PROJECT ENVIRONMENT AND PROCESS DESIGN OF BUILDING PROJECTS SUPPORTED BY VIRTUAL DESIGN AND CONSTRUCTION METHODS

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ABSTRACT: This paper discusses the project environment and process design of Virtual Design and Construction (VDC) supported building projects. Case studies of the use of VDC methods and tools in construction projects and comparisons made with the evolution of the product development process in the manufacturing industry reveals: (1) Relational contracting in combination with a concurrent engineering process and advanced ICT tools can provide the base for an adaptive Virtual Design and Construction process. (2) There is no single model that contains all project information, but rather a collection of discipline-specific models, including non-model data that can be linked to models. (3) Model information can be exchanged via files or can be available from product model servers. The data format can be proprietary or neutral. (4) An information manager, the Project Information Officer (PIO), is needed who specifies the requirements for model use and who ensures integration of models with other models and with non-model data.

KEYWORDS: virtual design, virtual construction, relational contracting, concurrent engineering.

1 INTRODUCTION

Application of Virtual Design and Construction methods heavily relies on the use of CAD and other IT systems, but is not limited to these tools. The organization of the process is as important as the applied technology in the process. Most of today's construction projects are structured according to a sequential product development process in which each design activity is separated in time and space. This process is often slow and reflects functional oriented organizations, leading to deficient communication and conflicts between the different functional teams in the design and production "relay-race".

Virtual Design and Construction is defined as "the use of multi-disciplinary performance models of design-construction projects, including the product (i.e. facilities), organization of the design-construction-operation team, and work processes, to support explicit and public business objectives" (Fischer and Kunz, 2004). That is, one would like to analyse, simulate and predict the quality of the end product (e.g. a building) and the characteristics of the process to build and operate the product. Both the product and the processes must be virtually designed and simulated, before construction commences, in order to be able to truly evaluate different design and construction alternatives against project objectives.

This paper discusses the project environment, the re-engineering of processes in building projects and information management needed to be able to implement Virtual Design and Construction methods. We believe that the project environment, that is, the distribution of responsibility, the selected remuneration and model for cooperation, is important for the implementation of new innovations in the construction sector. Also, the transition from a document based information delivery process to models must be accompanied by re-engineering of processes and working methods in construction projects. Here, a comparison is made with the evolution of the product development process in the manufacturing industry to get inspiration for change.

2 THE PRODUCT DEVELOPMENT PROCESS IN THE MANUFACTURING INDUSTRY

The manufacturing industry has radically changed over the past century, with a transition from craft production via mass production to lean production. During the 1970s, the product design phase in the manufacturing industry was followed by testing of physical prototypes. The introduction of Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) systems in the 1980s increased the speed of the design and documentation work, but did not radically change the product development process. A major paradigm shift took place in the nineties when the simultaneous product development process, as introduced by the Japanese car industry, was spread over the world. In a benchmarking study of major automotive manufacturers this technique did not only prove to be faster, but also appeared to require less engineering hours and results in products better adapted for the production process, which in turn results in better quality of the end product (Womack 1990). The change of the product development process from a sequential chain of activities to make things more concurrently reduced the time to market of new models. This transformation has taken place at the same time as the modelling methods have become increasingly sophisticated, Figure .

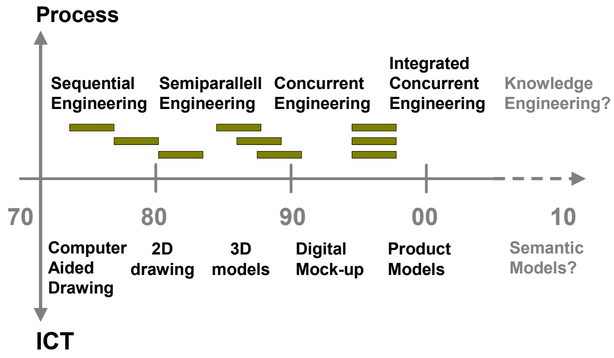

Figure 1. Schematic picture of the evolution of the product development process and modelling methods.

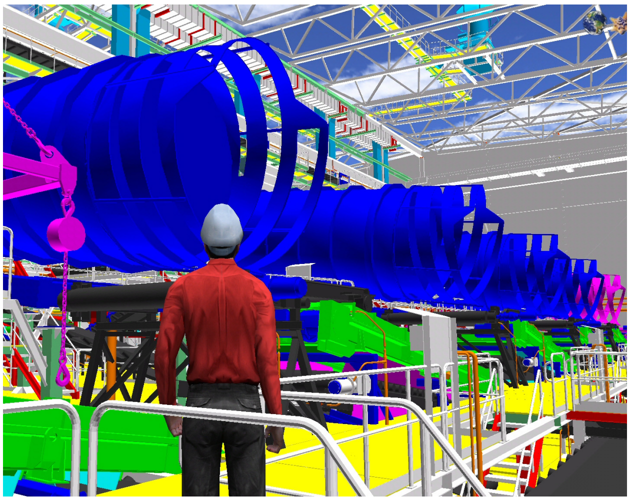

Figure 2. A digital mock-up of a pelletizing process plant under construction, (Woksepp and Olofsson 2006).

Concurrent engineering requires information sharing and tight coordination of the different design teams. The first practical use of virtual reality (VR) was introduced when "digital mock-ups" were started to be used in the design process. Digital mock-ups are VR models of the product, assembled from the different design teams' 3D CAD models (mostly sharing of geometrical data). Digital mock-ups are useful for coordinating design and for communication of design intents to stakeholders, (Woksepp and Olofsson, 2006), Figure 2. An Integrated Concurrent Engineering process (ICE) requires an even tighter integration between different design disciplines. Co-located multidisciplinary teams working on the same data have inspired the CAD developers to engineer product model servers, where designers work in a common model environment. Today, a product can be designed, tested and validated before the first physical prototype is built. Multiple design solutions can be evaluated in a computer, which leads to a faster design process and a more optimized end product. The next step according to many scientists is "knowledge engineering design" supported by semantic models, i.e. model objects have meaning and knowledge of their own performance.

But what has happened in the construction industry? This industry has also seen its transitions, although not as radical as in manufacturing. Some specialized niches in construction show similarities with the manufacturing industry. NCC, a Swedish construction company, launched a residential building concept in spring 2006 where 90% of all components are preassembled in factories, using among other things CAD-CAM technology. The building components are subsequently assembled on site, by craftsmen wearing white gloves, in half of the time compared to traditional construction according to NCC (NCC 2006). It may appear that things have changed in construction. However, the gross volume of construction is still concerned with an outdoor craft based manufacturing and assembly process on the construction site, where different organisations plan and execute their work using document-based information, produced by functional-oriented organisations.

3 PROJECT ENVIRONMENT

Several factors need to be considered when introducing new technology. First, we have to investigate if the new tool makes the process more efficient or if we have to re-engineer the way we work in order to make use of the benefits that the technology can offer. Also, introducing new working methods will affect the organisation and challenge the culture in the company. Secondly, what are the driving forces? In the automotive industry global competition has forced companies to implement new processes and technologies to speed up the time to market for new models. In this context we will discuss the importance of project environment to make use of the full potential of VDC methods and tools in construction projects. The *project environment* is defined as the contractual framework in which the distribution of responsibility, remuneration and cooperation model is determined. Here, time criticality, uncertainty in product design, access to resources and strategic considerations are important.

Miles and Ballard (1997) discuss the needs of contracting models facilitating and supporting cooperation in the construction process (a so called relational oriented contracting form) compared to the traditional transactional forms where the compensation is based on a fixed price model. According to Toolanen et al (2005), the framework for process design in construction projects depends on the distribution of responsibility, the remuneration model and model of cooperation. Table 1 shows some common forms for distribution of responsibility, remuneration and cooperation.

A relational contract supports collaboration and has incentives to reach common objectives in the project. A combination of, e.g. design-build contract using a transparent cost models and partnering will set the framework for a collaborative process to define and set common goals for the actors in a construction projects. Especially in complex, uncertain projects under time pressure a development towards relational contracting is important, (Miles and Ballard, 1997). This hypothesis was further strengthened by Toolanen (2004), who conducted in-depth interviews with 32 professional clients in Sweden where they were asked to act as advisors in different contracting situations. The situations ranged from certain, simple projects with no time pressure to complex fast-track projects with lots of uncertainties in the actual design. A majority of the clients recommended transactional contracting in the case of slow, certain and simple projects and relational contracting for fast-track, uncertain and complex project where the risk is much higher. Also in cases where strategic considerations played an important role, the relational contracting environment was recommended by the professional clients.

Table 1. Commonly used forms for distribution of responsibility, remuneration and cooperation in the construction industry.

Distribution of responsibility	Remuneration models	Cooperation models
Construction management Client/owner responsible for design and coordination of the project, building contractor(s) responsible for the execution.	**FP - Fixed price** The compensation is based on a fixed price when the contract is signed. TRANSACTIONAL	**Traditional,** e.g. no special form of cooperation is implemented. ORIENTED
Design-Bid-Build, Client/owner responsible for design, building contractor(s) responsible for the execution and coordination of the project.	**Cost reimbursable** or **transparent cost** model. The compensation is based on actual costs that the contractor have.	**Partnering,** Collaboration model to define and reach common objectives in a project. The model was invented in UK and has spread over the world.
Design-Build, The client distributes the responsibility of the design, coordination and execution of the project to the contractor(s) RELATIONAL	**Cost reimbursable with incentives** The compensation is based on actual costs + a bonus if project targets are reached. ORIENTED	**Strategic partnering** or **Virtual enterprise**. The project organisation functions like a single enterprise. Strategic and long term collaboration between stakeholders in the construction process.

To conclude, the project environments will affect the climate of collaboration:

- A transactional oriented environment with fixed price compensation, such as Design-Bid-Build, will strengthen the forces of fragmentation in the project. Any change in the project will be resisted by the stakeholders since the remuneration need to be re-negotiated. Therefore, it is not meaningful to introduce a VDC process where there is no incentive for sharing of information between stakeholders.
- In a relational oriented environment, it is necessary to involve all stakeholders, formulate common targets and have a strategy to develop trust and sharing of information to reduce project risks. Changes beneficiary for the project targets will also be beneficiary for the stakeholders and can therefore be implemented without re-negotiation of the contractual agreement. In this type of environment, the cost of introducing new ICT tools and methods and the benefits they bring to the project can be shared.

4 THE ORGANISATION OF A VIRTUAL DESIGN AND CONSTRUCTION PROCESS

Today, several applications exist to support a VDC process ranging from the conceptual phase to the detailing and production stages of a construction project. In recent case studies of Swedish construction projects the following applications have been reported (Jongeling 2006, 2007, Woksepp and Olofsson 2006):

- Applications for digital mock-up and walkthroughs, to integrate, communicate and review different design disciplines for use within and outside the project team.
- Model checking- and clash detection software. These applications check different models according to user-defined rules for tolerances between and interferences of different types of objects and systems.
- Building lifecycle design applications are software tools for the analyses of energy use, lighting design, space usage, maintenance planning, et cetera.
- Applications for “4D” (3D + time) modelling are used to link the various models of a project to different types of schedules. These schedules can subsequently be visualized in a 4-dimensional environment and enable the communication of different schedules to actors in the project.
- Applications for “5D” (3D + costs) modelling are used for cost estimation and link the model objects to so-called recipes. A recipe includes methods (i.e. a number of tasks) and resources (e.g. man hours) needed for a building component.

Figure 3 shows the organisation of a VDC supported construction project where identified benefits of the use VDC applications are marked. Three main concurrent processes are defined; the business, the model based design and the construction process. In a relational oriented environment, objectives and goals are defined from the client perspective. Incentives based on overall project targets such as costs, time, et cetera create the driving force for the stakeholders to evaluate alternatives and opportunities that can contribute to the outcome of these targets.

The identified benefits are as follows (Jongeling 2006, 2007, Woksepp and Olofsson 2006, Simu and Woksepp 2006, Miklos 2006); (1) Visualisation of the overall design improves communication and the decision process, resulting in less complaints and misunderstandings of the layout and effects on neighbouring environment. (2) Life cycle cost can be estimated early and design changed to meet design targets. (3) In development projects, selective price tags of attractive flats and offices can much easily be determined by the developer. Also, potential customers can get a visual impression of the layout and the view from the prospective flat before they sign the contract. (4) Early procurement of critical components with long delivery times, such as windows, can be made earlier with lower prices as a result. (5) Integrated design and bill of quantity take-off eliminates the work of manual estimation from 2D drawings. Quantity take-off is often performed several times by numerous stake-holders in a normal design-bid-build project. Also, the waste related to waiting for and storage of components and material on site can be avoided if design can be integrated with supply the chain management system for procurement, purchase and delivery. (6) The project coordination becomes more efficient and requires less engineering hours as a result of 3D model based design process. (7) Integrated architectural, structural and installations design leads to fewer collisions in the design and hence, less re-work on the construction site. (8) Integrated design and production planning (4D), improves the build-ability of the design, the site layout and work-flow and communication on the construction site with less waste as a result. (9) Concurrent engineering and digital mock-ups often results in opportunities for assembling larger parts of building installations off-site when the geometrical constraints of the different design can be controlled in advance. (10) Preparation for operation such as education of operational staff can start in advance using the digital mock-up of the as built model.

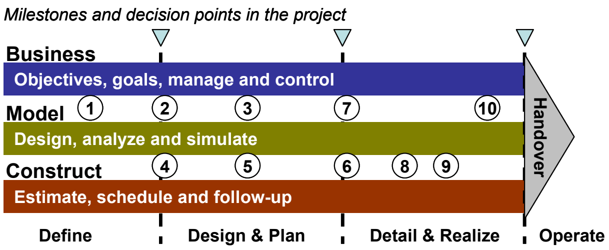

Figure 3. Schematic representations of a future concurrent construction project where identified use of Virtual Design and Construction applications can add value to the process and product.

The 3D model based design of a recently constructed process plant in Sweden can exemplify the iterative nature of a concurrent engineering approach, see Figure 4. The project coordinator is responsible for the overall design process while the design teams here denoted 1 to n, are responsible for the design of the subsystems in the plant, i.e. process equipment, building structure, installations et cetera. All design teams are also responsible for providing correct and updated input data to the "VR database". An independent VR consultant, working for the client, manages all the VR data and also makes updated and corrected VR prototypes accessible for everyone to use in the project. The provided VR prototypes, denoted VR1 to VRn, are also used in design review meetings that take place once every fortnight. Errors discovered during these design review meetings are immediately delegated to the design teams concerned. All errors that have been addressed are logged and later confirmed in the next meeting. Decisions on major changes in the design are taken after conducting a risk analysis of the three goals in the project; the capacity of the plant, time to operation and the economical impact. These decisions are always taken in the risk management group consisting of the client and the main subcontractors in the Partnering group.

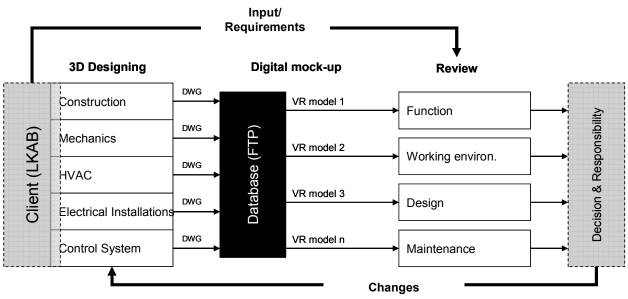

Figure 4. An iterative design review process using digital mock-ups in a concurrent design organisation, from Woksepp and Olofsson, (2006).

The example illustrates that there are a number of different roles that one can identify in a VDC supported design:

- *Information creators* are the professionals from different design disciplines that carry out the modelling work.
- *Information users*, or so-called model viewers, are those that use the models for their specific needs. This category includes actors such as the client, project management agencies, material suppliers, cost estimators, site managers, planners, et cetera.
- *Information administrators* help the client or project manager with setting up the right environment, sometimes referred to as the Virtual Building Environment, and ensures coordination of the model work that is performed by different professionals.

In this example the VR consultant acted as an information administrator with the specific task of gathering and optimizing the 3D models from the different disciplines and creating and distributing the VR models (digital mock-ups) used in the design reviews.

5 INFORMATION MANAGEMENT

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.

In a study by Jongeling (2005) a number of issues was identified 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. 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).
- 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. The majority of actors are consumers of information stored in product models, such as estimators, planners, suppliers, subcontractors, customers, et cetera.

The solutions applied in the pilot study to combine 2D data with product models and to make this data and product models available for all project participants were:

- Separate architectural, structural and HVAC models were created instead of an all-including single product model.
- 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 hyperlinked to the product model. Links were added to specific model objects, but also to parts of an object or to a specific section in the product model. For this purpose different pointer objects were used for different disciplines that contained links to the document server.
- A model viewer was used as client software to view the product model in the central database and to browse through hyperlinked data.

Working with 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.

The process of generating views from 3D models and adding 2D data proved to be feasible in 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 project there was one CAD system available at the project developer. No experienced CAD personnel were available to operate CAD systems as product model server clients. Using model viewers facilitated the uptake of product model use. 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.

Froese (2004a) suggests a Project Information Officer (PIO) as a resource in a project that acts as an information administrator. Tasks and responsibilities for the PIO can include (Froese 2004a):

- Setting up requirements for the modelling work by different professionals
- Coordinating and ensuring the use of templates and libraries for modelling work
- Model integration from different disciplines
- Management of the central information repositories such as digital mock-ups pr product model server
- Education and knowledge management of (potential) model users

The PIO can facilitate the uptake and successful use of 3D and product models in projects. The PIO relieves the design- and project manager from tasks that they are not used to and can successively transfer the required skills to these managers. Knowing that a PIO possesses the essential knowledge can facilitate the decision to conduct the design work in 3D.

6 CONCLUSIONS

There are several of lessons that we can learn from benchmarking with the manufacturing industry and case studies of the use of VDC methods and tools in real construction projects:

- The typical construction project is organised in chain of sequential activities, a relay run, that leads to fragmentation, long chains of design iterations and an error prone information flow causing waste of material and resources in the construction phase.
- Relational contracting in combination with a concurrent engineering process and use of advanced ICT tools can provide the base for an adaptive virtual design and construction process.
- There is no single model that contains all project information, but rather a collection of discipline-specific models, including non-model data that can be linked to models.
- Model information can be exchanged via files or can be available from product model servers. The data format can be proprietary or neutral.
- An information manger, denoted the Project Information Officer (PIO), is needed who specifies the requirements for model use and who ensures integration of models with other models and with non-model data.

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