nD MODELLING IN THE DEVELOPMENT OF CAST IN PLACE CONCRETE STRUCTURES

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SUMMARY: *The Swedish IT-stomme (IT-structure) project is a two year research project, which is aimed at applying product models in practice and developing modelling tools for cast in place concrete structures. Implementations and applications discussed in this paper are mainly driven by the interests from a ready mixed concrete supplier who identified product modelling as a threat and as an opportunity for its business process. A number of product model dimensions is discussed that result from combining different software applications. An example of a potential n^{th} dimension of product model development and use is given, in addition to a product model's 2^{nd}, 3^{rd}, 4^{th} and 5^{th} dimension. The n^{th} dimension is illustrated by integrating a product model with results from a program used to calculate the optimal drying process for concrete slabs. This paper concludes by discussing main challenges for the uptake of product models in practice in relation to findings and efforts from the IT-stomme project.*

KEYWORDS: *product modelling, cast in place concrete, nD*

1. INTRODUCTION

The Swedish IT-stomme (IT-structure) project is a two year research project, which is aimed at applying product models in practice and developing modelling tools for cast in place concrete structures. The project was initiated in September 2003 by Luleå University of Technology and aims to establish routines for design, estimation and planning in a product modelling environment.

In this paper we discuss the research and development work on the issues of integration of different model dimensions among different actors in the IT-stomme project. The main actors in the project are Betongindustri, a ready mixed concrete supplier, and JM which is a residential project developer. In a joint feasibility study it was 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 (Jongeling 2003). As a result, both companies joined the IT-stomme project to study the application of product models in a real construction project.

The definition and interpretation of product modelling are first discussed. Secondly, the concrete supplier's motivation to study product modelling is analysed after which the product modelling system used in the IT-stomme project is presented. Thirdly, the different model dimensions of product modelling are presented, illustrated by examples from a case study project. Finally, the result of the study on the different model dimensions are analysed and discussed. This paper does not discuss 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 ready mixed concrete supplier.

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 2004b; 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). An 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 Virtual Building Environment (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. 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 paper 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 2004b). Within the IT-stomme project a client-server modelling system has been developed and applied in a case study. Before we describe the product modelling system used in the case study, the motivation of the cast in place concrete industry to adapt product modelling and to develop product modelling systems is discussed next.

3. MOTIVATION: PRODUCT MODELLING FOR CAST IN PLACE CONCRETE

There is an increasing interest of the Swedish cast in place concrete industry in product modelling technology. 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 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. 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. The number of possibilities and limitations that we have identified from the reasoning above are summarized in TABLE 1.

TABLE 1: Possibilities and limitations in use of product models for cast in place concrete from the perspective of a concrete supplier

Possibilities	**Limitations / Constraints**
Simulation of innovative products and production processes.	Design objects differ from production objects.
Material specifications integrated in product models.	Limited support in CAD applications for modelling of cast in place concrete objects.
Product models linked and associate with data, such as results of technical calculations.	Material specifications are often not linked to or specified in product models

These possibilities and limitations serve as a starting point to formulate a number of improvements in product modelling environments for the cast in place concrete industry. Before these developments and applications are discussed, we will introduce the product modelling environment applied in the case study of the IT-stomme project.

4. PRODUCT MODELLING ENVIRONMENT

A residential construction project is modelled in the IT-stomme project with an Internet-based product modelling system developed by Enterprixe Software Limited (Enterprixe 2002). The system 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 central database, Fig.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 VRML viewer embedded in an Internet browser are used as software clients to the product model server in the IT-stomme project. Many actors are already familiar with AutoCAD in Sweden and the transition to a model-based practice using AutoCAD as an interface facilitates this process.

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 2004). IFC objects are uploaded from ADT to the central database, where they become available for all project participants.

check out a valuable product model server functionality that reduces the risk for double work and product model inconsistency.

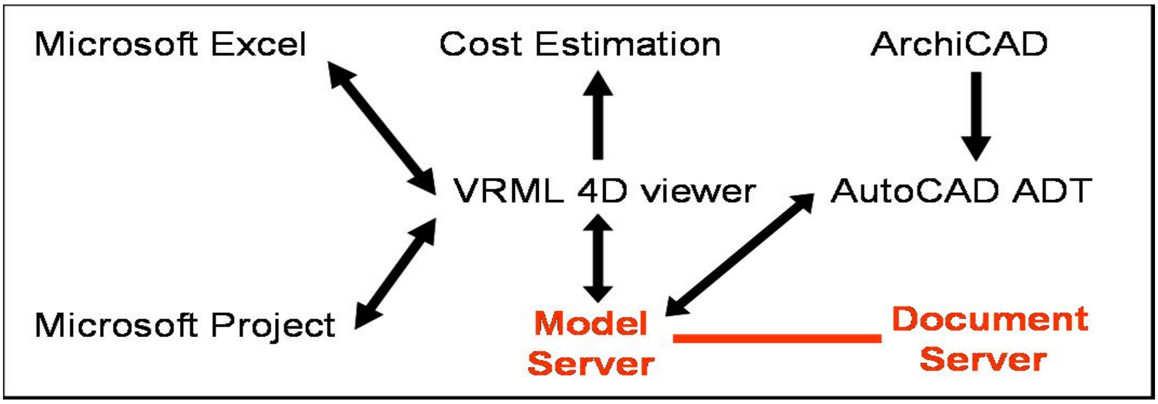

FIG. 1: The product modelling environment of the IT-stomme project. The model server and document server are two different systems, but have been integrated in the IT-stomme project and act as one system. Different software systems can be used to create, edit and use product model data. Examples of these systems are AutoCAD, Microsoft Excel, Microsoft Project and a VRML 4D model viewer.

The product model is loaded from the product model server to local computers and constantly updated when connected to the server. The case study product model contains approximately 3000 objects. It is possible to load or unload parts of the product model. The product model server keeps track of users who create an element or who edit one. Fig2. 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. Modelling work is concurrently carried out by multiple co-located users within the IT-stomme project. Project participants consider the partial product model check in and

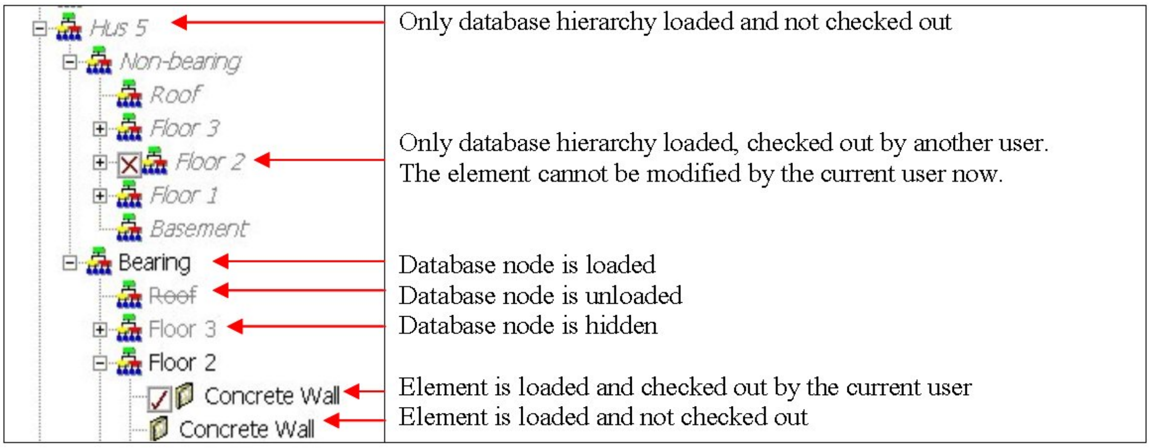

FIG. 2: A tree view of the product model at the product model server. Partial product model check in and check out functionality is used to reduce the risk for double work and product model inconsistency.

5. CASE STUDY

To illustrate the use of product models for cast in place concrete, a “real world” test case is used: the Hotellviken project, which is developed and built by JM. The project comprises the construction of 120 apartments of which the first phase is addressed in this paper. Phase one consists of five multi-storey apartment blocks (in total 25 apartments) of which two are connected with a parking garage.

FIG. *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 Hotellviken project is ongoing during the IT-stomme project and is modelled in parallel to the traditional 2D paper-based design and construction process. 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.
- Multiple production plannings are linked to 3D models resulting in 4D models.
- 3D models are mapped to cost estimation hierarchies providing a 5th dimension.
- Model use and configuration by the ready mixed concrete supplier provides an additional dimension.

These product model applications are discussed in the following section and illustrate the use of a product model beyond 3D graphics.

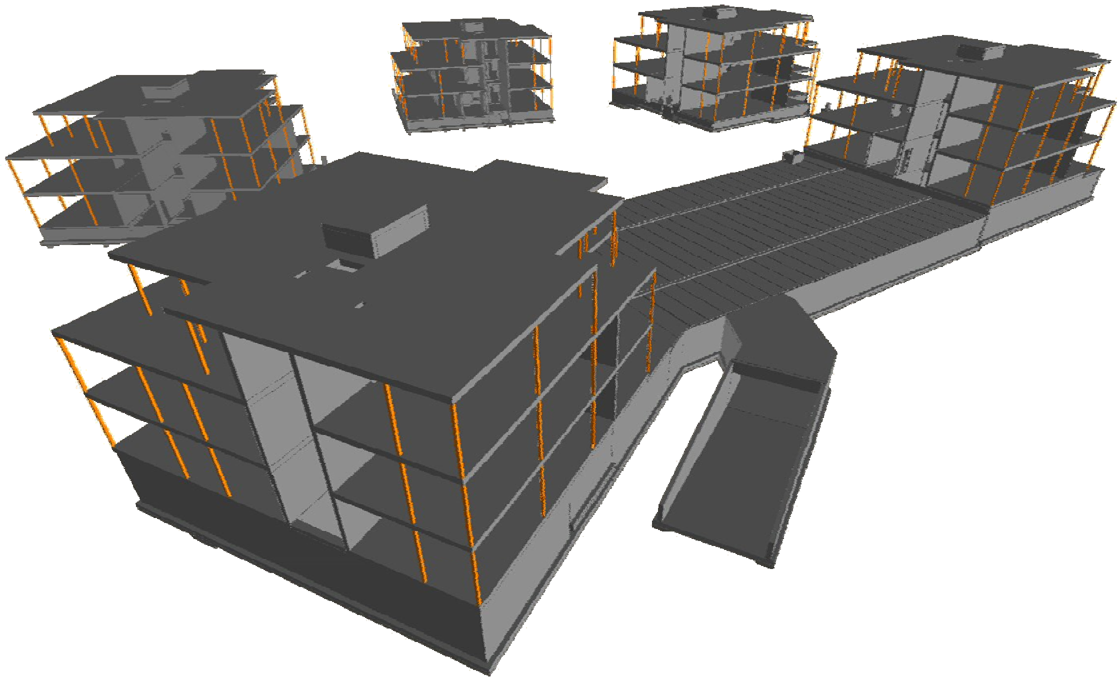

FIG. 3: Bearing structure of the Hotellviken project.

6. FROM 2D TO 3D

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, Fig.4 A. 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 exits 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.

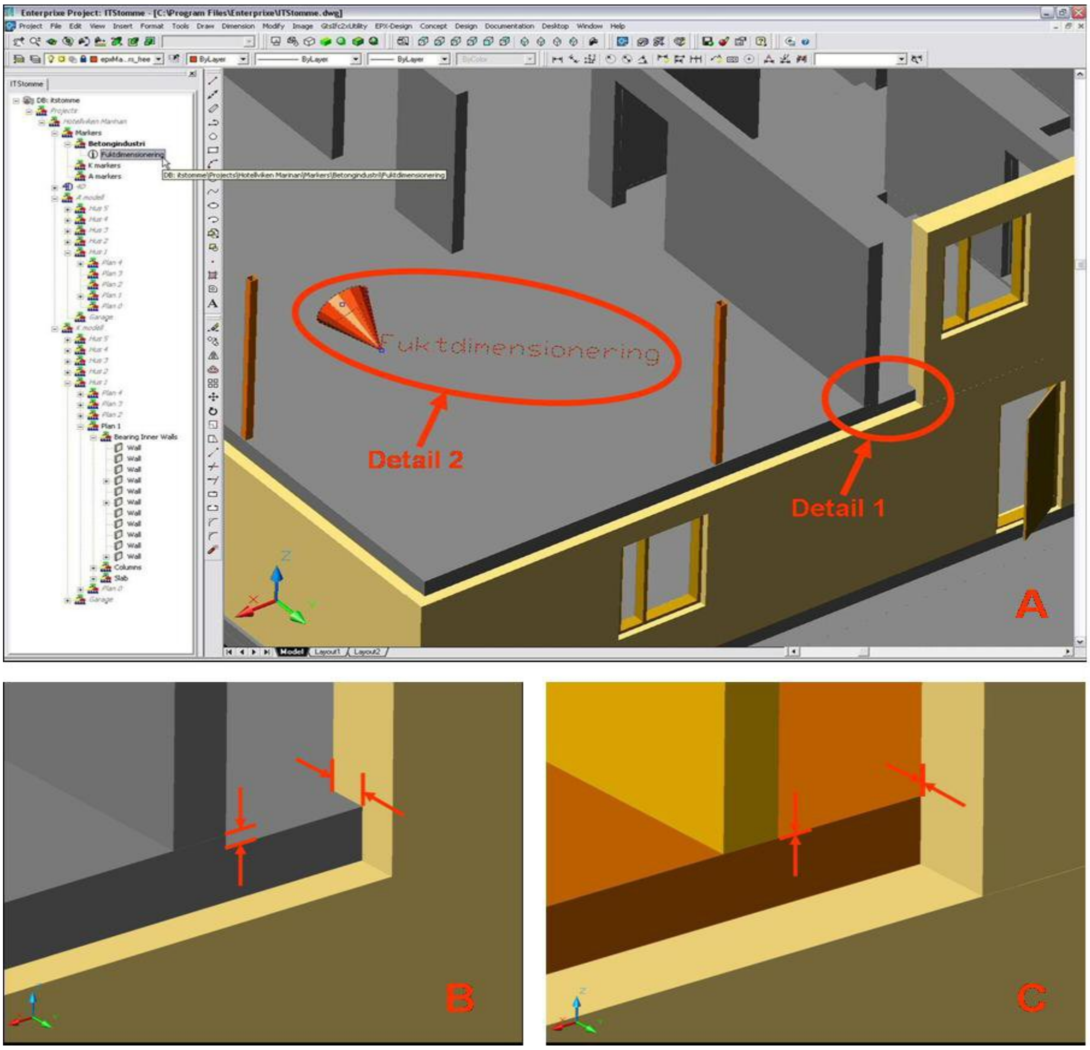

FIG. 4: (A) A product model in AutoCAD ADT connected to the Enterprixe product model server. Detail 1 illustrates different views on modelling by a structural engineer (B) and an architect (C). The architect modelled the slab as one volume, whereas the structural engineer modelled different concrete 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 sever.

The following solutions were applied in the IT-stomme project to combine 2D data with product models and to make this data and product models available for all project participants:

- Separate architectural and structural models were created of Hotellviken instead of an all-including single product model. All other design, such as building services design, was done according to a traditional 2D practice. The architectural model was modelled in ArchiCAD and exported as an IFC2x file to AutoCAD ADT. The IFC2x file was uploaded from AutoCAD ADT to the central database where it became available for all project participants. The structural model was modelled in AutoCAD ADT, used as client-software to the central database.
- Views were generated from 3D models to which 2D geometric primitives were added in paper space. We call this a hybrid design document type. The views were saved at the model server and could automatically be updated with product model data when required. 2D data, such as reinforcement bar detailing, could only manually be updated per view.
- Product model views and other documents were located at a document server and were hyperlinked to the product model. Links were 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 were used in the model that contained links to the document server. Different pointer objects were available for different disciplines to facilitate information management, Fig. 4 A.
- A VRML model viewer was used as client software to view the product model in the central database and to browse through hyperlinked data.

6.1 Analysis

Working with two separate product models proved to be beneficial, but also showed limitations. An advantage of a separate product model per design discipline was that both the architect and structural engineer could have their own view on their design practice, which they were familiar with. Legal concerns by project participants were minimized with this approach, which facilitated the acceptance and uptake of 3D modelling. A disadvantage of this approach was the lack of coordination between different models. Updates in the architectural model that affected the structural model had to be propagated manually in the structural model. Product model clash detection software (Commonpoint 2004; Navisworks 2004) or model checking software (Solibri 2004) was not used in the IT-stomme project, but could have saved time and increased the accuracy in the process of coordination product models from different disciplines.

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

Project actors that did not have CAD software installed could view and browse the product model with inexpensive viewing clients. To illustrate: at the start of the IT-stomme project there was one CAD system available at JM and one at Betongindustri. No experienced CAD personnel was available to operate CAD systems as product model server clients in the two organizations. Using Internet explorer-based product model viewers facilitated the uptake of product model use in both organisations. Model views and other documents, located at a document server, became centrally available by using product model viewers. Using the 3D model was believed to add to project participants' understanding of to what part of the model the different documents and views were 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 were 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. FROM 3D TO 4D

Architectural and structural models served as a basis for 4D modelling and simulation. 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). The method concentrates mainly on the temporal aspect of construction planning 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).

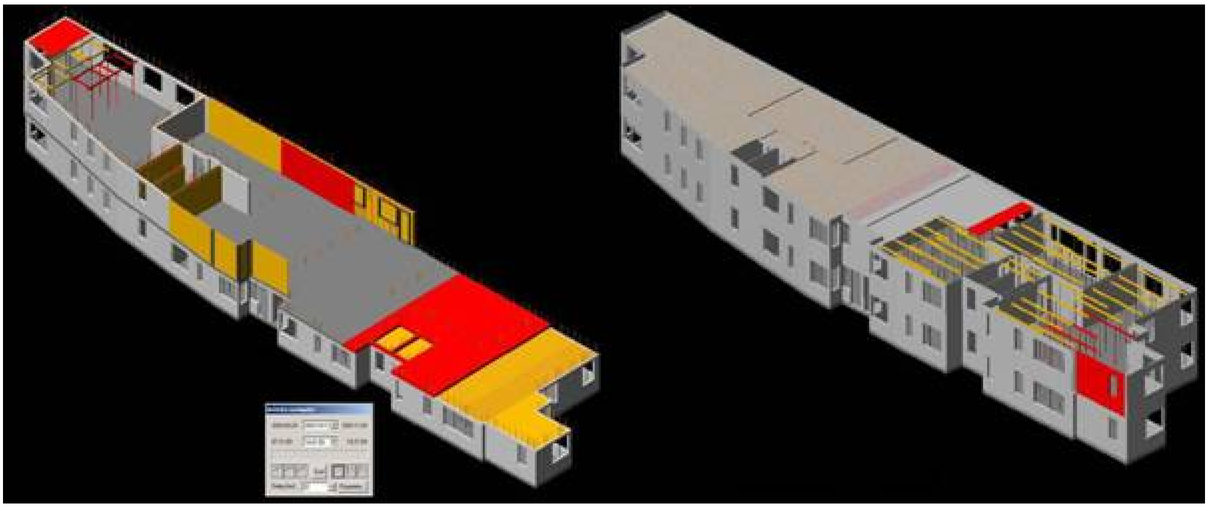

FIG. 5: Parallel simulation and comparison of construction alternatives in 4D CAD. (Left) Traditional production technology. (Right) Industrialized practice combining innovative technologies, such as permanent formwork systems, reinforcement carpets and self-compacting concrete. Colour settings in simulations: Red = in activity, grey = finished elements, yellow = traditional formwork and shoring elements

Within the IT-stomme project 4D CAD was used as an instrument to introduce construction innovations and to evaluate construction alternatives for cast in place concrete construction. Two alternative models were created of a project similar to Hotellviken in order to compare different construction methods (Jongeling 2004b), FIG. 5. The first alternative, the 0-Reference scenario, represented today's common practice for cast in place concrete construction. The objective of this scenario was to represent typical sequenced and concurrent activities on a construction site that are related to casting of concrete walls and slabs. The second alternative provided an industrialized approach to cast in place concrete construction. A number of innovative production technologies formed the basis for this alternative. The objective was 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 had not been applied in actual projects in Sweden and the possibility to evaluate these methods in a virtual environment was considered to be useful.

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

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

7.1 Analysis

Both construction alternatives were simulated in parallel in 4D CAD. A number of time-space conflicts was detected during the 4D modelling process, that had not been detected in the CPM schedule. Parallel visualization was considered effective to visually explain the differences between the two construction alternatives. The simulations were evaluated by a number of professionals and it was generally agreed that the 4D models helped to understand the different construction processes, but it was noted that the models were limited in scope and non-interactive. The client-server product modelling system was considered too slow and too unstable for presentation of 4D model results in project meetings and at seminars. Standard construction sequences were therefore recorded in AVI-format, limiting the interaction with the models.

Evaluation of alternative work flow strategies or changes in productivity could not easily be managed in the 4D models. The 3D CAD objects in the production models that had been created and grouped to represent specific activities, i.e. formwork, reinforcement and concreting, constrained the rapid evaluations of alternatives. Changes in the architectural and structural model and changes in the schedule implied often major changes in the production model. The detailed production models required considerable modelling effort and were due to their complexity and interdependencies difficult to manage. The complexity of the CPM schedules that contained a large number of dependencies between activities further constrained 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.

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

- Akbas (2004) proposes a geometry-based process model (GPM). The use of geometry in this approach is not limited to visualization, but is integrally used to model and simulate processes. 4D input models are decomposed into sub-systems. Every sub-system contains crew parameters, geometric work locations and interactions. The approach then reduces this process model into queuing networks and uses discrete event simulation to simulate construction operations. Each of these steps uses geometric techniques, such as triangle meshes and geometry sorting. Applying GPM to the comparison of construction alternatives in this study could possibly have reduced the modelling work related to splitting 3D CAD objects into production objects of appropriate size. GPM could also have reduced the level of detail of both the CPM schedules and 3D models, and could have facilitated the planning of work flow directions.
- Adding CAD objects to represent for example temporary structures, such as traditional formwork elements, 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 possibly have reduced the modelling work for the 4D simulations 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 scheduling techniques (Kenley 2004) can possibly provide an alternative for or addition to CPM based scheduling for 4D CAD.

As a future extension of the IT-stomme project and conducted 4D simulations, we plan a number of simulations with developed GPM prototype software. In addition to experiments with GPM, we plan a study to evaluate feature-based 4D models and integration of Line-of-Balance planning software (DSS 2004) with 4D CAD.

8. FROM 3D TO 5D AND BEYOND

In addition to the 2nd, 3rd and 4th dimension, we studied and developed integration of product models with cost data to facilitate the cost estimation process. This process is referred to as 5D modelling (Edgar 2002). Currently the quantity take off is done manually from paper drawings, which is time consuming and prone to errors.

The cost estimation process with the use of product models was not as straightforward as multiplying model object quantities with unit costs. Certain product model objects were abstract representations of object assemblies that required mapping of cost and resource recipes with product model objects. For this purpose, a separate estimation hierarchy was created in the database that was mapped to model objects from the architectural and structural object hierarchies. The process of mapping included the creation of an estimation hierarchy to which product model objects were linked. The estimation hierarchy was created according to a Swedish estimation process standard. Standardized model-based estimation files were exported from the product model server to cost estimation software. Data from the product model was mapped in the estimation software with recipes from JM's cost and resource database, resulting in cost estimates and a preliminary production planning. Recipes in the database contained the approximate amount of resources and materials needed for the construction of model objects.

By using standardized object types and recipes one can enhance standardization of products and processes, and can semi-automatically generate a 4th dimension (Jongeling 2004a). 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. Input to product models from expert systems used by a supplier to calculate material properties can be an example of the configuration of a product model by specialists and illustrates an nth dimension of product model use.

8.1 nth dimension

Within the IT-stomme project we illustrated a product model's nth dimension by using a program called TorkaS. TorkaS served as a typical example for the integration of product data into a product model. The program is used to calculate the optimal drying process of concrete slabs. 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% before they can be covered by other floor material. A relative humidity higher than 85% can result in moisture damage, such as mould, which is negatively affecting the indoor climate of a building (Hedenblad 1996).

The output of TorkaS consists of time frames for the drying process of slabs and material properties, such as specific concrete classes and Water to Cement ratios, Fig.6. The material properties, determining the drying process, were configured in the product model of Hotellviken by using VRML clients to the central product model server. The time frames were integrated in the construction planning and linked to the product model. The model was browsed in 4D, using the VRML model viewers. Standardized property reports, including product data specifications, were linked to slabs in the product model via pointer objects, Fig.4 A, in addition to configured slab properties and 4D simulations.

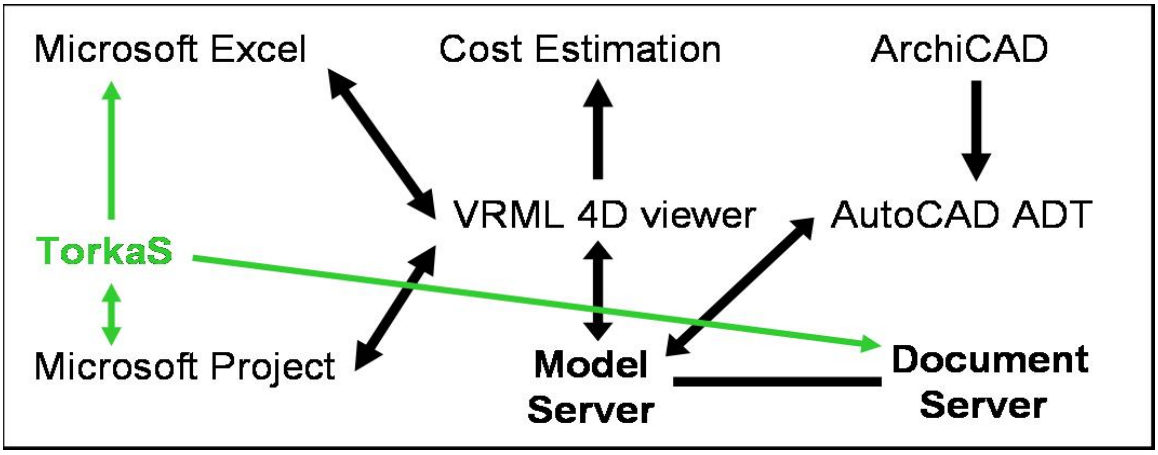

FIG. 6: TorkaS, a program to calculate the optimal drying process of concrete slabs, is used as an example of the integration of product data into a product model. The output from the TorkaS program is used to configure product model object properties, using Microsoft Excel. Planning data from TorkaS is used in Microsoft Project, which is linked to the product model and used for 4D simulations. Calculation reports from TorkaS are located at a document server and linked to the product model.

8.2 Analysis

The 5th dimension to product modelling has been demonstrated in a number of research initiatives (Edgar 2002; Kam 2002; Laitinen 1998) and is already commercially applied. As a result, 5D implementation in the IT-stomme project was a proof of concept for the project participants. 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 relevance of configuring product model contents by a ready mixed concrete supplier was 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.

9. DISCUSSION AND RECOMMENDATIONS

The objective of the IT-stomme study was to illustrate and develop the use of product models in practice beyond 3D modelling. Despite the possibilities of different model dimensions reported in this paper, the uptake is slow and the comprehensive use is poor. 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 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. According to (Lee 2004), the five biggest challenges for the use of product modelling that were listed by workshop participants are the following (in prioritized order):

- 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 findings and efforts from the IT-stomme project.

9.1 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.

If was found that professionals had 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 organizations, 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.

9.2 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 2004b).

We illustrated 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 was linked to 3D models. 3D models were used for 4D simulations and 5D cost estimation. In addition to 5D modelling we illustrated a potential n^{th} dimension by integrating property data from a supplier in a product model. These examples illustrated the use of product models beyond 3D modelling.

Although commercially available applications were used for most of the modelling work, there were a number of work arounds and implementations necessary to enable the transition from 3D to nD product model use. Project participants could access the product models by using software, which they already were familiar with. This greatly facilitated 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 IT-stomme 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.

9.3 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 IT-stomme 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 (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.

9.4 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 was adapted in addition to these different models in which 3D model data was combined with manually added 2D data. The architectural and structural models were combined in two production models, in which both models were extended and further detailed.

The multi-model approach implied 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 proved 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.

9.5 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 2004) 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 2004b).

Interoperability was not a major issue in the IT-stomme 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 contained basic objects, such as walls, doors, windows and slabs, and did not result in 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 IT-stomme project also showed that different dimensions can be added to a product model independently from standardized data schemas.

10. CONCLUSIONS

The use of product models beyond 3D graphics is currently limited. This paper illustrated a number of dimensions in addition to 3D by combining results from different software applications. Comprehensive use of product models is still limited and uptake is slow, despite advantages of model dimensions illustrated in this paper. Major challenges for the use of product modelling are education, cultural change and the need to demonstrate the value and effectiveness of nD modelling in viable business cases. Research initiatives have mainly concentrated around technical challenges, such as data issues and interoperability. Organizational studies should be prioritised to facilitate the uptake of product modelling in the industry.

Implementations and applications within the IT-stomme project were mainly driven by the interests from a ready mixed concrete supplier who 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 definition of objects. However, the case study project of this study showed that these challenges do not exclude the use of product models for cast in place concrete structures. Advantages and possibilities can be identified for a ready mixed concrete supplier 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.

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