been discussed within international research and development communities for some time (Eastman 1992; Fischer 2004; Gielingh 1989; Laitinen 1998). Different terms and concepts are used in discussions to denote these models and modelling systems. Recently, the concepts of a Building Information Model (BIM), nD modelling and Virtual Building Environment (VBE) have been added to the terminology describing information models for the AEC industry.

BIM was launched by major vendors of CAD applications such as Autodesk, Graphisoft, Bentley and Nemetschek. A BIM is a computer model database of building design information, which may also contain information about the building's construction, management, operations and maintenance (Graphisoft 2002). Research and development regarding nD modelling is currently mainly conducted at the University of Salford within the 3D to nD modelling research project (Lee 2004; Lee 2005). A nD model is an extension of the BIM, which incorporates multi-aspects of design information required at each stage of the lifecycle of a building facility (Lee 2003). A VBE is a 'place' where building industry project staffs can get help in creating BIMs and in the use of virtual buildings (Bazjanac 2004). A virtual building is a BIM, or an nD model, deployed in software. A VBE consists of a group of industry software that is operated by industry experts who are also experts in the use of that software (Bazjanac 2004).



Throughout this report we use the following terminology:

- A *product model* refers to data models that contain both product and process data supporting a building's life cycle. Examples of such data are geometry, planning and cost data. According to this definition we define BIMs and nD models as product models.
- *Product modelling systems* are used to access, manipulate and store information from exchange files and databases. Examples of such systems are CAD applications, but also project planning software and product model servers.
- We define the collection of product modelling systems used in a project, including the professionals that operate the systems, as the *product modelling environment*. We define VBEs as product modelling environments.

Although definitions of product models and nomenclature vary within the research and development communities, most actors agree that the main advantage of product models lies in tasks beyond 3D modelling and generation of drawings for a building (Fischer 2004). It is in this spirit that we explored different dimensions of product models applied to cast in place concrete construction beyond 3D modelling and 3D graphics. For this purpose we applied a client-server modelling system to two case study projects. Before we describe the motivation of the cast in place concrete industry to adapt product modelling, we discuss the product modelling environment that is used in the case studies of the ITstomme project.

### **3 PRODUCT MODELLING ENVIRONMENT**

Within the ITstomme project the product modelling work is performed with an Internet-based product modelling system developed by Enterprixe Software Limited (Enterprixe 2002). The system (i.e. the Model Server) uses a central database in which the product model is stored. Additional databases containing for example cost data or documents can be linked to the database, Figure 1.

When logged in, a project can be selected from the product model server and specific client software to view and edit the product model. AutoCAD-based software and a model viewer embedded in an Internet browser are used as software clients to the product model server in the ITstomme project. Many actors are already familiar with AutoCAD in Sweden and the transition to a model-based practice using AutoCAD can possibly facilitate this process.

The model viewer is used for navigation in 3D and for modelling of 4D models and 5D cost estimation. The model viewer is using VRML-graphics and was specially developed within the ITstomme project by Ceco AB (Ceco 2005). With this model viewer users can access product model data without having AutoCAD installed on their computer.

Exchange file import and export is used in addition to direct client-server connection to extend the product modelling environment. For example, IFC files are imported from ArchiCAD to AutoCAD Architectural Desktop (ADT), which in its turn is a client to the product model server. Industry Foundation Classes (IFC) is a product model data standard developed by the International Alliance for Interoperability (IAI) (IAI 2005). IFC objects are uploaded from ADT to the central database, where they become available for all project participants.

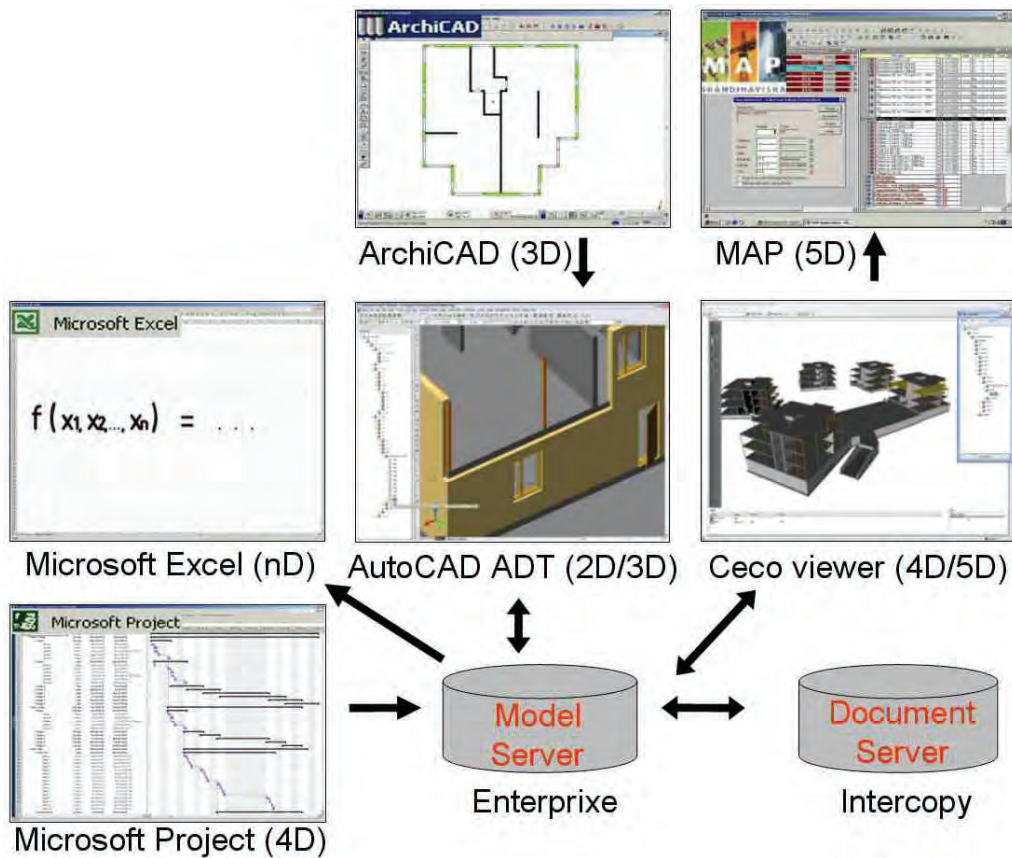


Figure 1: The product modelling environment of the ITstomme project. The model server and document server are two different systems, but have been integrated in the ITstomme project and act as one system. Different software systems can be used to create, edit and use product model data. Examples of these systems are AutoCAD, Microsoft Excel, Microsoft Project and Ceco viewer.

The product model is loaded from the product model server to local computers and constantly updated when connected to the server. The product model of one of the case study projects contains approximately 3000 objects, which is a workable amount of data to work with over the Internet. It is possible to load or unload parts of the product model and in this way it is not necessary to have all model data loaded to the local computer.

The product model server keeps track of users who create an element or who edit one. Figure 2 illustrates the partial model check out and check in functionality. Product model objects that are checked in appear as normal elements. Elements that are checked out by the current user carry a check-mark (☑). Checked out elements are locked for editing by other users. Elements checked out by other users, cross-marked (☒), are locked and cannot be edited.

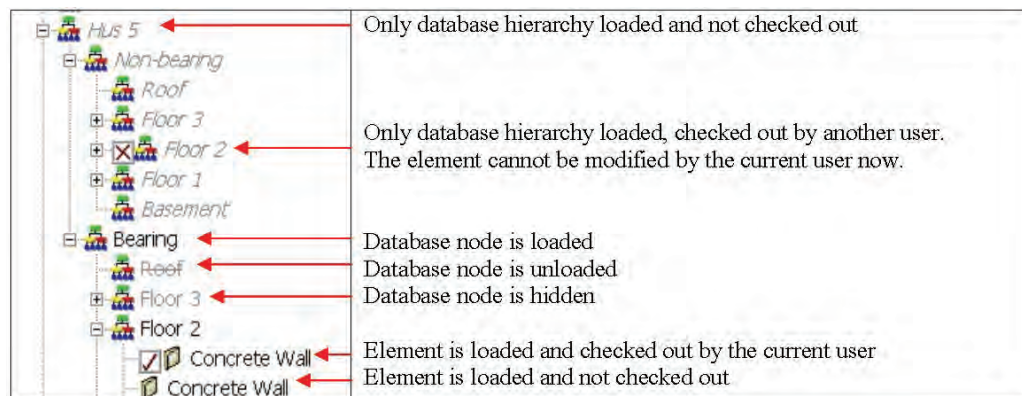


Figure 2: A tree view of the product model at the product model server. Partial product model check in and check out functionality is used to reduce the risk for double work and product model inconsistency.

Part of the modelling work is concurrently carried out by multiple distributed users within the ITstomme project. Project participants consider the partial product model check in and check out one the hand a valuable product model server functionality that reduces the risk for double work and product model inconsistency, but consider it on the other hand constraining to be forced to work online when editing product model data. On building sites or in project meetings for example there is often not enough time or no connection available to connect to the model server and then download specific parts of the project. This is further constrained by system restrictions, such as firewalls.

One of the case study projects includes about 50000 objects and when all loaded the performance of the system slows down considerably. The system performance becomes insufficient to work with. These performance and usability problems can partly be solved by improving the computing performance and partly be developing an offline mode for the system.

The offline mode will allow users to work on the product model without being connected to the model server. After their work the users can synchronize their

work with the central model at the model server. The offline mode functionality is expected during the autumn of 2005 and is expected to facilitate the work considerably.

## 4 CAST IN PLACE CONCRETE

There is an increasing interest of the ready mixed concrete suppliers in Sweden in product modelling technology. The interest is the result of the identification of the potential of product modelling technology for cast in place concrete. As an example in this respect the process of virtual prototyping can be given of innovative construction products and processes that are aimed at industrializing cast in place concrete construction (Jongeling 2004a). The interest is also partly the result of developments that are ongoing at competing building materials and building systems, such as steel and prefabricated concrete.

The steel and prefabricated concrete industries have already started to use a model-based construction approach. The main product modelling system developments and standardization efforts to date have focused on these sectors. This focus can partly be explained by the nature of the building technology. Steel and prefabricated concrete are strongly component oriented in both design and production as opposed to the design and production process of cast in place concrete structures. Product modelling systems imply an object oriented approach and are therefore well-suited for object oriented building systems, such as the ones based on steel and prefabricated concrete components.

One of the strengths of cast in place concrete is customisation of shapes and material properties. Basically any shape can be created by forming the concrete on site in tailor-made forms. The customisation and freedom of design partly explain the absence of standard product catalogues for cast in place concrete objects. However, the main reason for this absence is the fact that the product is a material and not a building object. Standard product libraries that are available in CAD applications for steel and prefabricated concrete objects do

not exist for the cast in place concrete industry. There is in other words no explicit integration of the design object and supplied product in CAD systems for cast in place concrete.

In addition to difficulties with product specification and design in CAD systems there is no single definition of an object. Design objects differ from production objects of which the latter is often not explicitly modelled. An example of a production object is a concrete pour, i.e. a cast sequence, which can be part of a design object. The design is used as a bounding box for production solutions, as opposed to steel construction where design information is used to direct production by Computer Numerical Control (CNC). Most of today's product models do not contain objects that are suitable for detailed construction simulation and optimisation of cast in place concrete structures.

Cast in place concrete construction is information intensive. Object properties such as concrete quality and Water to Cement ratio are continuously updated depending on changes in production planning and weather conditions. This information is in our experience currently not integrated or associated with production models by concrete suppliers.

#### **4.1 Possibilities and challenges**

We have identified a number of possibilities and challenges for the application of product models for cast in place concrete construction. For every issue we identified a dimension of the product model to which the issue applies. Most of these issues are specific to the cast in place concrete industry, but some have a more general character. However, especially the challenges have to be addressed, specific to cast in place concrete or not, in order to apply and benefit from product modelling technology.

Table 2: Possibilities for the application of product models for cast in place construction

<i>Possibilities</i>	<i>Dimension</i>
- Modelling and review in 3D improves constructability and quality of the structure.	3D
- Product models can be linked and associated with 2D drawings and documents, such as the results of technical calculations. This facilitates the process of document retrieval.	2D + 3D
- Simulation of innovative products and production processes facilitates the application of new technologies in practice.	4D
- (semi-)automated quantity take-off of concrete volumes and material specifications can save time and can reduce errors in quantity take-off.	5D
- Material specifications can be integrated in product models and are as a result a natural part of objects used in design and production.	nD



Table 3: Challenges for the application of product models for cast in place construction

<i>Challenges</i>	<i>Dimension</i>
- The architectural and structural views on modelling are different.	3D + 3D
- There is limited support in CAD applications for modelling of objects related to cast in place concrete construction. This applies to concrete shapes, definition of concrete pours, reinforcement bars, isolation, drainage, etc.	3D
- Design models differ from production models in which the latter is more detailed and includes non-building objects, such as scaffolding, work spaces, etc.	3D + 4D
- Material specifications are often not specified in product models	nD
- There are very few actors that can use CAD which limits the use of product models in practice.	All
- There is currently no role defined for someone who should coordinate the consistency of models from the architect and structural engineer and the models used for cost estimation, planning and production.	All

These possibilities and challenges serve as a starting point for the development and application of different model dimensions for the cast in place concrete industry. Before these developments and applications are discussed, we will introduce the case studies to which product modelling technology is applied in the ITstomme project.

## **5 CASE STUDIES**

The main case study of the ITstomme project is a project by JM called Hotellviken Marinan. In addition, a virtual project is studied that is mainly used for the development and application of 4D simulations and analyses.

### **5.1 Hotellviken Marinan**

The Hotellviken project comprises the construction of 120 apartments of which the first phase, Hotellviken Marinan, is addressed in this report. Phase one consists of five multi-storey apartment blocks (in total 25 apartments) of which two are connected with a parking garage. Figure 3 shows a 3D model of the concrete structure. The bearing structures are cast in place concrete. Facades consist of standardized non-bearing prefabricated plastered elements. Prefabricated lattice girder elements are used for slabs on which cast in place concrete is poured. Traditional formwork is used for the inner walls in which concrete is poured on site. The roof of the connecting garage consists of hollow core slabs.

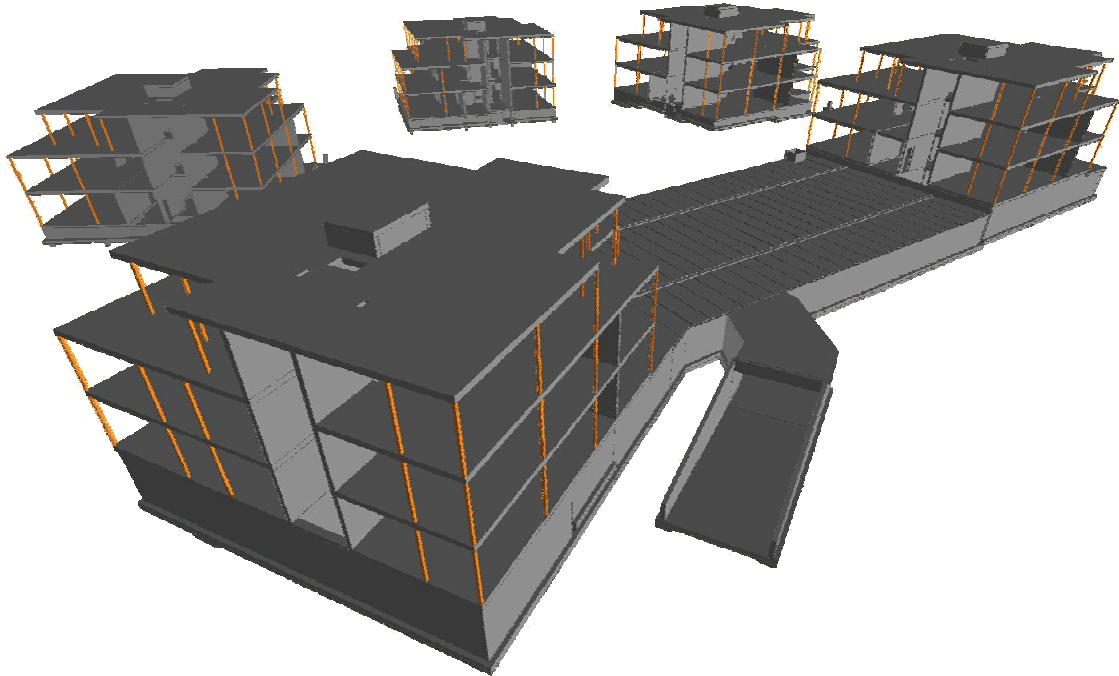


Figure 3: Bearing structure of the Hotellviken Marinan project.

Hotellviken is used to study and develop the following product model applications:

- Traditional 2D drawings and documents are partly generated from 3D models and hyperlinked to these models.
- Various types of 3D models from different disciplines are created by using file-based data transfers and a collaborative client-server environment.
- 3D models are mapped to cost estimation hierarchies providing a 5<sup>th</sup> dimension.
- Model use and configuration by the ready-mixed concrete supplier provides an additional dimension.

## 5.2 4D case study

In an effort to adequately support the introduction and evaluation of construction innovations, Betongindustri initiated a pilot study using 4D CAD simulations to evaluate two construction alternatives of a residential

construction project, Figure 4. The 4D case study is used for the development and application of 4D CAD.

Betongindustri conducted the experiments after the actual construction of the project was finished. The experiments are realistic and, where possible, are based on actual site data, but had no direct impact on the construction process performed by the contractor.

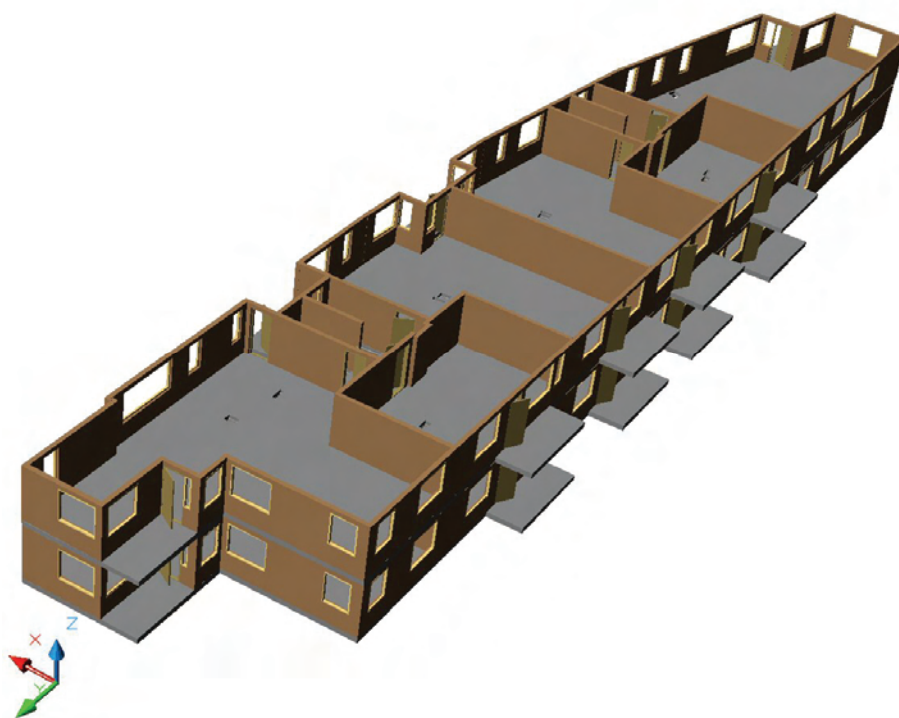


Figure 4: The 3D model that is used in the 4D case study by Betongindustri. The building measures 60 meters in length and is 12 meters wide. All displayed slabs and walls are cast in place concrete components, except for balconies that are prefabricated components.

The method and results of the 4D case study are discussed in Chapter 7. In the next section, Chapter 6, we describe our application and development efforts within this project regarding the second and third dimension of a product model.



## **6 THE SECOND AND THIRD DIMENSION**

### **6.1 Abstract**

The application and developments regarding the second and third dimension of product models for cast in place concrete focus on the use of multiple 3D models that are combined with 2D drawings and documents. This combination allows product models to be created by traditional design disciplines and allows them to be used in conjunction with traditional documents that are used in today's processes. In this way the use of product models is complementary to today's document-based information flow. The main benefits of this approach are the facilitation of design reviews and design coordination in 3D. In addition the 3D models can be used for document retrieval and linkage of information by different stakeholders in the projects.

### **6.2 Introduction**

Researchers (Lee 2004) and software developers (Autodesk 2002; Graphisoft 2002) envision a database constructed with intelligent objects from which different views of the information can be generated automatically; views that correspond to traditional design documents such as plans, sections, elevations, schedules, et cetera. As the documents are derived from the same central database, they are all coordinated and accurate.

We identify a number of issues that currently limit the use of product models to the extent envisioned in the above:

- First of all, generating views from product models is currently partly possible. Product models do not necessarily contain all information that

is required to produce design views. Absence of information is due to unavailability of adequate modelling tools, required effort to add this information to product models and the effort to extract the information. For example, modelling work of certain reinforcement bars is possible in a limited number of CAD systems. Generating views from these systems is constrained by national and local preferences of reinforcement bar detailing in shop drawings.

- Secondly, views of product models differ between actors. For example, a structural engineer models building objects differently from objects modelled by an architect, Figure 5 B-C. Generating specific views from a multi-disciplinary central model that contains all information is constrained by these different views.
- Thirdly, certain information is associated with a model, but not necessarily part of a model. Even in the most optimistic scenario for model-based approaches, the vast majority of current project information exists in the form of unstructured documents (Froese 2004b). At present there is very little linkage between information technologies for working with unstructured document-based technologies and model-based technologies.
- Finally, the number of actors in a construction project that can access and operate software tools to generate database views is mostly limited to actual product modellers. In addition to modellers we see a number of actors that are merely viewers of product models, such as estimators, planners, suppliers, subcontractors, customers, et cetera. These actors do not necessarily have product modelling systems installed and lack the knowledge to generate specific views from a product model.

### **6.3 Results**

The following solutions are applied in the ITstomme project to combine 2D data with multiple product models and to make this data and product models available for all project participants:

- Separate architectural and structural models are created of Hotellviken instead of an all-including single product model. All other design, such as building services design, is done according to a traditional 2D practice. The architectural model is modelled in ArchiCAD and exported as an IFC2x file to AutoCAD ADT. The IFC2x file is uploaded from AutoCAD ADT to the central database where it is

available for all project participants. The structural model is modelled in AutoCAD ADT, used as client-software to the central database.

- Views are generated from 3D models to which 2D geometric primitives are added in paper space. We call this a hybrid design document type. The views are saved at the model server and can automatically be updated with product model data when required. 2D data, such as reinforcement bar detailing, can only manually be updated per view.
- Product model views and other documents are located at a document server and are hyperlinked to the product model. Links are added to specific model objects, but also to parts of an object or to specific sections of a product model. For this purpose different types of pointer objects are used in the models that contain links to the document server. Different pointer objects are available for different disciplines to facilitate information management, Figure 5 A.
- A model viewer is used as client software to view the product model in the central database and to browse through hyperlinked data.



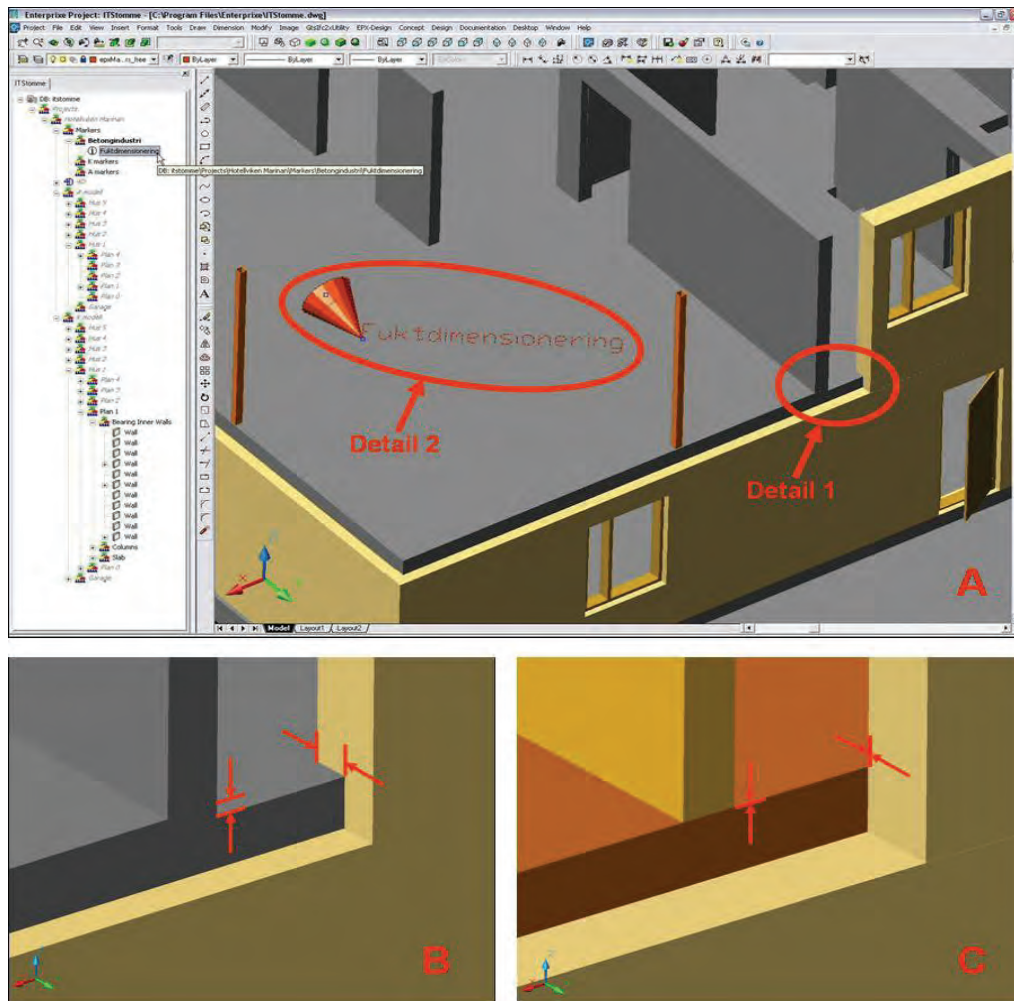


Figure 5: (A) A product model in AutoCAD ADT connected to the Enterprise product model server. Detail 1 illustrates different views on modelling by a structural engineer (B) and an architect (C). The architect models the slab as one volume, whereas the structural engineer models different concrete slabs individually. (A) Detail 2 is an example of pointer object for a concrete slab to which results from technical calculations are linked, which are located at a document server.

## 6.4 Discussion

Working with two separate product models is considered to be beneficial, but also shows limitations. Design coordination and design reviews are facilitated by the use of 3D models. An advantage of a separate product model per design

discipline is that both the architect and structural engineer can have their own view on their design practice, which they are familiar with. Legal concerns by project participants are minimized with this approach, which can facilitate the acceptance and uptake of 3D modelling. A disadvantage of this approach is the lack of coordination between different models. Updates in the architectural model that affect the structural model have to be propagated manually in the structural model. Product model clash detection software (Commonpoint 2005; Navisworks 2005) or model checking software (Solibri 2005) is not used in the ITstomme project, but is believed to save time and increase the accuracy in the process of coordination product models from different disciplines.

The process of generating views from 3D models and adding 2D data proves to be feasible for the Hotellviken project. Difficulties are experienced when updates are made in the central product model. Ensuring up-to-date 2D data in all separate model views of for example reinforcement bars is a process that does not provide significant advantages compared to the traditional 2D structural design process.

Project actors that do not have CAD software installed can view and browse the product model with inexpensive viewing clients. To illustrate: at the start of the ITstomme project there was one CAD system available at JM and one at Betongindustri. No experienced CAD personnel is available to operate CAD systems in the two organizations. Using Internet explorer-based product model viewers facilitates the uptake of product model use in both organisations. Model views and other documents, located at a document server, become centrally available by using product model viewers. Using the 3D model is believed to add to project participants' understanding of to what part of the model the different documents and views are related.

It became clear during the project that there was a need for a central person that would coordinate and ensure proper linking of the product model with information located elsewhere. A number of other tasks and responsibilities have been identified, in addition to management of linked information to the product model. Examples of these tasks and responsibilities are:

- Management of the product model server
- Coordinating and ensuring the use of templates for modelling work
- Integration of product models from different disciplines
- Education and knowledge management of (potential) model users

Research efforts by Froese on the integration of product models with document-based information (Froese 2004b) and on the definition of a Project Information Officer (PIO) (Froese 2004a) can be mentioned here as potential future developments that are relevant to integration and management of product models with 2D data.

## **7 THE FOURTH DIMENSION**

### **7.1 Abstract**

Within the ITstomme project 4D CAD is used as an instrument to introduce construction innovations and to evaluate construction alternatives for cast in place concrete construction. Architectural and structural 3D models serve as a basis for the 4D modelling process in which these models are linked to production schedules. The main benefits of this approach are that fact that project stakeholders can simulate and analyze what-if scenarios before commencing work on site. New construction materials or processes can be tested virtually under controlled conditions before committing resources and without risks for expensive failures.

### **7.2 Introduction**

4D modelling is an increasingly used process method in which 3D CAD models are visualized in a 4-dimensional environment. A currently widely used method for process modelling is the Critical Path Method (CPM) which is often graphically represented as a Gantt schema, i.e. a bar chart. The method concentrates mainly on the temporal aspect of construction planning (i.e. the time-aspect) and is seen as one-dimensional (Heesom 2004). Construction projects have unique spatial configurations and the spatial nature of projects is very important for planning decisions (Akbas 2004). CPM schedules do not provide any information pertaining to the spatial context of project components and requires users to look at 2D drawings to conceptually associate components with the related activities (Koo 2000; Koo 2003). This approach limits evaluation and comparison of alternative solutions. Construction plans

can be represented graphically by adding the time dimension to 3D models to allow project planners to simulate and analyze what-if scenarios before commencing work execution on site (Mallasi 2002). 4D modelling is identified as a tool to convey planning information (visualization tool), enhance collaboration among project participants (integration tool), and to support users to conduct additional analyses (analysis tool) (Koo 2000).

4D CAD is used in the ITstomme project to evaluate today's construction practice and to introduce innovations construction materials and construction processes that can add to the industrialization of cast in place concrete construction.

Appendix B includes a detailed description the application of 4D CAD for cast in place concrete in the ITstomme project. The main results are summarized below. For a more detailed overview and discussion of the results we recommend reading (Jongeling 2005b; Jongeling 2004a).

### **7.3 Results**

Two alternative models are modelled of a 4D case study project (see section 0) in order to compare different construction methods, Figure 6. The first alternative, the 0-Reference scenario, represents today's common practice for cast in place concrete construction. The objective of this scenario is to represent typical sequenced and concurrent activities on a construction site that are related to casting of concrete walls and slabs. The second alternative provides an industrialized approach to cast in place concrete construction. A number of innovative production technologies form the basis for this alternative. The objective is to visualize the potential for permanent formwork systems in combination with the use of prefabricated carpets of reinforcement and self-compacting concrete. Such a combination of innovative production technologies has not been applied in actual projects in Sweden and the possibility to evaluate these methods in a virtual environment is considered to be useful.

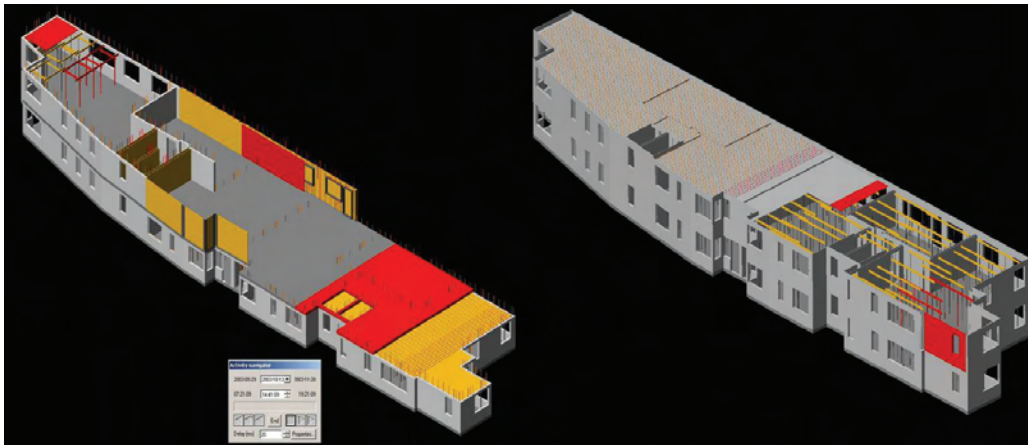


Figure 6: Parallel simulation and comparison of construction alternatives in 4D CAD. (Left) Traditional production technology. (Right) Industrialized practice combining innovative technologies, such as permanent formwork systems, reinforcement carpets and self-compacting concrete. Colour settings in simulations: Red = in activity, grey = finished elements, yellow = traditional formwork and shoring elements. See also Appendix B.

Production models are used, in addition to architectural and structural models, to suit detailed production simulation of both construction alternatives. CPM schedules are imported to the database and linked to production model objects. The architectural model and structural model are too abstract to be used for specific construction operations. In order to create production models from architectural and structural models:

- Changes are made in the 3D CAD object hierarchy. 3D CAD objects are regrouped to represent work packages and activities
- Certain objects have to be split and regrouped. This especially applies to large objects, such as slabs
- 3D CAD objects are added that are not present in the architectural model. As an example traditional formwork can be given. The objects solely serve a visual purpose and are abstract representations of actual formwork elements

## 7.4 Discussion

Both construction alternatives can be simulated in parallel in 4D CAD. A number of time-space conflicts were detected during the 4D modelling process that had not been detected in the CPM schedule. The parallel visualization is considered effective to visually explain the differences between the two construction alternatives. The simulations have been evaluated by a number of professionals and they generally agree that the 4D models help to understand the different construction processes, but they also note that the models are limited in scope and non-interactive.

Evaluation of alternative work flow strategies or changes in productivity can not easily be managed in the 4D models. The 3D CAD objects in the production models that are created and grouped to represent specific activities, i.e. formwork, reinforcement and concreting, constrain the rapid evaluations of alternatives. Changes in the architectural and structural model and changes in the schedule imply often major changes in the production model. The detailed production models require considerable modelling effort and are due to their complexity and interdependencies difficult to manage. The complexity of the CPM schedules that contains a large number of dependencies between activities further constrains the management of the production models. Akbas (2004) notes that when models accurately represent construction operations, the model complexity increases significantly and consequently the effort to create and maintain these process models.

The 4D models show activities related to building components, but no other aspects that are related to such an activity. As an example the space usage of a construction activity can be given. This is especially relevant for cast in place concrete construction, where the work with forms, reinforcement and casting on site implies different types of space usage, such as materials space, labour space, space for safety measures, etc. The application of 4D CAD to model and represent the space usage for cast in place concrete is studied within the ITstomme project by students at Luleå University of Technology (Carlsson 2005). The results of the work are manuals for production planners and 4D CAD modellers that include recommendations about what types of spaces that should be represented for different types of activities during the casting process of concrete walls and slabs.

We consider a number of developments that can possibly address the issues related to the creation and maintenance of space-loaded 4D CAD production models (Jongeling 2004a):

- Adding CAD objects to represent for example temporary structures could be partly automated by using feature-based 4D models. Feature modelling is an approach whereby modelling entities termed features are utilized to provide improvements for common geometric modelling techniques (Kim 2004, unpubl.). The application of feature-based 4D models could have reduced the modelling work and could have contributed to the quality of the temporary structures plans.
- Although 4D simulations are a promising method to evaluate complex schedules, the method still relies on CPM schedules. As noted in the above, CPM schedules do not provide information about the spatial context of production processes. An additional shortcoming of CPM is the difficulty of identifying work flow in a production system. Research initiatives within the Lean Construction Institute (LCI 2004) on the development and application of Line-of-Balance (LoB) scheduling techniques (Kenley 2004) can possibly provide an alternative for or addition to CPM based scheduling for 4D CAD.
- Space objects could be used to represent activities and space-usage, rather than using building objects as a representation. Space objects can provide a better visualization than building components of the space that is required for ongoing work in a specific section of a building. Spaces can also help to minimize the 4D modelling work as these spaces can include many different building components.

As a future extension of the ITstomme project and conducted 4D simulations, we plan a study to evaluate feature-based 4D models and integration of LoB planning software (DSS 2005) with 4D CAD. The combination of 4D CAD models and LoB diagrams has been used in a PhD and Industry course, called Virtual Construction, at Luleå University of Technology, during spring 2005 (Jongeling 2005a). The participants in the course considered the combination a useful mechanism to understand the spatial context of the production planning and to manage the flow of resources and materials through different locations on the production site. An article has been submitted to a scientific journal in which the combined use of 4D CAD models and the LoB planning method is explored (Jongeling 2005c).





## **8 THE FIFTH DIMENSION**

### **8.1 Abstract**

In addition to the 2<sup>nd</sup>, 3<sup>rd</sup> and 4<sup>th</sup> dimension, we studied and developed the integration of product models with cost data to facilitate the cost estimation process for cast in place concrete structures. This process is referred to as 5D modelling (Edgar 2002), in which project model objects or assemblies of objects are mapped with recipes that specify the activities and resources needed for construction of these objects. The objects with a specified recipe are subsequently used in cost estimation software to generate cost estimates. The main benefits of this 5D approach are the savings in time for cost estimators in the quantity take-off process and the reduced risks for omissions or mistakes in the quantity take-off. The savings in time and the fact that cost estimates are based on virtual models can possibly lead to a decision-making process in which more alternative (innovative) cast in place concrete products and processes are considered, which can lead to better informed decisions and ultimately to a better final product.

### **8.2 Introduction**

Currently the quantity take-off is done manually from paper drawings, which is time-consuming and prone to errors. Each time the design is revised the process has to be repeated and started over again. This is a cumbersome and time-consuming process, and limits the consideration of alternative products and processes during the cost estimation process. The goal of the development and application of a 5D cost estimation process is to partly automate the cost

estimation process in order to facilitate the consideration of multiple production alternatives.

In a typical project three types of cost estimates are made:

1. Pre cost estimate, which is based on experience ‘key values’ (Förhandskalkyl)
2. Base cost estimate, which is based on early stage drawings (Grundkalkyl)
3. Production cost estimate, which is based on building drawings.

In the ITstomme project we focussed on the base (2) and production (3) cost estimate. A detailed description of the research and development regarding the 5D cost estimation process in the ITstomme project is included in Appendix C. The main results are summarized below.

### **8.3 Results**

The cost estimation process with the use of product models is not as straightforward as multiplying model object quantities with unit costs. Most of the product model objects from the architectural and structural engineering models cannot directly be used cost estimation. The objects require mapping with recipes codes. A recipe code is an identifier of a recipe in the cost estimation software used by the cost estimator. A recipe includes the working methods, or activities, for the construction of a specific object and the needed resources.

The structure, or hierarchy, of the cost estimation is in many cases different than the structure of a product model and for this purpose, a separate estimation hierarchy is created in the database that is mapped to model objects from the architectural and structural object hierarchies.

The process of mapping includes the creation of an estimation hierarchy to which product model objects are linked, Figure 7. The objects from the product models can be selected from the product model hierarchy by filtering the product models on specific parameters, such as ‘wall width > 200mm.’, or by picking the objects with a computer mouse from the 3D models on a screen. For every cost item in this estimation hierarchy the cost estimator can specify a recipe code and the type of object, such as a slab, to which this code applies. The recipe codes are available in a user-defined XML file and are created

according to a SBEF classification system, which is in use at JM. SBEF is a classification system and file format for exchange of cost calculation data. After having specified a recipe code for all model objects the estimator can export the quantities and the recipe codes to cost estimation software where the cost estimates are completed.

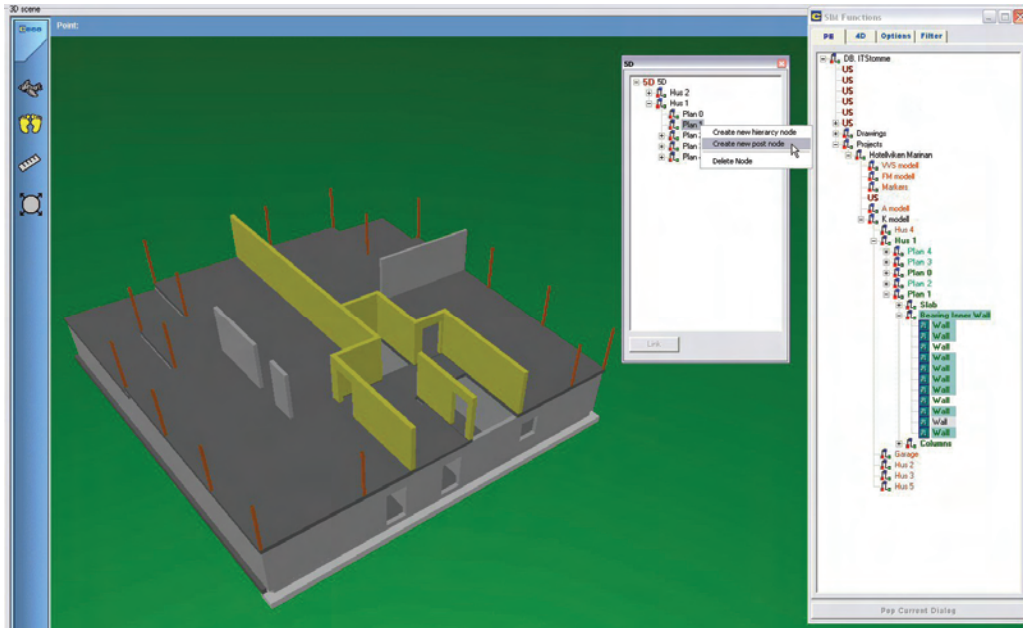


Figure 7: Screen capture from the 5D cost estimation process by using a model viewer developed in the ITstomme project. 3D objects are selected by an estimator in the 3D scene (left) or via the PE (Project Explorer) (right) after which a cost estimation post is created in a so-called 5D hierarchy (on the left of the PE) for which a recipe code is defined. A cost estimation file is created from the 5D hierarchy and is used in cost estimation software. See also Figure 22 and Figure 23 in Appendix C.

#### 8.4 Discussion

The process of selecting objects, adding recipe codes and exporting the cost estimation files to cost estimation software requires configuration of recipe files according to a company standard and requires training of cost estimators in the use of the software. Technically there are no major obstacles to start using the 5D technology.

Different approaches to the 5<sup>th</sup> dimension of product models have been demonstrated in a number of research initiatives (Edgar 2002; Kam 2002; Laitinen 1998) and are starting to be commercially applied (Graphisoft 2005). A number of companies currently emerges in Sweden that provide cost estimation services based on product modelling for project developers and construction companies. These companies use product models for a variety of analyses in addition to 5D modelling, such as energy simulation, lighting, accessibility, et cetera. Creating a product model solely for estimation purposes is considered a viable business case for these companies. Additional analyses that can be performed with product models add to the value of the models.

The use of recipes for cost estimates in projects has advantages and disadvantages for cast in place concrete construction. By using standardized object types and recipes one can enhance standardization of products and processes, and can semi-automatically generate a 4<sup>th</sup> dimension (Jongeling 2004b). However, cast in place concrete is not a single standard product and has no standard process. The products and processes are to a certain extent standard, but can require customization of for example material properties. With standard recipes for cast in place concrete one can only use known product and process information resulting in solutions not adapted to the actual construction site. There is a risk that models will contain generic information from for example cost estimation databases that is not tailored and checked by specialists. In this spirit we suggest that expert knowledge from concrete suppliers is integrated in product models. We discuss this process in the next chapter.

## 9 THE N<sup>TH</sup> DIMENSION

### 9.1 Abstract

Within the ITstomme project we illustrated a product model's n<sup>th</sup> dimension by the development of a program called BiDry. BiDry serves as a typical example for the integration of what we call production data into a product model. The program is used to calculate the optimal drying process of concrete slabs. The main benefit of this approach is the explicit integration of design and production data. Production data can easily be accessed via a product model and the production data itself is based on parameters from the product model, thus minimizing the risks for communication and data errors and ensuring the use of the right concrete products and production processes.

### 9.2 Introduction

The drying time of slabs often proves to be a bottleneck in projects, leading to costly delays. Slabs have to have reached a relative humidity of 85%, or sometimes 90%, before they can be covered by other floor material. A relative humidity higher than 85% or 90% can result in moisture damage, such as mould, which is negatively affecting the indoor climate of a building (Hedenblad 1996). Different types of concrete can result in faster or slower drying processes of slabs and can be delivered according to the requirements of the contractor. It is thus important to use the right type of concrete at the right place in a project and not to cover the slabs too early.

The process of ordering the right concrete and monitoring the relative humidity requires close communication between the contractor and concrete supplier. In today's projects this communication is done by telephone, sending faxes,

emailing, etc. In this process there is no explicit integration between the results from technical calculations and the design data that is produced by consultants, such as architectural and structural models. In the ITstomme project we illustrate the integration of production data and product data, by integrating BiDry and a model viewer.

### **9.3 Results**

The output of BiDry consists of time frames for the drying process of slabs and material properties, such as specific concrete classes and Water to Cement ratios, Figure 8. The material properties, determining the drying process, are configured in the product model of Hotellviken by using model viewers to the central product model server. The time frames are integrated in the construction planning and linked to the product model. The model can be browsed in 4D, using the model viewers. Standardized property reports, including product data specifications, are linked to slabs in the product model, Figure 5 A and Figure 9, in addition to configured slab properties and 4D simulations.

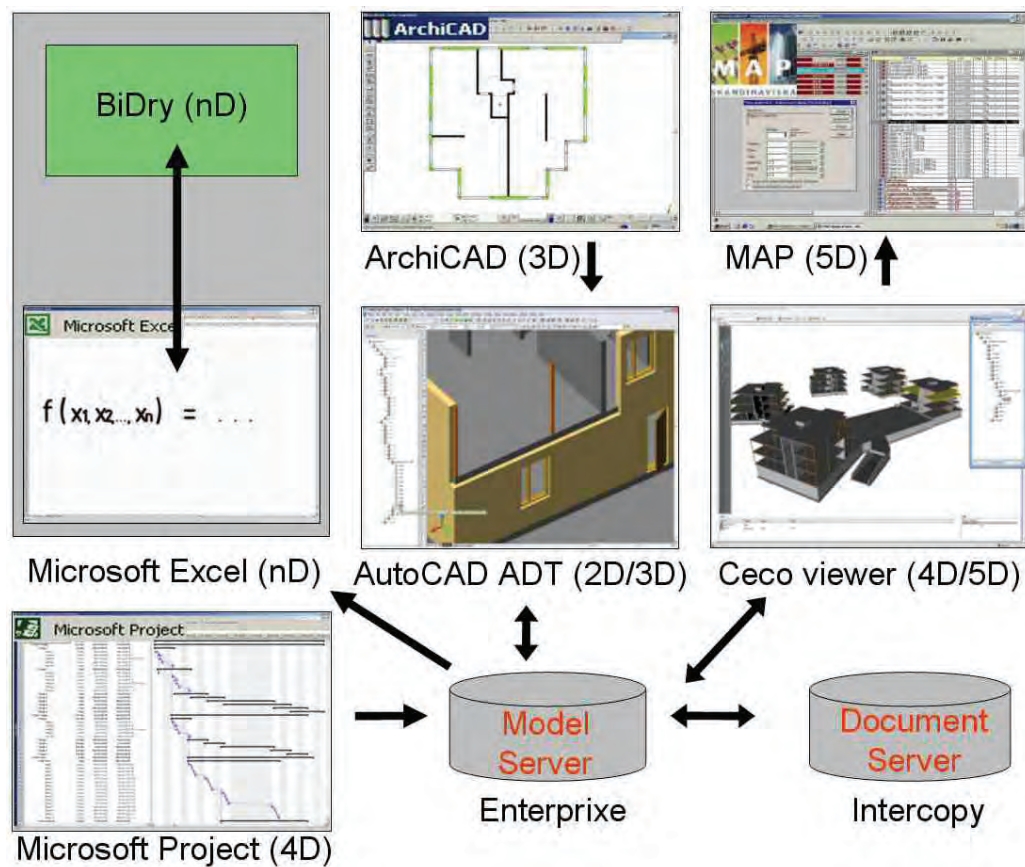


Figure 8: BiDry, a program to calculate the optimal drying process of concrete slabs, is used as an example of the integration of product data into a product model. The output from the BiDry program is used to configure product model object properties. Planning data from BiDry is linked to the product model and used for 4D simulations. Reports from BiDry are located at a document server and linked to the product model.



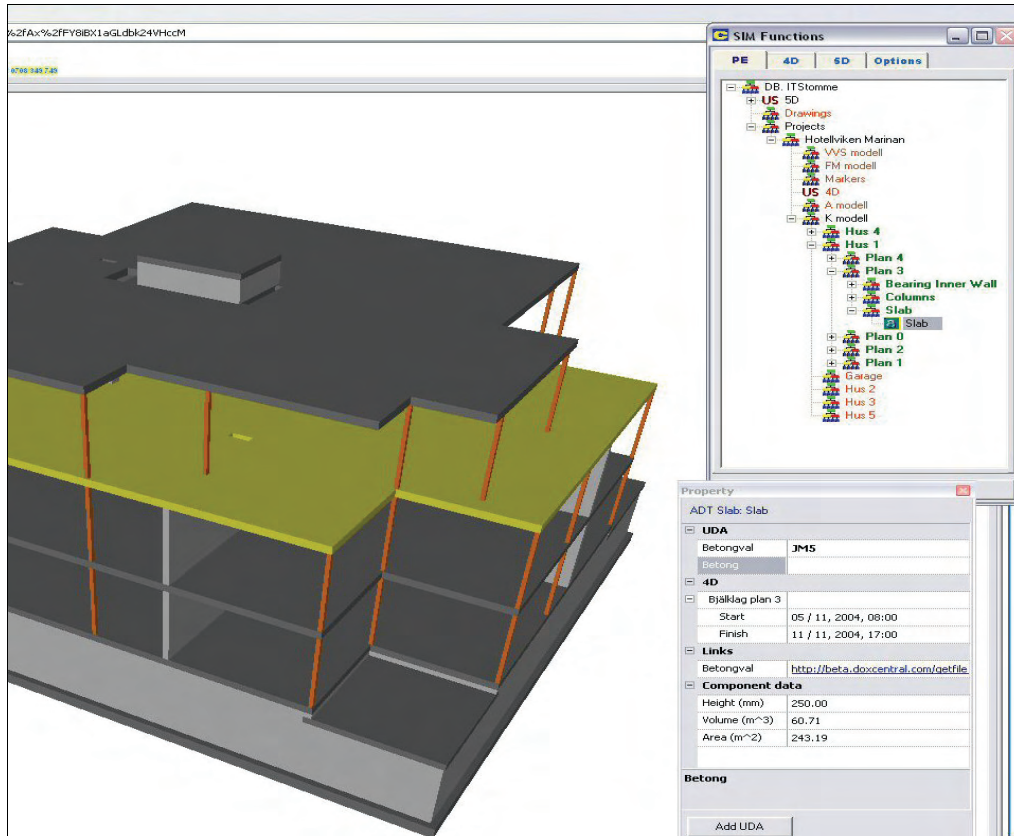


Figure 9: Properties of a selected (yellow) slab in the product model by the structural engineer. The slab contains a link to a document server on which the results of a technical calculation by the concrete supplier are located. The slab contains also time stamps, indicating when construction work will be ongoing.

#### 9.4 Discussion

The relevance of configuring product model contents by a ready-mixed concrete supplier is illustrated by using an expert program for calculation of concrete slab properties. The resulting model properties and 4D simulations that follow from this process are an example of a potential business case for the ready-mixed concrete supplier.

Technically there are no major obstacles to start cooperating in projects by using product models in a similar or identical way as illustrated in the example

above. However, it requires training from different stakeholders in a project. Furthermore it requires also clear formulation of the objectives for the use of product models.

We illustrated a number of use cases that can be based on the use of product models, but despite the potential benefits and possibilities the uptake is a slow process. In the next chapter we discuss the challenges for applying product models in practice.



## **10 CHALLENGES FOR PRODUCT MODELLING IN PRACTICE**

Despite the possibilities of different model dimensions reported in this report, the uptake is slow. Most of the modelling and coordination work was performed by a few individuals outside the core project team of Hotellviken. Motivating participating companies to commit resources for product modelling in future projects is hard due to difficulties in explicitly communicating benefits from model development and applications in the Hotellviken and 4D case study project.

Difficulties in explicitly demonstrating the benefits of product modelling is one reason why the uptake is slow, but there is a variety of other reasons why the comprehensive use of product modelling is limited to date. These reasons, or rather challenges, were discussed at an international workshop held in January 2003, as part of the 3D to nD modelling project at the University of Salford. Thus, the five biggest challenges for the use of product modelling according to the workshop are the following (in prioritized order) (Lee 2004):

- Improving education and changing the industry's culture
- Implementation and integration
- Demonstrating the benefits and value of a product modelling system
- Data issues, such as multiple design perspectives
- Developing a common data standard for interoperability

We will discuss these five challenges in relation to the findings and efforts from the ITstomme project.

## **10.1 Education and culture**

Improving education and changing the industry's culture were seen as the biggest challenges by workshop participants for an uptake of product modelling. Getting industry convinced of benefits and motivating professionals to increase their knowledge about product modelling would greatly facilitate the industry uptake.

It was found that professionals have difficulties in allocating time for education and implementation in addition to their ongoing project work. Due to a lack of education and implemented use cases it was difficult to motivate project actors to consider product modelling as an alternative or improved practice compared to their traditional 2D practice. Most of the modelling work and implementation was therefore performed by a few individuals that limited the learning experience for the total project team.

We suggest the allocation of resources within an umbrella organization, rather than in a single project, to facilitate the uptake of product modelling. Experience and gained knowledge from product modelling has a bigger chance to sustain within organizations, than in a project team that in many cases ceases to exist after a project has been finished.

In addition to strategic uptake of product modelling at a company level, we suggest partnering with other organisations and actors to form a product modelling environment, envisioned by Bazjanac (2004) as a Virtual Building Environment (VBE). A 'place' is needed where companies and individuals can get help in creating and using product models across different disciplines.

## **10.2 Implementation and integration**

Implementation and integration was seen as the second biggest challenge by the workshop participants. There are almost no commercial software applications that work with and add to product models beyond 3D modelling (Fischer 2004).

We illustrate different dimensions of product models by linking different applications and by combining results from these applications. For example, 2D data located at a document server is linked to 3D models. 3D models are used for 4D simulations and 5D cost estimation. In addition to 5D modelling we illustrate a potential  $n^{\text{th}}$  dimension by integrating property data from a

supplier in a product model. These examples illustrate the use of product models beyond 3D modelling.

Although commercially available applications are used for most of the modelling work, there are a number of work-arounds and implementations necessary to enable the transition from 3D to nD product model use. Project participants should be able to access the product models by using software, which they already are familiar with or with software which is very easy to learn. This can greatly facilitate the uptake and culture change in the project team towards product modelling.

We suggest starting implementation and integration efforts with existing and commercially available systems as a basis. Sophisticated applications are already available for 3D modelling, production scheduling, cost estimates, et cetera. The challenge is to combine these applications, rather than to develop an all-inclusive modelling system. We illustrated the combination of different commercial applications in the ITstomme project, instead of developing an own application tailored to our needs. An incremental approach should be adapted in combining different applications with end-user participation in the development process.

### **10.3 Demonstrating benefits**

Demonstrating the benefits and value of a product modelling system was considered the third biggest challenge. Business cases are needed that outlay the needs for product modelling in projects and within organisations.

As noted in the above, motivating participating companies in the ITstomme project to commit resources for product modelling in future projects was difficult due to difficulties in explicitly communicating benefits from model development and applications in the Hotellviken project. We plan to address this shortcoming by adapting formalized cost benefit analyses developed for the construction industry (Fox 2004).

In addition to cost benefit analyses we suggest performance measurement by *Key Performance Indicators* (KPI) (Blokpoel 2003), illustrated by a number of product models from different disciplines. One of the tasks of a possible Project Information Officer (PIO) (Froese 2004a) or product model manager could be the collection and analyses of model data to support performance measurement and demonstration of product model benefits.

#### **10.4 Data issues**

Data issues were considered a big challenge, but not a high priority to address in research and development of product modelling. Examples of data issues are multiple design perspectives and the information flow, exchange and accuracy in projects.

As a result of different design perspectives it was decided to work with two separate product models; one architectural and one structural model. A hybrid product model view is adapted in addition to these different models in which 3D model data is combined with manually added 2D data. The architectural and structural models are combined in two production models, in which both models are extended and further detailed.

The multi-model approach implies a number of advantages and disadvantages. We believe that separate models per discipline are feasible, but only if adequate tools are used to coordinate these models and to check the consistency of these models. Highly detailed production models are labour intensive to create and to maintain, but are considered valuable instruments to communicate process intend and to evaluate production strategies in a virtual environment, without committing resources on site.

The hybrid document approach proves to be more problematic than the multi-model approach, due to errors in updates of 2D data. With constantly improving commercial 3D modelling tools we believe that a hybrid approach is not a necessity in the future.

#### **10.5 Interoperability**

Developing a common data standard for interoperability was perceived by workshop participants as a big challenge, but not a high priority to address. Considerable efforts by the IAI (IAI 2005) to create the IFC product model standard have been made in the last years. Although promising (Kam 2002), the IFCs have not yet found wide acceptance among software vendors and construction companies (Fischer 2004).

Interoperability is not a major issue in the ITstomme project as a result of the use of one environment. An architectural model was exported from ArchiCAD and imported to AutoCAD ADT by using IFC2x. The model contains basic objects, such as walls, doors, windows and slabs, and did not result in major data losses. The import from ADT to the product model server proved to be

more problematic, but was solved in the course of the project. Interoperability is considered essential to start using product models beyond 3D CAD applications. However, the ITstomme project also shows that different dimensions can be added to a product model independently from standardized data schemas.





## 11 DISCUSSION

The ITstomme project illustrates a number of dimensions of product models that on the one hand are aimed at supporting new and existing products and processes for cast in place concrete construction and on the other hand are aimed at showing the potential of using product models beyond 3D graphics. The development of support for cast in place concrete construction is mainly studied in the 4<sup>th</sup> and n<sup>th</sup> dimension of this study. The potential of using product models beyond 3D graphics is shown by combining 3D models from different design disciplines that form the basis for document retrieval, 4D modelling and 5D cost estimation.

Developments and applications in the project are mainly driven by the interests of the ready-mixed concrete supplier, Betongindustri, who, in a prestudy (Jongeling 2003) identified product modelling as a threat and as an opportunity for its business process. Modelling cast in place concrete structures implies a number of modelling challenges compared to steel and prefabricated concrete structures, such as the differences in definition of design and production objects. However, the case study projects of this study show that these challenges do not exclude the use of product models for cast in place concrete structures. Possibilities and challenges that are listed in paragraph 4.1 (Table 2 and Table 3) are included in Table 4 and Table 5 below, and commented on based on results from the different model dimensions of this study. The challenges as listed in Table 5 are complementary to the challenges that are identified in Chapter 10.

Table 4: Findings from the ITstomme project that are related to the identified possibilities for the application of product models for cast in place construction

<i><b>Possibilities</b></i>	<i><b>Findings from the ITstomme project</b></i>
Modelling and review in 3D improves constructability and quality of the structure	By using the 3D structural model in the Hotellviken Marinan project we could identify in an early stage a bearing wall that was not located in the same vertical plane as a bearing wall at a lower floor. Although this issue also was identified by the structural engineer with 2D drawings, the issue became much more explicit and could easily be detected in the 3D model. In general the use of 3D models is believed to increase the accuracy and quality of the design and provides a clear basis for decision-making.
Product models can be linked and associated with 2D drawings and documents, such as the results of technical calculations. This facilitates the process of document retrieval	Special markers are used that carry different colours for different types of documents, Figure 5. The markers, or cone objects, link the structured information from the product models to unstructured information in documents and drawings. In the ITstomme project we linked information from the architect, structural engineer and concrete supplier to product models. This approach facilitates the combined use of 2D drawings and 3D models, and helps stakeholders in the project to quickly find documents that are related to specific objects in the product model.
Simulation in 4D of innovative products and production processes facilitates the application of new technologies in practice.	Parallel visualization of different construction alternatives is considered an effective way to visually explain differences between alternative construction approaches, Figure 6. In the 4D case study we were able to identify a number of time-space conflicts in the 4D models that we had overlooked in our CPM schedules. The 4D models require considerable modelling efforts and could possibly be improved by using different scheduling and modelling methods.

<p>(semi-)automated quantity take-off of concrete volumes and material specifications can save time and can reduce errors in quantity take-off</p>	<p>After having prepared property sets for all objects the quantity take-off is literally a process of a few minutes. These quantities provide a quick and reliable overview of the total amounts of concrete, windows, doors, etc, that are needed in a project. However, quantities also have to carry a recipe code and location to be used for cost estimation purposes. This process is developed in the 5D cost estimation process. The 5D process saves time in quantity take-off and reduces risks for calculation errors, but still requires input from the cost estimator about how and where objects will be calculated.</p>
<p>Material specifications can be integrated in product models and are as a result a natural part of objects used in the design and production process</p>	<p>By using model viewers one can navigate to specific components in the 3D models and can retrieve object properties by selecting objects in the 3D scene. Available information for objects, such as the volume, length, material, construction dates, etc., is easily accessible and is considered useful by participants in the ITstomme project for planning of production and ordering concrete deliveries.</p>

Table 5: Findings from the ITstomme project that are related to the identified challenges for the application of product models for cast in place construction

<b><i>Challenges</i></b>	<b><i>Findings from the ITstomme project</i></b>
<p>The architectural and structural views on modelling are different</p>	<p>Separate architectural and structural models are used in the ITstomme project. We believe this approach minimizes the need for radical process changes and minimizes legal concerns. A disadvantage of this approach is the lack of coordination between different models. Product model clash detection software is recommended in this respect.</p>

<p>There is limited support in CAD applications for modelling of objects related to cast in place concrete construction. This applies to concrete shapes, definition of concrete pours, reinforcement bars, isolation, drainage, etc.</p>	<p>The structural detailing of cast in place concrete structures is not part of the ITstomme project. Therefore the main structural modelling work is carried out with standard and general modelling tools, such as AutoCAD ADT. Only the main concrete components are modelled of which the results are satisfying. All shapes can be represented by using standard functionality in the program. For detailed modelling we recommend the evaluation of dedicated software packages for structural design of cast in place concrete structures.</p>
<p>Design models differ from production models in which the latter is more detailed and includes non-building objects, such as scaffolding, work spaces, etc</p>	<p>Production models consist of objects from architectural and structural models to which additional objects are added to represent non-building objects. We created detailed 4D models (production models) that required considerable modelling efforts. It is not clear how the relations between the different models should be managed, in case the architectural model for example is updated. We plan to study the use of a model server that can manage these relations. In addition we plan to study planning and modelling approaches that minimize the required modelling efforts for production models.</p>
<p>Material specifications are often not linked to or specified in product models</p>	<p>We illustrate the possible integration of results from technical calculations by a concrete supplier with design models. Although the implementation is limited in scope it provides an example of a possible business case for a ready-mixed concrete supplier.</p>
<p>There are very few actors that can use CAD which limits the use of product models in practice</p>	<p>At the start of the ITstomme project there was one CAD system available at JM and one at Betongindustri, thereby strongly limiting the access to product models. Using product model viewers facilitates the uptake of product model use in both organisations.</p>

<p>There is a need for someone who coordinates the models from and for different stakeholders in a project.</p>	<p>It became clear during the project that there was a need for a central person that would coordinate the linking, updating and use of multiple product models. Within the ITstomme project this person was a member of the research team. In construction projects this person should be a part of the project team.</p>
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From the tables it becomes clear that advantages and possibilities can be identified for the ready-mixed concrete supplier and contractor. We believe that other actors in construction also can identify advantages and possibilities in the different model dimensions of this study. When actors have identified benefits of product modelling for their own business process they might be more willing to participate in shared product model use in search of benefits for the project team as a whole.

The project developer in this study, JM, started to identify benefits of product modelling for its business process during the ITstomme project and is now actively searching for additional benefits by participating in research projects, such as the VIPP project, and by applying product modelling in practice. Examples of the currently identified benefits by JM are:

- Improvement of the quality and effectiveness of product marketing by using 3D models.
- The quality of design reviews and design coordination improves, which in its turn is believed to provide a better basis for planning and production, with fewer design mistakes and less rework.
- 5D cost estimation based on product models reduces the time needed for quantity take-offs and reduces the risks for mistakes in the estimates.
- Communication with project stakeholders improves by using 3D and 4D models. Especially the communication with the municipality about building permits and the communication with clients benefits from using 3D and 4D models.

## 11.1 Recommendations

Throughout the report a number of technical and organisational recommendations are made. In the following section we summarize these

recommendations and provide suggestions for further research and for use in practice. This report is written for audiences with differences in background and expertise. These differences are also reflected in the recommendations that we provide, of which some are general and others are more case- or actor-specific.

### **11.1.1 Model management**

Separate product models are created in the ITstomme project per design discipline. We believe this approach minimizes the need for radical process changes and minimizes legal concerns. A disadvantage of this approach is the lack of coordination between different models. Product model clash detection software (Commonpoint 2005; Navisworks 2005) or model checking software (Solibri 2005) is recommended for evaluation with the objective to save time and increase the accuracy of the process of coordinating and updating product models from different disciplines.

In a number of companies the roles of the architects and structural engineers have changed as a result of a model-based practice. The structural engineer's role has become broader and can be described as a building information modeller. This includes the modelling of structural and architectural objects in one single model, including the preparation of the model for cost estimation and production simulation. The role of the architect is more focussed on capturing client requirements and communicating these to the building information modeller. The companies experience this change as a satisfying approach. However, the approach raises many questions and we recommend case studies of companies where such changes in processes have been made. These case studies can provide a better picture of the advantages and disadvantages of this new process.

It became clear during the project that there was a need for a central person that would coordinate the linking, updating and use of multiple product models. Additional tasks and responsibilities for this person are:

- Management of the product model server, such as model exchange and updates
- Coordinating and ensuring the use of templates for modelling work
- Integration of product models from different disciplines
- Education and knowledge management of (potential) model users
- Providing an (up-to-date) information base for 4D and 5D modelling

Research efforts by Thomas Froese on the integration of product models with document-based information (Froese 2004b) and on the definition of a Project Information Officer (PIO) (Froese 2004a) should be further studied in this respect.

## **11.2 Model creation and access**

Structural design was performed with AutoCAD ADT in the project with satisfying results. However, we also recommend evaluating dedicated software packages for structural design of cast in place concrete structures, such as Tekla Structures (Tekla 2005), Enterprixe Structural (Enterprixe 2005), Impact and FEM-design (Strusoft 2005).

It is recommended to broaden the scope of research for product modelling applied to cast in place concrete construction by including civil works, such as bridges and tunnels.

Advanced 3D modelling tools are available for the design of HVAC and electric installations in buildings. We recommend studying the integration of models that are produced by these design disciplines with models from architects and structural engineers.

Model viewers are used in the ITstomme project to facilitate the access and use of product models by non-CAD users. These model viewers have a great potential to facilitate the uptake of model use and more research is recommended to design and optimize suitable user-interfaces, by for example studying game consoles, available tools in the manufacturing industry, etc.

The 4D modelling case study that is presented in this report shows a number of benefits for the ready-mixed concrete supplier and we believe there are many more benefits for other actors in the construction industry. Examples of these potential benefits are improving the instruction of sub-contractors, improving Supply Chain Management (SCM), etc. We recommend applying 4D modelling in practice at construction sites to further explore the benefits of this technology. Reviewing the research and application efforts by Johan Sjögren are recommend as a point of departure and source of inspiration (Sjögren 2005).



A number of research and development efforts are recommended to facilitate the 4D modelling process:

- Feature-based 4D models could minimize and rationalize the 4D modelling process. Practical test are necessary with the research results from Kim (Kim 2004, unpubl.).
- Space objects could be used to represent different types of spaces and locations that are required during the construction process by different actors on a construction site. The use of spaces to model and represent different types of construction activities should be further explored.
- The Line-of-Balance (LoB) planning method is a promising planning method to be used in combination with 4D CAD models. The combined use of 4D CAD models and the LoB planning method should be further researched.

Application of the 5<sup>th</sup> and n<sup>th</sup> dimension in a similar or identical way as illustrated in the report is not limited by technical obstacles. It requires training from different stakeholders in a project and a number of test cases to make the technology robust enough for different use cases. In addition to training and test cases, it requires well-documented protocols how the technology can and should be applied.

The 5D cost estimation process could be improved by creating the product models from the start according to company standards for the cost estimation process. This requires that consultants, such as architects and structural engineers, create their models with objects from a customized and company-specific library that includes the right codes and objects styles that match to styles and codes in the cost estimation database.

### **11.3 Organizational**

We identify a number of organizational challenges for the use of product modelling. The first challenge is education and culture. In order to have practitioners adapting product modelling technology they should have the resources and power to do so. This requires strategic decisions in companies that allow employees to try and learn the use of product modelling technology. To facilitate this process we suggest the allocation of resources within organizations, rather than in a single project to facilitate the uptake of product modelling.

We suggest starting the application of product modelling with small and well-defined examples internally. When benefits are identified for the internal processes, actors can participate in shared product model use in search of benefits for the project team as a whole. We suggest using formalized cost benefit analyses to explicitly express the benefits from model developments and model application (Blokpoel 2003; Fox 2004).

In addition to a strategic uptake of product modelling at a company level, we suggest partnering with other organisations and actors to form a product modelling environment where experiences can be shared and where companies and individuals can get help in creating and using product models across different disciplines.

A key factor and main challenge in the uptake of product modelling technology is education of practitioners. A course on Virtual Construction was organized at Luleå University of Technology during spring 2005 in an effort to provide such education. We recommend practitioners from different disciplines to participate in such courses. We also recommend setting up additional and dedicated courses for different types of model creators and users.

In addition to courses organized by academic institutions or by companies, there are many different seminars to choose from or publications to read. These are recommended to be further informed and updated about the development and use of product modelling technology.

Finally, we suggest considering product modelling technology in conjunction with research and development efforts that are made regarding industrialization, partnering and lean construction. These three areas of research are popular themes in the discourse about methods to improve construction and we believe that product modelling technology plays a prominent and facilitating role across these themes.



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## Appendix A PROJECT MATRIX

	Project Components				
Project Components	Drawings & Documents	Multiple design models	Production simulation	Cost estimation	Material specifications
Dimension	2D + 3D	3D + 3D	4D	5D	nD
Expected Results					
Specification of method					

Activities / phase:

1. prestudy					
2. pilot implementation					
3. system developments					
4. full scale tests					
5. reporting and evaluation					

Participants					
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## **Appendix B 4D CASE STUDY**

### **B.1 Introduction**

This appendix to the ITstomme final report describes a case example that includes 4D simulations of two construction alternatives. Both alternatives illustrate construction methods that are typical to cast in place concrete structures. The aim of the simulations is to provide a discussion basis for comparison of two construction approaches.

Figure 10 provides an overview of the main layout of the building that is used in the case study. The building measures 60 meters in length and is 12 meters wide. All displayed slabs and walls are cast in place concrete components, except for balconies that are prefabricated components.

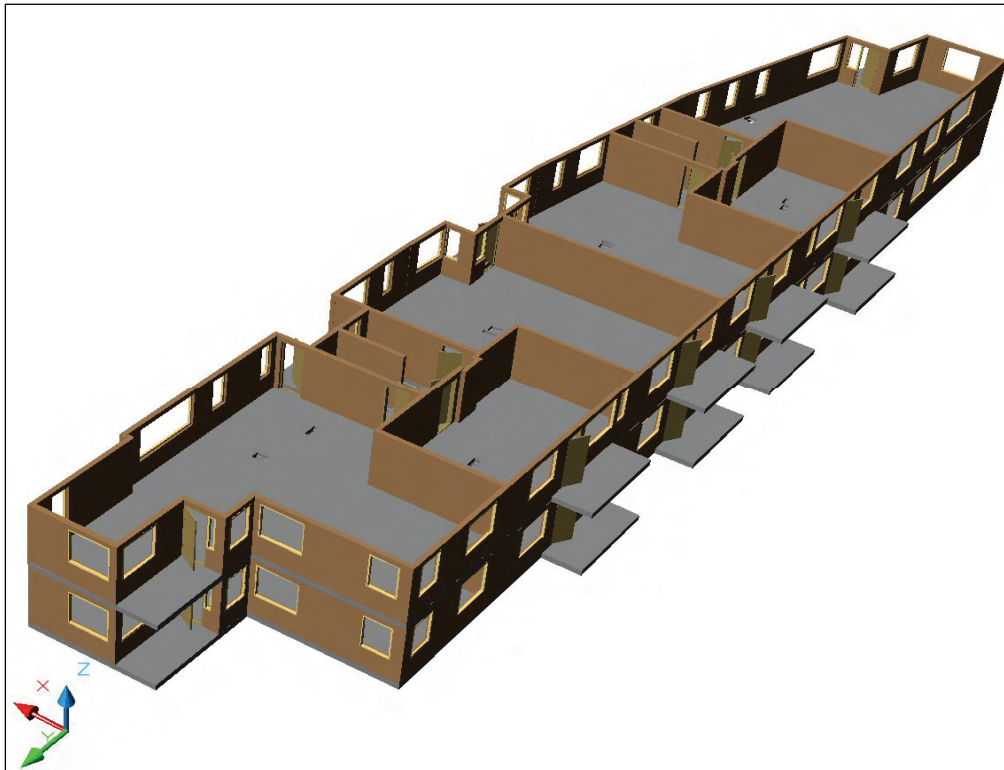


Figure 10: Generic 3D CAD model of case example.

## B.2 Set up

The 3D model is created by using AutoCAD Architectural Desktop (ADT) as client software to an Internet based database system, developed by Enterprixe Ltd. An object hierarchy is created for different CAD object groups by using the database system.

Two alternative practices are modelled for the same building model in two parallel object hierarchies.

- 0-Reference object hierarchy containing components related to the use of traditional formwork. The objective of this scenario is to represent typical sequenced and concurrent activities on a construction site that are related to casting walls and slabs;
- An industrialized object hierarchy aimed at representing the potential for permanent formwork systems in combination with the use of prefabricated reinforcement mats and Self Compacting Concrete.

Both scenarios contain the following main object groups, Figure 11:

- Building Model, including the geometry of building components. This model is the same for both alternatives;
- Reinforcement, containing reinforcement bars for wall and slab components;
- Formwork containing formwork elements for wall and slab components;
- Casting sequences including sections of walls and slabs grouped as individual casting sequences.

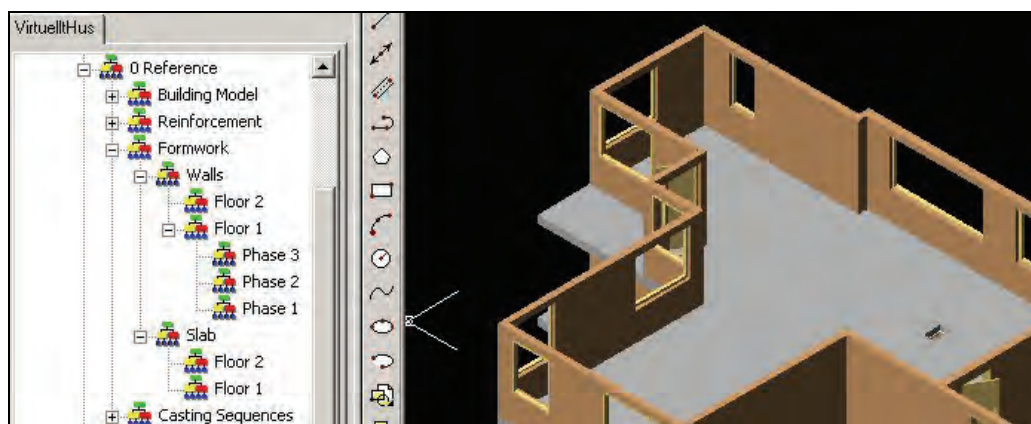


Figure 11: Main object hierarchy in AutoCAD ADT Enterprise client.

Sub-object groups are created for the main object groups. An example of this decomposition for formwork is included in Figure 11. Gantt bar charts, created in MS Project, are imported to the project database and manually linked to the respective objects and object-groups. Colour settings for the visualization of activities are made after the linking of activities to the 3D CAD models is completed.

In the next section the modelled construction processes are outlined in detail.

### B.3 Alternative I: 0 Reference

To illustrate today's common construction practice for cast in place concrete structures, a 0 Reference scenario is used. This scenario is planned and modelled by using existing and commonly used planning methods by participants in the project team. The 3D CAD building model forms a basis for planning casting sequences, formwork and reinforcement.

The objective of the visualization is to show typical sequenced and concurrent activities on a construction site that are related to casting concrete walls and slabs. In the following sections the planning and modelling processes are described that form the basis for the 4D simulations.

### B.3.1 Concrete casting sequences

#### Walls

Sequences for the casting process of walls are planned by using 2D drawings and a set of coloured markers. Coloured lines are drawn over walls of the structure; each line representing casting work for one day. The length and distribution of lines are manually determined by a number of iterations in which a set of decision criteria was used. Main decision criteria are:

- Required formwork;
- Volume of concrete;
- Work flow direction; and
- Work space planning.

Figure 12 shows the final plan for wall casting sequences, in which each number represents a work day; in total eight days. These lines are the key for sequencing casting work and determine formwork planning. Casting sequences are represented by eight folders in the 3D CAD model hierarchy, under which the individual wall CAD objects are grouped.

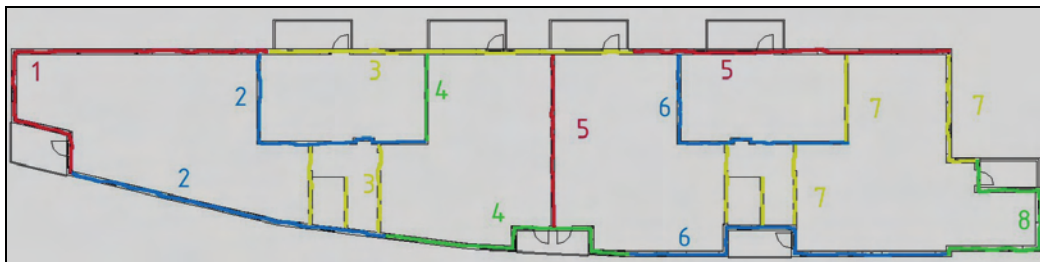


Figure 12: Eight casting sequences for concrete walls.

#### Slabs

Casting of slabs is planned by dividing slabs into sections of approximate equal size. These sections are modelled as 3D CAD slab objects. The size of sections

is determined by standard concrete delivery batches; i.e. m<sup>3</sup> of concrete in a concrete truck. All casting sections are grouped under two nodes in the 3D CAD model hierarchy, representing casting work for two days work.

### **B.3.2 Formwork**

#### **Walls**

Formwork for walls is modelled and represented by using standard 3D CAD objects, such as walls, beams and columns. Formwork elements in the model purely have a visual purpose and are abstract representations of actual formwork elements. Brochure material from formwork suppliers is used to select and model typical formwork. Form elements are grouped in the 3D CAD model by sections of standard length.

#### **Slabs**

Formwork for slabs contains shoring and plywood plates. This formwork is modelled in standard sections, partly according to product specifications from formwork suppliers. An example of the representation of formwork for slabs is included in Figure 13.

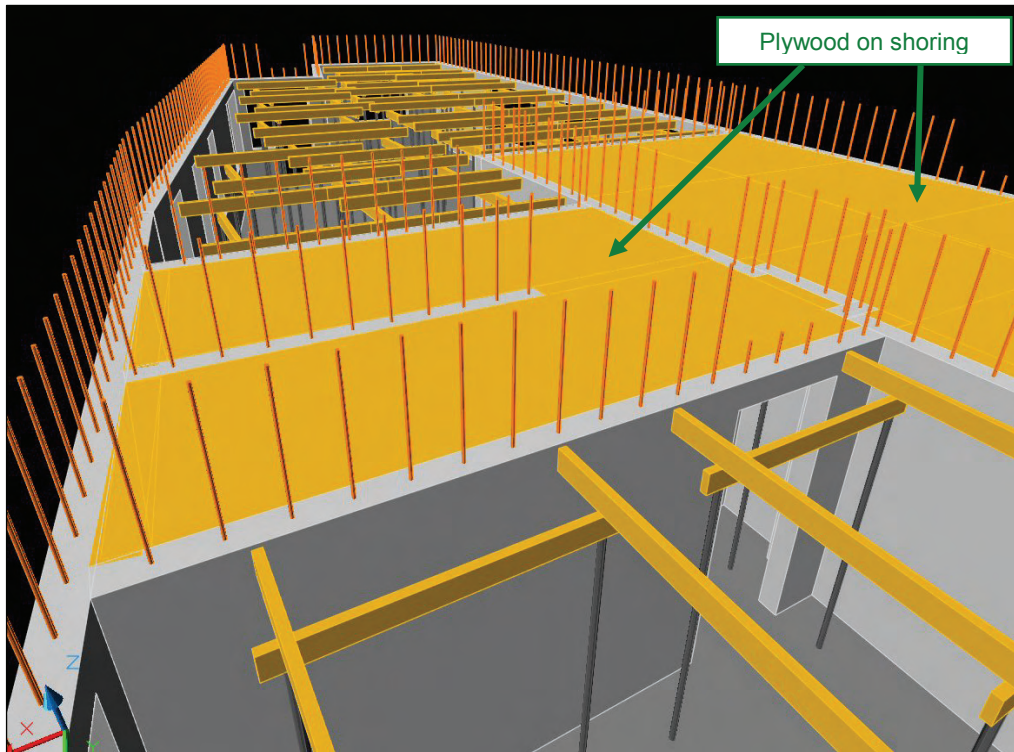


Figure 13: 3D CAD representation of formwork for concrete slabs and reinforcement bars in walls.

### B.3.3 Reinforcement

#### Walls

Reinforcement bars in walls are modelled by using 3D CAD steel section objects, Figure 13. Dimensions, locations, and number of reinforcement bars are determined by visual analyses of the 3D CAD model. The reinforcement bars serve a visual purpose and are not modelled for structural analyses.

#### Slabs

Reinforcement bars for slabs are modelled in one direction and distributed over equal distances. The reason to model bars in one direction is to minimize 3D modelling work. The purpose of these bars is to show the reinforcement activity work zones rather than the actual reinforcement components.

### B.3.4 Planning

Construction operations for the 0 Reference alternative are planned by using Gantt schemas, Figure 14. A work day for casting concrete walls and slabs is typically planned in four periods of two hours.

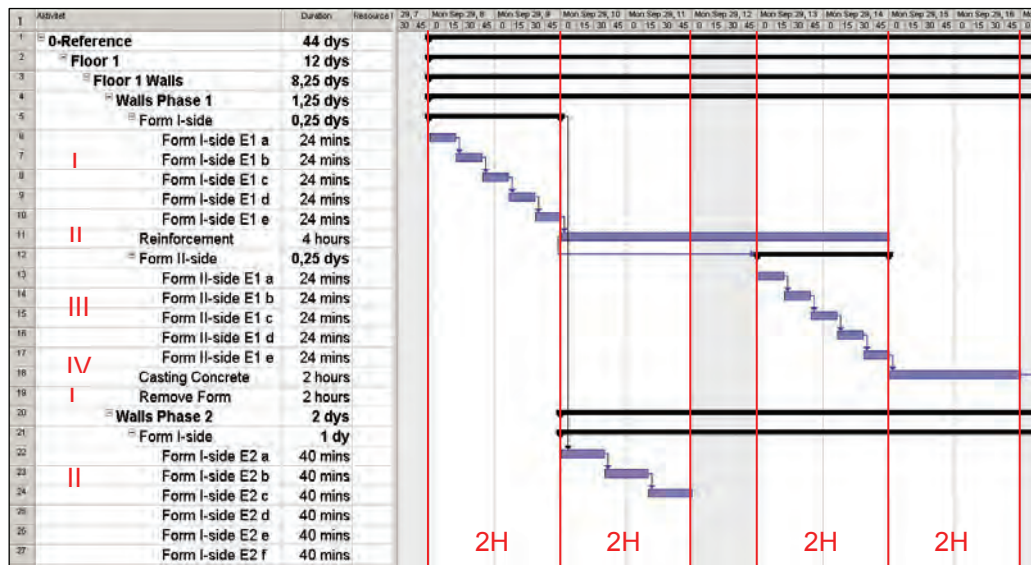
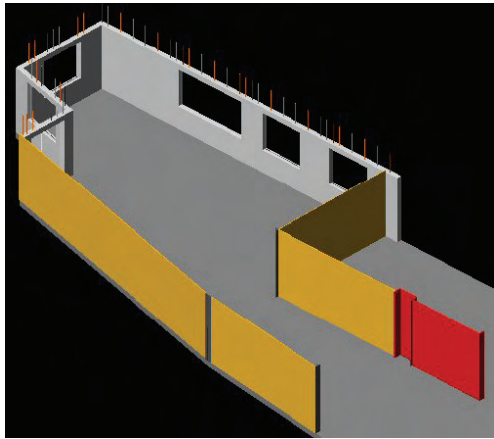


Figure 14: 0 Reference Gantt schema for casting concrete walls.

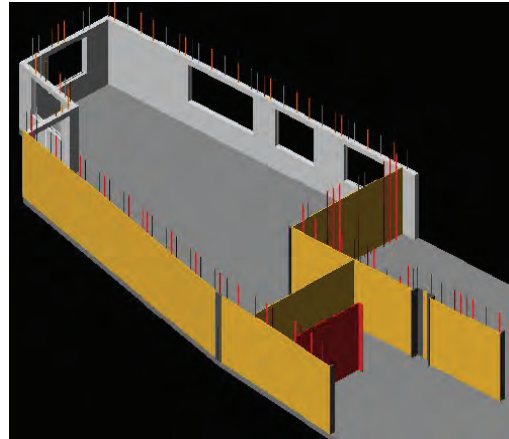
Work carried out during the four successive two-hour phases of a work day includes the following activities:

- I. During the first two hours formwork is installed on one side of walls that are cast later during the day, Figure 15-I. Formwork for this activity is taken down from the casting sequence of the previous day;
- II. Reinforcement activities start after the first two hours. During this phase the crew that worked on formwork during the first two hours, continues the work on the formwork for the casting sequence of the next day, Figure 15-II;
- III. Side two of the formwork is installed during the third two-hour sequence of the day, Figure 15-III. Reinforcement activities continue during this phase; and
- IV. During the fourth two-hour sequence of the day concrete is poured, Figure 15-IV.

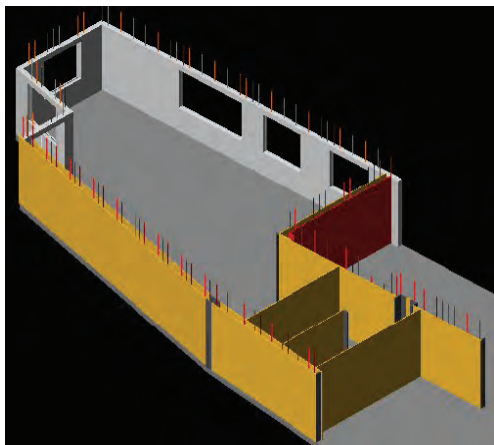




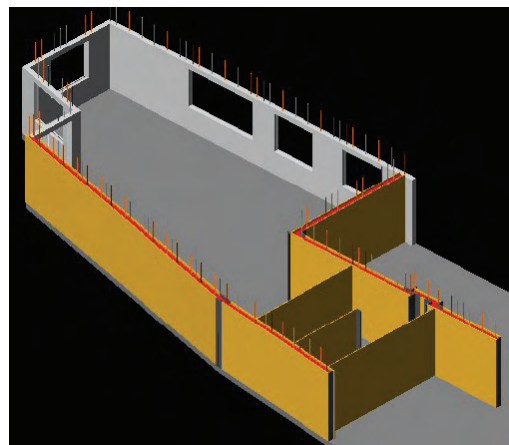
*I: Install form I day n, remove n-1*



*II: Install reinforcement n, form I n+1*



*III: Install form II n, reinforcement n*



*IV: Casting concrete walls*

Figure 15: Four successive two-hour construction phases on day n, related to casting of walls visualized in a 4D CAD model. Red components are in activity, yellow components represent installed formwork, brown components represent installed reinforcement bars and grey components represent finished concrete walls and slabs.

In the next section the 4D modelling process for alternative II is outlined in which an attempt is made to industrialize certain aspects of alternative I.

#### B.4 Alternative II: Industrialized

The objective of the industrialized scenario is to visualize the potential of innovative production technologies. Three production technologies are combined in 4D simulations:

- Permanent formwork systems;
- Prefabricated reinforcement mats; and
- Self Compacting Concrete.

This scenario is modelled in 3D CAD by using similar approaches as used for Alternative I. Because of the use of different production systems the planning process has a different character. In the following sections the planning process and representation of activities are outlined in further detail.

##### B.4.1 Formwork

As opposed to Alternative I, where casting sequences determine formwork activities; the permanent formwork objects determined the planning of Alternative II. A product specification is included in Figure 16.

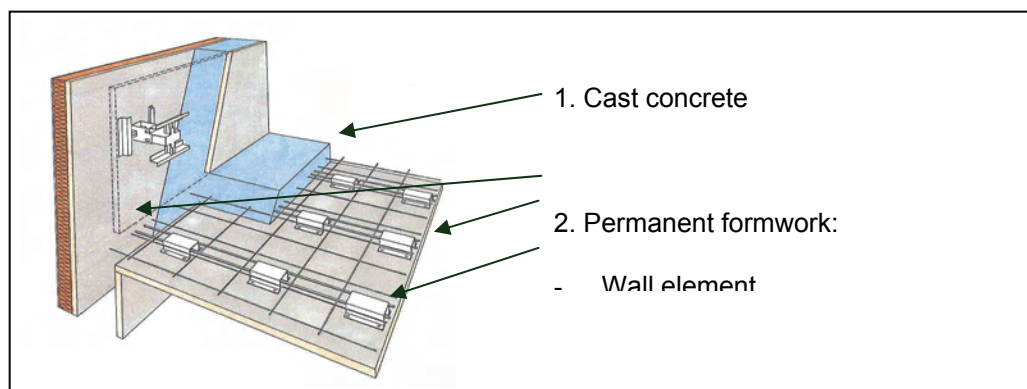


Figure 16: Permanent formwork system.

2D drawings were sent to a supplier of permanent formwork systems, who manually planned wall and slab form elements in the drawings, Figure 17. Geometric data was manually extracted by the supplier from drawings and used in spread sheets to calculate required resources and element costs. Hand

written element ID-numbers are the key in linking 2D drawings and spread sheets together.

All formwork elements for walls and slabs are modelled in a 3D CAD model that is organized according to element ID-numbers resulting from 2D drawings.

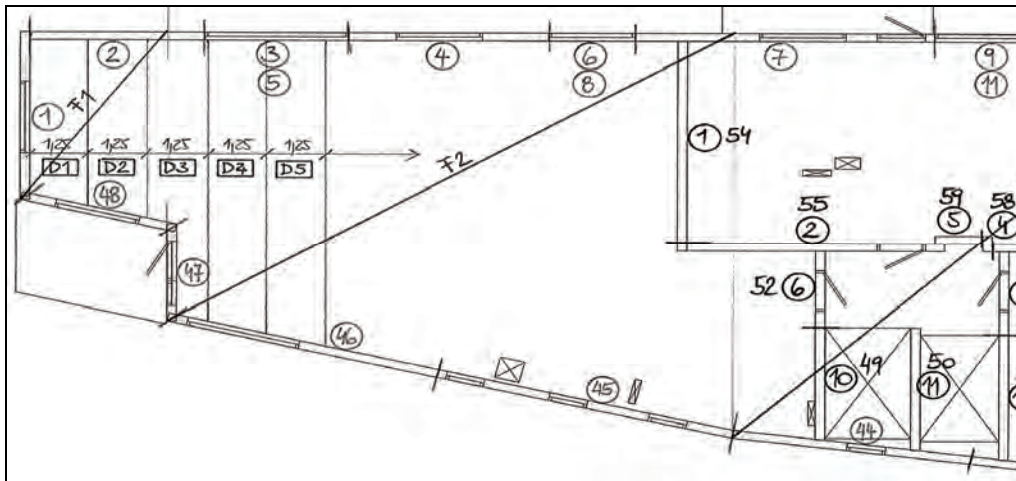


Figure 17: Wall and slab formwork specifications in 2D paper based environment.

## B.4.2 Reinforcement

### Walls

The permanent formwork system applied to the building used in the case study does not require installation of reinforcement bars in walls on site. Reinforcement bars for walls are therefore not modelled in 3D CAD.

### Slabs

Part of the reinforcement needed for slabs is pre-installed on the applied permanent formwork system, Figure 16. These reinforcement bars are not modelled in a 3D CAD model. A prefabricated reinforcement system is chosen for additional reinforcement bars that are needed, Figure 17. This reinforcement comes to site on prefabricated mats, rolled out on site. For the 3D CAD model of this reinforcement system a similar approach is adapted as

used for Alternative I. The purpose of these bars is to show the reinforcement activity work zones rather than the actual reinforcement components.



Figure 18: (Left) 3D CAD systems can provide input for reinforcement prefabrication. (Right) Prefabricated reinforcement mats rolled out, decreasing activities on site compared to traditional reinforcement.

#### **B.4.3 Concrete casting sequences**

By using the permanent formwork system there is no clear distinction needed between casting concrete walls and slabs. Walls and objects are cast in successive sequences. The 4D model objective is to show the flow of Self Compacting Concrete, Figure 19. Casting sequence objects as used in Alternative I are split in smaller 3D CAD objects (Figure 19) to better represent the flow of concrete in 4D CAD simulations.

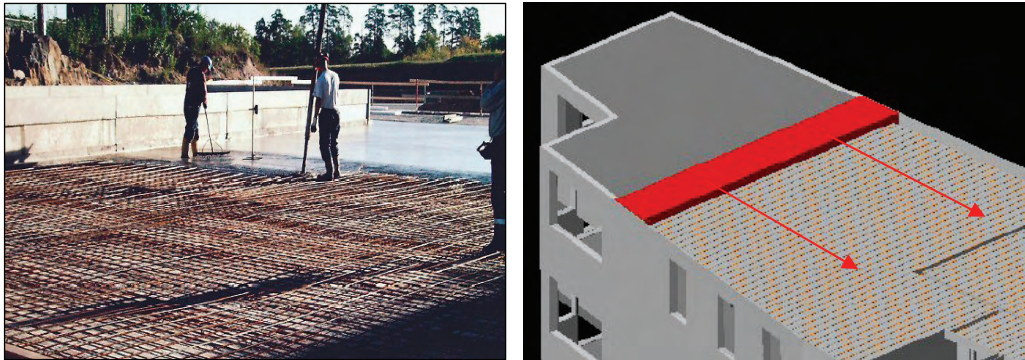


Figure 19: (Left) Casting process of Self Compacting Concrete (SCC) decreases activities on site. Less labour is needed during casting processes compared to traditional concrete. (Right) 4D CAD model representation of SCC-flow (arrows not included in 4D CAD model and later added to clarify image). Red components are in activity, brown components represent installed reinforcement bars and grey components represent permanent formwork, concrete walls and slabs.

#### **B.4.4 Planning**

Construction operations are planned by using Gantt schemas. All formwork elements, including activity length are imported from spread sheets to Gantt schemas. Installation sequencing is done in Gantt schemas by linking activities, i.e. elements. Main scheduling criteria are: work flow direction and work space conflicts.

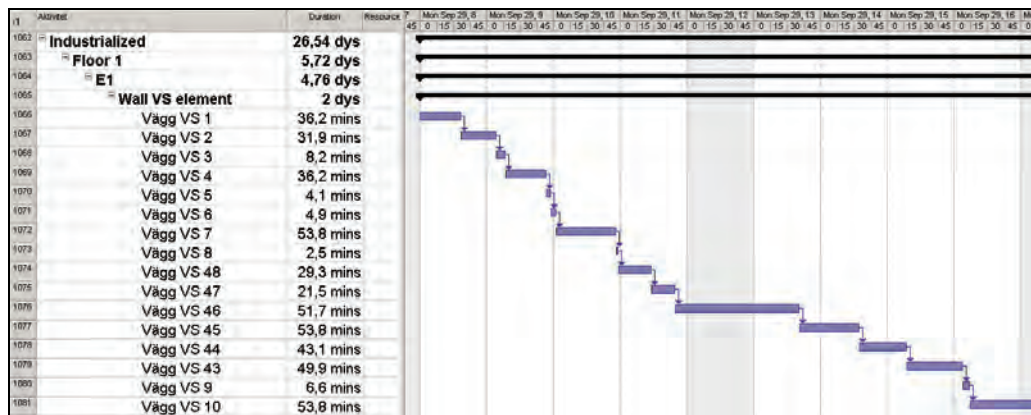


Figure 20: Gantt schema of Alternative II. Activity name and duration are imported from spreadsheets. The order of activities is determined by relations in the Gantt schema.

## B.5 4D results

Both construction alternatives can now be simulated in 4D CAD. The two processes show to some extent similar work flows. Activities for formwork, reinforcement, and concrete are carried out concurrently, enabling and constraining the execution of other activities. The main differences between both alternatives are the dependencies between work flows and the production rate.

In Alternative I these flows are interwoven in a four times two-hour cycle, Figure 15. Delay in one of these flows has almost directly impact on other flows, making it a vulnerable process. For example, a delay in installation of formwork for walls constrains installation of reinforcement and casting of concrete. One construction day is lost when concrete cannot be cast at the end of the day. Construction operations for alternative II are determined by the installation of form elements that do not follow a strict cycle. A delay in the installation of one element does often not have a direct impact on activity flows for reinforcement and concreting.

Simulation of the various work flows in 4D CAD provides users with a visual impression of the differences between construction alternatives and their work flows. However, these visualizations do not directly provide users with data to compare alternatives. As an example the 4D comparison included in Figure 21 can be given. What is compared in the two alternatives? What performance does one compare? Work spaces, resources, ect.? These observations and questions serve as a point of departure for research carried out at CIFE in 2004, which is reported in (Jongeling 2005b; Jongeling 2004a).

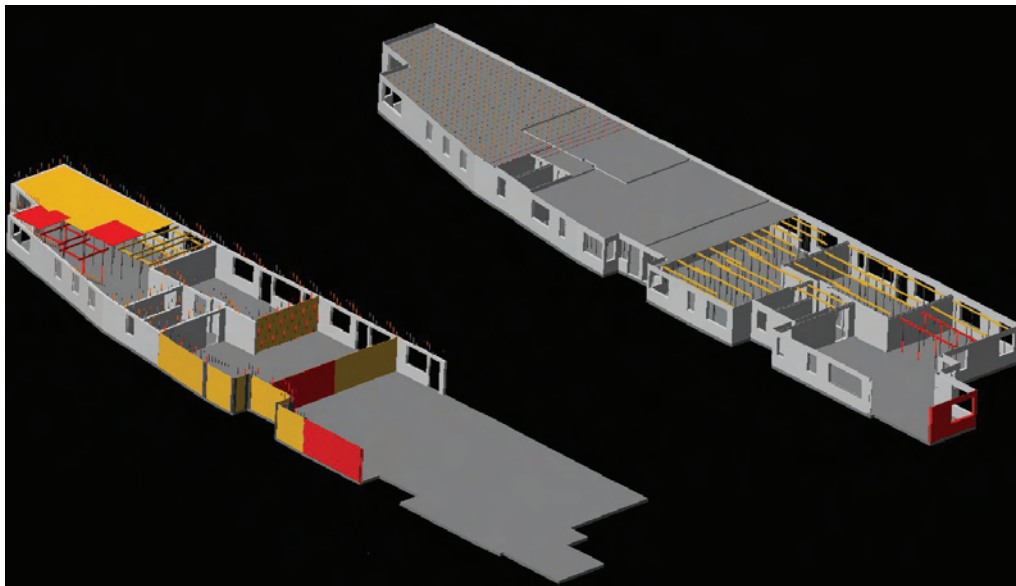


Figure 21: Comparison of construction alternatives in a 4D CAD environment. What is compared? (Left) Alternative I: 0 Reference process. (Right) Alternative II: Industrialized approach. Red components are in activity, yellow components represent installed traditional formwork, brown components represent installed reinforcement bars and grey components represent permanent formwork, finished concrete walls and concrete slabs.

## **Appendix C 5D COST ESTIMATION**

### **C.1 Introduction**

This appendix to the ITstomme report describes the background and developments regarding the 5D cost estimation process.

Today's modern object oriented 3D CAD systems can in most cases calculate and make reports of quantity of material needed in a building project, so-called BoM, 'Bills Of Material'. This is because the CAD objects are parametric and built up by different property values that generate the graphics like 'width', 'height', 'length', etc. The CAD objects can also have non-graphical properties like 'material', 'classification code' etc.

The current cost estimation process, are still based on 'non-intelligent' 2D drawings. All quantity take-offs are still calculated manually, by measuring the drawings. It is not a big difference if the drawing is created with a CAD system, or with a pen. This process is very time consuming and has to redone, each time a revision of the project is made.

The goal of the 5D developments in the ITstomme project is to automate the process of calculating bills of material, and also sort it in a way, so that it better suits the needs for the cost calculating process, and cost calculating software tools. The proposed method is to let the cost calculator organize the product model in a 'cost hierarchy', by grouping all CAD objects of same type, to a '5D cost object'. These objects are then mapped to a cost 'recipe' and transferred to the cost estimating system.



## **C.2 Current praxis**

Cost estimation is an important and time consuming process. It is done many times during a project lifecycle. At JM, three types of cost calculations are made in a typical project:

1. Pre cost estimate, which is based on experience ‘key values’ (Förhandskalkyl)
2. Base cost estimate, which is based on early stage drawings (Grundkalkyl)
3. Production cost estimate, which is based on building drawings.

In this project we will include number 2 and 3.

### **C.2.1 Quantity take-off process**

To be able to make a cost estimate, the amount of needed material (the volume of different building parts), needs to be calculated. The common praxis is to measure from drawings and store this data in a spreadsheet. Quantity take-offs are typically measured in units like perimeter (m), area (m<sup>2</sup>) or volume (m<sup>3</sup>).

Different quantity items are calculated with different accuracies. In some cases more generic (non exact) quantities are calculated such as ‘facade area’, but in other cases more exact quantities are used e.g. ‘number of columns’. Some quantities are calculated from drawings produced by the architect and some from the structural engineer’s drawings.

When JM makes quantity take-offs, they are typically grouped by the location in the building, or by the different contract boundaries. The quantity take-off can also be sorted by phases in a project. In a cost calculating system this is called (in Swedish) an ‘Upost’. The quantity calculation is either made by specialised ‘quantity take-off’ companies such as (in Sweden), ‘Mängda’ and ‘Bygganalys’, or by the contractor / project management themselves. Building parts of same type is summarized, as one quantity item, e.g. all inner walls at a certain location. One big drawback in current process is that the whole calculation has to be redone, every time the drawings are changed.

To define and transfer the semantics of the information, different classification systems are developed e.g. (in Sweden) SBEF, and BSAB. The SBEF system is quite old, and sorts the building parts in a logical system with codes from 0 to 99, where 0 means ground works and 99 means roof. The BSAB system is

newer and more comprehensive, and will substitute the SBEF system in due time.

### **C.2.2 Transfer quantities to cost estimation systems**

To transfer the bills of quantities, to cost estimating software tools there are standardised file formats available. The two most common are the SBEF file and the newer sbXML file.

The cost estimation process at JM is currently based on the SBEF system and for this reason this system is applied within the ITstomme project. However, the developed concepts in the project are fully applicable to the BSAB system and can be developed to support the sbXML file format.

### **C.2.3 Cost calculation process**

When the quantities are imported to a cost calculating system, it has to be mapped with a 'recipe' code, which is the way how a cost calculating system works: Each building part, e.g. a wall, can be constructed in many ways - by in-situ cast concrete, by wood and panels, by bricks etc. Each type of construction is called a 'building part type'. When later the building part types are constructed, these types are used as 'activities' or 'methods' such as building the form, pouring the concrete etc, and 'resources' such as concrete, reinforcement, labour etc. The result of these activities and resources is called a 'production result'. The geographical position of a building part inside a building is called a 'location'.

A recipe in the cost calculating system, knows the needed material and labour (resources) and also activities (methods) needed to build one unit of a building part type (typically 1 square meter). Using this principle it is not needed to manually calculate each nail in a building. The recipe knows how many there are needed to construct 1 m<sup>2</sup>. This process is called Activity-Based Costing (ABC).

## **C.3 Proposed method**

In product models from different design disciplines it is important to define which CAD objects (from a specific application and discipline) are the 'information carriers' to generate quantities for different building parts. This is due to the fact that there might be some overlapping between the design disciplines. In this project we made a study of the division between architects' CAD objects, and structural engineers' CAD objects.

Product models are typically sorted in a hierarchy that reflects the logical location of a building part within the building. This can also be expressed as a path in the model e.g.

BUILDING/STOREYS/GROUNDFLOOR/LOAD BEARING  
STRUCTURES/COLUMNS/COLUMNOBJECT

The traditional view of a product model is a reflection of the designers' view, resulting in a kind of logical sorted model, based on building parts or material. This is very obvious and explainable, if we analyse how drawing layers in the past have been defined. The common (in Sweden) 'Point' layer standard consists of a mixture of building parts (e.g. columns, beams, windows) and materials (concrete, steel, wood).

We have found out that the cost calculator's view differs completely from the designer's view. As mentioned earlier, their view is based on phases, contracts, or construction methods. Therefore there is a need for more than one static hierarchy. Actually, each actor in the building process might need to organize the data differently.

During 2002, a similar integration project between product models and estimating tools was performed (Edgar 2002). One of the conclusions of that project was that each separate CAD object cannot generate a separate cost item. There will be too many items and this is not the way a cost calculator works. Instead the CAD objects must be grouped by the same type; exactly in the same way as the quantity take-offs of today are grouped by building part types. As a first practical step, we propose that the cost calculator 'maps' (groups) the CAD model to different building part types. We call each such group a '5D object', and the quantity is the derived sum of all CAD objects that are mapped to it. After this the 5D object must be classified. To do so the cost calculator must define which classification code to use (or in other words: the recipe code that the cost estimating system uses).

The optimal case would be product models delivered by consultants that already have the recipe codes defined. There are a few pioneering companies that provide their consultants with standardized libraries that have to be used when the consultants created their product models. However this is not the main practise in the building sector today. Theoretically this is of course the optimal solution, but the building process and most of today's companies are not organised in this way today. To succeed with this method, the designers must be much more integrated and steered by their clients, such as JM.

To sum up: to be able to automate the quantity take-off process, and cost calculation process, the CAD objects needs to be :

- Sorted in a 5D cost hierarchy
- Grouped as 5D Cost Items
- Marked with a recipe code

Either this task is done by the cost calculator, or preferably by the designers, during the design process.

#### **C.4 Implemented method**

A product model is typically sorted in one hierarchy. The hierarchy reflects the different locations in a building (based on the designers view). This makes it easy to generate bills of quantities for a certain location. Queries can be asked to the database, such as ‘how many concrete walls of 160mm width exist on floor 2?’

In the hierarchy of a product model, objects are also sorted by building parts on a lower level in the hierarchy. These are called classes and typically define the characteristics or type of objects, e.g. columns, beams, walls etc. The classes can be compared with the way a 2D drawing is sorted by layer names. The class could in the future be marked with a classification code such as the (in Sweden) BSAB standard.

A model hierarchy can consist of many subclasses and at the lowest level in the hierarchy the CAD objects are stored. Each object is owned by another object. This is typically called a ‘master-slave’ relation. If a user makes a copy of floor 1 as floor 2 then all sublevels (called nodes) are also copied and e.g. moved.

##### **C.4.1 Mapping and grouping to 5D objects**

In the receiving cost calculating system MAP, the hierarchy (the locations), are expressed in maximum 5 levels. The locations are defined by a code in the format ‘1.1.1.1.1’. Instead of classes, MAP has codes such as the SBEF system mentioned above. E.g. ‘63’ means ‘Inner walls’. To be able to reflect the product model from a cost calculator’s view, a new 5D hierarchy must be created. In this hierarchy we could add classes, so that they reflect the SBEF codes, such as 63\_Innerwalls.

All standard recipes that JM uses must be stored in a library that accessible by all designers over Internet. For this purpose an XML file is developed and placed at a server. In the model viewer software developed in the ITstomme project, a new 5D user interface has been developed where the cost calculator can create a 5D hierarchy, and can perform the grouping and mapping work. The CAD objects that belong (that is owned) by a 5D node, is linked to the 5D hierarchy.

The final work order for the cost calculator is:

- Create a suitable 5D hierarchy, reflecting the calculation needs (e.g. based on a phase or contract)
- Choose a specific type of building part (e.g. walls). This will limit the amount of available SBEF codes, meaning choosing the right class (e.g. 63\_Innerwalls)
- Choose a recipe code, from the available recipe list for a class.
- Select from the screen, or by the tree view, the CAD objects that should be mapped with the 5D Object.
- Select 'Link', and the volume or another parameter of selected objects is summarized, and 5D-links are created to the objects.

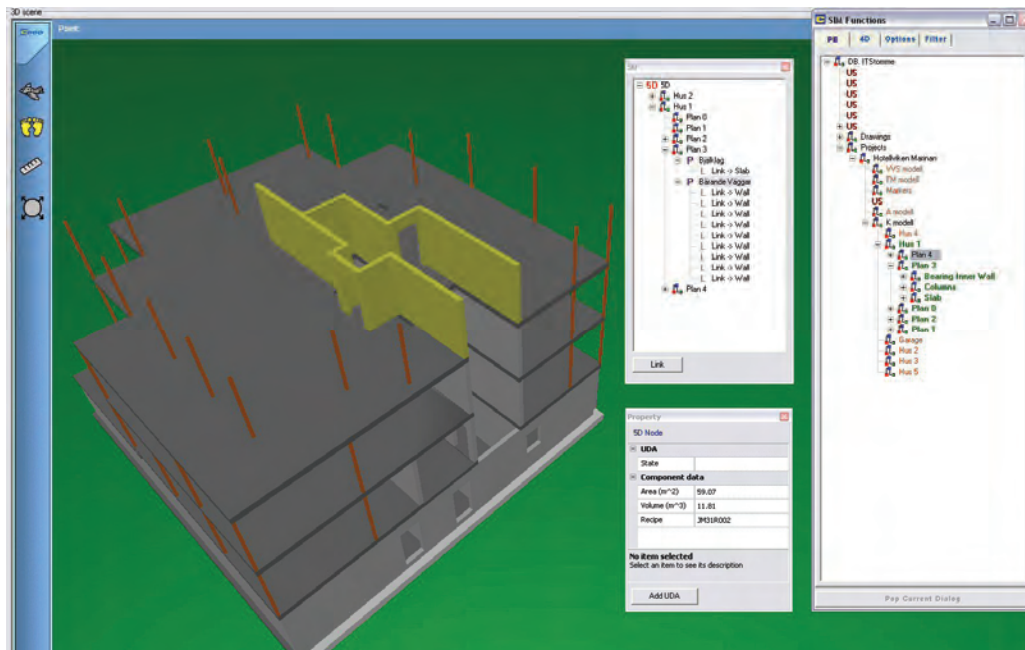


Figure 22: Screen capture from the 5D cost estimation process by using a model viewer developed in the ITstomme project. 3D objects are selected by an estimator in the 3D scene (left) or via the PE (Project Explorer) (right) after which a cost estimation post is created in a so-called 5D hierarchy (on the left of the PE). A cost estimation file is created from the 5D hierarchy and used in cost estimation software. The 5D and Property window are enlarged in Figure 23.

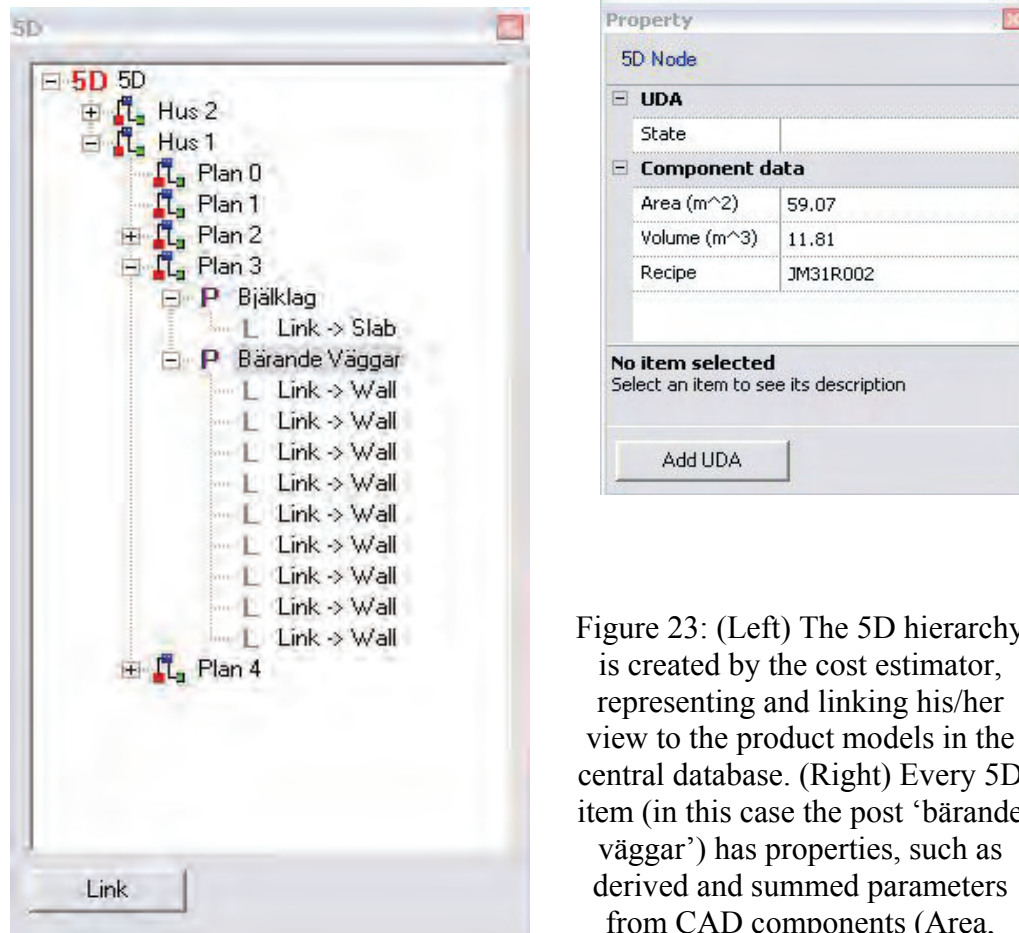


Figure 23: (Left) The 5D hierarchy is created by the cost estimator, representing and linking his/her view to the product models in the central database. (Right) Every 5D item (in this case the post 'bärande väggar') has properties, such as derived and summed parameters from CAD components (Area, Volume) and a Recipe obtained from a recipe database.

## C.4.2 Reports of quantities and 5D cost items

A special report definition to generate so-called 5D reports has been developed in the ITStomme project. A report can be generated via the Internet, by using a web portal to access the central database, Figure 24. From the reporting tool a XML file is exported and converted to a SBEF file by a program developed in this project, Figure 25.

The screenshot shows the 5DPost software interface. On the left is a tree view of the project structure, including 'DB: ITStomme', 'Projects', 'Drawings', and '5D'. The main window displays a table titled 'ITStomme 5D Posts' with the following data:

ID	Name	Building part code	Quantity	Unit	Recipe	State
30286	Bjälklag (Slab)				JM34R003	
30288	Bärande Väggar (Wall)				JM31R002	uncheck
30298	Bjälklag (Slab)				JM34R003	
30313	Bärande Väggar (Wall)				JMR002	uncheck
30323	Bärande 160mm (Wall)				JM31R001	uncheck
30438	Bärande Väggar (Wall)	07	87.78	m2	JMR001	uncheck
30463	Bjälklag (Slab)	07	80.32	m2	JM34R005	
30477	Bärande Väggar (Wall)	07	106.6	m2	JMR003	uncheck
30490	Bjälklag (Slab)	07	278.92	m2	JM34R006	
30501	Bärande Väggar (Wall)	07	99.09	m2	JMR004	uncheck
30514	Bjälklag (Slab)	07	243.08	m2	JM34R004	
30517	Bärande Väggar (Wall)	07	59.07	m2	JM31R003	uncheck
30518	Bjälklag (Slab)	07	243.19	m2	JM34R002	
30529	Bärande Väggar (Wall)	07	7.01	m2	JMR001	uncheck
30530	Bjälklag (Slab)	07	196.97	m2	JM34R002	

Figure 24: An example of a 5D report, which is saved as a XML file and converted to a SBEF file that can be imported to the MAP cost estimation system in use at JM



```

A      05-06-2110:17101åååååå
C111111 Enterprixe report ITSTomme_5DPOST_Ver_2.xml converted to TEST.SBF
D
E
F
M0001000003043807      000008778 m2      JMR001
T   Bärande Väggar {Wall}
M0002000003046307      000008032 m2      JM34R005
T   Bjälklag {Slab}
M0003000003047707      000010660 m2      JMR003
T   Bärande Väggar {Wall}
M0004000003049007      000027892 m2      JM34R006
T   Bjälklag {Slab}
M0005000003050107      000009909 m2      JMR004
T   Bärande Väggar {Wall}
M0006000003051407      000024308 m2      JM34R004
T   Bjälklag {Slab}
M0007000003051707      000005907 m2      JM31R003
T   Bärande Väggar {Wall}
M0008000003051807      000024319 m2      JM34R002
T   Bjälklag {Slab}
    
```

Figure 25: Example of a SBEF file that can be imported to by the cost estimator

### C.4.3 Importing the quantities to MAP

MAP has an import function to read SBEF files. When the file is imported, all cost items have full the intelligence. Different cost calculations can be made for different ‘Cost locations’ in the building.

MAP will calculate the cost, by using the attached recipe and quantity information. The whole process to quantify, to sort and to create 5D items in MAP is now much more automated and efficient compared to current praxis.