



# First International Conference on Improving Construction and Use through **INTEGRATED DESIGN SOLUTIONS**

CIB IDS 2009, 10–12 June





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**First International Conference on  
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THROUGH INTEGRATED DESIGN  
SOLUTIONS  
CIB IDS 2009**

10–12 June

Edited by

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## Preface

The work of CIB, The International Council for Research and Innovation in Building and Construction, is based on voluntary international cooperation projects involving its Task Groups (TGs) and Working Commissions (WCs). A pro-active approach in the form of Priority Themes is applied to facilitate and encourage horizontal work with higher impact.

The CIB Priority Theme “**Improving Construction and Use through Integrated Design Solutions**” (IDS) has been under development since early 2006. Two preparatory workshops of the IDS Priority Theme were organised in 2006, one in Ankara, Turkey, in the spring and another in Atlanta, GA, USA in the autumn. Thereafter the Work Programme has been developed to support and bring together the Task Groups and Working Commissions of CIB, each having a specific focus but all contributing to making construction more efficient and resulting built environment better for people and the environment.

CIB defines Integrated Design Solutions as those using

- collaborative work processes and enhanced skills, and
- integrated data, information, and knowledge management.

to minimize structural and process inefficiencies and to enhance the value delivered during design, build, and operation, and across projects.

A three-fold approach People – Processes – Technology was chosen in the early preparations of the IDS Priority Theme:

**Integrated Work Processes** – Effective implementation of IDS results in integrated work processes for each phase of the project, and throughout the project.

**Integration Technologies** – A set of technologies and capabilities for collaboration are essential for project teams to implement the integrated work processes.

**People** – Project teams with exemplary IDS delivery need people with special qualifications. These begin with technical and collaboration skills and a commitment to a team approach.

The development of Integrated Design is very much connected to the application of Building Information Modelling. Integrated Design Solutions are based on practices which are in many ways similar to lean manufacturing and lean construction.

Integration throughout the process minimize waste in time as well as in human and material resources.. IDS thus support the thrive towards construction and operation of a sustainable built environment. Owing to better interoperability errors become less likely throughout the whole process. Owing to integration of data, it is easier to adopt the resulting facilities to the developing needs of the owners and users.

The current event is the first conference of the IDS Priority Theme with open call for papers and acceptance of papers based on full paper reviews. While integrated design and delivery represent a strong trend in the sector, I have a good reason to believe that this conference is a beginning of a series of international events to be organised at least biannually in various parts of the world. A general feedback has been that the title of the Theme should not be about design only. It is likely that the future events will use the term Integrated Design and Delivery Solutions (IDDS).

I would like to thank the members of the Organising committee and the Scientific Committee in setting the stage for this event and, thereby, the foundation for the future development of CIB Integrated Design Solutions Priority Theme. Particularly, the role the Finnish Association of Civil Engineers (RIL) was instrumental in taking care of all practical arrangements.

I would also like to thank Skanska, Tekla, Nokia and SRV Group for co-sponsoring the event by organizing interesting additional programme and visits to the conference participants.

Prof. Matti Kokkala  
Chair of Scientific Committee  
CIB IDS 2009  
Chairman of CIB Programme Committee

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# KEY NOTES



# Champions for Integrated Design Solutions

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## Abstract

Integrated design solutions (IDS) offer many potential benefits for all types of facility projects but also require significant changes in the organizations that send key players to project teams. How can these firms develop the capability and reap the rewards of IDS? Changes in technology and work process are essential but both depend on the willingness and effectiveness of key people involved in making these changes. This paper focuses on one key role, the champion for IDS. This role requires two sets of activities. The technical champion changes technology and work practices in parent organizations and the integration champion fosters changes in key project activities required for successful use of IDS by the project team. The first two sections of this paper describe the motivation and context for the changes required to implement IDS in design and construction firms. The next two sections describe the champion's role and actions. The final section highlights conclusions regarding the value added by an effective champion for IPS and the resulting implications for practice, education, and research.

**Keywords:** champions, change management, collaboration, innovation, integrated work processes, integration skills, people and integration, roles

## 1. Introduction

As defined by CIB working group, "Integrated Design Solutions use collaborative work processes and enhanced skills, and integrated data, information, and

knowledge management to minimize structural and process inefficiencies and to enhance the value delivered during design, build, and operation and across projects”. Realizing the potential benefits of IDS for improving performance in meeting all project objectives requires key skills and actions by members of the project team. This paper analyzes one critical role to complete two types of key actions for successful use of IDS. We call this role the champion for IDS. The objectives of paper are to highlight the vital role and actions by the champion in the effective use of IDS and to describe how they do it. The key roles recognize that maximizing the benefits of IDS requires including three types of integration: vertical (between phases of the project lifecycle, such as operations and design), horizontal (within a specific project phase such as between engineering disciplines during design), and temporal (between projects, such as sharing best practices with the next project). (Fergusson 1993)

Major changes such as IDS require a champion, especially if they involve changes in technology and work processes. Champions for IDS complete the activities required by a dual role. The technical champion changes the technology and work processes to allow using IDS in the parent organizations that send representatives to project teams. The integration champion fosters implementation of the new technology and work processes on project teams. This requires information and knowledge sharing, functional and spatial coordination, and collaboration for integrated decision making.

In this paper, adopting IDS in any firm represented on facility project teams is considered an innovation. This follows the view of innovation as the first use of new technology within an organization. We use the most relevant findings from prior investigations of innovation in design and construction organizations as a starting point to consider IDS as an innovation and to focus on the role of the champion. The main sections of the paper describe the need and context for the champion along with the skills and actions required for success in the role. The final section highlights conclusions regarding the value added by this role and implications for practice, education, and research.

## **2. Strategic motivations for IDS**

Despite the many potential advantages it offers, effectively integrating work processes on a project team also presents challenges and requires many fundamental changes. These changes include aspects of firms as business

strategy and sources of competitive advantage, organization culture and structure, and new types of roles and actions.

In summarizing the key role of technology in competition, Porter (1985, p. 164) stated: “Technological change is one of the principal drivers of competition. It plays a major role in industry structural change, as well as creating new industries. It is also a great equalizer, eroding the competitive advantage of even well-entrenched firms and propelling others to the forefront. Many of today’s great firms grew out of technological changes that they were able to exploit. Of all the things that can change the rules of competition, technological change is among the most prominent.”

The major potential performance improvements offered by IDS make it a clear candidate for the types of competitive changes described by Porter. Enhanced building information models combined with emerging models of construction processes will finally allow widespread rapid prototyping and evaluation of alternatives for design approaches and construction methods and, most importantly, their interaction. But these exciting new technical capabilities will also require substantial changes in project and design work processes, and eventually in construction field operations. New types of competitive advantages based on IDS competence provide a strong incentive to overcome the challenge of the changes needed to develop it. Formulating and implementing a technology strategy to make IDS a core competence is one element of successful use.

Three major levels of strategy are corporate, line of business, and functional. Corporate strategy defines the business of the firm and allocates resources. Line of business strategy identifies plans to compete, needs from functional areas, and more detailed resource allocation. Functional strategies define how to best contribute to business and corporate strategies and how to maximize productivity. Examples of functional strategies are: human resource, finance, marketing, production, and technology. Porter (1985) described the technology strategy of a firm as its approach to the development and use of new technology. This involves three decisions: what technologies to develop, whether or not to seek leadership in the chosen technologies, and the role of technology licensing.

Prahalad and Hamel (1990) identified core competence as a key element of competitive advantage for the corporation. They defined core competencies as the collective learning in the organization, especially how to coordinate diverse production skills and integrate multiple streams of technologies. They also suggested the following tests to identify core competence in a company: 1) provides access to a variety of markets; 2) contributes to the perceived customer

benefits of the end product; and 3) is difficult for competitors to imitate. IDS fits these well.

Hampson (1997) identified four elements of technology strategy for construction firms. Competitive positioning defines the relative emphasis and state of technology as compared with other functional strategies. Sourcing of new technology includes activities by gatekeepers to monitor new technology and methods to acquire it. Breadth of technology capabilities describes the number and types of disciplines or functional activities included. Organizational fit includes structuring of information flows about technology and reward systems for advancement.

Examples of possible technology strategies for construction firms include: brokering for technology leadership, brokering for technology followership, efficiency-based cost leadership, innovation culture, internal construction R&D, interaction with lead supplier, forward technical integration, and backward technical integration (Tatum 1988). Examples of strategies to acquire technology for construction include: interact with a lead supplier, conduct internal or external development, improve repeated operations, and drive development on specific projects.

Christensen (2000) investigated why some companies fall from leadership positions when they confront certain types of market and technological change. He found that many good management practices, such as listening to their customers and investing in the new technologies required to provide the product capabilities that customers requested, led to decline. Understanding this contradiction required contrasting sustaining technologies that improve the performance of existing products with disruptive technologies that decrease product performance in the short term but offer features that appeal to other market segments. IDS is a potentially disruptive technology under this classification but progressive owners are recognizing the potential project benefits that it offers and asking about this capability as a part of selecting design and construction firms for their projects.

These elements of the research background highlight the strong competitive motivation for IDS. Potential competitive advantage is a significant factor in gaining the critical support of senior management. One possible technology strategy for IDS is to work with a lead supplier of BIM technology and a progressive owner on a demonstration project. The champion role is a key factor in the success of such strategies. But before we analyze this role in detail, we

need to review the most influential elements of the context in which this champion operates.

### **3. Culture and structure as organizational context for innovation**

Rogers (2003) reviewed prior research concerning the influence of six internal characteristics of organization structure and innovativeness. *Centralization*, the degree to which power and control are concentrated with a few individuals, is usually negatively associated with innovation. *Complexity*, defined as the range of knowledge and expertise of individual members, increases the recognition of the value of innovation, but also the difficulty in achieving the consensus required for implementation. *Formalization*, the degree of bureaucracy or focus on following rules and procedures, inhibits consideration but encourages implementation of innovations. *Interconnectedness*, the degree of unit linkage by interpersonal networks, increases the flow of new ideas and innovativeness. *Organizational slack*, the availability of uncommitted resources, relates positively to innovativeness. *Organizational size* relates positively to innovativeness, possibly because size is a surrogate measure of several of the above factors that lead to innovativeness (Rogers 2003).

Investigations of innovation in construction (Tatum 1989b) identified eight elements of an innovation culture. Senior managers clearly articulate an exciting vision of the firm and how technology can support that vision. This vision includes the core technical competence of the firm and the breadth and depth of experience and expertise required to maintain it. Actions and choices by the leaders of the firm clearly indicate a longer-term viewpoint and a broader view of risk. They state and demonstrate a freedom to fail. Operations managers challenge each function to innovate. Budgets and other resources allow devoting some time and money to learn and experiment. Managers at all levels show some tolerance for mavericks and zealots who bend the rules. The operations of projects and staff functional activities allow integration with other internal and external organizational units to foster innovation.

This background indicates that a favorable culture for IDS will begin with recognition of long-term market demands for the performance improvements that it offers and include the patience and resources for successful adoption. This will include recognizing the extent and difficulty of the change required and

possibly working with several firms that send key members to project teams to share experience.

## **4. Diverse roles and actions for innovation**

Viewing innovation as organizational change assists in clarifying the roles and actions of the champion for IDS. Rodgers (2003) defined a change agent as “an individual who influences clients’ innovation decisions in a direction deemed desirable by a change agency”. He described the following sequence of roles or activities for a change agent: develop need for change; establish information-exchange relationship; diagnose clients’ problems and reasons that existing alternatives do not meet their needs; create intent to change in the client; translate intent into action; stabilize adoption and prevent discontinuities; and develop self-renewing behavior by the client and exit.

Kanter (2005) defined “change masters” as people who know how to conceive and lead effective projects that bring new ideas into use. Examples of change include product innovations, new enterprises, social change, shifts in organization culture, organizational restructuring, development of new technology, and new business models. She identified seven fundamental activities and related skills that effective change masters use and encourage others to use:

- Sense needs and opportunities by paying attention to the environment and the problems and opportunities that it presents. This includes special attention to customers, competitors, and challengers.
- Stimulate breakthrough ideas by challenging conventional thinking and constructing new patterns to reframe the situation.
- Communicate inspiring visions to set the theme. This picture of the future should describe six elements: destination, where the team is headed; dream of differences because of this goal; prize or positive outcomes and who will benefit; target to define deadlines and metrics that make the outcomes concrete; message or memorable image, slogan, or headline that conveys the essence of the goal; and first step to give tangible reality to the goal.



- Enlist backers and supporters to form a coalition that will nurture the venture. This requires three kinds of actions: pre-selling, making deals, and getting a sanity check.
- Nurture the working team by shifting the leader's role from lead actor to producer-director. This includes serving as the team's advocate and providing required resources.
- Persist and persevere to overcome common problems that arise at the middle of developing new products or implementing new processes. These include: inadequate forecasts, unexpected obstacles, slowing momentum, and critics.
- Celebrate the accomplishment and recognize the efforts for success.

Hering and Phillips (2005) identified the following roles for successful innovation. A broader view of the champion for a technical innovation includes all of these roles.

- **Connectors** link people and technologies within an organization and also link the organization with customers and business partners. Their characteristics and activities include: mile wide and inch deep, one degree separated from almost everyone, build networks, jump the tracks to bring others along, and skyscraper to make connections with the upper levels of the organization.
- **Librarians** collect ideas and provide organizational access. They define the “meta-data” or the information that is important to capture about an idea, how to evaluate it, and the most beneficial format.
- **Framers** determine the schemes and frameworks to allow fair, transparent, and consistent evaluation of ideas. They understand where the organization is trying to go, who needs to be involved for meaningful evaluation, and how to evaluate ideas.
- **Judges** implement the framer's system to evaluate ideas, typically representing different business functions. They decide the fate of the idea, identify those that merit further investigation, and document their decisions in case the idea is considered again.
- **Prototypers** quickly provide a representation of the idea as a product or service for evaluation by potential customers. They also iterate until the

prototype matches the customer's needs and expectations. They are willing to continue the process but can also identify what does not work and help the organization fail forward.

- **Metric monitors** define initial metrics for an innovation and refine them as needed during the process. She also examines successes and failures, and recognizes patterns for use in subsequent innovations.
- **Storytellers** collect, keep, and tell stories about the organization to remind people about what is important and reinforce the corporate culture.
- **Scouts** identify and analyze new trends and potential impacts on the business. They anticipate market changes and draw conclusions about their significance.

## 5. Champions for innovation in design and construction

Based on detailed investigation of several cases, Tatum (1989b) identified three key roles in innovative construction firms. The design and construction *visionary* takes a broad view of owners' needs, constructed products, project constraints, and available technology. She anticipates changes in these and other factors that offer potential advantages and positions the firm to realize these benefits. The operations *iconoclast* is firmly convinced that an opportunity exists to improve all operations, even when there is no obvious need for change. This individual acts more as a "pre-champion," finding disguised opportunities, because these is nothing to champion yet, only discontent. The technology *gatekeeper* identifies external technology and anticipates potential applications in a firm.

Tatum's investigation of construction also confirmed the need for three types of champions described in prior investigations of other industries. *Executive* or management champions create a culture and select a competitive strategy that fosters innovation. They provide blessing and resources. They also sponsor new ideas. *Business* or commercial champions provide a business framework for innovation. This includes an acceptable level of risk. They make the planned actions "right with the contract". *Technical* champions (who are anointed not appointed) identify possible innovations and "move heaven and earth" to solve all the problems and make them happen. They carry an idea from initial concept through development to the final product or process.

An example of innovation in the use of high strength concrete resulted in the identification of a fourth type of champion. *Integration* champions inform, coordinate, and convert everyone with the potential to block the innovation. They build the consensus needed to adopt the technology among the many different stakeholders in the process (Nam, et al., 1991). They use the support of other team members and all the persuasive arguments they can muster to change the opinion of any team member who opposes the innovation. This process may involve several actions: providing additional information about the innovation, seeking input from recognized leaders in the field, further analyzing the risks involved and developing ways to mitigate them, or highlighting project advantages.

Researchers identified six characteristics of champions for integration in design and construction (Nam 1996). Their enthusiasm and passion for the new technology makes them fit Peter Drucker's description of a champion as a "monomaniac with a mission". They have well developed skills for critical thinking, especially to question experience and rules. Their confidence allows them to question authority. They are able to unlearn myths and break down barriers. They have a multi-dimensional spectrum of views, including strategy, structure, culture, and process. Their excellent communications skills allow them to explain and persuade.

## **6. Champions for IDS; the dual role**

The CIB workgroup for IDS highlighted required changes in technology and work processes. The extent of these changes requires the dual role of the technical champion focusing at the level of the parent organization and the integration champion focusing on the project team.

Firms considering integrated design solutions may initially experiment with trail use by project teams, but full scale implementation requires changes in the functional units of the parent organization that is the home of the project team members. For example, design disciplines, materials management groups, and construction operations units will need to adopt the technology and change work processes for IDS to allow successful use on project teams. The revised work process foster input and expertise from multiple project functional areas, design disciplines, and even construction trades. This means that each of these specializations must be willing and able to integrate, or at least more fully coordinate, their work activities with all others who could provide or would consider input that will result in project benefits. The technical champion

highlights the advantages of IDS for each of the functional units, provides expertise to plans and implementation, and helps solve problems. He or she must convince the people responsible for each activity that implementing IDS will bring project benefits that are worth the change effort.

The second focus in championing IDS is on the project team, or integrated community. This role parallels the integration champion identified for other design and construction innovations. The champion assists in building the collaboration, coordination, and information and knowledge sharing that is essential to realize the benefits of IDS. Once integrated work processes are established by each of the project team members, then the team itself must move its work processes (previously viewed narrowly as functional, spatial, or schedule coordination) toward true integration. This makes the team much more collaborative, proactive, and effective in meeting all of the project goals. It also illustrates the importance of the integration champion role in the success of IDS.

## **7. Conclusions and implications of champions for IDS**

The increasing capability and visibility of IDS is creating an emerging need for champions to help realize the benefits. Market pressures from owners pursuing increased performance of the project delivery team and the potential for competitive advantages will accelerate the rate of adopting IDS. This creates an opportunity and a challenge and for managers seeking to develop this capability. The necessary dual roles of the champion make the adoption of IDS more difficult but also increase the sustainability of potential competitive advantages obtained from effective use. The technical champion is most critical for changing to integrated work processes within the different parts of an organization. The integration champion fills a critical need in initiating the integrated work practices between the different design disciplines, construction trades, and other functional units that make up the integrated project team.

Three key elements of context in the firm and projects promote the effectiveness of the champion for IDS. Willingness to experiment with the technology encourages the intensive motivation of the champion. Related to organization culture, a long-term view of market demands and technological advancement in the firm encourages the champion to make the special efforts required for success. An organization structure that provides some resources and allows greater freedom to try multiple approaches is another very favorable factor.

The changes in technology use and work processes are so fundamental that successful adoption will require changes in organization culture and structure. This will create a favorable context for successful champions for IDS. Possible steps to adopt IDS include market analysis, identifying distinctive competence, experimentation with limited applications, and commitment to implementation if the results of demonstration uses are successful.

Research to further investigate differences in the role of the integration champion for IDS can greatly assist increasing its effective use. Recognizing the extent of the changes involved will increase attention to the roles needed to successfully complete it. While the most effective champions for many types of change are volunteers rather than recruits, creating a favorable context will increase the potential of find people who are willing to make the major efforts the effective championing requires. Because of the major changes it requires and potential benefits it may create, IDS may attract champions who consider it more of a cause than a job.

Educators can use the IDS tools to facilitate increased learning of the benefits, roles, and actions for collaborative teamwork. Classes using these tools will increase the students' knowledge of the technology, the required changes in work processes, and the most important knowledge of each organizational element involved in IDS.

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# Process Improvement in the Construction Sector

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**Keywords:** change management, integration, process improvement

Integrated design solutions (IDS) require a fundamental review of the construction sector and the development of holistic, pull processes. Technology brought into play in the last seven years both facilitates and stimulates process reexamination, with the promise of significant gains for client, developer and stakeholders. This paper examines these changes and places them within their current context and future horizons.

In construction, there is no standard project process (Latham 1994) that is explicitly followed. Latham and Egand (1998) suggested that learning from manufacturing, particularly from new product development, would aid project success. Cooper, et al. (2005) summarized a long project to attempt to define a ‘Process Protocol’ for the industry, based on Egan’s recommendation of using manufacturing as a reference point.

Unfortunately, these process inefficiencies in construction largely remain. They can be envisaged to lie in three domains: the regulatory and structural; the project/ programme/ portfolio; and the supply chain. The regulatory and structural elements have grown differently, depending on political and cultural environments; each has developed over centuries, in some ways becoming less efficient as they have done so. Many non-housing projects have traditionally been developed as projects in isolation, with little opportunity for integration into a modern programme or portfolio management structure. In terms of supply chain integration, the levels achieved in other industries, such as automotive, remain elusive, although there are isolated pockets of project excellence.



Much has been written in the last seven years about Building Information Modelling (BIM) and its specific benefits, such as cost reduction and more assured delivery through clash detection. However, BIM also at last offers construction the ability to integrate design and manufacture in similar ways to manufacturing. The development of Virtual Design and Construction (VDC), Integrated Project Delivery (IPD) and, in the future, Integrated Design Solutions (IDS) all address the lack of integration in the sector. These new technological applications will enable development of optimal holistic processes, rather than merely remapping existing processes in their fractured forms. True 'Lean Construction', addressing both process and material wastes can be contemplated, finally providing the improvements anticipated by Egan and others.

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# Technical Challenges for IDS

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## Abstract

Conceptually, the development of an extensible infrastructure for Integrated Design Solutions (IDS) would appear to be a straight-forward matter. However, there are few current implementations in existence, and the majority of those that do exist are bespoke developments which support a restricted number of processes and analyses.

This presentation characterizes the wide range of technical challenges which are faced by those delivering on the promise of integrated design solutions. It examines the levels of IT support that can be offered for aspects such as: collaborative work processes; repositories of integrated data; management of information integration; and knowledge management processes. Alongside each of these challenges it identifies current approaches to supporting IDS, both at a commercial level with tools that can be deployed today, and from the viewpoint of researchers working on future improvements to the IDS ideal.

The last part of the presentation establishes a technology foresight for the technical development of IDS. Providing a view of the technical future of IDS over the coming decades with projections of the pathways that will lead to adoption of various forms of IDS and the major obstacles where the dearth of solutions will delay the uptake of IDS.

**Keywords:** technology review, framework, IT future, interoperability

# 1. Introduction

The current status of technical support for Integrated Design Solutions (IDS) is not strong or ubiquitous. Only limited forms of integration are offered through the BIM-based approaches offered by major CAD vendors [1]. These approaches are typically vendor specific and tie together a small number of design tools (in comparison to the thousands that are available in the marketplace). The set of software tools available through any one CAD system are unlikely to be the set required by any particular grouping of professionals involved in a construction project, creating an immediate barrier to the IDS goal.

Creating a truly integrated platform for a project usually requires uniquely qualified individuals to be available in one, or more, of the companies involved in the project. With sufficient time and resource committed by a project team into support of their tools there may be a chance of reaching an IDS. However, the timeframe and resource required to achieve this is usually outside of the project scope and timeframe of any team.

There have been numerous demonstrations of interoperability utilizing the IFC data model standard [2]. This standard data model has been developed independent of CAD vendors and is now supported by the majority of large CAD vendors. The IFC data model is not yet complete, still only providing support for a limited set of construction processes, and has only just started the process of defining specific views for particular classes of software tools and for particular processes. In most cases utilizing the IFC data exchange still requires uniquely qualified individuals in each company to ensure the integrity of data exchanged.

Due to the limited number of applications supported in BIM, or interoperable solutions, the practice of manual re-entry, and checking, of data between applications is common. This re-entry is an extremely common point of error when dealing with building information exchange. Where automated information exchange is practiced the common experience is of loss of information and no guarantee of the semantic integrity of models being exchanged [3].

The usual characterization of information management with current BIM and interoperability solutions is to a document management system, where the complete model is exchanged and the only level of information management is achieved through interrogation of the different versions of the complete model being passed between project participants. This approach has limited support for concurrent activities and provides no level of granularity of information exchange.

## **2. A future view**

To be truly successful as a technological advance an IDS platform must provide interoperability that is so ubiquitous in the industry that practitioners do not understand that there is a complex and sophisticated technology underlying their software tools. This is reaching the state which is found with ICT tools such as email, where it can be utilized by the majority of the population, but the complex standards and interoperability agreements which ensure that emails work across all software platforms across the world and almost instantaneously are completely invisible to the users of the technology.

A successful IDS platform will support a seamless connection between any two software tools gathering, and updating, the particular view of information required for any particular process in the project. Specialist coders will not be required by companies to undertake project-based information exchange, though there will be new roles such as an interoperability manager [4] within companies to establish the right approach for the software tools required for a project.

## **3. Gaps to close**

Reaching this future state requires further significant international work on many technological aspects underlying IDS. A major part of this will be a focus on the numerous forms of information exchange developed over the last two decades.

In particular, the data models which underlie all information exchange require significant development to cover all major processes as well as an enormous effort in defining the information views required by particular classes of application and standard processes.

Sophisticated approaches to model and view-based information management need to be developed which cope with project structures common in the industry. Such approaches also need to develop to support basic operational aspects such as the long transaction times common in the industry, needs for resolution of ownership of data, security of shared information, and provenance of information.

Software developers will need to put significant resource into ensuring the adequacy of their products to exchange semantically consistent views of buildings under most conditions. Current approaches are invariably insufficient even though they are already lengthy and costly for the developers. Some levels of support from the standards developers (e.g., IAI) is likely to be necessary for

the majority of software vendors to reach the required level of interoperability which will be required by the industry.

These gaps indicate that the work still to be done to achieve an adequate technical infrastructure for IDS is immense. We may not even be half way on the technological side to achieving the vision of IDS that is being offered as the goal for a knowledge-based construction industry working in today's knowledge economy.

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# **A Survival Strategy – How to Integrate Design Systems and Processes in a Fragmented Industry?**

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## **Abstract**

The Real Estate and Construction Cluster is highly fragmented industry where most projects are based on low-bid contracts. This leads to ad-hoc project teams where most participants focus on minimizing costs and are not interested in developing new collaboration methods or adding value to other participants. However, all project participants have to collaborate and share information. This situation creates a significant challenge to companies who want to be in the leading edge. How far ahead of your competitors you can go? How to ensure communication with the other participants if your methods and tools are more advanced? How to build systems which can be used relatively independent of the business environment, but can also benefit from the information in the other systems used by advanced partners? This keynote will present the R&D strategy Olof Granlund has successfully used since the early 1990s to develop technical tools and business processes for integrated Building Information Modelling in the building services engineering and technical facility management.

**Keywords:** BIM, building information modelling, development, implementation, strategy

## 1. Introduction of the company

Olof Granlund is Finland's leading building services consulting company. Its core business areas cover all building services engineering areas, facility management consulting, and development and sale of design and facility management software. The company has five offices in Finland and one in Moscow and employs over 350 people. The company's R&D budget is over 10% of its turnover, which is exceptionally high rate for a consulting company in the Real Estate and Construction Cluster (RECC).

## 2. Granlund's R&D strategy

Granlund's current R&D strategy has its basis in the early 1990s when the company started to investigate actively the international state of ICT and its potential and applications for integrated information management. Since 1996 the company has been actively involved in the International Alliance for Interoperability (IAI, since 2006 buildingSMART).

Granlund's technology strategy is based on the utilisation of integrated Building Information Modelling (BIM) and open data standards. The focus is not only in the traditional building services design, but in the lifecycle information management from the client requirements through design and construction to use and maintenance of the buildings (Figure 1). In addition to the technology, development of service processes and business models is a crucial part of the company's strategy.

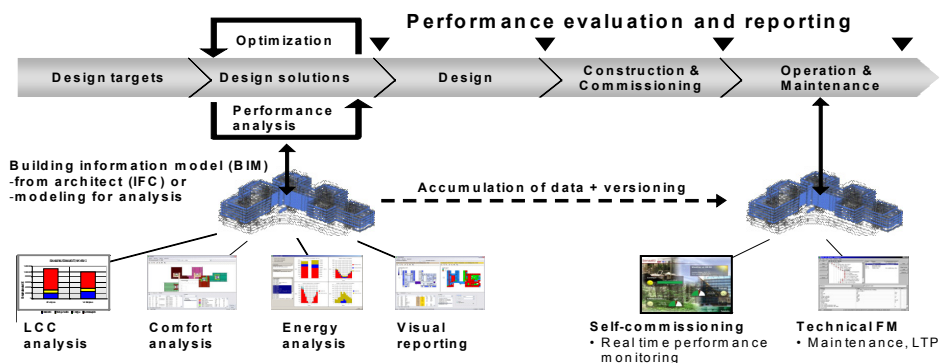


Figure 1. Integrated Analysis and Reporting Tools for the Building Lifecycle (© Granlund 2009).

### 3. Do not reinvent the wheel

Although software development is now a significant part of Granlund’s activities, it is not the core business of the company. Thus the basic idea has always been to find the best available solutions on the market and build only the integration platform and missing pieces which are necessary for the company’s strategic development and business processes.

Another central development principle in the company has been that the technology must be based on open international standards when ever possible.

These principles have led to Granlund’s international collaboration with several universities, software companies and different associations, such as ASHRAE and buildingSMART, as well as to active participation in the national technology development.

### 4. Technology as a part of the business strategy

When a company makes a strategic decision to invest a major effort in the technology development, the business goals must be clear, and the development must lead to a significant and lasting competitive advantage; a transformational change. If the investments are focused on automational or informational levels, the competitors can copy the solutions relatively fast on smaller costs, which can hardly justify the efforts (Figure 2).

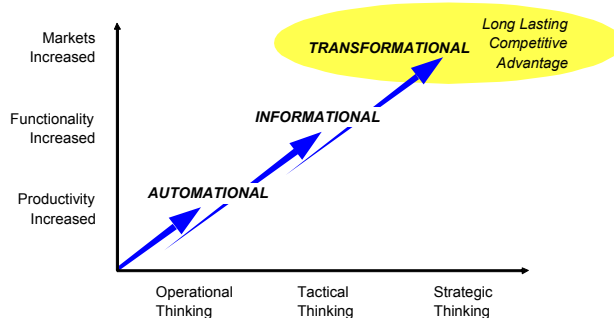


Figure 2. Business Effects of ICT. Source: Virtual Building Environments Project, Fox 2006 [1].

In Granlund’s case one of fundamental changes has been the transition from traditional project-based building services engineering to information lifecycle management service integrating separate tools into an efficient engineering platform.



## 5. Problems of being a forerunner

RECC is a highly fragmented industry where most projects are based on low-bid contracts. This leads usually to ad-hoc project teams where most participants focus on minimizing costs and are not interested in developing new collaboration methods or adding value to other participants. However, all project participants have to collaborate and share information. This situation creates a significant challenge to companies who want to be in the leading edge.

One of these challenges is that the pioneers must create the market for their new services, i.e. find customers who want to find another way of doing business or at least accept the risk of unknown, and to prove that the new services provide benefits to the client compared to the existing ones. Because of the many variables affecting project success or failure, it is difficult to measure the affect of an individual factor such as use of integrated BIM. This easily creates a wicked circle (Figure 3): It is difficult to convince the market of the benefits of new tools, if you cannot measure them, and you cannot measure the benefits without real use of the new tools. However, nobody wants to develop new tools if there is no sufficient market demand for them, and without tools you cannot start using them and get evidence of the benefits... To break this circle someone has to take the risk and start developing the tools based on his own strong vision of the future benefits.

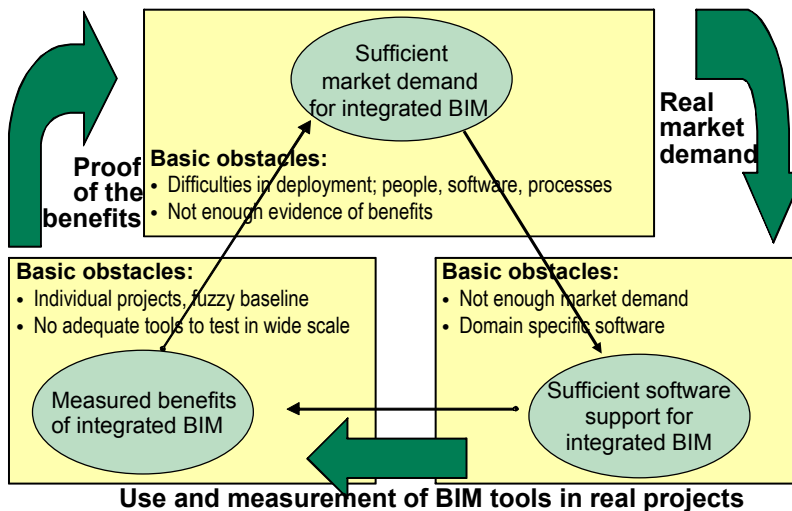


Figure 3. The Wicked Circle. Source: Review of the Development and Implementation of IFC Compatible BIM, Kiviniemi et al. 2008 [2].

## A Survival Strategy – How to Integrate Design Systems and Processes in a Fragmented Industry?

Another significant challenge in integrated information management in a fragmented industry, such as RECC, is how to build systems which can efficiently utilise the open data interfaces but are not dependent on the availability of data, i.e. how to efficiently create the missing information which is necessary for the system. In the building services engineering this problem culminates in the architectural BIM. Building geometry is mandatory for energy and comfort simulations, but in mid 1990s architects could not deliver models. Even today the lack of usable models is the case in most projects although BIM is rapidly gaining market share.

Granlund's solution to this problem was to develop an internal modelling tool with which the engineers could rapidly create sufficient building geometry for the simulations, and to link this tool to the company's integration platform using the same open, IFC-based data interface which was used for the architectural BIM whenever it would be available. This simple solution standardised the main process regardless of the availability of external data and the same basic solution could be applied between building services design and FM data as well as all different modules in the design system (Figure 4).

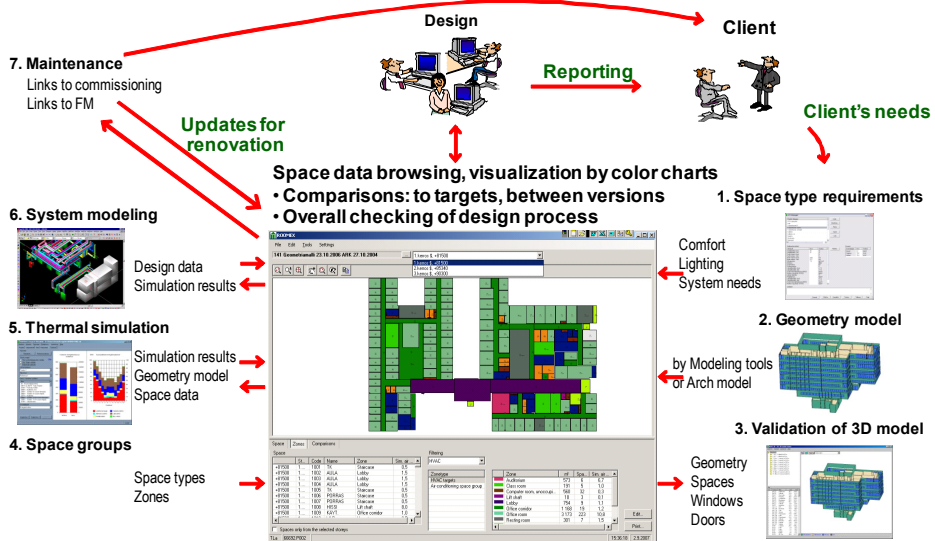


Figure 4. Integrated Building Services and FM Data Platform (© Granlund 2009).

## 6. Conclusions

Granlund is an excellent example of a RECC company which has built a successful, long-term technology development and business strategy which has increased its competitiveness and market share and at the same time created new market areas for the company. The total service concept is unique although many of its individual technological elements are available on the market.

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# **THEME: IDS Competences**



# **Design and Knowledge Integration in Architectural Education; A Dynamic E-Learning Environment**

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## **Abstract**

The integration of knowledge from different domains and the use of knowledge integration in problem solving are central issues for architectural design and education. A large amount of specialized knowledge on several levels and from several domains – varying from material sciences and structural engineering, to architectural history, city planning, infrastructure and spatial policy – has to be integrated in design projects. However, this integration is often not addressed in studio courses. To address this situation the authors have a Dynamic E-learning Environment (DEE), and employed it in a BSc course in Building Process Management. The DEE was developed as a pilot study directed at e-learning innovation within the Faculty of Architecture, at the Delft University of Technology. The aim of the project was to provide students with both an institutional and a personal knowledge base, directed at providing possibilities for the active production and use of knowledge in a consistent and integrated way throughout the curriculum. In addition, the DEE project aims at representing knowledge in such a way that it provides insights into knowledge levels (basic knowledge, domain specific professional knowledge, abstract scientific knowledge), and the relationships between knowledge domains as offered in a specific educational setting. This interactive knowledge environment is intended to enable students to actively explore and integrate knowledge into their designs.

The DEE was then further developed as part of Blend-XL, an EU funded Minerva project. This second version of the DEE was used with large cohorts of students to deliver both learning materials and support a peer evaluated case study project. User evaluations were solicited from students as part of the Blend-XL project, and these evaluations have been positive. The students showed a significantly greater interest in the complexities of real building projects, and in the integration of both the knowledge and design of the various building disciplines required in contemporary construction.

**Keywords:** design, knowledge integration, design education, blended learning, e-learning

## 1. Introduction

The integration of knowledge from different domains and the use of knowledge integration in problem solving are central issues for architectural education. A large amount of specialized knowledge on several levels and from several domains – varying from material sciences and structural engineering, to architectural history, city planning, infrastructure and spatial policy – has to be integrated in design projects. However, this integration is often not addressed in studio courses. The traditional role of the architect as Master Builder – one who can both design and oversee the construction of buildings, who displays a broad range of competences and is capable of integrating the inputs of the various disciplines and trades required for the provision of a building has been neglected. Yet, the task of integrating the design contributions of allied professionals into the design still lies with the architect.

Important as this point is to practicing designers, the integration of knowledge and design from other disciplines is often neglected in design studio courses, where the focus is primarily on concept and composition. The issue of integration is confined to knowledge-based courses taught alongside studios and is usually only presented as ‘theoretical’ material – sets of rules to be followed in projects. Usually also the integration of knowledge gained in previous studio projects is not explicitly addressed, f.i. in judgement criteria, as knowledge to be used in succeeding projects. Students rarely get the opportunity to see how integration works in practice.

To address this situation the authors have a Dynamic E-learning Environment (DEE), and employed it in a BSc course in Building Process Management. The



DEE was developed as a pilot study directed at e-learning innovation within the Faculty of Architecture, at the Delft University of Technology. The aim of the project was to provide students with both an institutional and a personal knowledge base, directed at providing possibilities for the active production, use and integration of knowledge in a consistent way throughout the curriculum. In addition, the DEE project aims at representing knowledge in such a way that it provides insights into knowledge levels (basic knowledge, domain specific professional knowledge, abstract scientific knowledge), and the relationships between knowledge domains as offered in a specific educational setting. This interactive knowledge environment is intended to enable students to actively explore and integrate knowledge into their designs. The DEE was then further developed as part of Blend-XL, an EU funded Minerva project. This second version of the DEE was used with large cohorts of students to deliver both learning materials and support a peer evaluated case study project. User evaluations were solicited from students as part of the Blend-XL project, and these evaluations have been positive. The students showed a significantly greater interest in the complexities of real building projects, and in the integration of both the knowledge and design of the various building disciplines required in contemporary construction.

## **2. Knowledge integration in design**

The integration of knowledge from different domains and the use of knowledge integration while problem solving, are both central issues for architectural design. A large amount of specialized knowledge on several levels, and from several domains varying from material sciences and structural engineering, to architectural history, city planning, infrastructure and spatial policy, has to be integrated in the design studio projects. Knowledge integration is an essential feature of design activity and is traditionally regarded as one of the key tasks of the architect [21]. This is particularly important now, as the spatial, functional, and technical aspects of building design and construction becomes increasingly complex and the number of parties involved increases. Little is known about the actual course of the integration process during design activity, though this is a source of many possible errors [3]. Improved design integration may be expected to lead to a faster building process, fewer building errors and higher architectural quality. Within this context, knowledge integration is considered in

terms of the integration of all building aspects within an architectural design into a single complete and coherent building design.

In their classic work on knowledge management Takeuchi and Nonaka [18] distinguish between knowledge and information in the following manner: “First, knowledge, unlike information, is about beliefs and commitment. Knowledge is a function of a particular stance, perspective, or intention. Second, knowledge, unlike information, is about action. It is always knowledge ‘to some end’. And third, knowledge like information is about meaning. It is context-specific and relational.” This suggests that unless educational information becomes meaningful in terms of being part of a coherent body of knowledge, it will not be integrated in the design. In the context of design Wamelink & Heintz [21] associate knowledge, with design reasoning required to solve the complex problems presented by modern construction. It is this context that presents the end and the context in which disciplinary knowledge becomes meaningful. Outside the practice of building design and construction, knowledge of engineering, architecture and construction is mere information, of little meaning or use and easily forgotten.

### **3. Student oriented learning**

Especially in the Netherlands, governments have stipulated a great deal of educational renewal. A shift was encouraged from traditional teacher oriented models to student-oriented models. The focus of education has shifted from the classic learning aims as for instance described by Bloom [2] – Knowledge, Insight, Skills/Application, Analysis, Synthesis, Evaluation – to so called competencies as in today’s constructivist approaches. The new approaches were based on a type of thinking in which learning is no longer seen as a process of transferring knowledge from teacher to students, but as a discovery process in which the student discovers his or her own personal learning needs, and acquires competencies with the guidance of a teacher or coach. Although these renewals can be seen principally in terms of new pedagogical and didactical insights in primary and secondary schools they have also had an influence on university education.

It has to be noted, however, that the concept of competencies is often misunderstood, and is frequently used as an equivalent for skills [12]. Actually competencies are meant as a limited series of keywords together describing the core of a profession [20]. They are not a series of behaviours but points of

reference including knowledge, insight, skills and personal attitudes [13]. In their basic form competencies can be related back to the ideas of Spencer and Spencer [17] in which a firm describes its core competency (that what distinguishes it in the market) and can then define the competencies needed to contribute to the mission of functional groups and employees. Projecting this thinking to education incorporates the danger that learning outcomes can be measured simply by developing checklists in form of an assessment of what has been achieved at the end of the educational process. In the educational interpretation of Vreugdenhil competencies open up the possibility of combining academic and professional education while using the concept to develop so called knowledge grammars in which the knowledge oriented fundamentals and grounded structures of a domain are combined with professionally oriented profiles.

Alongside the above developments, a technology push towards the concept of e-learning has emerged. E-learning started in the early nineties with names as 'computer based learning' or 'online learning' simply by putting learning material (information) on the web. Today e-learning is often oriented toward interactive and collaborative learning. Portfolios and learning material can be stored in Content Management Systems (CMS's) while the students behaviour (which learning object is loaded, which training activities are done) can be tracked in so called Learning Management Systems (LMS). Some had thought that classroom teaching would disappear and education would go online, using digital learning environments, without face-to-face contact. In practice, a blended approach is usually chosen, combining online and offline activities. Verkroost et al. [19] have extended this definition by adding three dimensions: structured/unstructured, group/individual, and teacher/student directed. In each educational setting these dimensions will be balanced differently because of different preconditions. It is a challenge to balance these dimensions in such a way that an optimal learning situation is established.

E-learning aims to make education faster, more efficient and more interactive, with powerful, flexible and so called authentic learning environments [7]. As e-learning is still developing rapidly no consistent well accepted definition exists [14]. In its most widely used sense e-learning compromises individual and group learning processes, the development and management of learning processes and learning material as well as the organization of learning activities [13]. Some authors, such as Cobb [4], even assume that new technologies like Web 2.0 are

the drivers behind a move to student-centric rather than teacher-centric learning bypassing decades of developments in didactics and learning psychology.

Despite all the developments in learning approaches, design education in the narrow sense seems still to be tied to traditional design studio training in which the master designer coaches the novices in learning while doing. Using Sfard's [15] distinction between Acquisition and Participation we can describe the design studio as a participation situation in which the student becomes a member of a community, learns to speak a community based language, and participates in discourse and cooperative learning. On the other hand, lecture courses typically conform to the acquisition model, and are directed towards conveying pre-specified knowledge and developing pre-defined concepts. Sfard's concept comes close to what Jonassen Peck and Wilson [11] describe as meaningful learning, which they define as active, constructive, intentional, authentic and cooperative. Collins and Moonen [5, 6] develop this further in what they call 'the contributing student approach'. In this approach students can contribute to the learning material based upon their own experience, can draw on each other's experiences, and can use material that they can obtain via the Web, or from their workplaces. Other similar approaches include Kearsley and Sheinderman's Engagement Theory and Action Learning [8, 16].

Zeisel [28] states: "Information used in designing tends to be useful in two ways: as a heuristic catalyst for imaging and as a body of knowledge for testing." Student oriented approaches can be used to provide students with problems requiring just such imaging and testing. By making the information presented in learning materials useful in the solution to an assigned problem, this information can be converted into knowledge as understood by Takeuchi and Nonaka [18]. Thus the prescriptions found in text books can become an active part of the students' resources to be applied in both knowledge based and design courses.

#### **4. DEE preliminary idea**

Between 1999 and 2001 Delft University of Technology (TUD) implemented the so-called Bachelors-Masters structure to its curriculum in order to harmonize with European standards in university education. The Faculty of Architecture used 'required' change for a complete re-design of the curriculum. The Faculty of Architecture at TUD is distinct in having a Department of Real Estate, Housing and Design & Construction Management (RE&H) in addition to the departments of Architecture, Building Technology and Urban Planning and

Design. The faculty provides a broad integrated building engineering and design curriculum at undergraduate level, while offering four opportunities for specializations at MSc. Level (Architecture, Urbanism, Building Technology and Real Estate and Housing). The BSc. curriculum is built around design projects in each semester with so called ‘knowledge lines’ providing the knowledge to be integrated within the design by means of a range didactical methodologies. The RE&H instructors (including both authors), with their process and management oriented scope, face the problem that the knowledge offered in their courses is rarely integrated into the design courses. Although officially the students’ designs ought to be judged on all educational information provided up to that moment, in practice the criteria of judgment remain vague and are dominated by considerations of architectural composition. Systematic student evaluations, carried out by the Faculty of Architecture, TU Delft, show that students perceive the knowledge provided outside the design studio as fragmented, and less relevant compared to the design studio training. As the development of the new curriculum of the Faculty also implied new courses and new learning material, the Design and Construction Management group (DCM) within the of RE&H department formulated a pilot project called Dynamic E-Learning Environment (DEE). The original aims of the DEE project included:

- Providing insight in the interrelation of the parts of the curriculum by structuring the knowledge within the DEE.
- Providing insights in the way the curriculum content of DCM can have its influence in design projects as well as on the level of the design studio projects as in practice cases.
- Making education for large groups of students more efficient.
- Stimulating students to actively explore their own knowledge base with all relevant knowledge produced by themselves as part of curriculum activities.

In general the aim of the DEE is combining an institutional as well as personal knowledge base in such a way that educational information becomes meaningful knowledge to be integrated within design projects.

A principle component of the DEE is of a content collection in which students could access content via several different routes including a generalized taxonomy of building knowledge, and a curriculum overview – allowing students to choose

for themselves what areas of knowledge were relevant to the solving of problems facing them in any course (see Figure 1).

## 5. Application of the DEE in blended learning

### 5.1 Stating the problem

The course design presented here was developed as part of Blend-XL, an EU funded Minerva project, aimed at developing insight into the application of blended learning in large groups. It is more fully discussed elsewhere [9, 10]. The Building Process and Law course is a 2 ECTS unit (56 study hours, 7% of the total load for the semester) in the second semester of the first year of the Bachelor's of Science program in Architecture at the Delft University of Technology. This program serves primarily as an entry qualification to Master's of Science programs in Architecture, Urbanism, Building Technology and Real Estate and Housing (including Design and Construction Management) in the Faculty of Architecture. The course has, as its task, to familiarize students with a managerial understanding of the building and development industry, the basic instruments in design and construction management, and to introduce students to the necessity and techniques for, and the difficulty of integrating knowledge in real design projects.

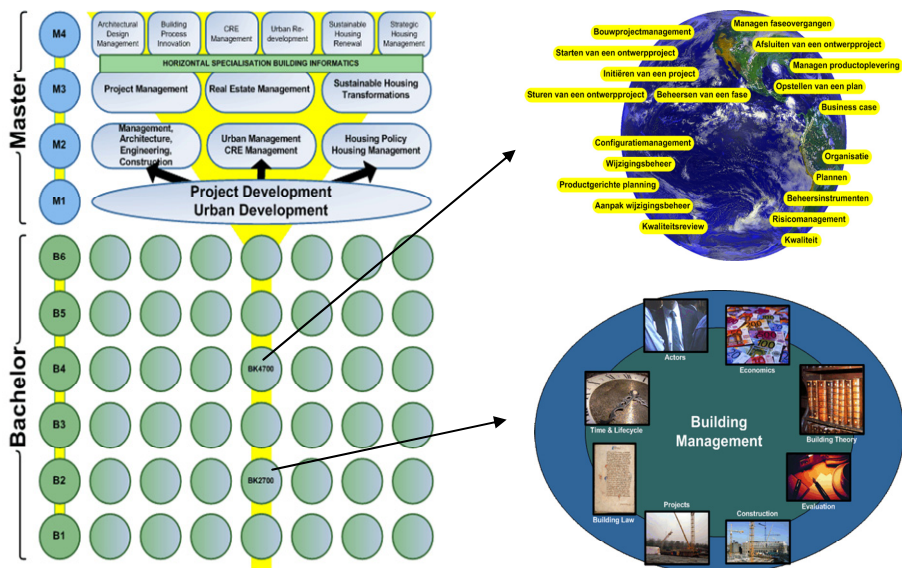


Figure 1. Examples of graphical interfaces of the resource tree of the pilot DEE.

As in many similar programs, architectural students at TUD are deeply committed to design studio. Many students perceive the values, knowledge and imperatives emerging from knowledge-based course in building technology, management, economics and law as externally imposed constraints on their design creativity. In the past, this has resulted in a lack of motivation among students, passive student behaviour, and poor results (including student drop out). Many students choose to defer the examination and those that took it often failed to perform particularly well. Typically only about 60% of the students passed.

## **5.2 Course design**

The development of the DEE was one of measures taken to address this problem. This was coupled with a redesign of the course on a student oriented basis making use of case studies and peer evaluation. The changes in the Building Process and Law course were intended to shift the educational design from an instructor centred model to a student centred model of learning. The new course design was based around a case study in which students were asked to relate the behaviour of actors in the building process (as reported in the literature) with the models of practice set out in text books, and research on building management – to compare what ‘ought’ to be done with how it really is done. The Dynamic E-Learning Environment was employed to deliver learning materials to the students and provide logical support for the peer evaluation process. This was done by providing access from the student’s workplace to an expanded range of materials. Further while the assignment provided students with an increased motive to communicate with each other and the instructor, the DEE gave students the means to do so – forums, group file sharing, and email. Together, the assignment and the DEE produced a blended learning experience.

Students were assigned case studies to perform in teams of 3 or 4. The case studies required students to describe the various actors and the narrative of a project, and then isolate 3 significant problems or issues from the project for further analysis. For each of these problems the students were required to describe the origin of the problem, the detection of the problem, and the solution. They were then asked to provide tips for future projects that would help to avoid, detect or remedy the problem. Then, working in groups of four teams, students reviewed and evaluated the project analyses of their peers. Evaluation itself is part of the assignment if the students are required to evaluate each other’s work. The evaluation was carried out with the assistance of a form

comprising a list of evaluation criteria, and space for both the grade and comments.

### 5.3 Results

The results of the redesign of the course were measured using four different sources of data: the student work itself, a cross case questionnaire developed for the Blend-XL project, reflections on their learning experience written by students, and the instructors observations. The new version of the course was offered as an optional alternative to the entire class in the winter term of 2006. 177 out of approximately 250 students in 42 groups indicated that they would like to participate. The use of a version of Blackboard to which the University had only a limited license created significant technical difficulties with the registration of students and granting of access to materials in the DEE. Thus, after a series of delays and extensions, 114 students in 29 groups submitted projects, and all but two students completed the entire course.

Students found the new course experience interesting (in the questionnaire 48% rated it 'very interesting', another 45% rated it 'interesting'), and enjoyable (61% 'fairly', and 39% 'very' enjoyable). They found the learning objectives clearly stated, and that the course met both the stated objectives and their own learning objectives. 73% reported that the course encouraged them in independent study.

Students relied primarily on email to communicate with each other and with the instructor. Several requested more face to face interaction with each other and with the instructor: *"Maybe some more interaction with the other groups who are following the program and some more contact with the teacher to ask questions"*. It seems that some students had difficulty using the internet facilities for communication: *"I think working together on one project is OK, but I think communication between each other by the internet doesn't work very good. Communications in real is much better, I think."* A contributing factor noticed by the instructor was that many students do not use their official student email address, and were therefore *incommunicado*.

The students made a number of recommendations for the improvement of the course, chiefly that the preparation of the DEE (still under development) and explanatory material could be improved. Further, they felt (as expected) that information about building processes and problems encountered with individual projects were difficult to find. One requested: *"More information about the*



*problems has to be better accessible for students.*” This comment points to a dilemma: should the course emphasize the acquisition of research skills by requiring students to find the project information themselves? Or should it emphasize the development of management insight by providing project information to the students?

In their reflections students were very positive about the case study approach to the material: “... *we have all been surprised of the difficulty we find on the ‘building way’.* *We never had imagined there were so many problems in that kind of project. We were also impressed by the diversity of the problems and what the solutions were. It is interesting to see how people imagine something and then find a way to go through the problems they come across.*” Students found the active approach to learning more exciting and more fulfilling, with 78% of them reporting the assignment to be either fairly or very helpful.

Students appreciated the collaboration, the research experience, the literature, and the degree of self-study. They also reported that what they had learned, in particular with respect to study and research skills, was directly relevant and useful to them.

Interestingly, one student reported that he was not confident that the information he had found himself was reliable or sufficient. This suggests that the student was beginning to develop an independent concern for the quality and completeness of data or information in answering research questions – learning to have a critical attitude towards information.

At first the learning outcomes seemed disappointing. Although students often rated the reports of their colleagues highly on the accomplishment criteria, they very often found their colleagues’ reports failed to meet the completeness criteria. The most common failures were incomplete lists of project participants, a lack of citations of theoretical material (i.e. the general readings on project management), and absent or incomplete bibliography. The students mostly failed to cite sources properly or frequently enough. Bibliographies were also not in an acceptable form. Two possible explanations suggest themselves: 1) that the students are not yet sufficiently familiar with the standards of academic writing, and 2) that the students did not read the instructions for evaluation before compiling their reports. The first explanation certainly pertains. The students did not receive adequate instruction in these aspects either earlier in their studies in the faculty, or as part of the course. It is the second explanation that is particularly pertinent here. Students behaved as if they had discovered that the

assignment was to be conducted in a series of steps, and had read the instructions for each step only at the commencement of that step.

As both of these explanations pertain to the relationship between performance expectations and the material delivered to them to allow them to complete the task, the instructor determined that in the spirit of an experiment, the omissions in citation and poor bibliographies could be overlooked. Adjusting for this factor, the student performance was quite good compared to typical performance on the exams in the old version of the course. 98% of the students passed the new version of the course, whereas only 40% of the students who choose to do the exam in the same period passed.

As stated above, students relied primarily on email for communication with their instructor. 50% reported that email with their teacher was very helpful, and a further 19% reported that it was fairly helpful. A small number of students dropped by the instructor's office for assistance. But little use was made of chats or discussion boards – 50% reported that chats were either not at all or not very helpful. This was at least partly due to the very poor participation rate. But that in turn seems to have been due to the lack of a meaningful and specific reason for the students to use the chat facilities. This meant that the instructor was obliged to spend a great deal of time dealing with the email. This was still, however, much less time than would have been required to grade the reports.

The distribution of files for peer evaluation required little management by the instructor. The students succeeded in using the file exchange directories within the DEE to find documents to evaluate and to post their evaluations.

## **6. Reflections and conclusions**

The new 'blended' design of the course apparently succeeded in addressing the problem of making design and construction management relevant to the students. There were 'teething' problems with both the DEE and with the instructor's experience in using educational software, but these will be overcome in future versions of the course. Given the technical and organizational difficulties experienced in this project, the students' evaluations of their experiences, as exemplified in the questionnaire responses as well as in the reflections were very positive. They seemed to have a great deal of patience for the problems associated with a pilot implementation of a new ICT enhanced learning experience. The students showed a significantly greater interest in the complexities of real building projects, and in the integration of both the

knowledge and design of the various building disciplines required in contemporary construction. It might be concluded that DEE types of educational environments significantly can contribute to enhance students to deliver better integrated design solutions.

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# IDS for Ideas in Higher Education Reform

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## Abstract

Increasing technical and socio-cultural information accompanied by a fragmented specialization in knowledge and skills, rapidly changing technology, and liberal economic growth that negates rational use and distribution of world's resources challenge ecological sustainability. These challenges and concurrent trends for sustainable development, e.g., sustainable construction, motivate the IDS approach in the delivery of projects for the built environment.

In the Ankara CIB IDS Workshop, 2006, Wim Bakens proposed investigation of best practices of IDS in the universities. Implied were the practices in universities overriding the compartmentalization and isolation of subjects. With no such survey done yet, this paper started with the questions of what IDS meant for universities. It dwells on the importance of cooperation, collaboration, and dialogue in the learning context, as well as on using the new technology, as preconditions of IDS. So international reform processes in higher education, general and architectural, are looked into for related action lines.

The competences-based education is assumed for innovative redesign of curricula. The results of research on competences show critical reasoning, lateral and creative thinking, and the competences of communication, collaboration, and participation in teamwork as rating high. IDS approach is suggested also for this redesign and for restructuring the university.

**Keywords:** architectural education reform, Bologna Process, IDS in education, qualification requirements, re-design of curricula

## **1. Challenges and the needs**

University reform is on the agenda as a result of changes that create problems in the global context and affect new dynamics in the everyday world. University reform is in a sense an acclamation of these dynamics. Changes in the structure and learning contexts of institutionalized education, where the roots of some problems in practice exist, should be expected. One of the problematic issues is the isolated fragmentation of disciplines. This is all the more critical for the procurement and management of the built environment which require concerted action of stakeholders, e.g. experts, users, for viable consequences.

The present world is characterized by great increase in the technical and socio-cultural information accompanied by the fragmented specialization of knowledge and skills, rapidly changing technology, and growth and prosperity in conflict with the aspired sustainability of development and poverty. The challenges thus presented require competences to relate to this world, to deal with complexity and heterogeneity, differences and contradictions, the isolation of the fragmented and compartmentalized, and interdependence of issues, besides the competence in using ICT. Integrated solutions aimed for in practice depend on acquisition of such competencies as learning outcomes of educational programs.

## **2. The Context of design for the built environment**

Sustainability has become an macro level conceptual demand and an ideal for the built environment in response to adverse environmental indicators. Meeting this demand beyond mere lip-service asks for commensurate policies of development, revaluing technology, and an integrated approach to design and construction. The adequacy of design for the built environment, i.e. architectural design, which is a synthetic act, will be increasingly at odds with the isolated fragmentation of knowledge and practices related with the environment. It will fall short of the expected, so long as new ways are not devised to incorporate diverse domains of knowledge and experience through the stakeholders involved.

Assessments of the existing built environment provide the demands for re-design, as well as the design of the new, based on an awareness of the sustainability demands. A comprehensive outlook and solutions are required from design, which is concrete action. Means and potentials of a technology revalued in accord with sustainability demands can supply design with new horizons in conceiving and realizing innovative solutions.

The wide variety of disparate conditions and factors and different aims are to be simultaneously taken into account and resolved through integration for a balanced solution, where some compromise is inevitable. Design as a synthetic activity is integration of contradictory and even incompatible purposes or motives. The synthesis or integration of such diverse issues as achievement of perceptual qualities, structural firmness, and propriety and convenience of use remains as the *raison d'être* of architecture. The responsibility of accomplishing such integration, which demands "*design control*", appears to be demanding a "*distribution of (this) control*" to allow "*different parties taking care of things on different levels in the environmental hierarchy*". [1] (p. 44):

“For today’s complex projects, partial tasks must be distributed among members of design teams. This also involves many consultants on building structure, utility systems, lighting and acoustics and so on, who, of course, are heavily involved in design decisions as well.”

The synthesis/integration to be achieved demanded by the present realities seems to require a new profile for the architect. Habraken emphasizes the need for cooperation and sharing of environmental qualities and values, and the importance of method as the tool of cooperation. Method, he says, facilitates coordination as well as stimulating improvisation.

Architecture, which involves design for the built environment, “...is a discipline which draws knowledge from the humanities, the social and the physical sciences, technology, environmental sciences, the creative arts and the liberal arts”. [2] (p. 3). It requires competences (skills, abilities, knowledge and understanding) related with aesthetic quality, technoscience, and human and social factors. Critical reasoning, lateral and creative thinking are integral to a balanced synthesis of these diverse aspects.

The isolated fragmentation and specialization of knowledge, skills, and practices related with the disparate factors in building design call for new ways to achieve integrated design solutions (IDS). A basis for new ways is interdisciplinary teamwork. The wide range in the inclusiveness of the “team” is connoted by the term “stakeholders”. The employability of all “stakeholders” further developed with action-oriented research and utilization of ICT. Education and training for the design of the built environment are expected to achieve competences of communicating and collaborating with others, and participation in teamwork.



### 3. University education

Fragmentation observed in the theoretical and practical spheres, due to miscarriage of the tenets of the Enlightenment, has its roots also in the “stove-pipe” or “domain silo” structuring of the universities. A process of restructuring seems to be needed. Sustainability as a conceptual macro level demand is expected by some to be the moving force behind a restructuring; e.g. Bergen Communiqué (2005) of the Bologna Process states that achieving education for all is to be based on the principle of sustainable development.

Sustainability is to be understood not as that of the status quo, but that of “progress” [3] (p. 2) towards an equitable distribution of sustainable development and wealth in the world against poverty and want. There is, on the other hand, the necessity to define the “needs” in the statement made by the World Commission on Environment and Development: *“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”*

Efforts for sustainability in development are needed at both institutional and individual levels [4] (p. 2). An important institution is the university. For an education and academic research that should not lead to adverse results, changes seem to be required in the educational programs. Cohen proposes the development of a “sustainable mindset” through undergraduate education. [5] (p. 84) This is justified by the adverse outcomes of an education, which harbors the roots of the fragmentation in practice.

Such a mindset, according to Cohen, comprises systems-thinking, both academic and practical grounding of knowledge, and ethical motivation. [6] (pp. 86–88). University can help create it not through what it teaches, but through through the educational effects of university life, which the author calls as “shadow curriculum”. Connecting traditional areas of academic study to their roles in the world through interdisciplinary study and research is still another way that the university can help inculcate such a mindset. Emphasis on collaboration/cooperation as a learning context besides the individualistic and the competitive, and on experiential learning by doing and reflective thinking, and on dialogue are the pedagogical indices of a concern for the “sustainable mindset”.

## 4. Attempts for IDS in architectural education

Few universities are mentioned to have been able to adopt IDS as the basis of their curricula. Urgent need is declared by Kokkola of new curricula for architects and engineers based on IDS with BIM as an essential aspect. Moving from 2-D drafting, autocad, archicadd, archidesktop, 3-D max modelling to integrated information models is considered necessary for a true integration and IDS. The potentials of the IC and BIM technologies (3-D parametric modelling platform and data models) and simulation and analysis tools (SAT) are to be integrated into the curricula for the relevant phases of projects. [7] (pp. 1–3).

In the “*Integrated Design Solutions (IDS) Workshop II*” held in Atlanta, Georgia in 2006 [8] the deans of schools present shared their practices and thoughts. Georgia Tech is told to have been introduced to BIM since mid-nineties. Pennsylvania University had an integrated design studio using BIM in 2006 for the first time. University of Nevada has moved to BIM in 2005. University of Maryland, too, has made a transition to BIM with archicadd and REVIT.

Georgia Tech has an interdisciplinary curriculum involving architecture and construction. Like twelve other schools in U.S. in 2006, Auburn University, too, had architecture and construction programs under the same umbrella; the architecture and construction students had to take at least one collaborative studio together. University of Maryland has a 4th year comprehensive studio with integrated curriculum of studio instruction, building systems and structures. An interdisciplinary and design-build oriented curriculum idea is adopted. Texas A&M University has interdisciplinary studios with faculty from several departments. Special common projects are worked on between the disciplines and departments.

In Georgia Tech architectural and construction firms, students and faculty are involved in research on BIM (3-D and nD) and interoperability for improving ways of planning, designing, building and operating buildings. They do research on and applications of digital manufacturing and fabrication through CNC machines and parametric nD modelling. Schools are asked to move toward linking production with the design of buildings considering the concurrency of design, engineering, and construction. (G. Hack) The path was suggested to be from the university to the industry (J. Baldwin). Partnerships were suggested between the university and the industry, especially with the all-in-one firms where (AEC) integration is observed. (C. Eastman) Texas A&M University involves leaders in industry to advise on their curriculum. Partnership with

companies with advanced innovative work helps the school to stay at the forefront of technological change and help shape the tools for lateral thinking and interdisciplinary study. (G. Rockcastle) Alliances are also advised between schools and research-based organizations (G. Hack) which are viewed as integrators. (T. Regan.)

Collaboration in practice is prevalent. So, a greater value is acknowledged to be placed on teaching how to work in teams and on teaching leadership skills to students. (G. Hack.)

Shifts in the delivery of buildings aspired and enabled by new potentials of knowledge and technology lead to rethinking design teaching. G. Hack and G. Rockcastle suggest to begin thinking of integrated building with modification of an extant building for better performance. Adaptive re-use or remodeling of buildings gained importance with the emphasis on sustainability. Achieving higher performance is a challenge. (G. Rockcastle.)

## **5. Higher education reform can support IDS**

The rate of change in technoscience and mobility of people, goods and services in an increasingly mobile world have made reforms necessary in higher education. In the official declarations and directives related with the reform processes in higher education that had a definitive start with the initial Sorbonne and Bologna meetings of ministers from European countries, there are allusions to cooperation and multi-disciplinarity as contexts of learning. (Table 4) The general and important aim of giving people the competences necessary to face the global changes and challenges is stated.

The Sorbonne Declaration (1998) signed by four ministers states that “undergraduates should have access to a diversity of programmes, including opportunities for multidisciplinary studies, development of proficiency in languages and the ability to use new information technologies” [9] (p. 2).

The Bologna Declaration (1999) mentions passingly inter-institutional cooperation, and integrated programmes of study, training and research. A preliminary step towards a common framework of qualifications based on generic competences was suggested with the adoption of the two-cycles for higher education.

Salamanca Convention of Rectors convened in 1999 to define the position of the universities with regard to the Bologna process of higher education reform. The reasons for developing communication skills and teamwork as transversal competences for qualification is declared:

“Employability in a lifelong learning perspective is best served through... (among others) the development of transversal skills and competences such as communication and languages, ability to mobilise knowledge, problem solving, team work and social processes. - (highlighting mine)” [10] (p. 8) “...response to demands for more employable graduates is for institutions to include more multi-disciplinarity at the first level of higher education, so that workers can communicate better with specialists from other fields.” [11] (p. 50).

European Commission document on “The Role of the Universities in the Europe of Knowledge” of February 5, 2003, raised the question of “How to establish closer co-operation between universities and enterprises to ensue better dissemination and exploitation of new knowledge in the economy and society at large”. [12] (p. 231).

In this document, besides long term planning and financing, and efficient management, interdisciplinary capability is considered as one of the conditions for excellence within the university:

“Organizing work on an inter-disciplinary basis requires that universities have flexibility in their organization, so that individuals from different departments can share their knowledge and work together, including through the use of ICT. It also requires flexibility in the way careers are evaluated and rewarded, so that interdisciplinary work is not penalised for being outside normal departmental frames. Finally, it requires that departments themselves should accept “cross-border” work as contributing to faculty-wide objectives.” [13] (p. 246).

The European University Association’s response to this document stresses that cultural and social innovation is as important as the purely scientific and technical progress. [14] (p. 1). Regarding the dialogue between the universities and the society, the universities were presented as cognizant of the necessity to respond to the needs of the stakeholders through activities that will promote interdisciplinary research. [15] (p. 3).

The Berlin Declaration (2003) in connection with its recognition of the doctoral studies as the third cycle, emphasised the importance of research training and interdisciplinarity. [16] (p. 7). Development of an overarching European framework, as well as of concurrent national frameworks, of comparable and compatible qualifications for higher education described in

terms of learning outcomes (knowledge, skills, and competences) was also a demand of this declaration. [17] (p. 4).

There were initiatives after the Bologna Declaration for realising the lines of action for reform, i.e. JQI and the Tuning Project, with work done on qualifications structures to clarify the cycles in higher education, and to establish the transparency, compatibility, and comparability of educational programs. During 2004 JQI's (Joint Quality Initiative) "Dublin Descriptors" of generic competences based on the Irish and Danish national frameworks were proposed to be adopted for the overall framework of qualifications of EHEA. Competence, as other than knowing and understanding, is knowing how to act, and knowing how to be. It is a synthesis of knowledge, its application, skills, and attitudes [18] (p. 20).

Bergen Communiqué (2005) adopted this overarching framework of qualifications (EQF) for EHEA, comprising three cycles and the generic descriptors for each cycle based on learning outcomes of knowledge, skills, and competences. EQF for EHEA would be the basis for the national frameworks to be developed. [19] (p. 2). According to the Communiqué, achieving education for all is to be based on the principle of sustainable development. The London Meeting in 2007 reiterated the institution of national qualifications frameworks in each country. [20] (p. 2).

The generic competences described for the three cycles in the EQF – EHEA are those heavily transposed from the "Dublin Descriptors". Of these generic competences for all disciplines in higher education there are those directly or obliquely relevant for interdisciplinary cooperation and collaboration as well as interpersonal communication and dialogue. Those that need to have been acquired by the time one completes the Master's – 2<sup>nd</sup> cycle – are listed in Table 1. [21] (p. 3).

The framework of generic ("key") competencies developed by the OECD countries from 1997 on became a reference for education and lifelong learning. These competencies were formulated in response to the rapid technological change, interdependence, diversity and compartmentalization in societies, and the growth in specialized knowledge and information. The other global challenges of sustainable development, e.g. environmental sustainability, social equity and cohesion are considered to depend on the competencies formulated.

Three categories of generic ("key") competencies have been identified in the DeSeCo project (Definition and Selection of Competencies) with the collaboration of scholars, experts and institutions. (Table 2) [22] (pp. 12–13).

Table 1. Generic competences seen relevant for interdisciplinary cooperation, collaboration, and communication and dialogue among (“Dublin Descriptors”).

- can communicate their conclusions, and the knowledge and rationale underpinning these, to specialist and non-specialist audiences clearly and unambiguously.
- can apply their knowledge and understanding, and problem solving abilities in new or unfamiliar environments within broader (or multidisciplinary) contexts related to their field of study.
- have the ability to integrate knowledge and handle complexity, and formulate judgements with incomplete or limited information, but that include reflecting on social and ethical responsibilities linked to the application of their knowledge and judgements.
- the knowledge and understanding gained provides a basis or opportunity for originality in developing or applying ideas often in a research (in its inclusive sense\*) context.
- has the learning skills that enable study in a manner that may be largely self-directed or autonomous.

\* The term ‘research’ in its widest sense is: “...a careful study or investigation based on a systematic understanding and critical awareness of knowledge.....original and innovative work in the whole range of academic, professional and technological fields, including the humanities and traditional, performing, and other creative arts.”

Table 2. The three categories of generic competencies (OECD DeSeCo project).

***Using tools interactively:*** a familiarity with the tool itself (language, knowledge, information, technology) and understanding how it changes the way we can interact with the world.

***Acting autonomously :*** to understand and consider the wider context of one’s actions and decisions; defining projects and setting goals; identifying and evaluating one’s rights, needs, and interests.

***Interacting in heterogenous groups:*** involve the competences of “relating well to others”, “cooperating, working in teams”, and “managing and resolving conflicts”. Learning, living, and working with others. As societies become more fragmented and diversified, managing interpersonal relationships for cooperation become important.

One of the tenets of university reform is increase in diversification. A diversified university system is seen fundamental due to emergent issues that require specialized knowledge in the complex world of knowledge-based society. This demands from the university a wide spectrum of graduate qualifications and different study programs to be instituted, modified, or closed when obsolete. It also demands a basis of unification and permeability between the programs. Methods of overcoming “stove-piping” by restructuring, interdisciplinary cooperation, and collaborative learning in the university can help prevent the

breach between the specializations in practice. A restructuring needs to see to the intra-departmental as well as the inter-departmental compartmentalization and lack of dialogue.

Consequences of the delivery process of the built environment directly affect the quality of life and sustainable development. Being n-dimensional, delivery of the built environment requires a multi-disciplinary concerted action of the stakeholders. An integrated design approach consistent with sustainable development presages interdisciplinary work and teamwork of participants who can communicate and collaborate. ICT with its potentials for nD-modelling and interoperability and teamwork is a significant means. Yet, the learning context is where the preconditions for concerted action need start, so long as the roots of fragmentation in practice are considered to be in the university.

IDS is a basis to consider in the re-designing of curricula by the architectural schools. It seems that the need for such a basis is generally assumed, while the breach between the parties that need collaborate for IDS is acknowledged. A major factor is the “stove-piping” or the “domain silo” structuring in universities. However, mere acquisition and use of ICT, BIM systems, simulation and analysis tools and methods may not lead to fundamental changes implied by IDS. The latter suggests an alternative structuring of the university.

## **6. The relevance of competences-based approach for IDS in architectural higher education reform**

Related with the field of building and construction, the education of the architect is being re-thought with new strategies for reform due to world-wide demands on architecture, which call for redefining the roles and profile of the professional architect. Aligned with the Bologna Process of reform in higher education in Europe and the impact of its internationalization, there are efforts to review the-state-of-the-art and develop strategies to reshape the higher education in architecture. A major aim is innovative re-design of curricula by educational institutions with reference to competences commonly identified for the professional architect.

European Network of Heads of Schools of Architecture which, during the process of the movement for reform in higher education (Bologna Process), worked on defining the position of architectural education in that process and on shaping the architectural higher education area, is in contact with the Tuning project. The latter is running studies for identifying learning outcomes (knowledge, skills, competences) as reference points to describe degree programs of different

disciplines or subject areas. The aim is to achieve comparability, compatibility, and transparency of educational programs in a subject area based on competences-based and learner-centered pedagogy. ENHSA took part in a “Validation Conference” of this project, organized in November 2007. It was a validation process of work done until then by various subject areas in the humanistic and social sciences, including architecture.

The integration of such diverse issues as achievement of perceptual qualities, structural firmness, propriety and convenience of use is the *raison d'être* designing and constructing for the built environment. To create, to think, to make, and to experiment are the four strongly interconnected objectives of building and architectural education. They are disparate due to the mode of thinking and knowing (scientific/technoscientific, artistic, intellectual). In the practice of building, which is synthetic and holistic, they are simultaneously present. In Louis Kahn's (American architect) words thinking can be creative, making can be thoughtful.

The scope of architecture or building requires “...*knowledge from the humanities, the social and the physical sciences, technology, environmental sciences, the creative arts and the liberal arts*”. The multi-disciplinarity of architecture is important for the framework of training for architecture. [23] (p. 3).

The Architecture Group Brochure submitted to the “Validation Conference” refers to the subject of architecture as having interdisciplinary and multi-disciplinary nature:

“(The architect)...is involved in the creation of the built environment by translating the socially and culturally defined demands of individuals, groups or bodies into built forms and spatial organizations.....An architect should be able to operate within a variety of client, architect, management and builder relationships in an effective and professional way, within the constraints imposed by the building and construction industry, the project budget and the brief.” [24] (p. 8).

The architect is “involved in” and “operates within a variety of relationships with others (stakeholders)” during the creation of the built environment.

With the increase in the complexity of information and knowledge about what is “involved in” the creation of the built environment (technical, social, cultural), and the heterogeneity of the various compartmentalizations to be related with, “*a redefinition of the multifaceted professional profile of the contemporary architect*” is needed. [25] (pp. 11–12). A restructuring of architectural studies and updating of educational content become two parameters of this redefinition.



An aspect of the need for redefinition of the profile is related to the observations of Habraken and to the competences which appear to be essential for the IDS approach made urgent by global changes. Need for change in profile and education is not limited to the architect and architectural education, nor to the procurement of the built environment. IDS for the built environment have social and cultural dimensions other than the technical, physical, and economic. Its achievement in practice depends on a restructuring at university level that will do away with “stove-piping” or “domain silos” and will help acquisition of competences relevant for IDS. This is one of the desired and expected outcomes of the movement for reform in higher education (the other cycles of LLL need not be neglected).

In rethinking and defining the profile of the architect and architectural education ENHSA adopted the methodology of the Tuning project and focused on a competences-based approach. Competences as an aspect of learning outcomes constitute reference points for the qualifications of degree programs – a European framework of qualifications for architectural education. They help indicate the profile of the graduates. This framework becomes the reference and a guide for a school attempting to define, design, and develop the appropriate methods and means of teaching, educational milieu, and learning context or pedagogy, besides the restructuring and updating of the content of the studies.

ENHSA conducted an inquiry through a questionnaire among academicians on the one hand, and professionals on the other, that would lead to a ranking of competences and present a picture of the graduate profiles of degree programs at bachelor, master’s, and PhD levels. The category of generic competences in the inquiry have been based on those identified by the Tuning project. Since completion of master’s program (2<sup>nd</sup> cycle) is the academic prerequisite for being a professional architect, the results of the inquiry for that level as well as the bachelor’s level (1<sup>st</sup> cycle) leading to it need be looked at. The ratings of competences by academicians and professionals which can be considered as having a higher relevance for the IDS approach in practice are given in Table 3. [26] (pp. 13–28).

While personal and social skills in expression and communication are commonly ranked high by both academicians and the professionals, ability in interdisciplinary teamwork and collaboration are among those ranked as highest by the professionals, while given importance by the academicians (as the 9<sup>th</sup> out of 21).

In the results of an inquiry by the Tuning project for universities in 15 Latin American countries, “Ability to work as part of a team” has been rated among the

highest (6<sup>th</sup> out of 27) by employers from diverse fields, while it was rated 14<sup>th</sup> by academicians (of 12 different subjects). Both considered the achievement of this competence by schools to be low in proportion to the significance it should have. Academicians from architectural schools in these countries thought that little importance was being given to “leading interdisciplinary work”. [27] (p. 89).

## **7. Competences-based framework of qualifications for architectural education and IDS**

A research project (\*) was started at METU Faculty of Architecture in 2007 to initiate studies for a sectoral national framework of qualifications for architectural education in Turkey. An inquiry has been carried out through a questionnaire among academicians, students, professionals, and employers, on the ranking of competences in relation to the different cycles and subject areas in architectural education. The category of generic competences was based on the EQF – EHEA (Dublin Descriptors) and the OECD DeSeCo project. The results of this survey will guide in-depth interviews and focal group studies. Emergent framework can be adopted by and guide schools in designing their curricula autonomously.

The design of the curricula by schools, too, involves an integrated design approach. There are levels of integration involved. Competence itself is integration of knowledge, understanding, skill and ability. Graduate profile as an objective of education is the integration of a number of generic (instrumental, interpersonal, and systemic) [28] (p. 9) and subject specific competences. Designing and managing the learning context for the identified graduate profile require both the autonomous work on different subjects, and collaborative work with the participation of diverse stakeholders.

These competences that qualify the cycles and the competences for different aspects of architectural study will have to be derived through research involving the action of diverse parties and relevant disciplines. This is what the research projects at METU are set out to try. [29] (p. 3).

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\* “Planning and Design in Action for A National Qualifications Framework for Architectural Education and Competence-Based / Learner-Centered Curricula for the Bachelor, Master, and Doctorate Cycles” research supported by TUBITAK (The Scientific and Technological Research Council of Turkey) Social and Human Sciences Research Group (SOBAG) – Project no: 108K138.

“At a time when we are talking about global change and how to respond to that in the university universally, we need to suspend the particular and involve all those concerned in interdisciplinary research and debate that will reveal points of consensus and guide the restructuring of architectural education at the institutional level. For a restructuring and curriculum design to be competences-based then would mean freedom to create diverse ways of achieving the competences universally expected to qualify the graduates for the intended profiles.” (Figure 1) [30] (p. 7).

The suitability of the learning context for acquiring and developing the competences most relevant for IDS depends on the possibilities of practicing IDS. It depends on the extent of “cross-border” relations between different subject areas and different programs of study. The architectural and urban design studios, which present a likeable model, but face the threat of getting isolated like other courses within the curricular activity, are to be rethought and reviewed in the light of IDS. Cooperative and collaborative context, besides that of the individual competitive work and the autonomous subject, has gained importance with the changes and challenges in the world and practice. With the competences-based approach, relevant competences will suggest and can bring about intra-departmental changes for an integrated learning context amenable for IDS. Yet, such a context desirable at the university level also requires a restructuring to facilitate inter-departmental permeability.

## 8. Conclusion

Challenges of a fast changing world and concurrent trends for sustainable development, e.g., sustainable construction, motivate the IDS approach in the delivery of projects for the built environment. Universities are needed to provide for the acquisition of those competencies that seem to be critical for sustainability issues and IDS. Among those which rate high are critical reasoning, systemic thinking, lateral and creative thinking, and the generic competences of communicating, collaborating, and participation in interdisciplinary teamwork. These are some important parameters for defining the profile of the graduate architect, and also for others to take part in the delivery of the built environment.

University reform has become an international agenda as a result of the new dynamics in the everyday world affected by the challenges and problems of the fast changing world. University reform is an acclamation of these new dynamics.

Changes in the structure and learning contexts of institutionalized education, where the roots of some of those problems exist, should be expected. The role of the university is to admit and deal with these problems that exist in the learning context and graduate people with the relevant competencies. This would require a revision of the existing curricula as well as that of the structure of the university for redesign.

The revision and redesign need be at university level and interdepartmental. Ideally, all diverse subjects concerning the making and sustaining of the built environment should be involved in such change, if, especially, competencies of priority in the elimination of “stove piping” are considered important for sustainability issues and IDS. With the needed competencies as common reference points, different institutions can come up with different and innovative ways and methods of achieving them. Method, as Habraken has seen it, is important as the tool of cooperation and improvisation. The university would need to have flexible structure in order not to hinder, but accommodate innovative improvisations and practices at departmental and interdepartmental levels.

The specific competencies needed to be achieved for the graduates are to be differentiated and articulated further than mentioned in the paper in general terms. It is important to identify the level of the competence to be achieved at different cycles of learning, the key indicators of that level, and the assessment criteria (descriptors). This is essential in guiding innovative designs of the learning contexts where these competences will be gained.

Sharing of the experiments and experiences by schools in the realization and achievement of a learning context and practice in IDS is felt necessary for comparability and compatibility, not only between schools, but also between schools and the practice. A survey of IDS practices (not necessarily the best) in schools, which this paper wished to have done or be based on, would be valuable.

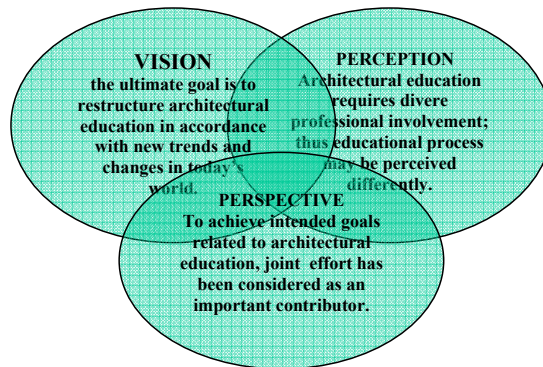


Figure 1. (Aközer, et al. Chania; figure by E. Kiraz) [31].

Table 3. Rating by academicians and professionals of the competencies seen as most relevant for IDS.

among the 10 out of 20 generic competences most valued by academicians:

*For Master's (2nd Cycle)*

- 4th Ability to develop a transdisciplinary understanding
- 5th Personal and social skills in expression and communication by speaking, writing and sketching
- 6th High level computing skills including the ability to use the internet critically as a means of communication and a source of information
- 9th Ability to work in an interdisciplinary team

*For Bachelor's (1st Cycle)*

- 1st High level computing skills including the ability to use the internet critically as a means of communication and a source of information
- 4th Personal and social skills in expression and communication by speaking, writing and sketching
- 10th Ethical commitment

among the 10 out of 18 research competences most valued by academicians:

*For Master's (2nd Cycle):*

- 1st Ability to communicate appropriately in written, oral and graphic forms
- 4th Ability to use IT and internet resources (statistical, cartographical methods, database creation, etc.)

*For Bachelor's (1st Cycle)*

- 1st Ability to use IT and internet resources (statistical, cartographical methods, database creation, etc.)
- 2nd Ability to communicate appropriately in written, oral and graphic forms

among the 10 out of 34 generic and subject-specific competences that concern the profile of the graduates according to the professionals: (professionals have also graded the schools for their success in providing for the achievement of each of the competences acquired by their graduates – their esteem has been quite low with the mean average grade turning out to be %57.52 for all 34.)

- 2nd Personal and social skills in expression and communication by speaking, writing and sketching (%61)
- 3rd Ability to work in an interdisciplinary team (%58)
- 4th Ability to work both with a high degree of autonomy and collaboration (%62)
- 10th Ability to develop a transdisciplinary understanding (%53)

Table 4. Declarations of Ministers' meetings during the Bologna Process of higher education reform with references to competences which can be seen as relevant for sustainability issues and IDS.

<b>SORBONNE DECLARATION 1998</b>	Opportunities for multidisciplinary studies Development of the ability to use the new ICT's
<b>BOLOGNA DECLARATION 1999</b>	Suggested a common framework of qualifications Inter-institutional cooperation / integrated programmes
Salamanca Convention of Rectors 1999	Communication skills and teamwork as transversal competences for qualification / Multidisciplinarity is fundamental - more multi-disciplinarity at the first level of higher education
JQI Tuning Project	Qualifications structures to clarify the cycles in higher education for establishing the transparency, compatibility, and comparability of educational programs
<b>PRAGUE DECLARATION 2001</b>	<p>Closer co-operation between universities and enterprises Interdisciplinary capability a condition of excellence in the university</p> <p>European Commission Document February 5, 2003 "Cross-border work; individuals from different deðartments to share knowledge and work together</p> <p>EUA Response to the EC Document May 2003 University activities to promote interdisciplinary research Cultural and social innovation is as important as the scientific &amp; the technical</p>
<b>BERLIN COMMUNIQUE 2003</b>	Emphasised research training and interdisciplinarity Demanded an overarching framework of qualifications
JQI's "Dublin Descriptors" 2004	"Dublin Descriptors"of generic competences based on the Irish and Danish national frameworks were proposed to be adopted for the overall framework of qualifications of EHEA.
<b>BERGEN COMMUNIQUE 2005</b>	Adopted the Overarching Framework of Qualifications for the European Higher Education Area (EHEA)
<b>LONDON COMMUNIQUE 2007</b>	Reiterated the institution of national qualifications frameworks in each country

**BOLOGNA PROCESS** - Meetings of Ministers Responsible for Higher Education

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# InPro training Environment and Model Based Working in Construction

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## Abstract

InPro project is European initiative which is developing a model based and collaborative way of working in early design phase in construction. To support project goals and facilitate the industrial transformation and industrial technology take-up, the project implemented tools and developed curricula and materials for training and education of management, architects, engineers, and construction workers, as well as university students. The paper presents training environment architecture with BIM laboratory that was developed to support training on model based work practices and enhancement of hands-on skills. Development process, technical solutions and experiences are described. Content of training courses and curricula is based on experiences from live project demonstrations and use cases. The paper presents one of the answers that address the problem of insufficient skills in construction industry that prevent adoption of novel methods of working and technology.

**Keywords:** education, training environment, business courses, university curricula, model based working

# 1. Introduction

Construction industry and related research constantly tries to overcome traditional and deeply rooted methods of work and to replace them with novel principles introduced by information society. In this way, the industry tries to keep the pace with other industries and increase its competitiveness and flexibility. The efforts are evident in research strategies [1] [2] and many specific research projects that can be followed through construction IT related conferences like CIB W78 or ECPPM and can be tracked back more than 10 years ago. In all these efforts we can recognise at least one common topic. That is model based approach to construction. This approach should introduce novel processes based on up to date information and knowledge.

Despite this rich body of research and knowledge and consensual acceptance of the fact that model based approaches bring many benefits to project stakeholders, construction industry processes are still mainly based on 2D drawings and poorly handled data exchange among the participants. The situation results in segmented design and construction processes, extensive data exchange problems and loss of information.

At his point, we could say that IT for construction industry is there, but the same industry should start using it. One alternative to make the step forward in tightening the gap between research and the industry is certainly education of practitioners. Such efforts can be recognised in projects back to SCENIC [3]. Fruchter [4] reported on combined research and curriculum development for multidisciplinary, geographically distributed architecture / engineering / construction (AEC) teamwork. Other successful attempts were reported from different research networks (e.g. [5]). Authors of this paper also contributed to the subject via development and operation of Euromaster program [6] [7], which is the basis for InPro training environment described here. To better understand InPro training environment principles and organization, Euromaster background is briefly described in the following chapter.

InPro training environment is a deliverable of InPro project performed under EU 6th framework programme for research and development. The project recognises the importance of dissemination of newly developed knowledge not only via research papers, professional organisations and media but also via formal university education and life-long education of current and future professionals. Introduction of ICT in business processes create redundancies in unqualified administrative services. These employees will need to upgrade their

knowledge to new and highly qualified work tasks related to the technology systems. The project devoted over 60 person months for development of requirements posed on engineers, architects, administration, etc. to work in a model-based collaborative environment. To achieve ambitious goal of construction industry transformation, targeted work packages are dedicated to development of training programmes for higher education as well as for professionals at all levels plus extensive dissemination activities. Educational content which is delivered via InPro training environment is direct result of the project research work. Therefore overview of project goals and research activities is presented also in this paper together with training and education strategy. Finally, technical solutions selected for platform implementation are described

## **2. InPro training platform background**

### **2.1 Euromaster project**

A discussion about the problems and potentials of ITC in building engineering curricula started in Reykjavik in 1999 among participants of the CIB W78 conference and resulted in a proposal of a postgraduate programme development project, which has been submitted to the Socrates Erasmus call in 2000. The main purpose of the project was to develop a curriculum on Construction IT to give students the possibility to extend their knowledge in research, development, and application of computer and information science in civil and building engineering.

Such programme should complement existing university courses because during undergraduate studies, subjects are typically available that introduce computer science, elementary programming, office and CAD software. The students are supposed to master skills so that they can use computers in the assignments given in the professional, engineering courses. During these courses they also learn about particular software that tackles that particular area, for example finite elements solvers, planning and scheduling software, proportioning and reinforcement design programs etc. A European Masters curriculum in ITC complements the existing portfolio of teaching programs and should meet the growing demand for such skills. It tries to advance construction IT education, introduce more holistic perspective of IT in construction industry and integrate the fragmented profession.

The accreditation process of a joint study program performed by several universities proved to be a problem, since different rules are in power in such many different countries and universities. To overcome formal obstacles and to open the program to the global community we have decided to form an open pool of ITC related courses. The initial ITC course pool has started to accept courses developed in the ITC Euromaster project. However, any institution with knowledge in the ITC field is welcomed to offer a course to the pool. Once the new partner institution is accepted by the steering committee, the institution can include any number of existing courses in its own programs, since the pool is based on reciprocity. Having a whole pool of courses at hand certainly gives each partner a strong background to form a whole new program and to offer their students specialized knowledge and skills which they could possibly never be able to offer by themselves.

## **2.2 InPro project**

InPro [8] is a European cooperation between 19 construction sector companies, IT companies, consultants and research organisations from 8 countries. The project runs from 2006 to 2010. As stated in the project's Description of work:

»The InPro project will completely transform the Early Design phase of a building (new or renovation) project. At this influential phase, which represents only a fraction of the lifecycle of a building, decisions are made that determine over 70% of the total lifecycle costs. The Early Design phase also has a direct impact on the building's added value for all stakeholders, as well as on the construction sector's efficiency and sustainability.«

The project develops strategies and business models for a new building design process which enforce open cooperation between project partners and consider the building's whole lifecycle. New business concepts and processes are defined that provide incentives for model-based working and open collaboration between all stakeholders. From technology point of view, smart, fully semantic ICT platform and tools are developed or specified enabling exchange, sharing and reuse of information throughout the building lifecycle. Beside methods and tools project runs support actions for direct implementation in the European construction sector. The project focuses on Early Design phase of construction project. The Early Design phase is the most neglected phase of the building lifecycle, where the decisions taken have a high impact on the lifecycle costs. InPro completely transforms this phase through new business concepts and

processes supported by advanced ICT solutions. InPro has a completely novel and innovative scope and approach, which will have a radical impact on the improvement of building processes, and on the widespread use of ICT throughout the lifecycle of a building.

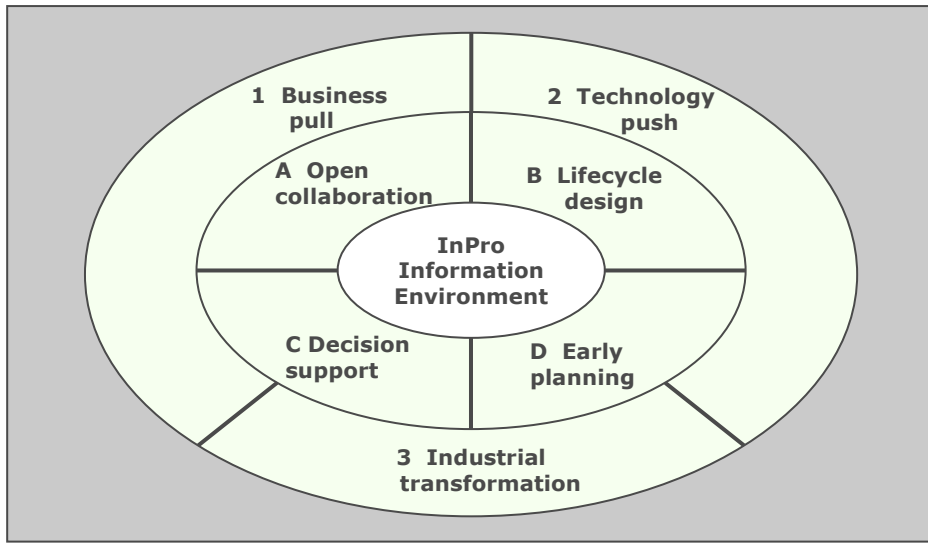


Figure 1. The InPro Open Information Environment supports the four aspects of Early Design (A–D).

The main output of InPro will be the “Open Information Environment” - an advanced system of Early Design processes, supported by radical business concepts and ICT solutions that integrate four crucial and closely interlinked aspects of Early Design: (A) Open and flexible collaboration between all stakeholders of the building value chain, (B) Design from a lifecycle perspective, based on 3-dimensional Building Information Models, (C) Decision support to make “informed choices” based on knowledge of each decision’s consequences on the building lifecycle, (D) Early planning of build and operation processes based on computer enabled simulation of smart digital prototypes.

To support this radical change in the industry and to facilitate the industrial transformation, project has strong focus on curricula and materials for training and education of management, architects, engineers, and construction workers, as well as university students. The need for education and further developments is covered both for the initial transformation of the industry, but also for the long term development of architecture and engineering sciences.

### 3. Training and education strategy

To bring the new InPro processes, methods and tools globally into life a dedicated strategy for change is needed. An appropriate and popular method to follow the steps of change considering the change management principles is given by the ADKAR Model:

#### **A – Awareness of the need for change**

Make all level of staff aware why the upcoming change is needed. Change implemented to improve business operations, stay ahead of your competition, and/or increase the bottom line, is not only wise, but also necessary for success.

#### **D – Desire to support and participate in the change**

It is imperative that management encourage the desire of their employees to support and actively participate in the forthcoming change, regardless of the immediate appeal or flash of the new procedures or processes.

#### **K – Knowledge of how to manage**

Management must provide the training and education to its staff of the methods of changing to the new procedures, software, or organization. High levels of awareness and desire will often be useless without the necessary knowledge of how to change to accomplish the goals desired.

#### **A – Ability to implement the change**

Along with the knowledge of how to affect successful change, everyone involved in the process needs to be given the specific training and information to achieve success in implementing the details of the change to be made.

#### **R – Reinforcement to sustain a change**

Reinforcing the new “habits” of the staff typically improves the success of the changes made.

The ADKAR model [9] reflects the necessary building blocks for individual change and was developed based on analysis of research data from over 900 organizations over a 10-year period, Hiatt J. M. (2006).

The main idea behind the InPro project is to completely transform the Early Design phase of a building project. The essential challenge is the change from traditional working methods to a knowledge-based construction process which starts in the Early design phase, and considered the whole lifecycle of a building

through business pull, technology push and supportive actions for implementation of the transformation in the European construction sector.

### **3.1 Business Pull**

Business Pull tasks defined process methods and tools which are the basis for the start of a major industry transformation. From this it follows that changes of the mindset of the management and changes of business conduct are necessary, i.e. the new business concepts are developed that promote and create incentives for an efficient collaboration and information sharing in the Early Design phase through 3-dimensional building information models. For Model-Based-Work regulations have to be supported. InPro also formulates requirements for ICT-based strategies that enable the different partners to bring in their knowledge efficiently, and systems to ensure that this information is conditioned and subsequently redistributed among the other stakeholders (knowledge management). This decision support is needed to make “informed choices” based on knowledge of each decision’s consequences on the building lifecycle (Access to Analysis’s data). The proposed early design processes are based on the business concepts and the key performance indicators. It develops model-based and knowledge-based working methods and decision-support for the early design phase. A model based design process will make it possible to analyse and prioritise design alternatives from a set of requirements.

The training and education strategy for the business pull will focus on the benefits for the main drivers of change in the sector, that is make them aware of the need for change and create desire to support and participate in the change.

### **3.2 Technology Push**

Technology Push tasks concerns inventoried ICT processes, tool needs and gaps.

ICT Processes are needed to enable collaboration over organizational boundaries and to get a lossless flow of information between stakeholders and the software applications used by them. The early planning of build and operation processes based on computer enabled simulations of smart digital prototypes (Access to Simulation).

Open ICT Platform is a working ICT infrastructure for the Early Design phase that provides a shared information space with ICT application access and content services for users. The 3-dimensional Building Information Model (3D BIM)



creates Design from a lifecycle perspective. The Web based database enabled an open and flexible collaboration between all stakeholders of the building value chain.

The training and education of the organization on processes, methods and tools will transfer the knowledge how to manage model based working methods.

### **3.3 Implementation of the transformation**

According to Kunz and Fisher [10] three levels of implementation of model-based processes in the building sector can be recognized:

- (1) Visualisation: 3D models are routinely created and used to predict performance metrics. Especially, gains in clarification of project objectives for stakeholders and resolving of coordination issues between different design disciplines can justify the relative inexpensive investments made in the project.
- (2) Integration: Projects develop computer based methods to exchange data among different modelling and analysis application either using standard formats such as IFC (International Foundation Classes) or propriety formats. For integration to work well vendors need to agree on exchange formats. The implementation costs in the integration phase are more expensive compared to the visualisation phase and cannot be justified on project level. Therefore the benefits need to be derived on company level over several projects.
- (3) Automation: Routine design task or manufacturing of assemblies (CNC - Computer Numeric Control) for on-site installation are automated. This enables a dramatic increase in design efficiency and effectiveness and dramatic decrease in duration of construction. The automation phase need more long term strategic partnership since the implementation costs are high and need to be depreciated over several projects.

Starting from a traditional 2D drawing process the suggested strategy starts with the simpler transformation to 3D visualization before continuing with the implementation of the integrated InPro process framework. The suggested two-stage implementation strategy in an organization is to ensure success in the Ability to implement change and Reinforcement to sustain change. Also, the visualization step is relatively easy to implement on project level [11].

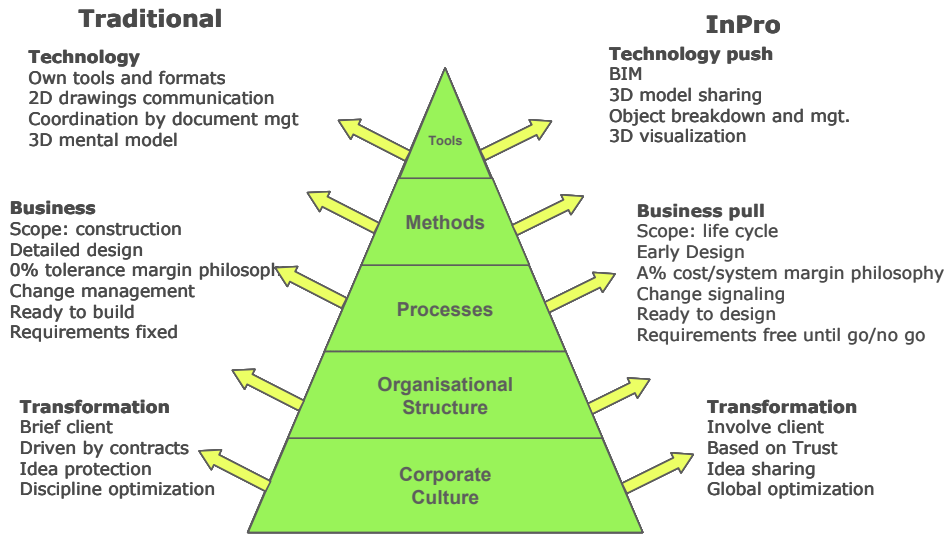


Figure 2. Summary of the estimated changes needed from a traditional process to the InPro way of working.

Described training strategy determines the content that should be incorporated into InPro courses. InPro training platform broadens the scope of Euromaster in a sense of target audiences. Beside universities, courses for building industry are developed. On the other hand, InPro learning content is more focused. It covers methods of work and IT tools related only to Early Design processes of construction projects.

## 4. Learning platform

To support collaboration and implement learning courses on such a broad scale it is inevitable to base learning platform on technically effective e-learning system. The platform should support wide array of teaching, lecturing and collaboration activities and tasks. Our experiences from Euromaster show that technical infrastructure is a vital part of the system.

When designing the system architecture, we set scalability, modularity and interoperability as the most important requirements. The system should consist of well established and open software tools that can be combined into overall system and that can be eventually replaced by competing products without too much effect on other parts of the system.

E-learning platform should be able to support preparation, storage and distribution of learning materials, implementation of self-study courses, online lectures, blended learning, student evaluation and assessment. Course planning and course management, student enrolment and study programme management should be supported as well. Beside traditional teaching activities, collaboration among participants, both student-lecturer and peer to peer are vital, therefore functionality like discussion groups, forums, blogs and wikis are necessary.

Since InPro training environment content covers both teaching about new methods of working and learning about software tools that enable new way of working it is necessary to combine hands on learning with tutorial and group learning [12]. Examples of constructivist approach to learning via problem based learning; getting hands-on experiences and learning by doing are used also by other groups in building industry.

From above mentioned requirements, system architecture was developed and is presented in Figure 3. It shows three vital parts of InPro e-learning environment, which are video/web conferencing tool, course and content management system and BIM laboratory.

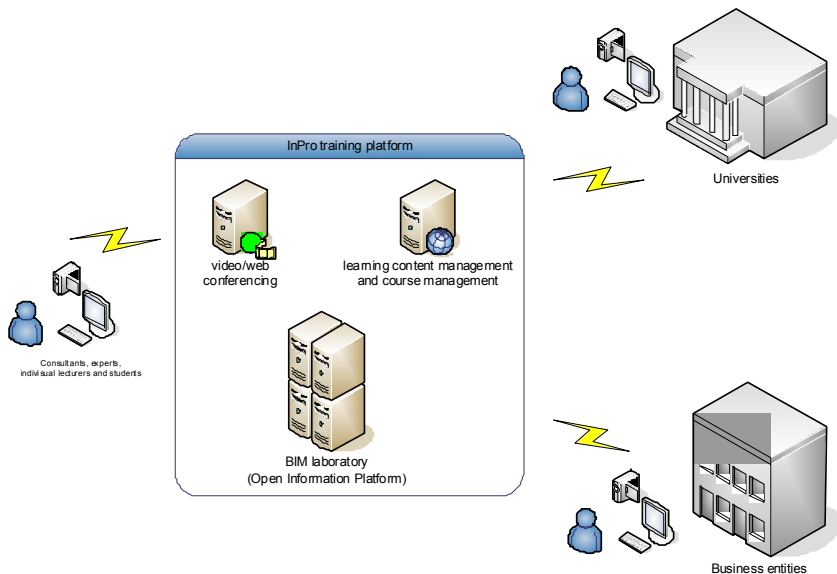


Figure 3. InPro training platform architecture.

## 4.1 Learning content and course management system

To be able to deliver and manage training and education courses, learning content management system (LCMS) takes central role in our e-learning environment. It is web based portal system which provides single point of access for content providers, lecturers and students/learners.

A set of functional requirements for the system was defined that include capabilities to:

- Browse learning opportunities and advertise courses. Potential users of the content should be able to find appropriate course that fits their needs. Opportunity should be given to universities to include published courses into their own curricula. Business entities can build learning paths based on their existing IT maturity levels.
- Store and distribute learning material and capture results of learning process. Students can get new knowledge via published textual, audio and video material.
- Support assessment of student achievements.
- Support standard interfaces (SCORM, AICC) for learning content distribution.
- Support communication and collaboration among student to student, teacher to teacher and teacher to student (and vice versa) relationships. In this segment of the system, communication should be at least asynchronous. Forums, threaded discussion groups, notification possibilities, wikis and blogs are part of the solution.
- Support for platform extensions and integration with other subsystems.

System selection started with literature review (like [13] [14]) where most important LCMS/LMS systems available today have been compared. From these results and using broad experience with Moodle system both by Euromaster and University of Maribor we decided to use open source portal based software tool Moodle – Modular Object-Oriented Dynamic Learning Environment [15] as the LCMS tool. Beside the core Moodle there are also many third-party Moodle plugins that are freely available to enhance this infrastructure.

## 4.2 Video conferencing system

Selection of appropriate video conferencing (VC) system was a two stage process. In the first step, we preselected seven VC systems and performed analysis of functionality stated by the system providers. We also performed qualitative tests of the candidate systems by a group of expert users. The same teaching scenario was executed on all preselected systems and results were reported by each participant using predefined questionnaires. In our assessment criteria the highest impact was assigned to content presentation capabilities including audio and video quality and to application sharing. The later is very important for InPro learning platform because of the nature of learning content that is tightly coupled with software tools and Open Information Platform. In our case and according to our selection criteria, most promising tools were WiredRed Nefsis VC system and Cisco WebEx Training Centre.

In the second step, two most efficient tools were compared in more detail with support of system provider personnel and WiredRed Nefsis system was selected for implementation.

We should point out that online lecturing via video conferencing system should always be supported by other communication modes like chat, forum or VoiP to counterweigh the lack of face-to-face contact among class participants. More effort should be put into preparation of visual aids, lecturer training, timing and group size because online courses require more concentration from participants. The VC systems also usually pose some additional technical limitations on commonly available presentation techniques (ex. animations, shared video content). On the other hand, well prepared tutorials can easily be taped for future re-use for self-study.

## 4.3 BIM laboratory

To complement theoretical lectures and to make a step toward new technology acceptance, online BIM laboratory is established to enhance training experience. It is a set of software tools and systems used in model based working. In the laboratory setting, teachers can present real world examples of BIM use. Students can get in touch with best practices from construction projects and state of the art tools that support BIM. They can perform exercises and get hands on experience with the latest technology and methods. In business courses, they can also experiment on their own project scenarios and content. In relation to other

parts of the system, application sharing in video conferencing tool is essential for use of BIM laboratory.

## 5. Conclusions

In the context of information society, construction industry has been trying to adopt and take advantage of new collaborative software environments. For such fragmented industry like construction, computer mediated collaboration have great potentials. Flexibility in setting up project environments, knowledge sharing among project partners and making informed decisions from the very beginning of the project could be organised in new ways and be well supported by IT tools. Technology of Building information models and related work habits try to break through all the difficulties to become everyday construction project praxis. InPro project described in this paper focuses on early design aspects of construction project. This is the point where model based working can bring great benefits to the whole life cycle of the building because in the early design decisions are made which determine 70% of total life cycle costs.

To support and somehow enable this big transformation of construction industry by spreading InPro principles into everyday project life, we are launching InPro training environment. Training environment brings together and shares the knowledge on model based working methods and supportive software tools. It is e-learning environment that provides on demand and location independent learning experience. Development of the environment takes into consideration integration of courses into existing and future university curricula as well as sharing of knowledge and best practices with business entities and construction professionals. Important part of the training environment is BIM laboratory, which provides problem oriented learning, where students and professionals can get hands on experiences with state of the art work methods and tools.

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# **IDS and the Need for Knowledge on Relations Between Processes, People and Technology in the Practice of Architectural Design**

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## **Abstract**

This paper presents the key findings of a PhD project about relations between the architectural design process and ICT and discusses these findings' relevance for research on integrated design solutions (IDS). The main focus of the project was on design teams' interdisciplinary and collaborative use of technologies supporting 3D object modeling and BIM in four real-life projects. What were the main factors affecting the practitioners' use of new technologies, and how did these impact the practitioners' work and interactions? A central contribution of the work is a holistic research approach, which has been developed to explore issues related to the implementation and use of new technologies in real-life practice. The holistic approach is based on two elements; a descriptive and multi-level framework and the use of a story-telling technique. The findings show that much of the practitioners' focus was on up-grading skills and on improving technology. Nevertheless, a number of the identified barriers and challenges were linked to the nature of the architectural design process, particularly to its "hard-to-grasp", iterative and intuitive features. A main conclusion of the research is that the implementation and use of technology is affected by the many interdependencies, relations and interfaces embedded in the highly complex and partly unpredictable real world practice. A future challenge would be to understand, master and balance these relationships – upstream and downstream across multiple levels, processes and actors. The presented holistic research approach and the related findings

contribute to research which attempts to embrace the complexity of real-life problems and to gain a more comprehensive understanding of what is going on in integrated design practice.

**Keywords:** design process, real-life projects, story-telling, holistic approach, 3D object models, BIM, multi-level framework, case-study

## 1. Introduction

This paper presents the key findings of a PhD project about relations between the architectural design process and Information and Communication Technologies (ICT). Furthermore, the paper demonstrates the relevance of these findings for research on integrated design solutions (IDS). The PhD project was conducted at the Norwegian University of Science and Technology in the period of 2004–2008 with the title “Exploring relations between the architectural design process and ICT – Learning from practitioners’ stories” [1]. The main focus of the project was on design teams’ interdisciplinary and collaborative use of technologies supporting 3D object modeling and Building Information Modeling (BIM) in four real-life projects. What were the main factors affecting the practitioners’ use of new technologies, and how did these impact the practitioners’ work and interactions? An important issue was here to gain knowledge *about* practice by unlocking knowledge embedded *in* practice. A central contribution of the work is a holistic research approach, which has been developed to explore issues related to the implementation and use of new technologies in real-life practice. This paper presents this approach, as well as the key findings from its application on four real-life projects. Concluding remarks about the findings’ relevance to IDS are rounding up the paper.

## 2. Background

### 2.1 The architectural design process: baking bread and playing jazz

This paper is based on the understanding of the design process as a complex conglomerate of interactions, interrelations and interdependencies. Kalay [2, p. 13] refers to design as a cyclical relationship between two paradigms; design as problem solving, where the designer attempts to produce solutions to ill-defined problems,

and design as puzzle making, where design is seen as a process of discovery where given parts are synthesized into a new and unique whole. Lawson [3, p. 49] describes the design process as “a negotiation between the problem and solution through the three activities of analysis, synthesis and evaluation,” and challenges the comprehension of the design process as a sequence of activities. Schön [4] characterizes design practice as a reflective dialogue between the designer and the design situation. Cuff [5] considers design as a social construction where buildings are collectively conceived. The building design teams’ efforts are crucially based on a successful interplay between iterative and interdependent processes, actors and actions. Barrow [6, pp. 272–273] introduces in his thesis the term Cybernetic Architecture: “... cybernetic architecture is a return to the pre-Renaissance comprehensive integrative vision of architecture as design and building (...) the emerging architecture process is a ‘collective’ body of knowledge and specialty skills found in many individuals”. A whole range of predictable and unpredictable issues are impacting the design team members’ individual and collective efforts. These issues are placed on many levels, from Architecture-Engineering-Construction (AEC) industry level down to the level of the individual designer.

These features of the architectural design process are closely related to cognitive and collaborative processes. Several features of the architectural design process are, however, also given by regulating external factors. In a typical building project, the practitioners must deliver design information and project material to the client, the building authorities and the contractors. The process is regulated in phases, each presenting a higher level of detail and information depth, and each to be approved by the stakeholders before moving on to the next phase. Furthermore, the time and performance related definitions of these phases are specified in the project contracts, or regulated by guidelines or regulatory demands on the national level.

The highly simplifying metaphors of “baking bread” and “playing jazz” can be used to highlight the different character of these features of the architectural design process. “Baking bread” could be seen as a sequential, predictable, explicit and measurable process – based on for instance repetition and routine. This can be related to the regulated and linear activities described above. “Playing jazz” is on the contrary a rather improvised, intuitive and tacit process leading to a unique individual or collective performance, based on “the feeling of”, on talent, practice and experiences. This process might be compared with the hard-to-grasp elements of the architectural design practice described in the beginning of this section. The “baking bread” and “playing jazz” metaphors are representing co-existent processes in the architectural design practice. The

interplay and balance between these are crucial for what actually gets built. The practitioners involved in the architectural design process must deal with the interplay between highly iterative, unpredictable and non-linear activities on the one hand, and regulated and linear activities on the other.

## 2.2 Winds of change

*“Design is a complex process that continues to grow in complexity because of the dramatic increase in specialist knowledge. There are now many contributors to the design of a project from a wide variety of organizations. This gives rise to design processes that consist of a continual exchange and refinement of information and knowledge. Even the most experienced design teams can fail to manage this complex process and supply information at the wrong time and of the wrong quality to members of the production team.”* Gray and Hughes [7, p. 1].

Gray and Huges [7] indicate the challenging task to manage collaboration and design in order to achieve good architectural design solutions and economic successful one-off real estate. Different trends in the society, as for instance globalization and the increasing focus on sustainability and environmental issues, have contributed to raise the complexity of the design process even more. At the same time, the productivity status in the AEC-industry as described by Latham report in his report from 1994 [8], still gives raise to concerns. A substantial part of the building costs can be related to failures on the building site and to poor interactions within and outside the building design team. One might say that the time has come for a change in the architectural and engineering profession and construction management. The practitioners are aware of the inefficiencies and the problems related to the many interfaces in the building process. There is a growing interest within both research and practice in integrated practice and collaboration, where specialized participants with different backgrounds, preferences and experiences try to achieve a common goal and IDS [9, 10, 11]. Kolarevic [12] describes three separate paths towards integrated design; the expansion of design-build enterprises, the emergence of increasingly complex building forms, and the introduction of BIM.

Bearing the above-mentioned trends in mind, the technologies supporting 3D object modeling and BIM are important change agents, which facilitate and trigger integrated design and collaborative work processes in order to *“minimize structural and process inefficiencies and to enhance the value delivered during design, build, and operation, and across projects”* [13].

## 2.3 Visions of a new era

*“BIM will lead to fewer errors and delays in the building process – and cheaper and better buildings.”*

This was stated by Øivind Christoffersen, the general director in Statsbygg (the Directorate of Public Construction and Property Management), the major public client in Norway in a press release April 2008 [14]. The potential of the technologies supporting 3D object-based modeling and BIM have caught the attention of an increasing number of stakeholders in various countries. In May 2007, “Statsbygg”, announced their intention to demand the implementation and use of IFC compliant BIM in all their projects from 2010 [15]. In Denmark, a regulatory client directive was issued from January 1 2007, requiring the use of 3D object models in public building projects with building costs exceeding 20 million Danish kroner (approx. 2,65 million Euro) [16]. Similar activities can be reported on in the USA and Finland, to mention some.

The many visions, aims and expectations connected to the technologies supporting 3D object-based modeling and BIM and their ability to enable more integrated work processes, started to manifest decades ago. In the famous “Islands of Automation in Construction”, a group of Nordic researchers illustrated the vision of a “land-raising”, where the new technologies will connect the islands of automation into one big island, without the borders between planning phases and roles which today are a source of communication friction, delays and misunderstandings [17]. Another expected effect of implementing these technologies is the “front-loading” of the design efforts from detailed design phase to an earlier phase of the building process. Such “front-loading” is enabled by the potential of the technologies to support earlier concretization of design solutions and decisions making, and the participation of actors traditionally involved in the later phases of the building process. Expected effects are for instance the reduction of the building costs which can be related to (too) late design modifications. The “Building Information Circle” illustrates the idea and vision of BuildingSMART; a consistent and smooth flow of information across all involved actors and throughout the entire life cycle of a building based on three open standard pillars (IFC: Industry Foundation Classes, IDM: Information Delivery Manual and IFD: International Framework of Dictionaries) [18]. These three pillars, together with applications and modeling tools, are essential technologies supporting 3D object modeling and BIM.

## **2.4 Visions meet reality: a story from practice**

The CAD director in a major international company, explains that the description of BIM as something superior and different from 2D CAD has resulted in unreasonable expectations, and ultimately frustration. “I find myself bucking a certain amount of misguided attitude about ‘having to model everything in 3D’ and answering questions like, ‘Why hasn't BIM taken off?’” [19]. In an interview conducted by the author in 2007, he explained that the major theoretical problems and visions addressed by the many R&D efforts are eventually turned into smaller and more practical problems in their building projects. According to him, the basic problem architects and other practitioners have is how to deal with new digital tools within a project where there is much work to be done and drawings to be produced. Although his company is a key actor in an international industry consortium for integrating building information modeling in the AEC industry, and they are very enthusiastic about implementing new technology, the practitioners involved are constantly running into practical problems that make it easy to fall back into traditional ways of working.

## **2.5 The need for knowledge on relations between processes, people and technology in the practice of architectural design**

This story from practice indicates several challenges arising out of what Wikforss [20] calls a big bang between the traditional AEC industry and the rapidly developing ICT industry. Some of these challenges are related to practical issues. Others are related to the complex nature of the still not fully understood architectural design process. Chastain et al. [21] describe two paradigms of problems related to the encounter between the practice of architectural design and the digital world. They call the first paradigm trying to put “a square peg in a round hole”, which describes the problem of adapting new technology to current practice, indicating a mismatch between the designers’ tasks (holes) and the tools applied (pegs). This mismatch or gap might be caused by a failure to understand the designers’ tasks, or by the replacement of traditional tools with new ones that have the wrong affordance (a potential for action, the perceived capacity of an object to enable the assertive will of the actor) [21, p. 238]. They call the second paradigm ‘the horseless carriage’, which characterizes “the shifting perception of a practice as it transforms in relationship

to a new technology” and where “the task of transportation is described through the lens of a previous technology – even though the practice of travel had changed” [21, p. 239]. The tools used by the architects are changing with the development of new technologies, but without reflection on how this affects the practice of architectural design.

The story relates in a wider context to an observation made by several researchers [for instance 4, 22]; there is a gap between the professional knowledge established in research and academia and the actual demands of real-world practice. Heylighen et al. [23] question the traditional one-way flow of knowledge from research and academia to practice. They call for more focus within academia on ‘unlocking’ and using knowledge embodied by architectural design practice. Schön’s [4] famous description of how studio master Quist supervises and reviews the work of one of his architectural students is one example which illustrates that by studying real-life situations, more understanding can be achieved; in this case about what he calls a reflective conversation within architectural design.

The number of interesting studies of practice is continuously growing. Howard and Björk [24] are reporting from a qualitative study on experts’ views on BIM and industry deployment. Khanzode et al. [25], Ku et al. [26] and Manning and Messner [27] are dealing with the results from case-based research related to building projects adapting 3D/4D tools and BIM. In Eastman et al. [28] the authors are reporting on experiences made from using BIM in several building projects. However, these studies are either focusing on the AEC-industry and implementation strategies on general level, or on experiences made from adapting BIM to single building projects or activities. Several researchers [29, 30] point on the slow adaptation of BIM and open standards in practice. Wikforss and Löfgren [30, p. 337] criticize that current research “has not resulted in a comprehensive understanding of how new technology works (...) if we consider human, organizational and process-related factors in addition to purely technological factors” (the authors relate this problem to research on collaborative communication within the industry). We lack a comprehensive understanding and overview of non-technological factors, as well as of the relationships and interdependencies embedded in the encounter between the practice of architectural design and ICT.

### 3. The holistic research approach

The holistic research approach attempts to address this need for more knowledge. The main idea behind the approach mirrors the architects' holistic handling of problem identification and solving, and their ability to synthesize and coordinate bits and parts into a whole without detailed knowledge about each of these. The approach is based on two elements; a descriptive framework and the use of building stories.

#### 3.1 The descriptive framework

The descriptive framework has been developed for gaining a better overview and understanding of the implementation and use of ICT in real-life projects [31]. The framework is grounded on two dimensions of design practice. First, there is the process dimension. The framework focuses particularly on four central design process aspects; the generation of design solutions, the communication of design solutions, the evaluation of design solutions and decision-making. Second, the framework is based on the level-dimension, where three levels representing different social constructions in a building project are suggested; a macro-level (overall project), a meso-level (the design team) and a micro-level (the individual practitioner). These three levels are again embedded in the context of the AEC industry, in this work represented by national or international R&D programs which aim to stimulate the integration of ICT in practice (Figure 1).

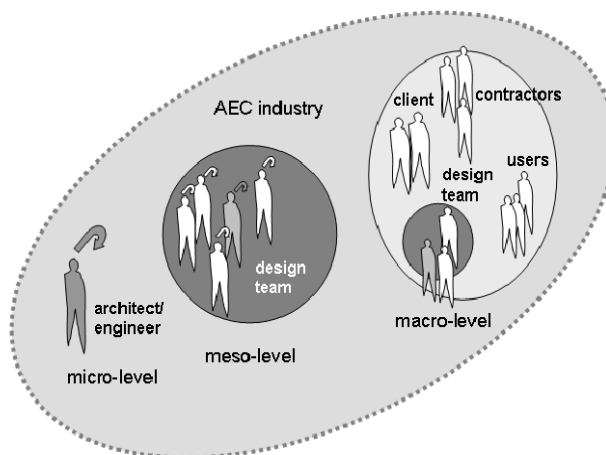


Figure 1. The three project levels embedded in the AEC industry context.



Based on the main framework elements, different tools and models are introduced to provide an overview of the factors affecting the implementation and use of ICT. One example is the ICT impact matrix (Table 1), which provides an overview of key benefits and challenges from using ICT in the architectural design process, related to all four design aspects and all three levels. The matrix has been used to organize both benefits and challenges explored in current literature, and those perceived by the actors involved in real-life projects.

Table 1. The ICT impact matrix.

	macro-level	meso-level	micro-level
design generation			
communication			
design evaluation			
decision-making			

The development of the descriptive framework is based on reviews of relevant literature and research, as well as on observations of practice. The framework and its tools have evolved and improved throughout its application on several real-life projects, and it has been presented at several workshops, seminars and conferences.

### 3.2 Building stories

“The story format provides a dense, compact way to deal with and communicate the complex reality of a real-world building project, while respecting the interrelated nature of events, people and circumstances that shaped its conception.” [32, p. 35].

Martin et al. [34] suggest that storytelling is a vehicle for communicating the knowledge embedded in practice. They have used this technique actively within teaching, where students have carried out case studies of building projects by

establishing what they call “Building Stories”. The aim of their case studies was to explore “the knowledge embodied by the best practices of significant architectural firms” [32, p. 36]. In this research this narrative technique has been used to capture and communicate the broad and complex array of the case studies findings into different stories. They represent detailed elaborations of situations and factors identified by using the framework. Each story represents a “spot” on significant bundles of findings and relations addressing the research questions. In addition to being the basis for the further explorations and discussions, the stories are also regarded as contributions in themselves to a repository of knowledge about real-world practice. Flyvbjerg [33] points out that good case studies are narratives in their entirety, whereas summaries and generalizations may fail to communicate important relationships and the contextual value of the study.

Thus, the holistic approach is on the one hand based on a broad and comprehensive approach to the problem field manifested by the framework, and the detailed and narrative exploration of real-life situations identified by its application.

### **3.3 The application of the research approach on real life practice**

The holistic research approach has been applied to one main and three reference case studies of ongoing or just completed building projects. These projects are middle- to large-scale European projects and at the time the case studies were carried out (2005–2006), all of them were pioneer building projects in their countries due to the interdisciplinary use of 3D object models or BIM in design teams (to the best of the author’s knowledge). All the four studied projects are connected to national or international R&D programs for promoting the integration of ICT in the AEC industry. Key persons in these programs were at the same time involved in the projects studied, either as managers or coordinators of the implementation and use of the new technologies. The main case is the new Icelandic national concert and conference centre in Reykjavik (the CCC project). Furthermore, reference studies have been undertaken of the new Akershus university hospital (the AHUS project), of the Tromsø university college (the HITOS-project), both in Norway, and of a Audi production plant in Germany (the AUDI project). The purpose of the reference studies was to provide empirical data that opened a discussion on the findings of the main case in a wider context.

The case-study data have been collected from several evidence sources, a strategy recommended by Yin [34] to ensure the construct validity of the qualitative study. The findings presented here are generated from more than forty semi-structured and open-ended interviews [35] conducted in 2005–2007 with around thirty practitioners' involved in building design and project management. To gain broad insight into the studied project beyond the subjective world of the single respondent, project actors have been selected who represent different backgrounds, experiences and points of view (architects, engineers, clients, IT-managers). Further sources of evidence were; passive observations of design meetings, “guided tours” on computers with the users of BIM, observations of the workplace of the design team as well as investigations of project material

### **3.4 Experiences from application**

The descriptive framework was useful in defining focus and scope, in establishing the research and case-study design, in selecting the respondents and in guiding the interview situations. It has particularly supported the analyzing and organizing of the collected data. In addition, combining the application of the framework with a number of research strategies and instruments for data collection, and particularly with the story-telling technique for reporting the findings, turned out to be a powerful research approach for acknowledging some of the complexity of the studied real-life situations. Altogether, the holistic research approach helped to operationalize the exploration of relations between the architectural design process and ICT. Identifying enablers and barriers, as well as benefits and challenges, has been helpful for gaining insight into the studied projects with respect to factors affecting the implementation and use of the technologies, and to how ICT impacts the work and interactions of the practitioners involved.

The holistic and multilayered nature of the approach also resulted in several challenges. One of these was to handle the complexity of the interconnectedness and the relations between the tasks and levels. The structure of the framework, and in particular the ICT impact matrix, required effort and care in allocating the collected data. Although challenging, these efforts were also useful as they increased sensibility when it came to the complexity of the observed situations. The broad and holistic nature of the approach challenge furthermore its user's previous knowledge and understanding of real life practice.

## **4. Learning from practitioners' stories**

The findings of the PhD project show that BIM is powerful in its support of many central activities in the architectural design process. The technologies supporting 3D object modeling and BIM seems to have gained foothold particularly related to what could be seen as the “baking bread” parts of the processes. However, the findings show also clearly that there is an array of barriers and challenges to be handled before the full concept of BuildingSMART and BIM is operable in real world practice.

An array of enablers and barriers were identified in the four building projects, placed on different levels in the studied projects, and in their context; here the R&D initiatives. The findings show that factors affecting the role of BIM are linked both to implementation efforts and the strategies formulated within national R&D programs or by the project stakeholders and managers, and to the experiences gained from using them in real-life building projects. An important and overall finding is that understanding and balancing upstream and downstream interrelations between these factors is crucial for the successful implementation and use of the new technologies (Figure 2).

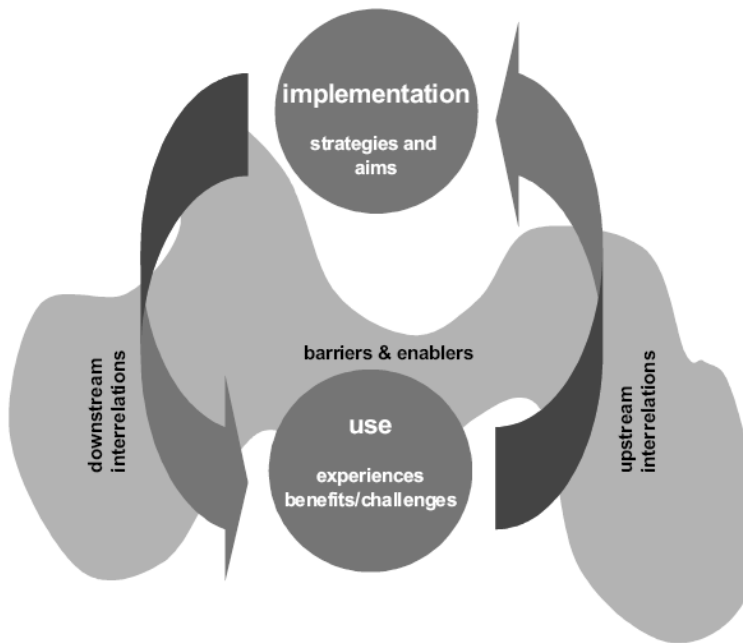


Figure 2. Exploring the relation between strategies for implementation and the experiences gained from using them [36].

Particularly three relationships between the identified factors were impacting the role of BIM in the building projects:

- The power of the implementer versus the expected benefits and challenges.
- The strategies and guidelines versus the resources available for learning and the traditions for technology use.
- The level of ambition versus the skills of the users and the affordance of the technologies supporting 3D object-based modeling and BIM.

What are the processes, strategies and routines within the building projects related to the generation of design solutions, communication, evaluation of design solutions and decision making? How do the architects and the engineers use the tools to perform these tasks? What do they find are the main benefits and challenges from this use? Based on identified barriers and enablers concerning the use of BIM, and the data explored, analyzed and organized by using the ICT impact matrix, the storytelling technique were used to communicate the broad and complex array of case study findings. Five themes were identified as the most relevant and central issues regarding the use of ICT in architectural design

processes: 1) Developing complex geometry, 2) Achieving shared understanding, 3) Handling painful change processes, 4) Formalizing processes in a dynamic design environment, and 5) Handling the interface between design and production.

The many factors impacting the implementation and use of technologies supporting BIM in architectural design practice can be particularly related to three main areas:

- The skills and behavior of the project participants when it comes to adapting to new tools and related work methods
- The affordance of the tools with respect to the complexity of the work and the interactions of its users
- The tasks and interactions embedded in the practice of architectural design.

The “wheel of tasks, tools and skills” below attempts to illustrate the relation between the efforts for implementation, the three main fields of enablers and barriers, and the practitioners’ perceived benefits and challenges from adopting BIM (Figure 3).

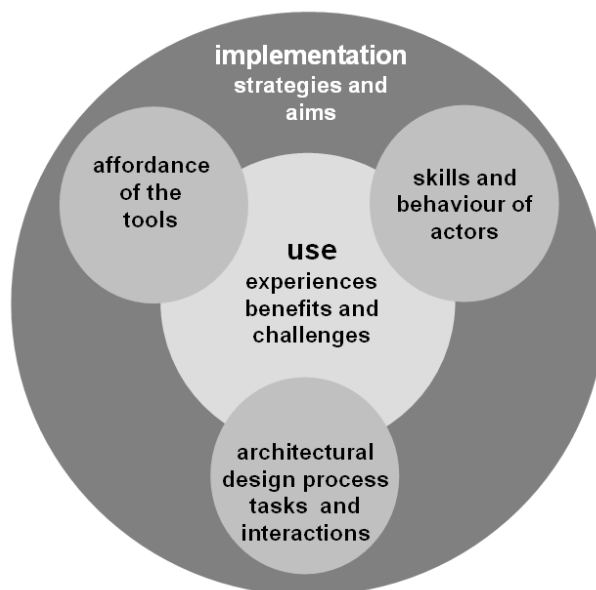


Figure 3. The wheel of tasks, tools and skills.

It is likely that skills and tools will be substantially upgraded in the next few years. Also in the case studies, much of the focus of both the R&D efforts and the project actors was on up-grading skills and on improving technology. The practitioners could report on steep learning curves and a continuous (although slower than expected) improvement of the tools. Nevertheless, a large number of the identified barriers and challenges are linked to the nature of the architectural design process, particularly to the “hard-to-grasp” and “playing jazz” features of individual and collective design development.

## 5. Conclusions

*I have yet to see any problem, however complicated, which, when looked at in the right way did not become still more complicated.* Poul Anderson.

One of the practitioners interviewed pointed out that the world of practice is not as easy as some software vendors might believe. A conclusion of this research is that the role of BIM in the architectural design process is affected by the many interdependencies, relations and interfaces embedded in the highly complex and partly unpredictable real world practice. A future challenge of implementing and using technologies supporting 3D object modeling and BIM would be to understand, master and balance these relationships – upstream and downstream across multiple levels and across processes and activities. The elements of the “wheel of tasks, tools and skills” must be brought into balance before it can roll smoothly into the future of architectural design practice.

The presented holistic research approach and the findings generated by its application could contribute to research which aims to embrace the complexity of real-life problems and to gain a more comprehensive understanding of what is going on in practice. The shift from “assembly-line” processes to integrated work methods and IDS urges even more the relevance of such research and the need for knowledge on relations between processes, people and technology. Together with appropriate approaches and methods for ‘unlocking’ knowledge in practice, this establishes an important foundation from which to tackle and have impact on the changes to come. The research presented in this paper represents one of many bricks in this foundation, where the connecting and stabilizing mortar should be the practitioners’, researchers’ and academics’ shared responsibility for ensuring good architecture and physical environments.

## 6. Acknowledgements

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# **THEME: BIM Utilisation**



# **A Qualitative Evaluation of Implementing Virtual Prototyping in Construction**

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## **Abstract**

The use of 3D computer-aided design (CAD) models to support construction project planning has been increasing in the previous year. 3D CAD models reveal more planning ideas by visually showing the construction site environment in different stages of the construction process. Using 3D CAD models together with scheduling software to prepare construction plan can identify errors in process sequence and spatial arrangement, which is vital to the success of a construction project. A number of 4D (3D plus time) CAD tools has been developed and utilized in different construction projects due to the awareness of their importance. Virtual prototyping extends the idea of 4D CAD by integrating more features for simulating real construction process. Virtual prototyping originates from the manufacturing industry where production of products such as cars and airplanes are virtually simulated in computer before they are built in the factory. Virtual prototyping integrates 3D CAD, simulation engine, analysis tools (like structural analysis and collision detection), and knowledgebase to streamline the whole product design and production process. In this paper, we present the application of a virtual prototyping software which has been used in a few construction projects in Hong Kong to support construction project planning. Specifically, the paper presents an implementation of virtual prototyping in a residential building project in Hong Kong. The

applicability, difficulties and benefits of construction virtual prototyping are examined based on this project.

**Keywords:** virtual prototyping, construction project planning, simulation, prefabrication

## 1. Introduction

The use of prefabricated components in residential building is increasing in Hong Kong. The increase is driven by better built quality, faster construction and government support. The shift from on-site fabrication to off-site factory production increases the risk of miscommunication of requirements and design changes, as the inclusion of suppliers of prefabricated components increases communication layers. The use of prefabricated components also introduces additional construction joints which require higher design accuracy. The traditional 2D drawings as a mean for communicating building design and construction operations are found to be not sufficient. Construction planners often realize that they have to rethink the construction project many times because there has been no way to capture best practices and carry them over from one project to another. Thus, there is a need to present building components in 3D and to present construction operations in virtual environment so that the ideas of planners can be captured, communicated and reused.

By implementing virtual prototyping for construction operations evaluation, constructability data can be evaluated and captured. The data can be used by construction manager to check design feasibility and provide feedback to the design team. It allows the discovery of constructability problems early in the design stage to minimize cost of change. During the construction stage, constructability data can be used to produce a detailed process plan and generate 3D construction operation instructions for workers and foreman. The data can also be used for future maintenance planning. 3D maintenance and repairs instruction can be built based on the data.

Construction project planning has been considered as a critical process in the early project phases that determines the successful implementation and delivery of project. During this stage, project planners need to develop main construction strategies, to establish construction path and assembly sequences, and to arrange construction methods and resources required for the execution of work packages [1, 2, 3]. Traditionally, construction documentation has been normally prepared in standard two-dimensional (2D) format, consisting of plans, elevations, details,



schedules, and specifications [4]. These traditional ways of 2D drawings and paper-based delivery processes, however, limited the capability of visualizing and understanding the design and subsequent construction work involved [1]. Members of project teams may develop inconsistent interpretations or imagination of the project images when viewing the 2D drawings, and resulted in ineffective communication [3]. On the other hand, the critical path method (CPM) and bar charts have still been widely employed by project teams as a main tool to express the project schedules and coordinate the activities of members of project team [3]. Many project planners have continually relied on these traditional ways in selecting construction equipment, reviewing constructability, and, arranging construction methods and site layout. These approaches impose a heavy burden on project teams due to the large amount of information and the interdependence between different elements [1]. In addition, tougher building codes, higher performance requirements, tighter construction schedules, and the need to deploy innovative construction methods and technologies have forced project teams to seek for new tools to facilitate the better planning and management of contemporary building design and construction.

Such shortcomings of traditional communication tools together with the advances in digital technologies have stimulated various research and development efforts to develop new innovative construction process planning techniques in order to enhance the visualization of the construction sequence and finished product. The development of the three-dimensional (3D) computer-aided design (CAD) systems have reduced the burden on verbal and written communication, allowing product designs to transcend differences in location and time [5]. A number of software products have been designed to accomplish the digital design (i.e., Bentley Architecture, Graphisoft ArchiCAD, VectotWorks ARCHITECT, Digital Project and Autodesk's Revit and Architectural Desktop). The latest research development relates to the development of graphical presentation of construction plan via the four-dimensional (4D) geometric models (i.e. 4D-Planner) [1]. A 4D CAD model is generated from the combination of 3D graphic images and the time. The 4D visualization technique provides an effective means for communicating temporal and spatial information to project participants [3]. Finished projects are visualized and spatial configurations directly shown. Visualization of construction plans allows the project team to be more creative in providing and testing solutions by means of viewing the simulated time-lapse representation of corresponding construction sequences [6], and prompting users to think about all missing details (e.g. site access) [2]. Despite such advancements,

4D CAD model relies heavily on the availability of full plan or schedule information to provide a graphical simulation of the project schedule. The planner mostly uses these tools as means of visualizing and comparing, rather than for implementing different decision alternatives [1]. In addition, 4D CAD systems cannot effectively simulate construction processes in which various resources are used to transform construction from one stage to next of the time-laps. In view of these practical deficiencies, the current paper purports to report on the development of a Construction Virtual Prototyping (CVP) system. The CVP is a construction process simulator developed based on the Dassault Systemes (DS).

Virtual prototyping (VP) is a computer-aided design process concerned with the construction of digital product models ('virtual prototypes') and realistic graphical simulations that address the broad issues of physical layout, operational concept, functional specifications, and dynamics analysis under various operating environments [7, 8, 9]. Dedicated VP technology has been extensively and successfully applied to the automobile and aerospace fields [10]. For instance, an automobile can be fabricated virtually via the VP technology and allows various team members to view the 3D image of the finished products, evaluate the design, and identify the production problems prior to the actual start of mass production. However, the development and application of VP technology in the construction industry (i.e. construction process simulation) has been limited. This is probably because that each construction project is unique in term of their conditions, requirements, and constraints. The production line in the manufacturing industry is almost constant and stable as the machine's operation is predictable; whilst the construction project is human-dominated, involving various construction parties and uncertainties.

Given the successful implementation in manufacturing industries, various research efforts have attempted to apply the VP concept in forming an effective dynamic construction project planning and scheduling tools. Researchers at the University of Teesside (UK) developed the VIRCON (VIRtual CONstruction) as a prototype application for evaluation, visualization, and optimization of construction schedules within a virtual reality interface [2]. The Virtual Design and Construction (VDC) method was also designed as a model for integrating the product (typically a building or plant) so that the contractor can design, construct and operate based on the model [11]. Virtual Facility Prototyping (VFP) was another interesting work developed for visualizing the building facilities during the construction planning phase by Penn State and Immersive Virtual Environment (IVE) was designed to improve the project planning process by

generating and reviewing construction plans in a virtual environment [12]. Waly and Thabet [1] developed an integrated virtual planning tool called the Virtual Construction Environment (VCE) which allows the project team to undertake inexperienced rehearsals of major construction processes and examine various execution strategies in a near reality sense before the real construction work.

## **2. Method**

Case study is the method used in this research. The residential building project that implements virtual prototyping consists of constructing two 41<sup>th</sup> floors building blocks with 16<sup>th</sup> flats per floor. The structure of these building blocks are made up of more than 60% of precast components ranging from load bearing wall and slab to toilet and kitchen units. Figure 1 shows the layout of a building blocks in the virtual prototyping environment. This project is pioneering in adopting large percentage of precast construction in residential building of Hong Kong. Major concerns of the contractor are on the capability of tower cranes in lifting all the precast components, materials and temporary work facilities, and the sequence of installing precast components. The objectives of virtual prototyping in this building project are to verify and optimise the 6-day floor construction cycle in the areas of resources utilization, space allocation, sequence of works, and design of temporary work facilities and precast components. The expected outcomes of this virtual prototyping are reduced construction schedule variances, avoidance of unbuildable or ergonomically unsafe conditions, minimised change orders after design completion, and shortened response time to changes and unplanned conditions in construction site.

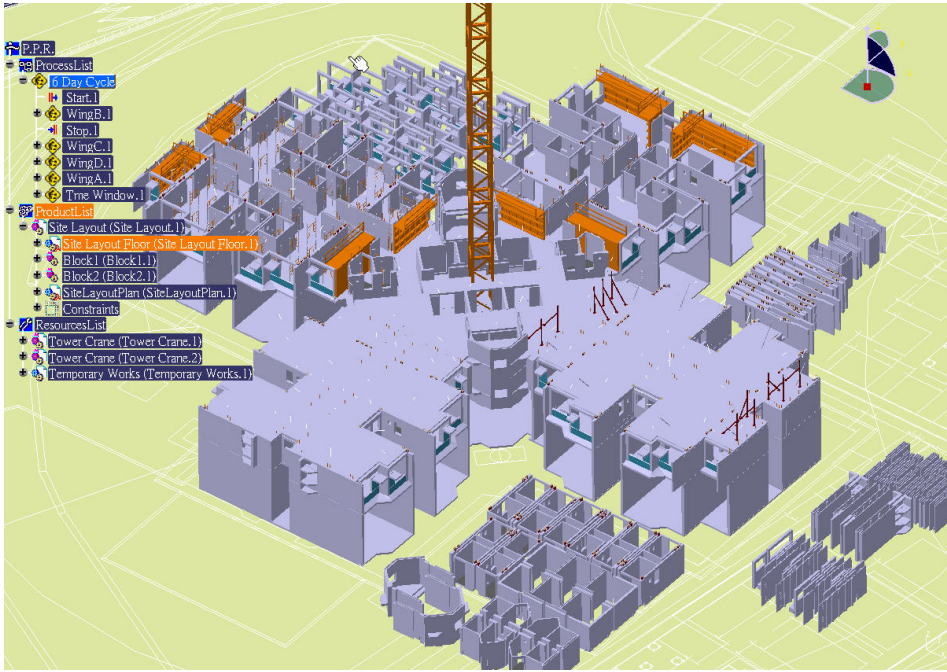


Figure 1. Building block layout in virtual prototyping environment.

### 3. The implementation of virtual prototyping

There are three main phases in implementing virtual prototyping. They are project requirement collection phase, 3D models building phase, and process simulation phase. Table 1 depicts the tasks, information, and people involved in these three phases. They are discussed in detail in the following sections.

Table 1. The three phases of virtual prototyping implementation.

	<b>Project Requirement Collection Phase</b>	<b>3D Models Building Phase</b>	<b>Process Simulation Phase</b>
<b>Tasks</b>	Identify design and construction challenges; Define scope of works.	Create 3D models of building components, temporary work facilities and plants;  Carry out digital mock-up to check dimensional conflict.	Simulate planned construction process;  Validate construction sequence;  Find time space conflict;  Check and optimize resources utilization;  Try alternative construction plan.
<b>Information Required</b>	Preliminary construction method statement;  Architecture drawings of major building components;  Master construction program;  Preliminary floor cycle program.	Workshop drawings and layouts of building components, temporary work facilities and plants;  Detailed floor cycle program showing divided working bays.	Detailed process program;  Productivity rates of different activities;  Safety plan.
<b>People Involved</b>	Architect;  Engineer;  Project manager of main contractor;  Representatives from major sub-contractors.	Project planning team of the main contractor;  Suppliers of building components and temporary work facilities.	Project planning team of the main contractor;  Representatives from major sub-contractors.

### 3.1 Project requirement collection phase

In the project requirement collection phase, major project challenges are identified and these become the basis for defining the scope of works. The challenges can be divided into design related and construction related. Design related challenges come from coordination of building components and temporary work facilities design details to ensure a harmonized building design and construction operations. The major design challenges in this building project

are coordination of welding joint and reinforcement layout of precast components, and coordination of working platform design. Construction related challenges come from uncertainty in method of construction, duration of an activity, and level of resources utilization. The major construction challenges in this project are ensuring not to overload tower cranes, and preparing the best sequence of installing precast components to streamline other construction works like concreting, rebar fixing, formwork fixing, etc. The information required in this phase include a preliminary construction method statement, architectural drawings of major building components, a master construction program and a preliminary floor cycle program. The people that usually involved in this phase include the architect, engineer, project manager of main contractor, and representative from major sub-contractors.

### **3.2 3D models building phase**

In the 3D models building phase, 3D CAD models of building components, plants and temporary work facilities are built according to the need for tackling design and construction challenges. Building components, including both precast and in-situ parts, have to be broken down into small unit that suit simulation of construction operations. For instance, the slab reinforcement and in-situ concrete have to be broken down into units that fit the divided working bays. The level of details of the 3D models has to be discussed in this phase so that the models can reflect the situation that need to be examined. It is obvious that we cannot build 3D models into every bolt and nut details. The models just need to be built to the details that can reflect both dimensional and space conflicts, and sometimes enough for examining safety issues. The plants in virtual prototyping can have its physical properties like degree of freedom in movement, speed and acceleration of movement and association between different mechanical joints. Physical properties are set for evaluating reachable area, travelling time and viewing angle of plant operator. The 3D models prepared in this building project includes precast components, reinforcement and in-situ concrete components, conduits and boxes, steel wall and beam formworks, shoring, struts, working platforms and tower cranes. After creating 3D models, digital mock-up will be arranged for checking dimensional conflict between building components, between temporary work facilities, and between building components and temporary work facilities. Figure 2 and 3 shows dimensional conflict checking between working platforms and between wall formworks and precast slabs

respectively. The works in this phase have to be done after producing the first version of workshop drawings and before manufacturing of building components and temporary work facilities, so that dimensional conflicts can be rectified before manufacturing to reduce reworks in the actual construction. The information required in this phase include workshop drawings and layouts of building components, temporary work facilities and plants, and a detailed floor cycle program that shows divided working bays. The people involved in this phase include project planning team of the main contractor, and suppliers of building components and temporary work facilities.

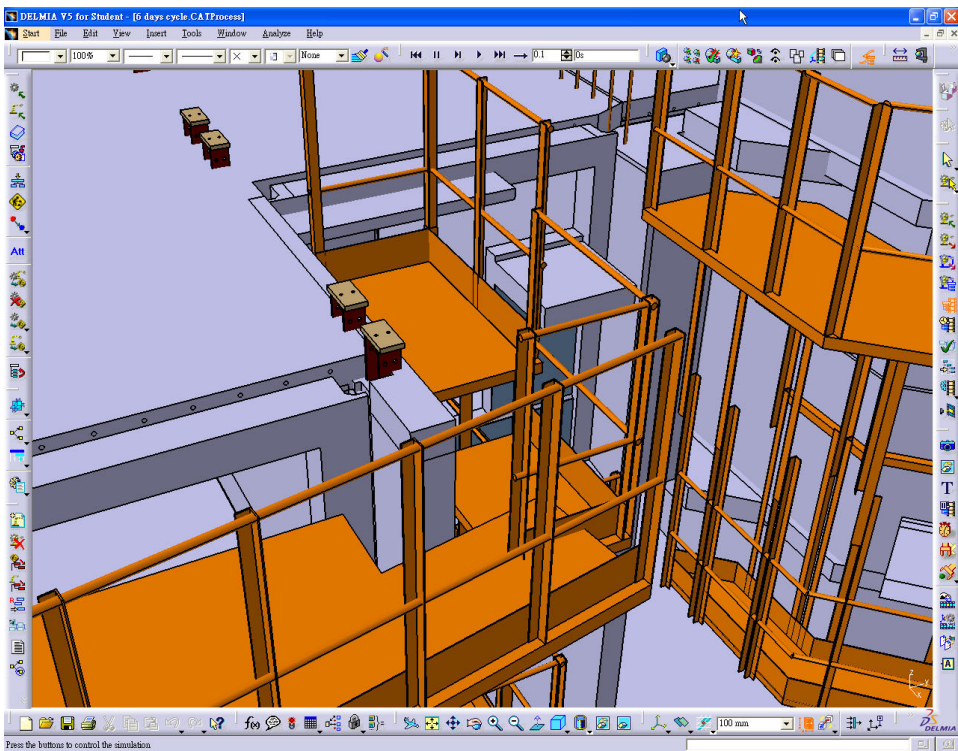


Figure 2. Digital mock-up to check dimensional conflict between working platforms.

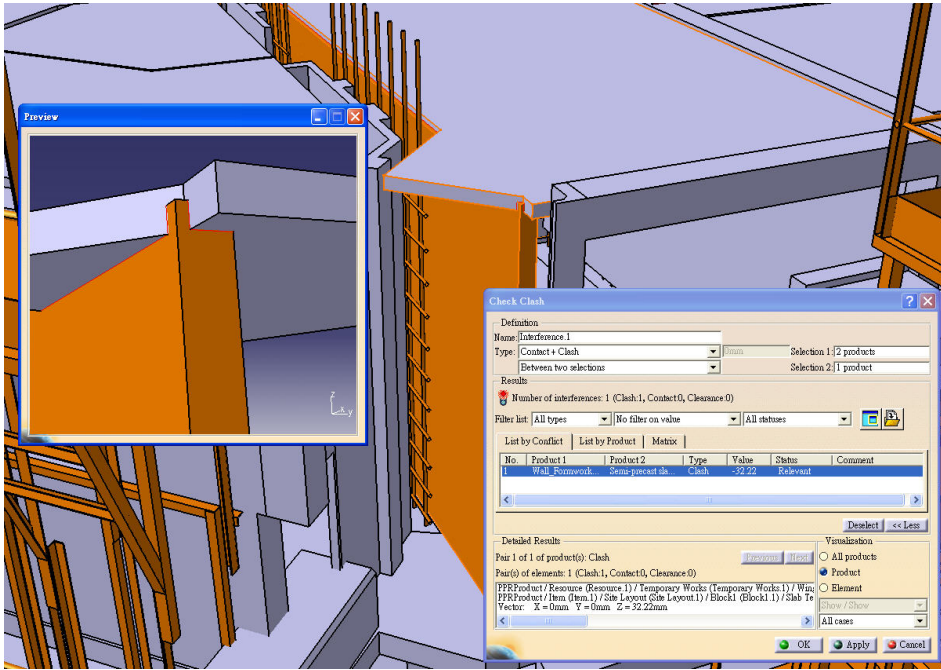


Figure 3. Digital mock-up to check dimensional conflict between wall formworks and precast slabs.

### 3.3 Process simulation phase

After building 3D models and validating design of building components and temporary work facilities, the next process simulation phase is to simulate planned construction process, validate construction sequence, find time space conflict, check and optimise resources utilization, and try alternative construction plan. Construction processes are simulated to tackle identified construction challenges. The process as detailed as every movement of a human or plants can be simulated in the virtual prototyping environment. Figure 4 shows simulation of a worker moving a table formwork to its final position for slab concreting, and Figure 5 shows the mobilisation of workers when installing precast building components. Sometimes it is not necessary to simulate behaviours of workers or every detailed work process, but just to highlight building components that are under construction. Figure 6 shows simulation of fixing wall reinforcement by using blue colour highlight. The level of details of the simulation depends on the nature of the construction challenges we need to



tackle. For tackling workspace related problem, we probably need to simulate every step of a construction process and the movements of both human and plant involved. But for reviewing overall work sequence or resources utilization of a floor cycle, using colour highlight can be good enough to reflect the physical conditions of the construction site. Higher level of details require more effort from the virtual prototyping team to make the simulation, and also from the contractor's project team to provide more detailed productivity and planning information, which sometimes are difficult to get due to limitation in time and information. The information required in this phase include detailed process program, productivity rates of different activities, and safety plan. The people involved in this phase are contractor's project team and representatives of major sub-contractors. A floor construction cycle involves the works of different sub-contractors. It is necessary to collect information on resources deployment, productivity rate, and work sequence from them in order to produce the simulation.

The process simulation phase usually starts at the construction project planning stage and stops at the actual construction stage. Process simulation helps contractors to tackle construction challenges in the planning stage. The simulation can then be used as 3D work instructions for communication among the project team members and for giving guidelines to workers. During construction stage the actual productivity data are recorded and compared with that of the simulation. Adjustment to the simulation will be made if there is any discrepancy. The adjusted simulation will serve as a knowledgebase for reference by future projects.

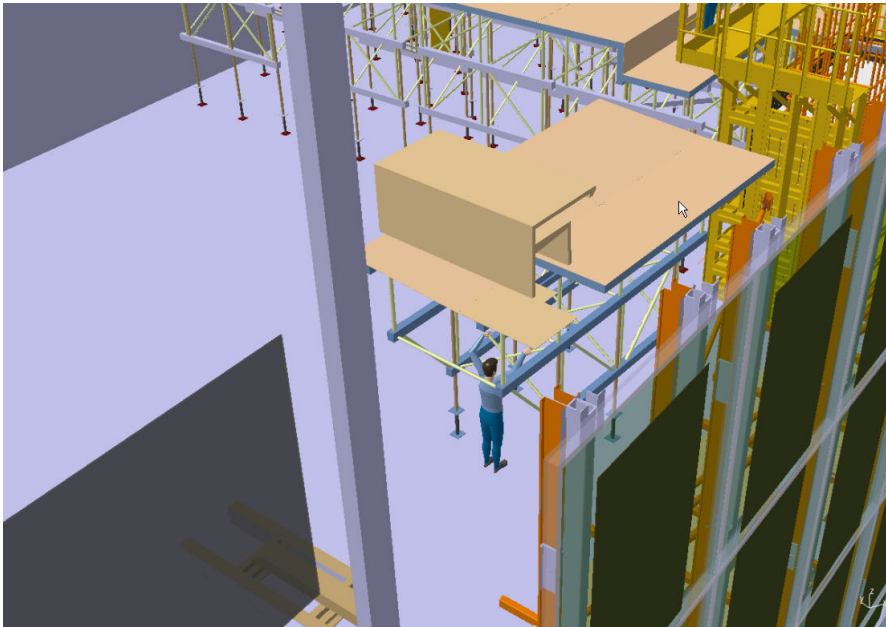


Figure 4. Human movement simulation in detailed process analysis.

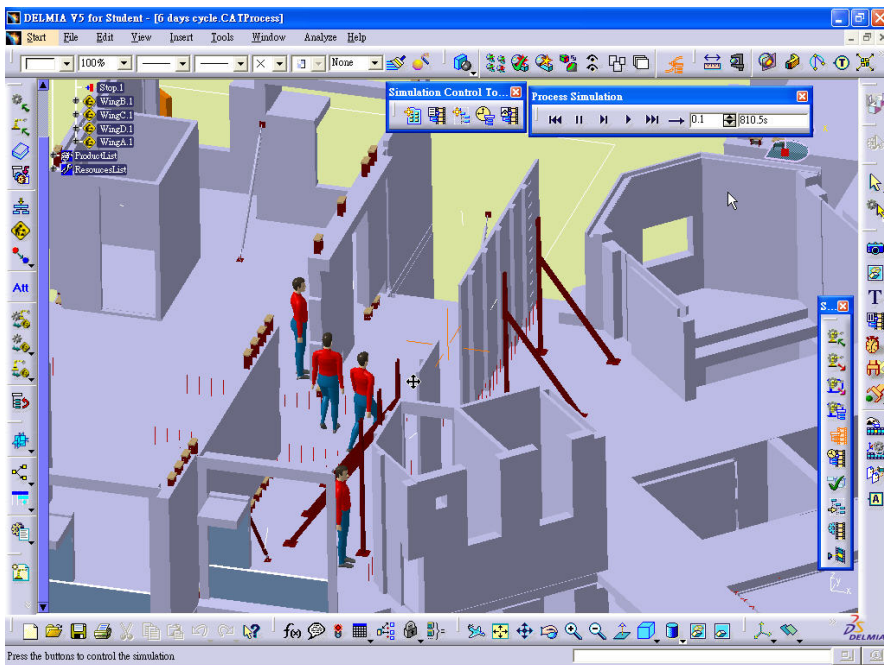


Figure 5. Simulation showing mobilisation of workers.

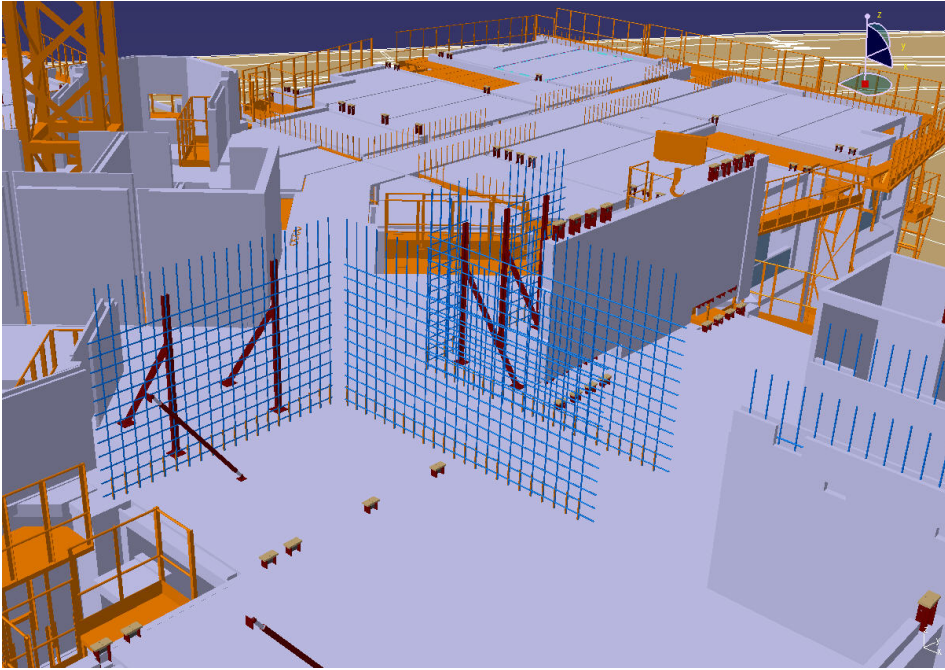


Figure 6. Simulation of reinforcement fixing process.

## 4. Benefits of virtual prototyping

Through the process of virtual prototyping, the 6-day cycle, which was initially planned by the main contractor, was incrementally improved and optimised through a loop of try and error process. The finalised plan is a 6-day cycle with every aspect of constructability and safety examined and confirmed by the virtual prototyping process. During the process of constructing 3D models of all prefabricated cast-in-situ components, over 10 design errors, which can contribute to over 40% of rework, have been identified and corrected. In addition, the virtual prototyping process has also identified a number of “unsafe” spots where possible human-machine interaction can occur, which will result in severe accidents.

In addition to the tangible benefits, the main contractor accepts that the virtual prototyping system is an ideal platform to capture and manage knowledge and expertise of the main contractor. As the virtual prototyping system provides a rich environment to capture all properties and attributes needed to represent construction processes and sequences, the simulated construction processes

eventually become the most valuable knowledge asset to the contractor, and the virtual prototyping system becomes an effective knowledge management tool to the firm. With the incremental accumulation of simulated construction projects, it is possible for the contractor to try different what-if scenarios within the virtual prototyping environment, and to achieve incremental improvement of efficiency and productivity over time. Arguably, this is how the car industry has managed to achieve over 10% productivity improvement annually over the last decade or so.

## **5. Difficulties of implementing virtual prototyping**

The difficulties of implementing virtual prototyping in construction project come from three major areas: 1) computer hardware requirement, 2) information collection and dissemination, and 3) communication of virtual prototyping ideas.

Virtual prototyping applications compute activities sequence and illustrate the activities in a real time 3D virtual environment. It requires massive computational power to drive the simulation. Even the workstation computer with a very fast CPU and graphics acceleration card can just simulate construction of a typical building in acceptable speed. The contractor has to purchase workstations dedicated for the virtual prototyping works. This can become the hurdle for contractors as they need to invest in the start up. Currently the virtual prototyping applications are run on 32-bit version of Microsoft Windows XP which allows it to use 2 GB of physical memory at maximum. This amount of physical memory is sometimes not enough for simulating complicated scenario. Adjustment to the 3D models is needed to reduce memory usage. An alternative is to use 64-bit version of Windows XP which does not have this memory limitation.

Difficulties in information collection come from conflict of interest. The main contractors in Hong Kong usually sublet major works like concreting, reinforcement fixing, building services installation, system formwork, etc. They usually do not have a comprehensive database of productivity rates of different trades. In order to accurately simulate construction process, productivity rates and number of workers for different trades have to be collected from sub-contractors. However sub-contractors usually refuse to give this information due to confidentiality and protection of their interest. The main contractor has to make their own estimate based on experience in the planning stage and then make measurement of it during actual construction. Difficulties are also

encountered in disseminating simulation information to the workers, as the communication chain from the main contractor end at the leader of the sub-contractors but not the workers. It is up to the worker leader on how or whether to disseminate the information to workers. Similar to the manufacturing industry, the effectiveness of virtual prototyping will be largely hampered if not all people involved in the construction works understand the results of simulation.

In order to produce a practical and thorough simulation of construction works, input from the planning personnel of main contractor and sub-contractors is necessary. Their ideas have to be collected in the initial simulation planning stage and also in the simulation review stage. However it is found that calling up all the parties to attend meeting for virtual prototyping works is difficult due to the lack of interest of sub-contractors. It is necessary to persuade sub-contractors on accepting benefits of virtual prototyping at the very beginning.

## **6. Conclusions**

This paper presented an implementation of virtual prototyping in a residential building project in Hong Kong. The framework and process of implementation are discussed, and benefits and difficulties identified. The implementation framework presented in this paper can be used as a basis for future virtual prototyping works. In addition to the project presented in this paper, the virtual prototyping technology has been applied to other 5 construction projects including 2 office building, 2 sports stadiums, and 1 infrastructure project. Concurrent studies are currently conducted by team members of our Construction Virtual Prototyping Laboratory to calibrate the accuracy between the simulated construction processes and those in real-life, as well as to measure tangible time and cost savings brought by the use of the virtual prototyping technology. In addition, discussions and preparatory work are underway to work closely with a well-known virtual prototyping software provider to develop a construction-oriented commercial system of virtual prototyping.

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# **BIM-based Site Layout and Safety Planning**

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## **Abstract**

This paper deals with the opportunities building information modelling (BIM) offers in supporting occupational safety in construction projects. The main focus is in BIM- based site layout planning and visualization. The paper demonstrates BIM-based site layout planning and the usability of the model. The main findings concerning the modelling tools available and the requirements for BIM-based site planning are also described. Additionally, the potential of 4D-simulation in safety planning is presented. The paper is grounded in the research project called SafetyBIM: Building Information Model (BIM) promoting safety in the construction site process. The main objective of the research project was to encourage and develop utilization of BIM technology in construction planning and management from the viewpoint of occupational safety. In the project, the potential of the building information model in safety management was studied, 3D site planning objects were collected and created, and BIM-based building site modelling and visualization tests were carried out using data from an completed building project. Additionally, the object library was tested and developed further in an ongoing BIM-based site planning pilot project. As a result, there is the first version of a site planning object library available for use in building projects. In addition, the needs, ideas and potential of BIM-based safety management were surveyed by workshops with industry representatives.

Utilization of BIM technology connects safety more closely to construction planning, provides more illustrative site layout plans, effectively supports communication, and finally promotes occupational safety on building sites. From the viewpoint of occupational safety, the 4D production model enables visualization of safety arrangements in construction projects at different moments of time. This can be used for example in safety planning, day-to-day safety communications and managing changing situations. However, more experience and knowledge are needed concerning 4D safety simulation as well as further development of modelling tools such as object libraries to broaden the use of the BIM-based safety planning in the design-build process.

**Keywords:** Site planning, Information management, Building information modelling, BIM, Safety Management, Risk management, Safety Communication, Visualization, 3D objects, 4D3D objects, 4D

## 1. Introduction

Over the past ten years, building information model based design has changed from single trials and pilot projects into standard practice in the various design and engineering fields in the Finnish house building sector. There is positive and encouraging experience of utilization of BIM technology in building design and production planning [7], [8], [2]. The use of 4D production planning is now at an early stage in the house building sector, but is increasing all the time. Great potential has been consolidated to 4D, especially regarding its suitability for solving conflicts and preventing problems pro-actively in an effective manner [3]. However, there is still little research and experience considering the use of BIM technology in safety management and its potential for promoting safety.

The high accident frequency is still a real safety challenge in the building industry in Finland. An accident always prejudices the operations of the construction site and incurs both direct and indirect costs. The challenges of accident prevention are effectively organising the construction site, planning the use of the site and the tasks, as well as communication and influencing the safety attitude of personnel. [10], [5]. Also safety planning and management methods can be improved by using BIM-based plans. At the same time, implementation of new technology is a chance to change customary workflow and include a safety viewpoint more fully into production management. Traditionally



construction safety management has been based on official demands, which has led to separate planning viewpoints and methods. [9].

This article is based on the TurvaBIM research project, the main target of which was to encourage and develop the utilization of BIM technology in construction planning and management, from the viewpoint of occupational safety. The key questions were the potential of BIM technology to promote occupational safety in the construction sector, the possibilities of a BIM-based site layout plan, and the possibilities of 4D modelling in safety-related activities planning and management. The project was carried out 10/2007–2/2009, and financed by The Finnish Work Environment Fund (TSR), VTT and Skanska. The research work was carried out by VTT in close co-operation with the industry. More information is available at the project web-site [11].

## **2. Method**

The utilization, research and the potential of building information modelling in safety planning and management, as well as available model-based software, services, and object libraries were first surveyed by a study of the literature and expert interviews. BIM-based site layout planning was developed by carrying out a site layout modelling test and demonstration, and by developing a component library for use in BIM-based site layout planning. Hands-on modelling was also carried out to test and demonstrate 4D-visualization opportunities regarding safety-related tasks, and in addition, in a BIM-based site planning pilot project, in which model-based site planning, visualization and the object library were developed further. In addition, ideas concerning building information modelling in safety planning and management were surveyed more widely in the research project in collaboration with industry representatives during workshops.

## **3. BIM-based site layout planning**

### **3.1 Requirements for BIM-based site layout planning**

The project supervisor makes the written site plan. The aim is to plan the site operations and the arrangements required in order for work to proceed as efficiently as possible during all stages of construction. The site plan is used to inform all parties of a construction project about internal and external logistic

arrangements and the arrangements concerning work and safety. [4]. During the site planning phase there is a need to evaluate and plan things like site exclusion and separation, logistic arrangements, site limitations, dangers and protection, the number and location of office facilities and personnel rooms, working places and areas, site electrification and lightning, lifting arrangements and transportation, intermediate storage arrangements and logistic solutions for materials, fire fighting and prevention of other special risks on site. The site plan needs to be kept up to date. In practice the site plan can be made in a variety of ways. There are site plans made on town plan drawings with the use of a CAD program, plans that are drawn by hand or made with using sticker labels. [9].

The same standards and good design principles apply to BIM-based site layout planning as with current two-dimensional planning. However, building information modelling also offers completely new opportunities for site planning and presentation when passing that information on. For example, different levels and roughness or other comparable risk factors in the site area cannot be appropriately presented in 2D plans, but can be shown in a three-dimensional model. On the other hand, because a BIM-based site plan is visually illustrative, accuracy is even more important than with a traditional site plan. For example, 3D-presentation of site equipment should be illustrative and recognizable, but not misleading. [9].

Today, a static three-dimensional site layout plan can be considered as a basic method for creating a BIM-based site plan, in which case a BIM-based site plan is created for various construction stages. Nevertheless, the target is to use more dynamic 4D site models in the future. [9]. The site layout planning and management systems based on 2D drawings can no longer meet planning needs, especially when some resources or facilities are put inside the building under construction. Additionally, in different phases, the site layout will change accordingly to meet the changing demands for materials. So a site layout should never be static and two-dimensional, instead, it should be a dynamic activity across the whole 3D site. [12].

### **3.2 Site modelling tools**

Over the last few decades several computer-based site layout systems have been developed. Research has been carried out and attempts made to optimise site layout solutions for example by means of artificial intelligence and knowledge-

based systems. However, to date, no standard tool has gained wide acceptance by the industry [6].

Today, there is the same software available for BIM-based site layout planning as is used in 3D building design and 4D production planning, as well as object technology related to modelling software. The strength of BIM-based software is the opportunity to use building information models created in the design process for BIM-based site layout planning. However, from the viewpoint of site layout planning and BIM-based safety planning, there are strengths and weaknesses in each example of modelling software. No single software has all the suitable features, such as tools for land surface modelling, 3D materials for illustrative and realistic 3D presentation, suitable tools for managing schedule information and offering appropriate 4D simulation, and the ability to handle time in adequate short term periods.

Object and component libraries in various modelling software aims to provide ready-modelled 3D descriptions or structures to facilitate and accelerate modelling of building components that can be installed permanently into a building. In addition, objects and components support product information management and product marketing. However, site equipment such as office containers and other spaces, machinery and material storage in the site area, needed for example during precast unit installation, are temporary parts and circumstances for which the libraries do not offer ready 3D descriptions. In addition, libraries are software-specific, so that for example, GDL-objects used in ArchiCAD software cannot be directly used in other modelling software.

There is hardly any experience considering the suitability of various designers' building information models for safety management. BIM-based site planning can be based on the architectural model and the architectural modelling software can also be used for model-based site layout planning. Alternatively, BIM-based site planning can be started with the structural model, or with a 4D-production model based on the structural model, and use the same software employed to create those models. In addition, a BIM-based site plan can be a combined model, if the separate models of the buildings and the site area, modelled with different software, can be merged in an appropriate manner. Combining can be done with the help of the IFC-format or with specific software. IFC is a neutral data exchange format, the goal of which is to respond to the problems occurring in practice during data transfer and sharing between various computer applications used in AEC and FM. [9].

### 3.3 Site planning objects

One of the main objectives of the TurvaBIM research project was to demonstrate BIM-based safety planning by carrying out a site layout modelling test using data of a real case building project and study the potential of a BIM-based plan. For the test, 3D representations of temporary structures and equipment occurring in site plans were needed. A 3D site object library was created in the project by searching available ready objects and modifying some of them so as to be more suitable for site layout planning, as well as modelling missing objects needed for the test. As a result, a 3D site component library was developed for research use, including approximately 70 GDL objects found, modified or created in VTT. The so-called TurvaBIM-library was created without any business goals and site planning objects have also been given for use in real building projects.

The main objective was to create three-dimensional and identifiable site planning objects. The development work does not cover constructing object parameters, in other words objects' adaptability concerning materials, dimensions or other properties. Most of the 3D objects look real and are understandable, for example the wood saw, the trash pallet/skip, bundled reinforcing bars, window packages, and polystyrene-insulation bales. A general 3D-object was created to represent storage areas for less frequently occurring materials. When using a general object, the 3D appearance can be improved by selecting a suitable 3D surface material for the case. Examples of site planning objects created in TurvaBIM project are presented in Figure 1. Examples of safety-related objects included in the TurvaBIM library are the pedestrian shield and the precast element stud, and the safety railing found as ready-modelled. Useful ready-modelled objects were found mainly in the Construction Equipment library from Graphisoft Object Depository [1]. The standard library of the used modelling software (ArchiCAD 11) contained only single usable 3D objects for site planning, such as a truck.



Figure 1. Examples of site planning objects created in the TurvaBIM-project.

The TurvaBIM-library was used to create a building information model-based site layout plan for the case project. Additionally, the library was later tested and developed further in an ongoing BIM-based site planning pilot project. The possible future development of the objects could be related to the creation of parameters or developing usability in other modelling software.

### **3.4 A BIM-based site plan, a residential building project as a case example**

The BIM-based site planning test was carried out using data from a completed residential building project (As Oy Vantaan Ankkahovi). The owner and the contractor of the building project was Skanska, the architectural design and modelling had been done by Arkkitehtitoimisto L-N Oy, and the structural engineering and splitting the architectural model to precast units had been done by Finnmap Consulting Oy. Besides the models, there was the traditional 2D dwg site plan available. The site plan was modelled and visualized in the research project at VTT. The aim was to demonstrate new BIM-based site representation and illustration opportunities, and the potential offered by modelling tools.

The construction site area was modelled according to the traditional site layout planned for the precast unit installation stage. Additionally, the immediate surroundings including streets and buildings were modelled roughly. At the first stage of the testing, modelling was based on the architect's model, modelled with ArchiCAD 9, and the site plan prepared by the contractor (Figure 2). ArchiCAD 11 software and the TurvaBIM-library, created in connection with the modelling test, were used to model the site plan. The land surface was modelled approximately with the mesh-tool included in the modelling software, and corresponds more closely to the designed final finished surface than the real site elevations in the element assembly stage at the construction site.

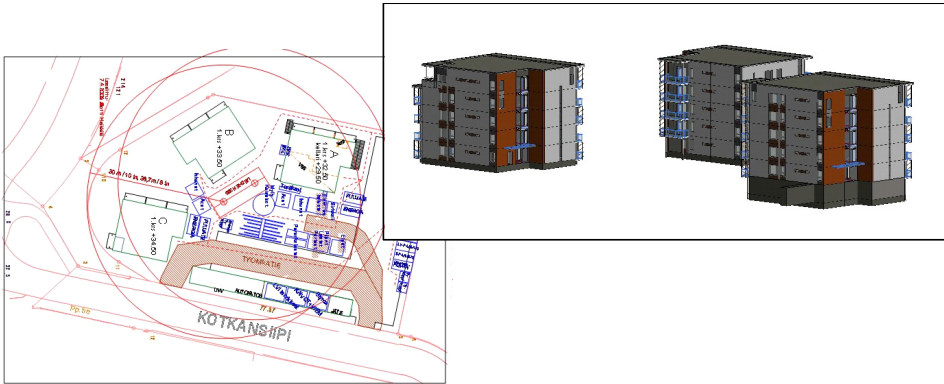


Figure 2. The original 2D site plan and the architectural model in the case building project.

The essential contents of a BIM-based site plan are 1) the construction site area and adjoining streets, and other immediate surroundings, that the construction site may impact 2) temporary site facilities, structures and equipment 3) temporary site situations, such as area reservations for material storage, and 4) visualizations that promote safety, such as illustration of risk zones. There are general views to the case project's site layout model in the following figure (Figure 3). The contents of the demonstration model are precisely the following:

- **Buildings:** three blocks of flats modelled by the architect
- **Site and surroundings:** the construction site area and site road, adjoining streets and street names, opposite city blocks and buildings roughly, parking slots (that are not included in the original site plan)
- **Site facilities and enclosure:** office facilities and storage, site fencing
- **Machinery and equipment:** tower crane, wood saw, concrete-mixer
- **Electrification and lighting:** main distribution board
- **Material storage:** thermal insulation, reinforcing bars, windows, HVAC pipes, trash skips with 3D-text (e.g. wood waste), precast element rack, and storage areas for various concrete precast units and utilities needed for their assembly (modelled with a general material storage object, which can stand for any material and presentation improved by selecting a suitable 3D surface material)
- **Visualizations:** crane reach, site walkways, vehicles.



Figure 3. General views of the model based site plan created in the TurvaBIM research project.

To be able to demonstrate BIM-based planning of fall protection related to precast unit installation stage of a building project, the BIM-based site model and the structural engineer's ArchiCAD model, that included precast concrete members, were combined. Splitting the walls of the architectural model into precast units had been done using the ElementtiApi-application. Additionally, the 4D simulation test was carried out by using the same combined model, linking schedule information to the site layout objects.

### 3.5 BIM-based site and safety visualization

BIM-based site plan can be used to produce many kinds of illustrative images and visualizations, both as static views and animations.

**Static views:** A three-dimensional site layout model can be used to produce various illustrative views of the site plan, from the desired viewpoints and perspectives. Static views can represent general overviews or details of the site plan. Challenging points or solutions can also be highlighted from the plan for example with the use of colours. Additional information can be also added to the 3D view by 3D text, for example adding explanations to the model such as the "site road". Images from desired viewpoints can also be produced as rendered images, which are usually photorealistic images of the model as snapshots, aiming to produce the most understandable and life-like views of the plan.

**Animation:** The same model can be used to produce animations. Animations can provide a general understanding of the site quickly, and can be used for example as virtual sightseeing when introducing the project to site staff, or when presenting site arrangements to the client. In the pilot project, fire truck route was also illustrated using an animation.

**Visualization opportunities regarding site arrangements and risk zones:**

- Visualization of temporary site area or space reservations: Temporary site area or space reservations for storing materials or performing a specific work task effectively and safely are visualized.
- Visualization of site walkways: Visualization of temporary site walkways can be used when informing the site staff about the safest walkways at each stage of construction.
- Visualization of risk zones related to cranes: Visualization of crane reach was carried out by making a 3D reach-cylinder object, which was used together with the crane object (Figure 4). 3D visualization can be used to examine the risks in case of load fall, or to evaluate what the crane jib could hit. The significance of this kind of examination increases if there is limited space around the construction site and clashes become possible. In the pilot project risks associated with the fall of the crane were evaluated with the help of 3D visualization. 3D objects were used to show the affected zone, and two different fall cases were examined, using empirical information concerning the behaviour of the crane in a fall situation.



Figure 4. Figure 4. Visualization of crane reach [9].

- Other guard zone visualizations: Taking advantage of visualization when informing site staff about safety hazards, could also mean, for example, warnings about cables, pipe lines, excavations and protection areas related to those, as well as showing location or affected zones of contaminated soil or other hazardous substances, such as asbestos and microbes.



Besides the new kind of 3D visualization material, building information models are also intended to be used to produce drawings, such as the traditional 2D site plan containing text descriptions, and the drawings can be used in parallel to the three-dimensional plan. In addition, the quantities and product data can be produced from the model, concerning for example construction machinery and equipment planned for use on site.

## 4. The potential of 4D in safety planning

When the schedules are linked with the building parts of a three-dimensional BIM, the result is a 4D-model. In this case, the planned or the actual construction status can be reviewed as, for example, a view corresponding to a specific calendar date. From the viewpoint of occupational safety, the 4D production model enables visualization of safety arrangements in the construction project at different moments of time. [9]. There is also a strong need for more effective planning and management of site space and facilities, which can be supported by 4D, combining 4D building and 4D site models [12].

Today, construction simulations are done mainly for the building components that will be assembled to permanent parts of the building. There is most real experience concerning precast element assembly. This is related to schedule planning and simulation, and monitoring the actual construction status at the building site. For safety reasons, it would also be useful to model and simulate temporary situations and arrangements on site, such as fall protection and excavations. In future, the safety aspect should be included in a 4D-production model, so that besides the parts of the building, safety arrangements related to each working phase are shown in the model.

The following figures demonstrate the connection of safety tasks within 4D-production planning. The case example is a model-based fall protection plan related to precast unit construction, which is the first major step towards BIM-based safety management (Figure 5). Additionally, getting fall protection planning into part of 4D-production planning promotes safety, because a concrete fall protection plan is rarely seen on site in practice. Besides guard railing and protective lids shown in the Figures, relevant safety-related components to be modelled include safety nets and safety harness anchor points. [9].

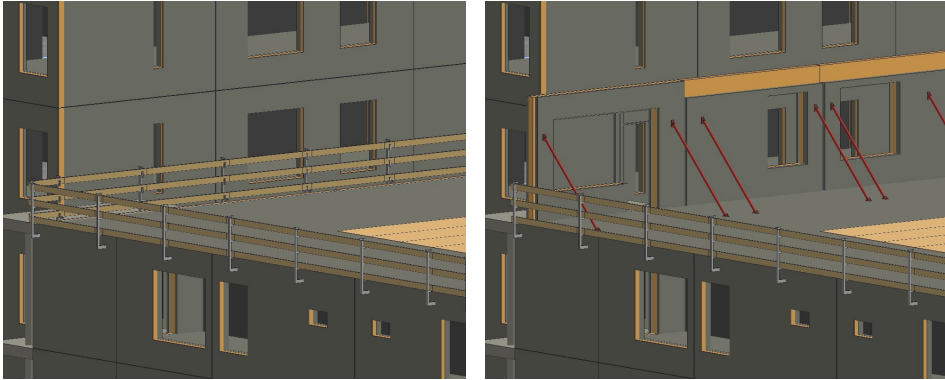


Figure 5. Model-based fall protection planning related to precast unit construction [9].

4D-model, and site status views and simulations produced from the model, could be used to support safety especially at the following ways:

- **Safety planning and identifying safety hazards:** Planning and analyzing construction sequencing and related safety arrangements simultaneously supports risk assessment and identification of special safety hazards. At the same time, coordination, clash detection and evaluation of adequacy of space for conducting work tasks safely can be done.
- **Task guidance and instructions:** Briefing work performance and safety issues illustratively.
- **Informing staff about current work, hazards and safety arrangements:** Up to date 4D-model can be used when communicating the progress of the project, future work, current work, and related safety arrangements, as well as issues requiring special attention from staff.
- **Recording and verification of inspections:** Status information concerning various inspections related to safety management could be recorded or linked to the 4D-model, so that in addition to the component status information such as planned and actual erection date of safety railing, there would also be a registered auditor and the date of inspection available in the model.

## 5. Benefits and challenges for the industry

From the viewpoint of safety, the most important benefits of building information modelling are related to the graphicness of a 3D plan, the potential for using BIM to plan and analyze safety, safety management, communication and promoting motivation of personnel. Additionally, 4D connects safety more closely to production planning, and provides up-to-date safety plans as well as making simulations possible.

The concrete benefits of a BIM-based site plan are related to its visual nature, which encourages more accurate planning concerning site area use, and improves both risk management and communication. BIM-based site planning is a method for managing, connecting and using information. A BIM-based site plan provides different views needed in the same plan, and the information can be used for many purposes. A BIM-based site plan can be used to produce illustrative representations of the site and safety arrangements, and the views can be used for orientation, for informing about risks and for discussions with the client concerning site arrangement, enclosure and temporary roads and walkways. Because of the third dimension it is possible to visualize and evaluate the risks that relate to the crane placement, for example by carrying out clash detections and analyzing collapse situations with help of 3D. In addition, it is possible to see from the BIM-based site plan the site and safety equipment, the quantity at is required, as well as the product information, which is needed in the ordering and selection process.

The three-dimensional BIM-based site plan is an intermediate phase en route to extensive 4D product planning. The most important benefits concerning 4D BIM and the materials produced with help of a 4D BIM instead of a 3D BIM-based site plan are related to the potential for producing real time safety planning and connecting safety plans to product planning.

Full exploitation of the opportunities for improving safety with help of BIM technology requires still further developing of the programs, tools and working methods. There is a need to get more practical experience of safety planning using BIM and more competence in construction projects to use BIM methods and programs.

New methods of preparing BIM-based site plans need to be tested in real construction projects. On the basis of the feedback collected during this research project, the testing will take place in many companies. Furthermore,

opportunities for using combined BIM of various design fields in safety planning should be inspected and tested.

## 6. Conclusions

Experience concerning the use of building information modelling for safety planning, especially concerning BIM-based site planning, was good and encouraging in both the case project test and in a pilot project. The BIM-based site plan proved to be a versatile visualization source and it was also useful in real projects. It seems that in the future the BIM-based site plan will constitute one clear case of building information modelling being used in the construction industry.

The modelling software developed for building design can also be used for BIM-based site planning. Nevertheless, there are certain strengths and weaknesses in the software with relation to this use. For example, suitable tools for land surface modelling can be found today in architectural modelling software, but better tools for an updated site plan and safety planning can be found in structural modelling software and so-called 4D-applications. In addition, the site equipment and safety utilities needed in BIM-based site planning, have received little attention in object libraries included in modelling software. One crucial precondition in regard to BIM-based site planning in real-life projects would be that planner has ready 3D descriptions for repeatedly used site equipment to facilitate and accelerate the site planning.

4D production planning is a breakthrough in construction production management, and at the same time an opportunity to integrate safety management more intensively in the construction process. Connecting safety tasks into the 4D-model opens up entirely new opportunities to review and evaluate safety as part of construction production, to increase cooperation in safety planning, and to enhance safety communication. In early stages, essential safety arrangements to be modelled and included in 4D-modelling are related to protection against falls, such as guard rails, protective lids and safety harness anchor points. Significant potential is also related to BIM-based planning of scaffolding and form work, and modelling other temporary frame supports. Besides 4D safety planning, one significant development area is managing information concerning construction site status with the help of 4D-models. This offers opportunities to identify safety risks caused by changes and interruptions occurring at the building site. BIM-based plans also provide a basis for

developing computer-aided analysis aimed at improving safety, for example in relation to crane reach with different loads. In addition, BIM-based safety plans provide illustrative 3D-presentations, which should be used in safety communications all the way to the employee level.

The proposed BIM-based methods support the vision of IDS (Integrated Design Solutions) by providing opportunity to use the same modelling software and the models created in the BIM-based design-build process also for site and safety planning. The methods also increase collaboration in safety management and integrate safety data with other construction data. Nevertheless, significant further development in the research area is needed.

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# Integrated Design System for the Home Building Industry

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## Abstract

The development of reliable residential construction drawings has become a necessity for construction companies, builders and trades seeking to enhance labour productivity and project profitability. Through the automation of construction drawings, not only can these matters be enhanced, but better quality control can be obtained and a reduction can be achieved in the time spent on building design. The introduction of parametric modeling tools, a concept well known as Building Information Modeling (BIM), allows end users to input rich information to CAD models. At this point in time, however, not every BIM platform provides the ability to automate specific design tasks for construction. As a result, the introduction and further usage of Genetic Algorithms (GAs) in CAD environments has produced interesting results when specific tasks are mimicked. This research centers its attention on the development of GAs for building design for those specific design tasks which are unavailable in current BIM packages. This research demonstrates its extensibility through the automation of construction drawings of drywall layout for wood stick-frame dwellings. Previous research in this area has proven the benefits of automating building designs for wood framing by minimizing material waste and improving its usage. Today, the need to become lean and environmentally friendly is one of the targets many construction companies are seeking. With the development of

GAs in CAD environments, decision makers in residential construction can benefit by improving their current practice and obtaining better control over specific tasks. This research has developed a methodology based on the  $i^3$  (i-cube) concept – a combination of intelligence, innovation and information—to help designers and constructors enhance their practice. This paper also presents the application of a knowledge-based system for quantity take-off and cost estimation. In order to minimize material waste from the design end, this research has focused on the utilization of mathematical algorithms for two-dimensional materials based on the cutting stock problem.

**Keywords:** genetic algorithms, material waste, design automation, 3D modeling, building information modeling, cutting stock optimization

## 1. Introduction

From 2004 to 2008, many regions of Canada experienced significant economic growth – especially in the construction industry, where more than CAD \$72 billion were invested in 2008 alone [1]. These numbers denote the significant contribution in terms of the generation and utilization of primary materials, without taking into material waste disposed to landfills. During 2006 in Canada alone, more than 27 million tonnes of material waste were disposed of [2]. Previous research in this area has found that the construction industry accounts for as much as one third of the total waste produced in cities and municipalities [3]. The stick-frame method entails several shortcomings, including high construction material waste, long schedules, a need to contend with adverse weather conditions, poorer quality products, low efficiency, and negative environmental impacts from transportation and equipment use. Previous research findings have shown CO<sub>2</sub> emissions during the construction process of a conventional dwelling to amount to more than 45 tonnes of CO<sub>2</sub> emissions [14]. For instance, in 2007 in the province of Alberta, Canada, almost 50,000 residential units released more than two million tonnes of CO<sub>2</sub>. These numbers demonstrate the potential economic and environmental impact of building construction and its relationship with CO<sub>2</sub> emissions.

There are materials which should be used more efficiently in order to reduce the problems mentioned above. Drywall waste, for example, which accounts for a significant share of material waste, is generated from new construction (64 percent), demolition (14 percent), manufacturing (12 percent), and renovation (10 percent) [4]; this accounts for 10 percent of the total construction waste



generated in cities and municipalities [3]. During the installation of drywall sheets, an average of 12 percent of material waste is generated as a result of design and workmanship factors [4]. Drywall is the most utilized material in North America for finishing interior walls and fire-rating partitions, ceilings and structural members. The utilization of drywall in the residential and commercial industries has been successful due to its fast installation and relatively low cost (US \$3.12/m<sup>2</sup> 12.7mm thick [6]). Nevertheless, during the production of drywall, the embodied energy required for making these sheets is high (approx 8.64 MJ/Hg [5]), combined with high emissions of green house gases (GHG) (approx 24 Kg of CO<sub>2</sub> per Kg of drywall [7]). It should be noted that energy is used not only to produce primary materials but to transport goods to their final location. In this case, for drywall, the demanded energy in transportation is in the range of 3.36 MJ/Kg-Km [5]. In the province of Alberta, Canada, 61,100 tonnes of drywall waste is deposited in landfills annually [3]. With the rapid growth of green building practices in both the public and private sectors, the lack of solutions to waste management and other environmental issues is becoming problematic. Commitments by private institutions, the federal, provincial and municipal governments, and developers to using strict measurement tools, such as the Leadership in Energy and Environmental Design (LEED) and Alberta Build Green, speak to the urgent need to provide solutions. In today's construction practice, the production of drywall accounts for one percent of the total GHG emissions on the planet per year [13]; leftovers from construction are used for soil compost, and no harm to the biosphere as a result of this process has been documented to date [3]. Nevertheless, the need to optimize the use of drywall has become evident – either by creating optimum layout designs and enhancing current construction drawings, by providing incentives to trades and contractors to reduce material waste, or by optimizing the cutting of drywall in effective ways.

## **2. Motivation and rationale**

The automation of construction drawings in the residential industry has garnered excellent results, both for manufacturing and for on-site construction. The benefits of introducing logical components to drafting tasks have also resulted in the minimization of errors during the production of construction drawings, as well the reduction of drafting hours per job, among other improvements [8]. On the other hand, current practice in this industry is lacking in terms of communication between consultants and contractors due to the generation of poor sets of

construction drawings [9] and [10]. To date, the residential industry relies primarily on the ability of tradesmen to build dwellings, with the consequence of inconsistent use of primary materials during building. [11] has found that, on average, between 0.7 and 1.4 tonnes of material waste is generated during the construction of a single-family stick-frame house (See Figure 1).



Figure 1. Drywall waste in residential constructions.

The precise amount of material waste within that range is a function of tradesmen expertise, the amount of planning during pre-construction stages, and the availability/lack of construction drawings. This paper seeks the enhancement of current construction practice through the automation of reliable sets of construction drawings and the application of mathematical algorithms to minimize material waste. It presents the development and implementation of GAs for construction and shop drawings in the residential industry, as well as the utilization of the cutting stock problem [12] in order to optimize the use of drywall sheets. To this point, the pre-planning and design stages in the homebuilding industry have the most impact in terms of either reducing or exacerbating material waste. Through the application of the proposed methodology in residential construction, it is possible to generate an added value through a reduction of material waste to be hauled to the landfill. As such, the minimization of material waste should have both an economic and an environmental impact by facilitating sustainability in construction practices through the responsible use of primary resources. In contrast, due to the efficient use of materials, a reduction in CO<sub>2</sub> emissions comes as a positive result for sustainability.

### 3. Proposed methodology

Parametric modeling has its roots in feature-oriented objects, a primary characteristic that allows end-users to modify object-oriented designs in a timely

fashion and retrieve vital information among other characteristics from computer models [15]. In order to enhance end-users' drafting capabilities with such features in computer-aided design (CAD) packages, the proposed methodology has centered its attention on the development and further incorporation of logical tasks to mimic the layout installation and optimization of drywall sheets for stick-frame dwellings. Figure 2 shows the roadmap to project management analysis for residential facilities based on a repository model called  $i^3$  (i-cubed).

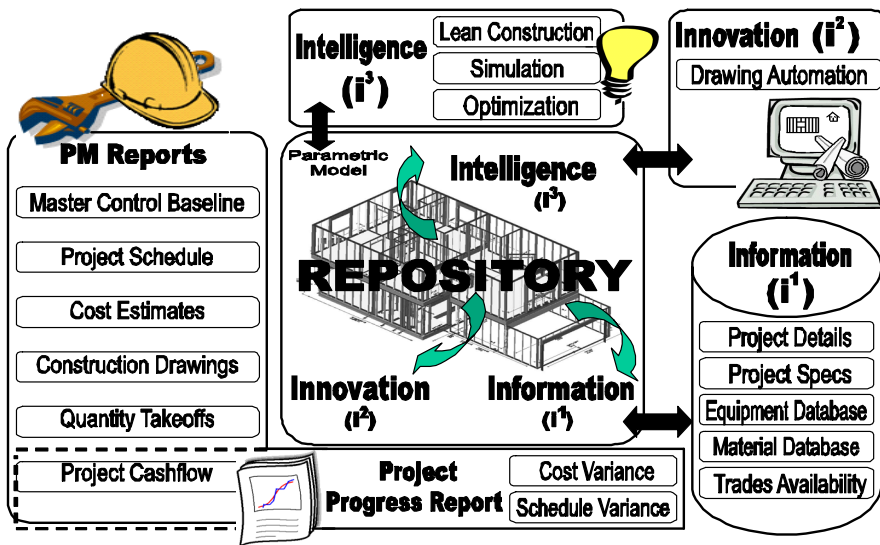


Figure 2. Repository Manager System.

The repository model acts as an intelligent management database in which three principles interact with each other: intelligence, innovation, and information ( $i^3$ ). Furthermore, the success of this paper is the result of the integration among various disciplines, thus eliminating or reducing the gap between discipline-specific models. The proposed 3D model becomes an active virtual model throughout the lifecycle of the project. ( $i^3$ ) serves as a registry attached to each activity, each process, and each link between activities throughout the various construction stages. At each node of the registry, practitioners assess project information ( $i_1$ ) (project details, specifications, materials and equipment, and trades available); consider potential innovations ( $i_2$ ) in terms of alternative materials and methods of construction (on-site vs. panelized or modular construction); and provide the intelligence ( $i_3$ ) used to evaluate material and process wastes, utilizing lean thinking and simulation in order to assess the proposed construction method. Most of the vital information is expected to be added to the

3D-Solid model during the design stage and throughout the progression of the project (during construction and commissioning). Construction schedules, quantity takeoffs, cost estimates, construction drawings and project cash flows can also be obtained from the repository model. During the construction stage, the earn value analysis can be depicted as construction continues its progression.

This paper has been built on the results obtained from previous research [8], in which the automation of construction drawings for framing design was developed through the use of GAs. The principles of the platform framing method [16] were applied to design on-site stick and panelized wood-frame houses. The GA, FRAMEX, generates sets of construction drawings with a mean error of 3.17 mm (1/8-in) to match current cutting precision. The GA has the capability to generate a 3D model and shop/construction drawings for stick-frame dwellings as well as to quantify the material required for construction. Based on the market's material availability, another GA, CUTEX, uses the output generated during the design stage to optimize the use of studs and sheathing. Based on the (i3) concept, this paper presents the methodology used to generate drywall layouts for interior wall finishing. A genetic algorithm, DRY-X, has been developed to identify the spatial constraints from any architectural model, as well as to utilize the framing design previously generated by FRAMEX. Figure 3 shows the steps followed by the algorithm to mimic the layout of drywall sheets within a CAD environment. DRY-X uses as input parameters building specifications such as floor-to-ceiling heights, wall dimensions (Length, width, openings, connections, etc.) and wall characteristics (exterior load bearing, interior non-load bearing, interior mechanical, etc.). The materials required for boarding any type of wall are also specified (drywall thickness, fire-rating characteristics, available sheet sizes in the market, etc.). The end user can also select the orientation of the drywall sheets to be installed in the dwelling (horizontally vs. vertically positioned). These essential parameters in combination with (1) the design principles for installation (see Table 1); (2) the core of the algorithm (logical rules for design); and (3) the optimization layout procedure will generate a model output for final review. During this design stage, the principles of the (i3) concept apply to all processes in terms of innovation (through the use of spatial analysis and coding for 3D models), information (material types and installation rates) and intelligence (by optimizing the boarding layout based on material size availability). By automating logical sequences for design, the algorithm, DRY-X, is capable of producing 100% accurate

construction drawings, a complete take-off list of materials for each panel/wall and the installation sequence for material storage during the cutting process.

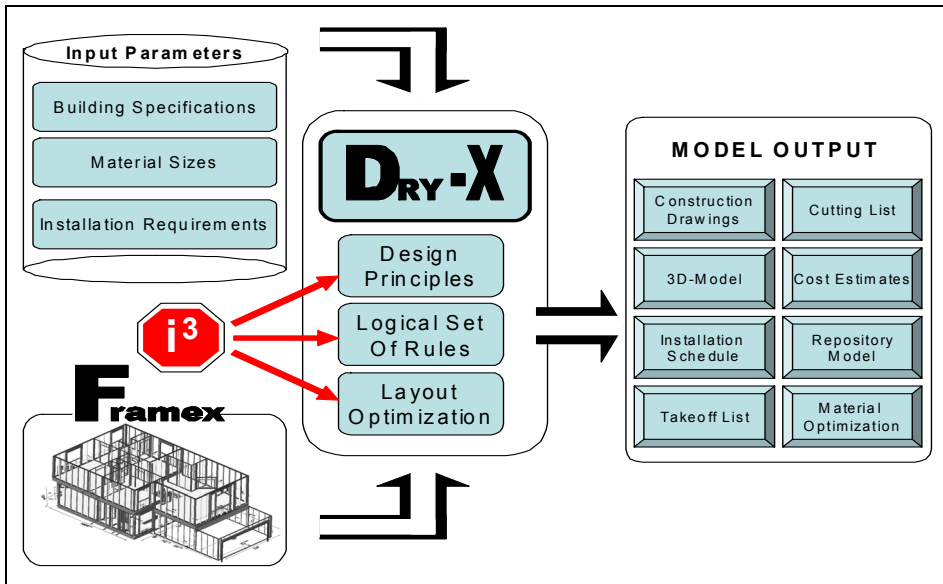


Figure 3. Proposed Methodology for DRY-X.

By using CUTEX, a 2D combinatorial algorithm that optimizes material usage, the end-user can provide a final cutting list and link it to a database for material costing; (this concept is explained in Chapter 5). The final repository model will be composed of all materials required for framing (nominal lumber and sheathing), as well as a complete list for interior drywall boarding. The repository model is the summary of a rich parametric model that provides to end-users a well-detailed 3D model with all its components within a CAD environment.

#### 4. Design process

In order to reproduce accurate sets of construction drawings for drywall layouts, it was necessary to follow the design principles for boarding stick-frame dwellings as presented in Table 1. Due to spatial constraints, the authors have included only the rules required for boarding exterior walls. Although the same principles apply for interior walls, some variations in regards to wall connections and sheet installation on both sides of the wall – among other details – need to be kept in mind. Once the algorithm, DRY-X, is launched in the CAD

environment [17], a dialog box will appear with some design questions to be addressed by the end-user (see Figure 4).

Table 1. Design principles for boarding wood-stick dwellings, Exterior Walls.

Item #	Description	Figure
Design Principle 1: Start/End point	When there is a 90-degree connection, the drywall sheet for the butt-in wall will start flush with the first stud of the panel. By doing so, the flush end can be easily screwed against the stud. The drywall on the Butt-out wall will have to finish half-in before	
Design Principle 2: Start/End point	When there is a 90-degree connection, the drywall sheet for the butt-out wall will start half-inch after the Butt-in wall. The principle is the same as in the previous case. Same rule applies for the end of the panel/wall	
Design Principle 3: Start/End point	When the connection between walls/panels is not at 90 degrees, the drywall sheet for the interior corner will start half-inch after the corner. Same rule applies for the end of the panel/wall	
Design Principle 4: Drywall joints	Drywall joints do not have to run staggered between horizontal and vertical rows. This will allow tapers to finish the walls with higher quality and less touch-up work.	
Design Principle 5: Wall Openings	When there is an opening, the drywall sheet ends/starts flush at the beginning/end of the rough opening. Use left overs to cover bottom and top of windows, and top of doors.	
Design Principle 6: Mechanical walls	If a mechanical wall happens to run parallel to an exterior wall, do not drywall in between both walls, unless there is a fire-rating requirement.	
Design Principle 7: Connections with interior wall	The installation of the drywall sheet on a exterior wall when an interior wall connects to it should end/start 1/8-in before/after the interior wall frame. The drywall sheet for the interior wall should end/start 1/2-in before/after the last/first stud.	

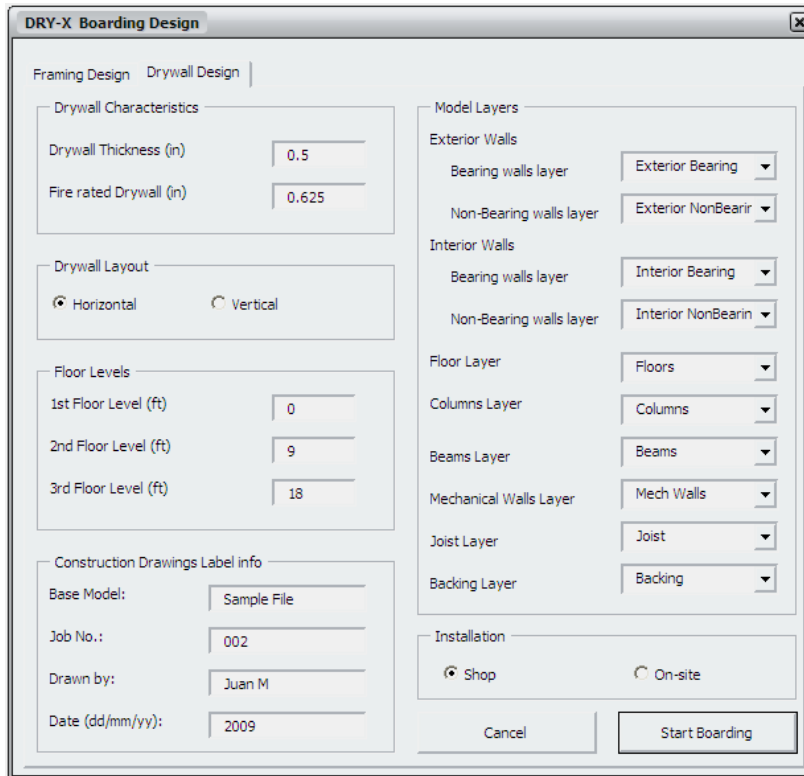


Figure 4. DRY-X Dialog Box.

Figure 5 shows a flowchart of the logical operations followed by DRY-X for exterior wall boarding. DRY-X identifies the different types and locations for each wall component in the architectural drawing. For instance, after the user having only selected the exterior non-load bearing walls, it determines the wall characteristics and proceeds to lay out the sheets of drywall per panel/wall according to the design principles.

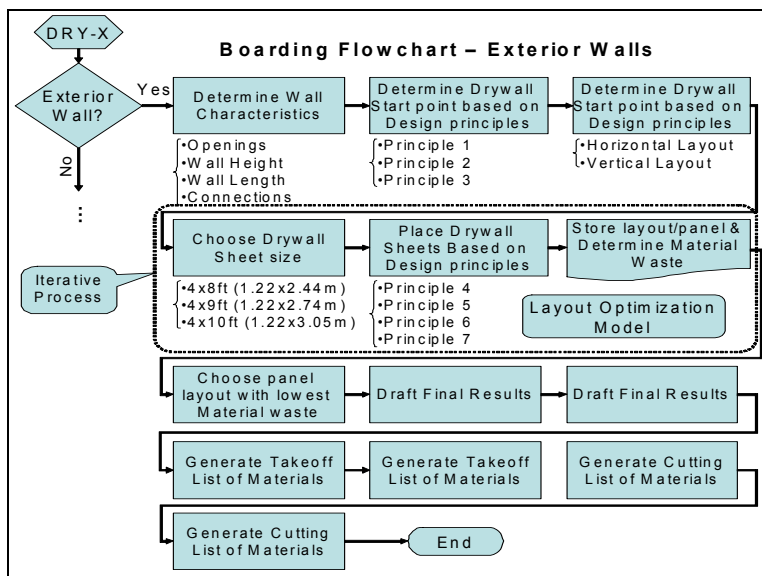


Figure 5. Exterior boarding with DRY-X.

During this process, the layout optimization model determines the design that will create the least amount of material waste. In this way, the optimum utilization of material can be achieved. The model runs under iterative logical loops and records all possible combinations to fit the best cut of drywall on the panel based on the available material sizes in the market. For instance, if the panel length is 9ft-3in (2.82m) by 8ft (2.44m), the algorithm will choose 2x4x10ft (2x1.22x3.05m) sheets rather than 2x4x8 or 2x4x9 with an additional strip, (a configuration which would generate more material leftovers). The algorithm also accounts for the panel’s inner characteristics, such as openings, connections with interior walls, etc. DRY-X also minimizes joints, which is why it may shift sheets from a horizontal to a vertical position. This reduces the amount of extra work required in mudding and taping after installation. Once the layout is determined, the panels are drafted as shown in Figure 6. Final takeoff lists of materials for each panel/wall and for the entire home are summarized and exported to the repository model for further cutting analysis and cost estimating. As shown in Figure 6, each sheet is identified by a particular number. Each sheet also has a description of the corresponding size and quantity required. An experiment was conducted in order to determine the amount of hours saved by a CAD operator when drafting the layout design of drywall for a stick-frame dwelling. The findings showed that for an average 2-storey home with an area of 157 m<sup>2</sup> (1700 sq. ft.) and a 2.44 m (8ft) floor-to-



ceiling height, an experienced drafter would spend 33.5 hours with 12 errors. When utilizing DRY-X, on the other hand, the drafting of the drywall layout only takes about 15 seconds. Another advantage of designing with a parametric tool is its ability to adapt to drafting changes generated by the user. For any CAD operator, any change in the design implies checking and redrawing components, a cycle which can be avoided through the use of GAs.

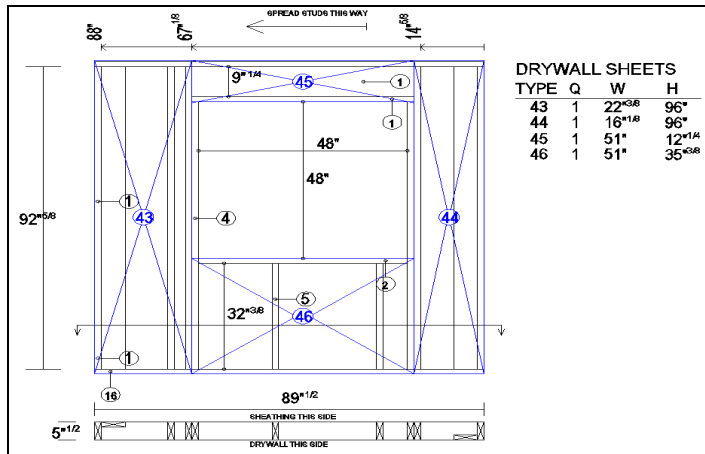


Figure 6. Panel Shop Drawing with Drywall.

## 5. Optimization model

The optimization algorithm, CUTEX, follows the principles of the guillotine cutting method. In this method a planar (2D) sheet (i.e., drywall) is cut to obtain two pieces of material following the sequence of horizontal-vertical cuts (see Figure 7). The guillotine pattern has been chosen because of its compatibility with current practice.

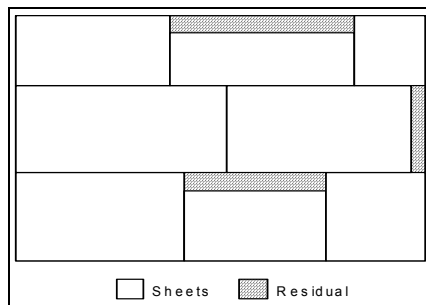


Figure 7. Guillotine cutting method.

Figure 7 shows that the problem of generating the areas required for drywall is an optimization problem in which the trim waste is minimized. The Gilmore-Gomory model [12] for the two-dimensional cutting problem can be formulated as shown in Equation 1, in which  $J_0$  is the set of valid cutting patterns during the first stage,  $\lambda_j^n$  is the  $j^{\text{th}}$  cutting pattern associated with the  $n^{\text{th}}$  set of patterns of the second stage.  $M^{(m')}$  represents the first  $m'$  and last  $m$  rows of the matrix  $M$ , which contains all possible cutting patterns at the various cutting stages. The cutting pattern vector  $\bar{\lambda}$  and the demand vector  $D$  follow Equations 5 and 6:

$$\min \left( \sum_{j \in J_0} \lambda_j^0 \right) \quad (1)$$

Subject to [2, 3, and 4]:

$$M^{(m')} \bar{\lambda} = 0 \quad (2)$$

$$M^{(m)} \bar{\lambda} \geq D \quad (3)$$

$$\bar{\lambda} \geq 0 \text{ is a vector whose elements are integers} \quad (4)$$

$$\bar{\lambda} = (\lambda_1^0, \dots, \lambda_1^1, \dots, \lambda_1^{m'}, \dots)^T \quad (5)$$

$$D = (d_1, d_2, \dots, d_m)^T \quad (6)$$

The associated 2D stock cutting problem was also optimized, leading to the results listed in Table 2. Based on the takeoff list of materials for boarding a house, it is possible to determine the percentage of wasted material with respect to the original stock; the pieces of drywall to be used must satisfy Equation (7):

$$W(\%) = \frac{\sum_{i=1}^{23} S_i}{\sum_{i=1}^{23} n_i A_i} \quad (7)$$

where  $S_i$  is the scrap corresponding to the cutting pattern  $i$  and the product  $n_i (\times) A_i$  is the total area of the stock that must be cut in order to generate the

appropriate number of instances of the cutting pattern. Consequently, for the tested architectural model, the waste is determined to be 2.02 percent of the total amount of material required. For practicality and in order to show part of the obtained results in this paper, Table 2 presents only the optimization results for one floor. One can see that from the total amount required of drywall, only 2.49 percent is wasted. After running the optimization model, 64 percent of the sheets are 3.048x1.219 (4x10ft), 32 percent are 2.438x1.219 (4x8ft) and less than 4 percent are 2.743x1.219 (4x9ft). Once the cutting list of materials has been generated, the information is stored in the repository model. A database for cost estimation of construction materials has been set up internally to reproduce the final costs for materials and installation. The database must be updated on a regular basis in order to match the system to current labour and material prices in the market.

## 6. Results and conclusions

The development and further utilization of Genetic Algorithms (GAs) for the design of accurate construction drawings in the residential construction industry can provide ample benefits in terms of the optimization of the use of primary materials. The capabilities of parametric modeling have been fully exploited by developing a GA that utilizes spatial analysis and repetitive design rules for the layout design of drywall sheets for stick-frame dwellings. The algorithm, DRY-X, has been developed to mimic the installation of on-site and panelized constructions when using the platform framing method. Through the use of this algorithm, it is easy to visualize the installation method to be followed, as well as to determine the most cost-effective and least wasteful process for finishing interior walls. A repository model has been automatically created to store information pertaining to the design of wall framing and drywall, from which it is possible to retrieve vital information for procurement, cost estimation, and the establishment of guidelines for construction. The application of the ( $i^3$ ) concept has helped this research to find an innovative way to apply mathematical algorithms based on the cutting stock problem as defined in the proposed methodology of this paper. The proposed methodology stresses the importance of enhancing the current construction practice, considering its implied incoherent communication between designers and contractors. It also guides users toward optimizing material usage by denoting the most appropriate method of planning cuts, an application rarely seen in the residential construction

industry. The benchmark of this research is the reduction of drafting hours incurred by CAD operators, the reduction of errors during design, the automation of cost estimates, and the positive impact on the environment. After the optimization model was run, the amount of drywall waste per dwelling was reduced to 2 percent. Moreover, the proposed methodology can save up to 370 Kg of drywall and almost 9 tonnes of CO<sub>2</sub> per dwelling. The proposed methodology can encounter challenges with regard to the material storage and sheet identification required to dress every wall in the dwelling. For manufacturing plants, a bin system needs to be set up to store cuts. This disadvantage can also affect the on-site installation because of the lack of space combined with the considerable number of different trades personnel working simultaneously in the facility. Nevertheless, procedures for applying the proposed methodology can be found to benefit greatly as a result of the material savings.

Table 2. Optimization results.

RESULTS - (Main Floor Only)													
INPUT PIECE		CUT LAYOUT		Q	Waste	INPUT PIECE		CUT LAYOUT		Q	Waste		
3.048	1.219	2.299	1.219	2	0.379	3.048	1.219	3.048	1.219	12	0.333		
		0.722	0.510			3.048	1.219	2.581	1.219				
		0.610	0.584			0.406	0.991	2	0.557				
2.438	1.219	2.438	1.200	2	0.094	3.048	1.219	2.489	1.219	2	0.008		
2.438	1.219	2.438	1.219	2	0.000			0.406	0.991				
2.438	1.219	2.438	1.181	2	0.184	3.048	1.219	1.324	1.219	2	0.019		
2.438	1.219	2.057	1.219	2	0.449			1.721	1.219				
		0.295	0.813										
2.435	1.219	1.969	1.219	2	0.332	3.048	1.219	1.527	1.219	2	0.021		
		0.406	0.991									1.513	1.219
2.438	1.219	2.438	0.610	2	0.032	3.048	1.219	1.682	1.219	2	0.057		
		2.438	0.603									1.358	1.219
2.438	1.219	1.838	1.219	3	0.592	3.048	1.219	1.497	1.219	2	0.047		
		0.584	0.914									1.527	1.219
2.435	1.219	2.143	1.219	2	0.171	3.048	1.219	1.340	1.219	2	0.101		
		0.295	0.914									1.689	1.219
2.438	1.219	2.028	1.219	2	0.195	3.048	1.219	1.635	1.219	2	0.077		
		0.406	0.991									1.372	1.219
2.438	1.219	2.438	1.165	2	0.000	3.048	1.219	1.683	1.219	2	0.109		
		2.438	0.054									1.334	1.219
2.438	1.219	2.438	0.693	2	0.074	3.048	1.219	1.527	1.219	2	0.340		
		2.438	0.511									1.476	1.219
2.438	1.219	2.438	1.016	2	0.001	3.048	1.219	1.385	1.219	2	0.026		
		2.435	0.102									1.524	1.219
		2.435	0.102									1.602	1.219
2.743	1.219	1.883	1.219	2	0.612	3.048	1.219	1.435	1.219	2	0.341		
		0.406	0.914									1.385	1.219
		0.406	0.914									1.524	1.219
Drywall required (m2)								229.630	Waste (m2)		5.492		

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# **THEME: Integrated Processes**





# On the Management of Integrated Design Solutions. Does it Work?

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## Abstract

This paper reports on a research into the relationship between process design, process management and the level of integration that is being reached between the building design and the design of the HVAC installation. To measure the level of integration a study of a series of projects published in architectural journals was done. Based on this study 12 criteria were derived. With the aid of these criteria a range of projects were asked to be reviewed by professionals on their level of integration, on which in almost all cases there was a substantial agreement on the level reached. From more than 50 other projects the design process was analyzed by means of interviews about the intensity of management procedures directed at process integration. The results of these projects were measured at three levels of integration based on the criteria mentioned above. Within the research no significant relationship between management procedures and the level of integration reached, could be found.

**Keywords:** design management, integration, design integration, process integration, management effectiveness

## 1. Introduction

The past years in the Netherlands as elsewhere in the world the need for integrated project delivery in construction, as part of national reform programs for the construction industry, got a sharp rise [27], [32], [29]. Ethics, trust, collaboration and conflict resolution often are given as the main success factors for this, these whether to be realised by means of design team integration in general or by integrated contracting [14], [7], [39]. Theoretical foundations concerning design and process integration can be found in management and organizational theories (e.g. [20], [13], [15], [24]), in knowledge management theories about effective knowledge co-creation and sharing in case of knowledge workers (e.g. [28], [17]), in design -computation- theories (e.g. [36], [1], [10]) as well as in more applied sense in Concurrent & Collaborative engineering [6], and Lean Construction (e.g. [41], [8], [16]).

As design specifies what has to be constructed real integration starts with integrated design solutions, traditionally specifically an architect's task in terms of 'coordinating' the contribution of the parties involved in the process. Beyond this the increasing complexity and functional and organisational differentiation within the building-design-sector results in an increasing number of designing or consulting parties acting concurrently. This growing complexity has given rise to the need of a distinct design management function in the design process especially with the aim of more integrated processes and products [14]. Although there is a massive amount on theories about -design process-integration less methods and tools are formerly implemented in construction, especially not when designers are considered. This is for instance illustrated and confirmed by McAdam and Canning's [23] and in Munting's [25] research. Regularly one expects as a result of process integration a more rational production, less construction waste, better life cycle cost performance, faster delivery or even product and sector innovation. Petruccianni [31] states that it's essential to define and formalise success factors if one wants to measure successes. However it might be stated that while doing so in case of innovation, one measures to a certain extend a self-fulfilling prophecy. In case of building projects, innovation and cost efficiency often is assumed to arise out of the multidisciplinary collaboration of parties involved within the integrated process, more specifically those from the designers, engineering consultants on the one hand and the construction and supply side parties on the other [32]. In general in most literature it's just assumed that better integration and good management

will be effective. Within the literature survey executed for this research project rarely empirical evidence was found in which these effects are proven, beyond exemplary, mostly single case based examples [2], [9], [11], [12], [17], [34], [35], [37], [38].

As a result of an integrated building process one might expect a more qualitative integrated product. “Value is generated when knowledge flows” [17], seems to be the regular expectation. How to define integration within buildings in this respect almost is a full neglected area in research. Definitions of integration as well as empirical evidence how integration might result out of integrated processes are almost lacking. In the literature survey of this research we didn’t find any evidence concerning what at least architects might consider one of the most important benefits of process integration; design integration, this in terms of architectural expression, on which this study focuses. Research on these so-called ‘soft’ architectural values seems to be an even more diffuse area. To a certain part this might be self-evident given Akins [3] notion that designers, especially as these types of difficult to specify values are concerned, face problems without clearly defined objectives, methods or evaluation criteria. Or as Allison [5] states, design has a problem finding character by nature. As most designers and others in the building industry might share a certain common sense idea at first sight, formal definitions on integration as part of the architectonic expression of a building however are lacking and apparently difficult to constitute. This might be partly explained also by the normative subjective connotations one might have. Looking for instance to the famous Centre Pompidou from Rogers and Piano one might come to the conclusion that this is an ultimate example of integration as the HVAC installation for a great deal is essential to the architectonic expression of the building. However, from an engineering perspective one might argue that there are better and more efficient solutions for the HVAC systems. Another aspect concerning design integration, which has to be taken into consideration might be called ‘architectonic integrity’. Mies van der Rohe’s Barcelona Pavilion shows a roof, which is bearded by walls as well as columns. At some places in the building the columns specifically are used as spatial structuring elements, trying to suggest load-bearing walls. Actually the roof is only beard by the columns. On the lower level of the column itself they appear as monolithic but actually they consist of four connected L-shaped steel profiles covered by a chromium plated finishing. Also the horizontal roofing seemed to be monolithic plates, but they actually consist of a covered steel structure. Although usually one might say this Miesian

example of architecture might be unique in terms of integrity between spatial and structural elements, actually what one perceives is different from reality.

## **2. Research design**

Often design integration is seen as a positive quality of a building which largely depends on the talents of the architect to integrate the contributions of engineers and advisors or/and the talents of the engineers and advisors to adapt and add to the architectural concept of the architect, or is resulting out of an integrated process characterized by collaboration, trust and mutual understanding [29]. It's often stated that in the latter case process complexity asks for better -design-management. However as has been stated there is almost no literature in general empirically proving the effectiveness of managerial efforts in these instances. Within this research we couldn't find any on the subject of the effectiveness of design management efforts directed at product and process integration in construction and resulting architectural value. It was the aim of this research to discover whether or not a relation could be found between management efforts on process integration and resulting product or design integration, especially concerning the soft architectural values. It was chosen to restrict the research to design integration of the architectural expression and the HVAC system of building designs. It was planned to constitute a normative definition of design integration by means of a literature survey and interviews, in such a way the integration could be measured in levels. As it seemed no definition with enough operational potential could be defined the strategy was altered. A range of selected projects, varying in terms of integration level according to the researchers was ranked on the level of integration by a range of respondents. Afterwards they were asked to motivate there ranking. Based on these motivations criteria were developed and design integration was defined in levels. The validity of this approach was tested by asking a range of respondents to rank a limited series of projects according to the defined levels with the aid of the criteria found. After having constituted an operational definition of design integration with enough validity some indicators were defined, based on interviews with professional experts and a short limited literature survey, to measure the level of management intensity on integration. Not surprisingly given our literature survey we didn't find enough projects in which we could measure the effectiveness of specific methodologies and tools directed at integration, so it was chosen to work with relative simple indicators mostly influencing the

collaboration between the architect and engineer. A series of ex-post cases was done in which the management intensity was ranked on these indicators. Next the involved experts ranked the buildings on their level of design integration. Finally it was tried to establish correlations between the indicators of management intensity and the level of design integration.

### **3. Towards defining a concept of design integration**

As is illustrated with some examples in the introduction it appeared to be difficult to define a systematic unambiguous definition of design integration, which can be shared by all parties involved in building design. This because the concept of integration in architecture involves subjective, normative as well as domain bound elements. This was the reason for this research it was tried to limit the approach to just a part of the set of elements constituting integration in design. More specifically we looked at the level of integration reached between architectural design and HVAC design. To come to a set of criteria constituting design integration in this respect a large series of pictures taken out of architectural magazines was taken and discussed with several professionals as well as design studio trainers and architectural students. They were asked to rank all buildings into three categories: no integration, average integration, excellent integrated design, and these judgments specifically to be made concerning the integration between HVAC system and architectonic expression. After they had done that, they were asked to motivate their decision as explicit as they could. All these judgments were recorded by the researcher who, based on these motivations found 12 more or less generic criteria constituting integration between architectonic expression and HVAC systems. These criteria are summarized below:

1. The HVAC installation does not disharmonize with the architectonic concept.
2. The HVAC installation contributes to the quality of the architectonic concept.
3. The HVAC installation itself to incorporates elements of aesthetic delight.
4. The HVAC installation contributes to the functioning of the building.

5. A design vision can be determined from the perspective of the HVAC installations as well as from an architectonic point of view.
6. The HVAC installation is designed as explicitly visible or not visible.
7. The HVAC installation is in accordance with the architectonic style of the building.
8. The HVAC installation is consequently designed throughout the whole building.
9. Collisions between HVAC and other parts of the building are explicitly designed
10. No evident mistakes, or ad-hoc solutions can be found.
11. There are no contrary solutions concerning HVAC installation and building design.
12. There is unity in the expression of the materials chosen for the HVAC installation and the rest of the building.

In general the idea behind the criteria is that they cannot be weighted, this because their importance is depending on the type of architectural design. The more criteria positively addressed within a design, the higher the degree of integration is assumed. With the aid of these 12 criteria the three main categories of integration were defined. The following descriptions were used to categorize three levels of integration between HVAC installation and architectonic expression:

- **High:** The HVAC installation contributes to a significant extend to the architectonic quality of the building. The HVAC installation has aesthetical qualities on its own, as well as in relation to the architectonic concept of which they are an intrinsic part.
- **Average:** The HVAC installations are designed in accordance with the building. While not being a dominant visual part they are integrated on a proper way in the building with elegant technical solutions.
- **None:** The HVAC installation is purely functionally designed, and not directly contributing to the architectonic -visual- quality of the building.

To test the developed categories and criteria for integration it was tried to find a range of different projects. With 9 projects, documented by some photographs out of architectural magazines, 12 professional architects (all of the same firm)

were asked to qualify the level of integration by putting them in one of the three defined categories. Most of the projects got a remarkable consistent judgment. One project was categorized as level 1 by 82%. Two projects were categorized as level three by respectively 91% and 73%. The level two projects scored as such by 73%; 55%; 73%; 55%; 55%; and 55%.

During their judgments the architects were observed by the researcher, which also had an evaluating talk afterwards. All respondents react very positively on the three categories defined. Remarkably most of the respondents first made their judgment and afterwards motivated them with the aid of the 12 criteria and not the other way around as asked and expected. Respondents were asked if criteria were missing or badly defined but they all agreed on them. The observing researcher got the impression that esthetically negatively judged projects rather easier are put in the lower levels of integration than more qualitative others which might seemed being more severely judged.

With these samples it is made reasonable that a workable concept of design integration concerning architectonic expression and HVAC systems has been developed.

#### **4. Managing design process integration, does it work?**

For long the idea of managing design has been considered an oxymoron [26]. The prevailing view amongst designers was that tampering the mystical, sacred design process by managing with this, it would rob it of its vitality if not destroy it altogether. Unless all the -research- work done the last decades this view has not exactly disappeared, but forward looking practices more and more now do understand that the design process can – and should – be managed. The answer on the best way to manage design resembles the old question about how porcupines make love: very carefully. Although especially in the academic world the opinion rises that architectural design needs domain specific managerial approaches [33], in practice one observes at the best more or less straightforward applications of organizational, project and entrepreneurial management. For the sake of this research it was tried to define easy observable indicators of the management efforts and intensity, directed at the collaboration between HVAC engineers and architects. Given the limited resources for this research project it was chosen to only do ex-post case studies for which data could be retrieved by means of document analysis and interviews. In total 55

projects were evaluated from 2 architectural offices (respectively 20 projects and 19 projects) and one HVAC engineering office (16 projects).

### **Early involvement of engineers in the design process**

In case of integrated design it is assumed that all parties more or less with varying intensity are collaborating together during the whole design process. However also in traditional procurement types the client -or his project manager- and architect may choose for early involvement of the HVAC engineers. ‘Within the design team engineers have to play a more important role. Due to the high specialization grade early involvement of specialist designers is a necessity’ [18]. The first indicator of management intensity on design process integration chosen was the moment of involvement of the HVAC engineer in the design process. According to the regular standardized phasing of building design processes in the Netherlands three main moments can be distinguished: Sketch design phase; Preliminary design phase; Definite design phase. These phases are more or less similar to for instance the British RIBA stages D, E and F.

In total 55 projects were evaluated from 2 architectural offices (respectively 20 projects and 19 projects) and one HVAC engineering office (16 projects). In 22 projects the climate consultant was involved from on the sketch design phase. In 24 projects from on the preliminary design phase and in 9 projects from on the definite design phase. For each project the respondent who provided the case was asked to rank the reached integration level according to our definitions given above. (1 high, 2 average, 3 none). See table 1 at the end of this section. No significant relation was found between the level of integration and the moment of involvement of the HVAC engineer within the process. Although depending on the office providing the cases figures differ, also in these individual cases one cannot find a significant trend. In the interviews held in accordance with this experiment some remarkable statements were made by the professionals involved which might partly explain these results:

“HVAC engineers have insufficient knowledge of architectural design development to be involved in the early phases.”

“Practice differs from theory when the early involvement of the HVAC engineer is taken into consideration. The HVAC engineer is lacking the needed creativity and mental abstract thinking abilities to join in successfully.”



“The fee of the HVAC engineer is not excessive. This added to the fact that for a large part of the fee they only can declare in the latter phases of the process, doesn’t stimulate them to be intensively involved earlier.”

“As in the early phases the design often changes drastically several times, the fee of the HVAC engineer isn’t sufficient to make every time all the needed drawings while being actively co-designing.”

“A HVAC engineer in the early phases only can deliver added value in case of complex technical requirements which cannot be dealt with by the architect himself.”

“Most HVAC engineers are acting passive in stead of pro-active.”

“Architects regularly don not understand the drawings of the HVAC engineer, so they have no insight in the quality he delivers and the potential this provide for the design.”

### **Information plan**

Design can be defined as an information generating and information specifying (from brief to detailed design and production information) process. When more designers are involved in a project adequate information exchange becomes of essential importance [14], [30]. In this respect the attempts to formalize the information exchange between design participants might be considered an indicator for the intensity of the management on design process integration. One easy to detect indicator within case studies for the management intensity on this issue is whether or not a formal information exchange plan is established and actually used. Distinguished were four levels of management intensity concerning the information plan. These were: An information plan is formulated at project start and actively used; An information plan is formulated at project start but according to the designers not actively used; Later on in the process the need for an information plan arises, it’s formulated and used from on availability; No information plan formulated.

The same 55 projects were evaluated with the same methodology as described above. In 20 projects an information plan was used from on the beginning. 22 projects felt in the second category (not actively used). In 7 projects an information plan was established during the process. For 6 projects no information plan was used at all. For each project the respondent who provided the case was asked to rank the reached integration level (1 high, 2 average, 3

none). A weak relation was found between the level of integration and the availability and use of an information plan. In case there is no information plan at all, all projects end up on level 3 concerning their integration (no integration). For all projects in total the highest percentage level 2 integration is reached in case of active use of an information plan from on the beginning. See table 1 at the end of this section. It has to be noted that within this research project the information plans themselves were not evaluated on their content and quality. The researchers were surprised that in 76% of the cases studied an information plan was used. In the interviews held in accordance with this study it was remarkably stated by some respondents that they didn't expect real influence, while in the results found this is the most significant relation. From the range of demands, which can be found in the project management handbooks on the information plan the respondents stress on timeliness and reliability of information. Another remarkable statement was made on the side of the HVAC engineers as was said that they were often too much informed by the architect on all the design changes. Also some respondents stated that exchangeability of data is considered less important as drawings which can be understood.

### **Frequency of meetings**

Frequency of meetings might be an indicator of conflicts, or of complexity, but also on the level of collaboration. Collaboration is considered to be an intrinsic property of process integration. In the case of the collaboration between architects and HVAC engineers we assumed that the frequency of meetings is one of the indicators for the level of commitment to collaborate and to reach an integrated project result. Within the case study based on archived minutes the amount of face-to-face meetings in which architects as well as HVAC engineers were present, was measured. Based on a quick survey it was chosen to distinguish in three categories: Meetings held more frequent than every two weeks; Meetings held average every two week; Meetings held average every 3–4 weeks. We didn't measure informal and formal communication by fax, telephone, e-mail and so on, just because these types of data we could not retrieve in this study. Again the same 55 projects were studied as described earlier. Only 2 projects had meetings with a higher frequency than once every two-week average. None of them reached integration level 1. For 24 projects we measured meetings every two weeks, none of them reached integration level 1, 9 level 2 and 15 level 3 (no integration). 29 projects had meetings every 3–4 weeks, almost equally resulting in integration level 2 and 3. It can be stated that

no relation is found between frequency of meetings and the resulting level of integration. If there is a tendency than this is that less frequent meetings leads to more integration. In table 1 the results are summarized. Remarkable statements of the respondents when they react on this part of the study were:

“A bad project cannot be turned into a good one by good communication. Reversely however bad communication can really harm a good project.”

“It’s not the amount but the quality of communication that counts”.

“The real essential communication is done bi-lateral and informally.”

### **Who is leading**

Coordinating and integrating often is the architect’s task according to the most used professional regulations. The idea that managing architectural design processes requires domain bound skills and experiences on a designers level is widespread. This might have lead to the tendency that still of lot of architects prefer to manage the project themselves above professional project managers. This opinion characterizes also most of the comments made by the professionals involved in this case study. As the discussion on who can better manage closely is related to the integrating design task this issue also was studied in this research. A distinction was made in the following categories: The project is managed by the architect; The project is managed by a professional -building-project manager; The project is managed by someone else (client). Again the same 55 projects are used. Of the 55 projects studied, 36 projects were managed by an architect, 13 by a professional project manager, and 6 by others. In case projects are managed by professional project managers, projects are equally spread in integration levels 2 and 3, remarkably 40% of the projects managed by architects resulted in level 3 integration (lowest level). Table 1 summarizes the results. Remarkable statements made by the professionals involved in this part of the study are:

“Nevertheless who is the manager, we manage during design.” (An architect.)

“The real influence of a project manager starts at the end of the process, fortunately most project managers know they have to put themselves aside during the early phases of design.”

Table 1. Overview of research findings.

	Integration level		
	High	Average	Low
<b>Management intensity</b>			
<b>Moment of involvement</b>			
Sketch design	1	10	11
Preliminary design		10	14
Definite design		4	5
<b>Information plan</b>			
Actively used from start		13	7
Not actively used	1	7	14
Formulated later in the process		4	3
No info. Plan formulated			6
<b>Amount of meetings</b>			
More than every two weeks		1	1
Average every two weeks		9	15
Average 3–4 weeks	1	14	14
<b>Design Leader</b>			
Architect		14	22
Project manager	1	6	6
Other		4	2

## 5. Conclusions and reflections

Whether or not good management leads to better design integration was the main question of this research, more specifically whether or not this is true when the so called soft architectural values are considered. As soft architectural values are hard to quantify and measure specifically was chosen for design integration in terms of the amount of integration reached between the architectonic expression of the building and the HVAC installations. Within the research three levels of integration between the architectonic expression of the building and the HVAC installations are defined loosely based on twelve belonging criteria. There seemed a remarkable redundancy when professionals, design studio

trainers and architectural students are asked to classify buildings in one of the three categories of integration defined.

Some easy to detect and measurable indicators on management intensity were defined based on some almost common sense like hypothesizes. These were: A higher level of design integration might be reached by: an early involvement of the HVAC engineers in the process; the existence and use of an information plan; a high frequency of face-to-face meetings; a domain bound specialist i.e. an architect, as project leader. We studied 55 projects delivered by two large architectural offices and one HVAC engineering office. In this research no significant correlation could be found between our managerial indicators and the level of integration reached. Several reasons might be due to this of which the most important are: actually management intensity was measured and not managerial quality; of the three offices involved, none of them explicitly had a reputation on delivering architecture with high integration levels as is meant within this research; the case study projects were delivered and evaluated by in total 7 project leaders of the three offices, none evaluations are done with the architects and engineers involved or are executed by independent judgments.

Results might had been different if more projects of different offices were taken into consideration, or when projects had been chosen in which integration was an explicit ambition. The methodology and data used cannot lead to the ultimate conclusion that there exists no significant empirical relationship. The researchers however consider it to be rather remarkable that even no slight trend could be discovered which supported what seemed to be common sense hypothesizes on the relation between managerial effort and resulting 'soft' architectural value in case of design integration.

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# Integrated Scope-Schedule-Cost Model System for Civil Works

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## Abstract

The purpose of this investigation is to illustrate the potential use of integrated scope-time-cost model systems in civil construction. This study is important to help provide an example of how a civil project completed using common methods could have alternatively been planned and monitored during construction using CIB's identified vision of an integrated design solution. Specifically, this is the use of collaborative work processes, enhanced skills, integrated data and information and knowledge management. Publishing the results of this example will highlight some of the issues with integrated model systems particular to the civil industry. A recent questionnaire survey completed at the Center for Integrated Facility Engineering (CIFE) resulted in 175 responses from all types of construction industry professionals, 50 responses were from the heavy civil construction subdivision. None of the civil contractors reported using an integrated model system though some used components. More needs to be done to facilitate ascertaining the relation of product model objects, schedule 5-week lookahead activities, cost estimate operations and production monitoring feedback. These will further integrate recipe-formula relational knowledge of explicit and implicit components into an exchangeable format available to different disciplines across all phases and the life cycle of the project.

**Keywords:** integrated system, scope, cost, time, BIM, PIM, civil works

# 1. Introduction

The ultimate goal of the project planning and control process is to know what the resource demands to construct a project are and how these resource demands change during the construction process in response to existing conditions. This study used a system of integrated software tools to construct an integrated scope-time-cost model system utilizing a civil information model, these are: AutoCAD Civil 3D, Tocoman iLink, Tocoman Express, Tocoman Quantity Manager, Vico Control, Sage-Timberline Estimating, Sage-Timberline Commercial Knowledgebase, NavisWorks Manage and the RSMeans production library. As a case example a \$180M (US 2005) rail project consisting of mass excavation, concrete retaining walls and structural backfill was used to provide the project scope, object geometry, operation list, lookahead schedule and as-built schedule. In a questionnaire survey accompanying the case study, 50 civil contractors responded, of these: 42% reported using at least one component of an integrated model system, these are: product model 8%, scope software 6%, cost software 19%, schedule software 14%, integration software 6%, 4D model 0%, no software tools 8%. This compares with the 2008 biannual Construction Financial Management Association (CFMA) questionnaire survey [1]. They found the following from 114 US heavy and highway contractor responses: product model 73%, scope software (NA), cost software 94%, schedule software 75%, integration software 55%, 4D model 0%, no software tools (NA). These results while different, still reinforces that many civil contractors already possess the components needed for an integrated system and if desired only need to add a few select tools to configure into a system.

The following five results are provided in this paper. (1) The integrated scope-time-cost model system found an approximate variance of 85% between the 5-week lookahead and as-built project schedule durations. (2) The manual take-off contained a double count (3% of total material) and two of the 28 (7%) project locations are missing from the schedule. (3) The recorded level-of-detail was able to be increased from a single project location to 13 locations and two sub-locations. (4) The Location-based scheduling tool provided a resource leveled schedule that defined resources similar to those actually utilized on the project through pull demand. And (5) the importance of a uniform classification method across the system is reinforced.

These results positively show the integrated model system would have provided a benefit to this project. One source of the benefit is through project

quantity takeoff locations and sub-locations breakdown. By defining where (location) and when (monitoring) and activity occurs plus the expected quantity, reliable feedback is supported. It was not expected that applying an integrated model to a civil project would fit so well. Two limitations prevented further exploration. First, compiling the existing 2D paper-based documents into a common format with the integrated system was time consuming and not exact. Second, the 4D model utilization of multi attributes is limited, making the location attributer difficult to exploit.

## **2. Scope-time-cost project assessment**

Construction status assessments are notoriously inaccurate and labor intensive. Many researchers have contributed to the realization that project success is independent of project controls [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. An analogy to current project control practice is an early 20<sup>th</sup> century doctor during the 1918 influenza pandemic<sup>2</sup>. The only benefit the doctor could hope to provide was to collect as much information and samples as possible for future researchers. At that time with the technology available, it was not possible to affect the pandemic or the outcome of an individual. Much in the same way, field engineers today can realistically only be expected to collect project information for future use in the estimating department and not to actively affect project outcome. Additionally, attributes such as: what information to collect, in what level of detail, with what level of accuracy and precision, with how much delay and at what frequency, are uncertain since the future use is not always foreseen. These uncertainties result in: some collected information never providing any use, collected at too low a level of detail to provide a full benefit or only collecting data with no context. Integrated system tools advance the possibility that one day engineers will be capable of affecting the outcome of a project after the planning, design and fabrication stages.

With an integrated system a changed quantity either in project scope or progress to-date, is passed to the process and the cost models. Any change in the cost model also results in a revised process model and any change in the process model results in a revised cost model. In this process rework and errors are

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<sup>2</sup> Human Virology at Stanford “The Influenza Pandemic of 1918” updated February 2005 [virus.stanford.edu/uda/](http://virus.stanford.edu/uda/).

avoided. Optimization algorithms requiring accurate and precise up to date information, such as that proposed by Märki [14] and described by Leu [15] are reliant on these integrated system tools. Current project planning and monitoring methods requires knowledge of the quantities' sources [16]. A common method is Earned Value Management (EVM). To illustrate project schedule and cost variance this method relies on a graphical monitoring of: project duration, actual cash flow (billings less cost), planned cash flow, planned value, earned value (billing less planned margin) and actual cost to monitor project progress. For a more complete review of the EVM method please reference the *Project Management Body of Knowledge (PMBOK)* [17]. Note that in the PMBOK many of the fine points of how to implement the method are left to the reader, indicative of the difficulty in achieving such a method. The EVM method can not be any more accurate and precise than the methods utilized to supply information to the model, for example the measured quantities of billable work in place used to quantify the progress billing.

### **3. Technological & professional context**

Professor John Fondahl helped introduce the Critical Path Method (CPM) to the construction industry in 1961 [18]. Not developed for construction specifically, CPM was adapted from the 1950's Program Evaluation Research Task (PERT) analysis used in the ballistic missile industry and the Project Planning and Scheduling System used by the US Navy on submarine projects [19]. Like construction projects, missiles are a large, complex, constrained duration production product. As such, the transferability of project management methods is straightforward due to the shared terminology and concepts as a sub-domain of the industrial engineering field. Since 1961, through incremental innovation of analysis methods such as CPM, project management methods are increasingly integrating points of the project management scope-time-cost triangle into integrated systems [20], see Figure 1. Integration of the product model (scope) and process model (time) resulted in a new tool called a 4D model [21]. The adoption in the building industry of information models, specifically termed as Building Information Model (BIM), provides a new source of information. Used as a database, information models facilitate greater integration of information across the various efficiency analysis and graphical information representation tools.

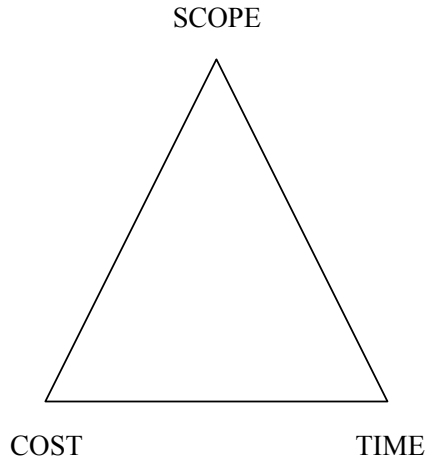


Figure 1. Integration of scope-time-cost results in an integrated system composed of the product, process and cost models. The process of finding the efficient optimum solution for given valued attributes is iterative and results in a circle integration model as proposed by Fischer and Kunz 1989.

Scope-cost, scope-time and cost-time are the triad sides of the project management triangle. Properly determining these sides is often the task of separate professions such as: cost estimators, schedulers, and financiers. These professions rely on scattered information sources such as: product, cost, process and quality models, efficiency analysis tools and object, operation, production and cost; direct and indirect specifications databases. Examples of what these sources can manifest as: RSMMeans production database<sup>3</sup>, AutoCAD 3D model, Field Engineer's Manual<sup>4</sup>, company knowledge-base, project specifications, CalTrans standard specifications<sup>5</sup>, quarry material properties, and US government Bureau of Labor Statistics<sup>6</sup>. Integration through an information model allows pulling these scattered resources together and provides a more precise and accurate model of the resources necessary to construct a product. Integrating scope, time and cost as the takeoff, schedule and cost estimate, with the geometric product model as a 4D model, provides a check of plans in a human digestible format.

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<sup>3</sup> <http://www.rsmeans.com/>.

<sup>4</sup> R. O. Parmley, P.E. 3rd Edition McGraw-Hill, 2002, ISBN 0-07-135624-X.

<sup>5</sup> <http://www.dot.ca.gov/hq/esc/oe/>.

<sup>6</sup> <http://www.bls.gov/>

In the higher level of detail method of bottom-up estimating, production rates drive the process and the cost models. To obtain a production rate, recognition of constraints such as: climate, learning curve, site conditions and resource leveling [22], as well as object, laydown and work space clashes [23, 24, 25, 26] across the process model is necessary. It is well known the importance of leveling resources to reflect the physical limits of local resources, avoid fluctuations of resource demand and to maintain an even pace of application of resources [27]. Less well known is that once resources have been leveled the durations of activities change, resulting in adjusted time-dependant costs, therefore providing a different cost than simply multiplying quantity by unit cost [28]. Even less commonly practiced is adjusting production based on the other three constraints (climate, learning curve and site conditions) and the various clash conditions, though they have an effect on cost. The increased work necessary to account for additional factors such as climate and work zone congestion is mitigated through the use of integrated model-based systems, therefore providing a more precise representation of the project management triangle tradeoffs.

Proficiency in preparing scope-time models<sup>7</sup> (schedule) and scope-cost models (cost estimate) is difficult; many steps are repetitive and time consuming. A careful analysis of these steps provides a metric to measure performance against and provides a current performance measurement relatable to information model-based methods, see table 1. When placed in general categories, these break down into one of six categories: project planning and setup, takeoff project scope also termed a *quantity survey* in the U.K., schedule process model, create 4Dmodel so to detect time-space and laydown space conflicts [29, 30], estimate cost model, and optimize for efficiency for the preferred characteristic, such as: quality, cost, time, material and environmental or social impact. An analysis and quantification of the steps as shown in table 2, indicates that of the 32 steps, 13 (41%) have software tools available now, 29 (91%) are repetitive, 16 (50%) are manual and nine (28%) have potential software tools or are included in some software tools. Assuming increases in software maturity will address the potential applications in the next few years then the number of tasks with software tools increases from 13 (41%) to 22 (69%).

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<sup>7</sup> Two examples are Program Evaluation and Review Technique (PERT) which calculates start and finish dates and Critical Path Method (CPM) which calculates free float then finds shortest free float path through process model.

Table 1. Tasks necessary to create integrated scope-time-cost model.

**Integrated scope-time-cost tasks:**

**project planning and setup**

1. ▲ develop project strategy
2. ▲■ define what object are explicit in the product model [assembly implicit object-component]
3. ▲■ determine Work Location Breakdown, project, location, sub-location and work-zone

**product model takeoff (scope)**

4. ■ define operations & associated objects [assembly operations]
5. ▲■ define implicit objects from explicit objects [assembly implicit object]
6. ▲■ create recipe formulas for implicit objects [assembly object recipe formula, type template & specific]
7. ■ map objects to operations [assembly operations]
8. ●■ calculate quantity takeoff from object dimensions using recipe formula

**process model (time)**

9. ●■ lookup operation production rates
10. ■&/or derive production rate from process analysis
11. ■ create activities from single or multiple operations
12. ▲■ determine driving production rate for activity
13. ▲ apply locations from project planning
14. ●■ assign sequence logic [assembly operation]
15. ●■ assign resources to activities [assembly operation]

**4D model (scope-time)**

16. ●■ map activities to 3D model [code match]

**cost model (estimate)**

17. ●■ look up and assign unit cost
18. ■ adjust unit cost for current conditions [contextual library]
19. ▲■&/or derive unit cost from labor, equipment, material, haul, & subcontractor

**optimize for efficiency (recognize risk efficiency not met) – after each of the following steps restart at step 20**

20. ●■ calculate durations
21. ▲■ adjust locations for production (20)
22. ●▲■ level resources & workflow (20)
23. ●▲■ laydown & workspace detection (20)
24. ▲■ recheck driving production rate
25. ●■ forward pass (ES, EF)
26. ●■ back pass (LF, LS), free float
27. ●■ determine critical path & total float
28. ▲■ adjust production for climate & conditions [climate record/degree days] (20)
29. ●■ calculate cost (over-time, time variable, marginal cost)
30. ▲■ adjust location sequence (20)
31. ▲■ optimize process model logic for required attributes efficiencies – local optimum (20)
32. ▲ create alternative project plan – global optimum, iterate from develop project strategy

● software tool ▲ manual conceptual task ■ repetitive task [ ] potential software tool



Table 2. Analysis of tasks necessary to create an integrated scope-time-cost model system. The items in bold font are the most likely candidates to have repetitive tasks embodied in software tools.

tasks	total tasks		software		repetitive		concept		potential tool		if tool avail.	
tasks	32	100%	13	41%	29	91%	16	50%	9	28%	22	69%
planning and setup	3	9%	0	0%	2	7%	3	19%	1	11%	1	5%
<b>product model takeoff</b>	<b>5</b>	<b>16%</b>	<b>1</b>	<b>8%</b>	<b>5</b>	<b>17%</b>	<b>2</b>	<b>13%</b>	<b>4</b>	<b>44%</b>	<b>5</b>	<b>23%</b>
process model	7	22%	3	23%	6	21%	2	13%	2	22%	5	23%
<b>4D model</b>	<b>1</b>	<b>3%</b>	<b>1</b>	<b>8%</b>	<b>1</b>	<b>3%</b>	<b>0</b>	<b>0%</b>	<b>0</b>	<b>0%</b>	<b>1</b>	<b>5%</b>
cost model	3	9%	1	8%	3	10%	1	6%	1	11%	2	9%
optimize for efficiency	13	41%	7	54%	12	41%	8	50%	1	11%	8	36%

Repetitive tasks are those requiring repeating the same task for each activity or component-operation. Repetitive tasks include all except developing project strategy, applying the location breakdown, and creating alternative project plans. Some potential software tools counted for product model takeoff, process model, 4D model and cost model, either exist in an existing software tool or have had substantial research completed. These are included since they are not generally included in similar software tools. None of the four following potential automation functions are universal to project management software, each has limitations and likely no one software tool contains them all. These four examples of potential software tools are: Automated adjustment of production rates based on expected climate conditions as researched by Akinci [31]. Automated linking of object to activity in Navisworks 4D and CommonPoint Project 4D<sup>8</sup>. Both have an auto-link function if the classification code is the same, for example, 1,2,3 is not a match to 1.2.3. Automated schedule generation, Building Explorer<sup>9</sup> provides automated Primavera Project Manager CPM schedule with all logic links complete and Sage-Timberline Estimating Extended and HCSS HeavyBid both produce a Primavera P3 schedule without logic links. Last, assemblies or bundles of operations likely connected, Sage-Timberline Commercial Knowledgebase (CK) provides operation assemblies linked by

<sup>8</sup> <http://www.commonpointinc.com/products/project4d/project4d.asp>.

<sup>9</sup> <http://www.buildingexplorer.com/>.

recipe formulas and provides an extension function to create custom assemblies. Tocoman provides an assembly takeoff function utilizing CK assemblies for some implicit objects. The greatest gains in potential software tools will likely come from utilizing common classifications so to allow the use of assemblies in applications other than estimating.

Prior to integrated tools, a complete scope-time-cost project plan contained about five reentries for each of three applications, resulting in manually keying each entry 15 times for every operation or activity. A typical project schedule prior to adding five week look-ahead activities can have around 1000 activities. If thoroughly completed, this indicates 15,000 items are keyed during project planning. Iterations of change results in further keying, assuming a 50% change in planning material, results in over 20,000 items keyed. Human error ranges from 1:300 to 6:100, automation errors range from 1:394,000 to 1:5,400,000 [32, 33]. The expected human error results in about 100 errors, or ½% error rate, in the 15,000 items given above. In practice the measured error rate in the construction industry is likely much higher; the human error range given here is from the medical field, providing a conservative range. Where and when in the project documents errors occur is an additional unknown factor. An error rate of ½% seems small, equaling about \$3,000 to \$5,000 per \$1M of project scope. On a medium size (\$250M 2009US) civil project this error could initially result in over a million dollars in misplaced resources.

This analysis is assuming as a baseline the use of electronic CPM process model, cost model and onscreen takeoff software tools. The use of these generally minimum project monitoring software tools is not universal as shown in the CFMA and CIFE survey results. The survey results are from a small sample size and determining how to define the heavy civil population, for example by project, by company or some combination, presents some difficulty. Assuming a confidence interval of 9%, somewhere from <1% to 18% of heavy civil contractors rely on triangular scaled rulers for takeoffs, dry erase white board schedules and note-pad estimates/forecasts. For these contractors a paper-based scope-time-cost plan results in more keying or the use of paper tables/chalk boards for each software tool not used, likely introducing an increased risk for human errors beyond 1:300 to 6:100.

Scope-time-cost planning tasks are tedious and prone to short cuts, the goal of optimizing project planning becomes lost, and soon the engineer cannot see the forest for the trees. A survey of Auburn University undergraduate building science students and industry professionals highlights the poor perception that

students have about estimating tasks [34]. If this same attitude permeates the estimating departments where many new engineers start their careers, the results can be poor bid and project performance due to engineering shortcuts. In the same way, engineers can become focused on less important but time-consuming tasks<sup>10</sup>, these then can outweigh core tasks<sup>11</sup> of facilitating maximize productivity, minimize risk, and ensure feasibility. The result is like an error-plagued estimate, poor results.

#### 4. Scope-time-cost defined

Project planning, scheduling and execution depend on valuating and trading of project control attributes so as to gain the optimum efficiency in resource utilization. As shown by the project management triangle in Figure 1, there are three project management process and control parameters, these are scope-time-cost, and a fourth quality<sup>12</sup> is implied to exist within the other three. A more difficult to conceptualize but still relevant factor is efficiency, which can never be 100%. Efficiency is the waste that does not result during implementation of the project plan. The decision to construct a project often depends on the balance between scope and cost.

Scope, as given by the plans and specifications, is the work required, both implicit (i.e., temporary structures) and explicit, to complete a project [35]. Scope indicates the project benefit and cost represents resources consumed, therefore defining project viability. To obtain scope, a takeoff is completed. If completed manually this is an error prone, time-consuming process [36].

Cost reflects the scarcity of resources at any given time and places a value on this scarcity. Cost is more difficult than scope to capture fully, due to the many affecting variables such as production, resource demand and the time value of money. Cost includes: definition, associated externalities, design, fabrication,

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<sup>10</sup> Calculating durations, completing the forward pass and back pass, calculating free float and determining the critical path & total float.

<sup>11</sup> Such as: adjust production rates for climate & conditions, level resources, optimize process model logic, adjust location sequence, check laydown & workspace detection, and calculate cost effect from changes.

<sup>12</sup> This material is offered to individual readers who may use it freely in connection with their project work. It may not be used by commercial or non-commercial organizations without permission, [www.maxwideman.com/](http://www.maxwideman.com/).

construction, operation and demolition; this series of costs is known as the life cycle cost.

Quality and time are the last two parameters. Time and quality affects cost in that absent any innovation, a reduced duration or increase in quality results in increased cost. This holds true as long as the project is operating at perfect efficiency, which is not possible, so in practice, duration can be reduced and quality can be increased through an increase in efficiency with no affect on cost. Time is the duration to move, arrange and assemble these resources. The quality factor reflects how these resources are used and what specific grades of resources are needed.

### 5. Integrated scope-time-cost system

Before describing the three project management points embodied in software tools, a short overview of each point and the types of models used is needed, refer to Figure 2 and 3.

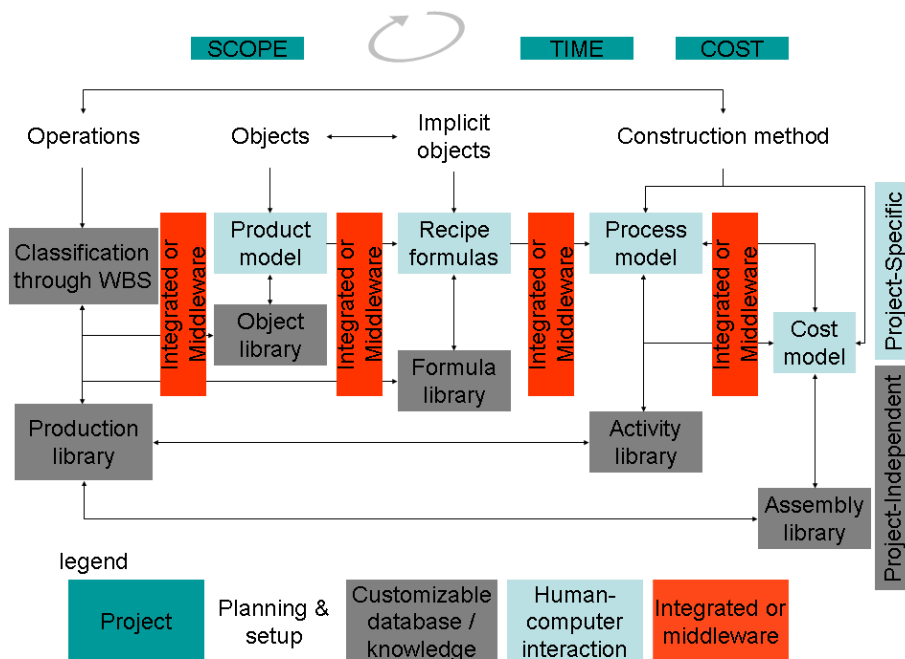


Figure 2. A general outline of interaction between scope-time-cost-quality software application tools within integrated scope-costing. Note the role of libraries to provide standardized information to models. Ideally, all models integrate with one another preventing the need to reenter data redundantly or manually transfer results to other applications.

Be aware, these systems are manifesting as two types, single vendor systems and integrated multi-vendor systems. The multi vendor system is illustrated in this case study. First, there is scope, represented by a product model; these can be a paper-based 2D drawing, represented as an electronic 2D or 3D drawing, as 3D Building Information Model (BIM) or as an animation incorporating time, i.e., 4D model. Second is cost, represented by a cost model known as a cost estimate. Cost models have a varying level of detail from typical project to parametric. The most detailed cost models are categorized into horizontal and vertical formats including [37]: overhead, labor, temporary material, permanent material, equipment, subcontractor and haul<sup>13</sup>. The third and last is time, represented by a process model also know as a schedule. Process models have varying forms from spreadsheet three-week look- ahead, two month preliminary schedule, six month project planner and project billing schedule, each with an increasingly lower level of detail. These three models, scope-time-cost, ideally are integrated with quality models and efficiency analysis software to create a complete Project Planning and Control (PPC) system. With accurate and precise quantities, forecasting becomes more accurate and precise [38].

Within the described scope-time-cost models, there is a distinction between *project specific* and *project independent data* to categorize the source of information, see Figure 2. Project independent data is that universal to any project, an example is material density. Project specific data is that which is peculiar to a project and may not be true for any other project. An example is the sequencing of project phasing on a hospital project which may be determined by the helicopter flight path. Though this phasing is the most efficient for that project with its constraints, it is not necessarily the most efficient solution for any other project.

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<sup>13</sup> Haul, the cost for hauling material, is calculated and entered in its own column in cost models. Haul is also given its own subcode in job cost accounting to better track this cost separate from other activity cost. Distance hauled is an implied component of cost since haul cost is a per hour rate. The equation for haul cost is  $(\text{quantity}/\text{capacity})(2 \times \text{haul distance})(\text{rate of transportation})(\text{cost per hour})$ . This equation ignores load/unload time and assumes zero queue time at load/unload, these require additional calculations dependent on equipment and site layout. Cycle time calculations incorporate the number of haul trucks and load/unload time.

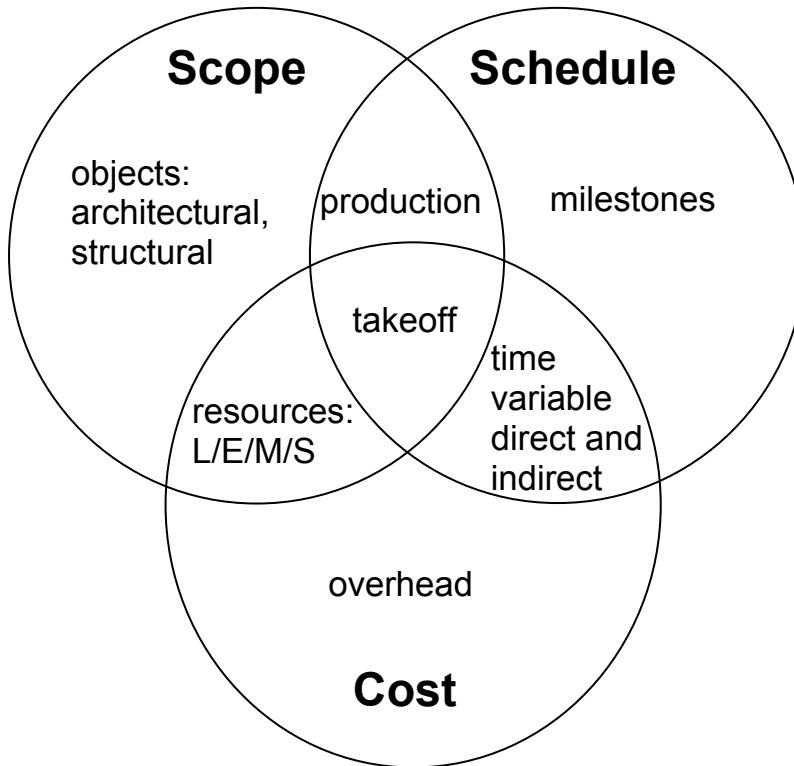


Figure 3. Venn diagram of scope-time-cost. The takeoff is central in all three areas and provides the foundation of all further modeling and analysis.

## 6. Integrated software tools

The process model or schedule can manifest in several forms, the most common are as a Gantt chart or a line of balance chart, see Figure 4. The line of balance chart is commonly associated with Location-based Scheduling (LBS). A key benefit of LBS is the need to only link activities for the work sequence once rather than repeatedly link the same type of activity for each location. This means that a project with ten locations requires 1/10th the work to: create the baseline process model, update the process model to design changes, change activity sequence, or make mid-project adjustments to process model level of detail. The value of this reduction in links is most observable in updates to the work process sequence to reduce project duration or stay on schedule, a common change due to changes in conditions and constraints. As a scheduler the more frustrating tasks is to be told to change the work sequence due to some change,

then be told to change the sequence back the next week when the expected change did not materialize or the re-sequence fails to bring the expected benefits. For a single scheduler, on a large civil project, a re-sequencing of only a small portion of a project phase can take eight hours or more. Removing links and creating new links can take several hours, often completed at night after the scheduling meeting so to provide an updated schedule for approval the next morning. At some point on the study project the construction manger became hesitant to re-sequence the schedule since the labor required and uncertainty of benefits outweighed the labor required to model different options.

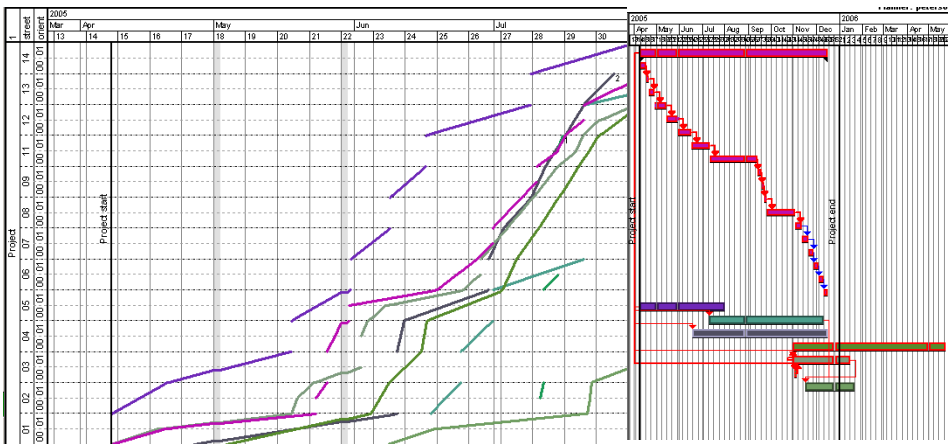


Figure 4. Side by side comparison of flowline (left) and Gantt (right) illustrates the affect of location phasing on production and which operation is the driving production rate. Four core concepts in Location-based Scheduling (LBS): 1) one task per task type is occurring in any given location, 2) workflow locations can be completed in any order, 3) maintain minimum 1–2 days buffer between tasks and 4) use the same location sequence for all the tasks.

A beneficial function in Vico Control is the resequencing of locations. In schedule updates, the sequence of individual activities is not what is changed but often it is the location sequence that is changed. Changes in sequencing should not require relinking of activities but simply rearranging the location sequence, leaving the underlying work logic the same. Resource leveling is a fundamental component of duration calculations. Through adjustments to the number of crews productivity is adjusted to attain the needed durations. In addition factors such as: crew size, labor resources, production rates and quantities must be defined in location-based schedules.

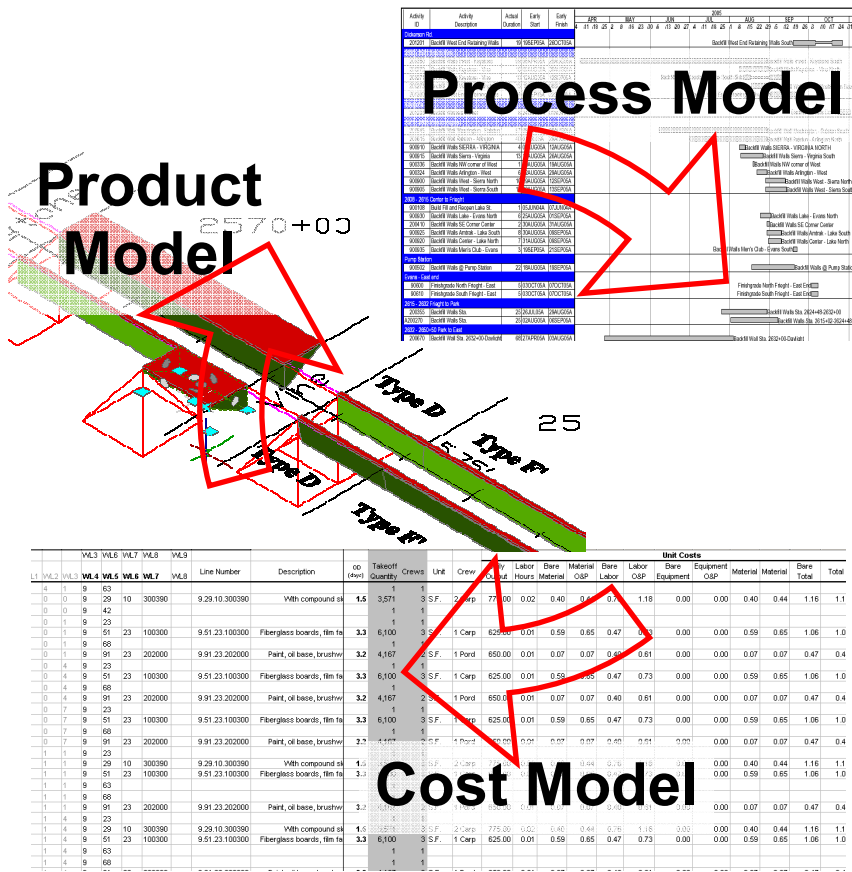


Figure 5. Iteration of changes in the method, scope or sequence requires a new pass, resulting in: 1) a new optimization of the schedule for project constraints, 2) a check of the 4D model for constructability and 3) a review of the cost estimate.

The following five software tools are used in this case study, see Figure 5: (1) Tocoman Group Ltd., a Finnish company, provided a takeoff and quantity calculating middleware software suite consisting of: iLink, Quantity Manager (QM), Construction Model Server (CMS) and Express. This software suite enables takeoff of quantities directly from multiple types of product models and integration with many different vendors' software tools. This is desirable since the user can select the software applications: best suited to the task, they are most comfortable with or fits best with their legacy system. (2) Another Finnish company, Vico Software Ltd., provided Control, a Location-based Scheduling (LBS) software tool containing labor and material resource leveling and risk analysis features. The Vico company has positioned themselves for construction



industry specific project planning and control applications<sup>14</sup>. (3) Sage-Timberline in addition to their estimating extended tool, provided their estimating Commercial Knowledgebase [39] which has operations grouped as assemblies with the necessary recipe formulas predefined. Recipe formulas are equations to convert from measured units to reported units and to infer quantities based on associated measurements. In this way, the user only needs to enter a quantity for one item and a group of associated items, or an assembly, is given an assumed takeoff value. (4) RSMMeans production and cost libraries are used to provide the operation descriptions, classification codes, work breakdown structure (WBS), production rates, unit costs and the crews' compositions. (5) As the information model AutoCAD Civil 2007 was used with custom properties defined for location, sub-location, soil properties and compaction zones, see Figure 6.

The following section reviews three software tools common to civil work that were not included in this case study but should be in any future work on civil integrated systems. These are: HCSS, DynaRoad and Trimble Pay dirt<sup>15</sup>. Due to the preliminary nature of civil integrated systems a collection of tools providing existing integration solutions was selected. The integration of these tools is not currently thought possible but due to market share should be investigated. In the CIFE survey 6 of 56 (10%) civil contractors defined HCSS HeavyBid as their cost estimating tool, 2 of 56 (3%) defined Maxwell American Contractor, the remaining 87% are assumed to use excel or non-electronic methods, @ 95% CL, confidence interval is 13%. The 2008 biannual Construction Financial Management Association (CFMA) questionnaire survey [40] found that 36% of civil contractors use HeavyBid and none used Maxwell. They found 18% use Hard Dollar, 12% use Excel, 11% use BID2WIN, 5% use Sage-Timberline, 2% use MC2 and 4% use an assortment of other vendor tools. A partial integration is provided by HeavyBid as an import function for takeoff quantities from Trimble Pay dirt. Paydirt is intended to takeoff earthwork quantities and not mass concrete. In addition to Heavy Bid and Paydirt, location-based scheduling software could provide a powerful integrated solution. A location-based tool with many of the advantages in reduced activity linking, duration calculations, and resource leveling of Control is available; developed specific for earthwork

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<sup>14</sup> Vico Software Inc. <http://www.vicosoftware.com/>.

<sup>15</sup> <http://www.trimble.com/paydirt.shtml>.

called Dynaroad<sup>16</sup>. DynaRoad is intended for balance cut and fill operations similar to the Trimble pay dirt tool.

## 7. Results and findings of integrated system

The initial setup required for integrated system tools is less forgiving to skipping setup than with other software [41]. Once the planning and setup, see table 2, are determined, they are difficult to adjust later in the design process or during the construction phase. Key to setup is a strategy for construction methods, planning of work locations based on this strategy, and the definition of a Work Breakdown Structure (WBS). From this WBS a derived numerical code acts as a common classification providing an identification of the same operation, object and activity across multiple software tools, see Figure 6. Due to the correlation of location and WBS hierarchy, Location-based scheduling requires more attention to the WBS planning than the Critical Path Method (CPM) [42]. In Primavera Project Manager (P6) and Microsoft Project it is possible to start with no defined level of detail or location hierarchies. If mid-project, defining level of detail and/or locations becomes necessary or the current version is inadequate, adding these is not difficult. As a consequence the utilization of the WBS is traded off and so is also weaker.

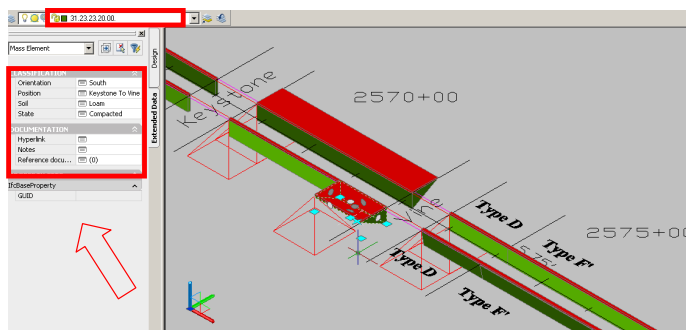


Figure 6. Product Model – the information model properties expanded to include: Level 1 – project, Level 2 – location (position), Level 3 – sub-location (orientation), Level 4 – discipline, Level 5 – Master schedule activity, Level 6 – resource, soil type and soil state, i.e., compacted, and Level 7 – object, backfill mass elements and grade slabs. The object classification codes are Construction Specification Institute (CSI) Work Breakdown Structure (WBS). Notice the layer naming embodies level 4 through level 7 while custom properties embody level 1 through 3 and expand on the level 6 resource properties.

<sup>16</sup> Dynaroad website accessed 1/25/2008 <http://www.dynaroad.fi/>.

The Tocoman, Vico, Sage-Timberline, RSMeans, AutoCAD and Navisworks software worked without any impossible problems. The operations CSI classification, description and unit of measure were imported from the Sage-Timberline estimate to the Construction Model Server (CMS) through Tocoman Express. Later the quantities were returned to the estimate through the same method. The Commercial Knowledgebase assemblies allowed associated operations to be selected as a group, therefore saving time. The cost estimate assemblies' technology could be leveraged more with the associated recipe-formulas remaining "live" therefore eliminating the need to redundantly assign recipe-formulas in the CMS. Once the associations between operations and objects were mapped in Tocoman ilink, any changes to the existing objects resulted in a revised takeoff as hypothesized in earlier research on integrated systems.

Through a wizard, the location-based schedule Control imported quantities, operation descriptions, unit of measure and locations from the Construction Model Server (CMS). The next jump from Control to Navisworks 4D required the use of either Primavera or Microsoft Project as these are the only two supported by the 2009 Navisworks version. Opening the object geometry is simple since the AutoCAD file format is interoperable with Navisworks.

These integrations from scope to time and then cost saved data entry labor and eliminated the risk of keystroke errors and transpositions. However, the production rates available in the RSMeans operation library could not be imported to the CMS, and so could not be imported to Control in one operation. As an alternative to manual keying the production rates were printed from Sage-Timberline to a spreadsheet and imported to Control. The key attribute allowing this data transfer was the CSI classification common to both data sets. It was not a smooth process, though if completed routinely the process may seem less out of place and a macro function could be written to automate the process.

Manually generating the estimate's list of operations from the *operation library* is necessary. The initial sample product model used a text-based description to differentiate objects. The RSMeans operation library uses a numeric coding system based on the 2004 50-divisions Construction Specifications Institute (CSI) Master Format work breakdown structure. Manually mapping from the text based description to MasterFormat codes is required to create a list of object to operation maps in 4D. This step is time

consuming and non-standardized, what object is associated with what operation is not clear. If the naming convention used for the object<sup>17</sup> is equal with the coding system used for the operation library, then an automated process of both selecting operations and mapping objects to these operations is provided in 4D software. A second model using classification for layer naming was developed. An issue with delineation format was then noticed in the 4D auto-linking function. Revit architecture 2009 includes a library of object MasterFormat and Unifomat [44] codes, though they have assigned the object classifier using a different numerical sequence than RSMean, therefore again preventing an exact match.

Integration of software was negated by version changes of the tools several times during the case study, requiring a new integration solution. Tocoman has been good at maintaining version compatibility between Architectural Desktop, Vico Control and the Tocoman Construction Model Server. An interesting secondary discovery is that software support located in an opposing time zone results in great turnaround. Tocoman would receive support requests from the days work with the integrated system and usually had a solution the next morning. The Tocoman software as configured for this application had a steep learning curve. An online server host<sup>18</sup> was used to simplify installation rather than a local install and this at first was a bit confusing. The concept of middleware seems simple in concept but in practice it takes time to acclimate to applying a half dozen software tools as one single tool. Once adjusted this is a more versatile system since any issues with a software is mitigated by swapping a comparable tool in its place.

## 8. Conclusion

In this case study the following five points have been shown: First the integrated scope-time-cost model system found that even the project 5-week lookahead schedule, considered to be the most accurate, contained coarse errors. Second, the manual take-off contained undiscovered double counts and omissions, thus embedded in the project documents, these were easily found with an integrated

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<sup>17</sup> Layer-style or some other exportable parameter.

<sup>18</sup> Citrix is a company that provides server space for a fee, thereby removing the need to maintain servers.

system. Third, the recorded level-of-detail could be increased to provide production rates specific to project locations and not general to the project itself. Fourth, facilitated by the integrated system, the location-based scheduling tool provided more accurate and precise dates and resource demand than available to the project team. And last, a uniform classification method across the system is important to allow project team members to correlate an item located in one aspect of the model with its representation in another.

If the first four results given above are high risk items for your market and the fifth result does not present an issue to implementation, then civil contractors should consider making a shift towards integrated model systems for the following reasons consistent with CIB integrated design solutions. An integrated model system helps project staff to focus on best practices in scheduling techniques and network analysis such as: defining where critical activities, activity float and total float reside, sequence of operations, access conditions, duration impacts, optimal crews, minimizing mobilizations, buffer, and feasibility. These result in a reduced emphasis on repetitive tasks such as: scope take-off, data entry and calculations for floats, start-finish dates, durations, total cost and delay. The integrated system promotes collaboration between non-concurrent team members through explicitly relaying information often contain implicitly in project documents.

To facilitate exchange of information across projects, research to define guidelines across for those project components usually and usually-not modeled is needed. From these guidelines it may be possible to define a library of recipe formulas to quantify unmodeled components from modeled components. These would reduce much of the redundant and error prone tasks involved in product model takeoff (17% repetitive tasks) and the project setup (7% repetitive tasks). If you are interested in a more detailed map of the system used for this case study, please contact the author.

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# Pinpointing and Classifying Challenges in an Integrated Design Process

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## Abstract

This paper focuses on the implementation of integrated design methods in construction projects and in particular the change that the integration development calls for in the construction process. By a qualitative case study of a project using the latest technology we analysed the current process and pointed out its problems and benefits. They were pinpointed into their context within the process and classified into categories: technology, process, and people. The paper describes a unique study method that helps to create a shared understanding of the process and its development within the participants of the research: the researchers as well as the interviewees. The aim of the paper is to help industry to understand why the implementation of integrated design solutions (IDS) is slow and to encourage the shift from mainly technological development to a systemic development of the construction process that considers the optimum of the whole life cycle and value chain.

**Keywords:** integrated design process, integrated construction project, process development, BIM

# 1. Introduction

The idea of enhancing the effectiveness and the value created in the construction with help of information and communication technology (ICT) and integrated data management has driven the research and development of design and management software. New technology and new design tools like building information modelling (BIM) have become available but their adoption into the industry has been somewhat slow. [10], [12], [2], [3], [19], [17].

Many researchers studying the implementation of BIM have concentrated on the interoperability of BIM technologies, e.g. [5], [16], [14]. More recently, researchers have identified that understanding and developing inter-organizational work practices is important to efficiently utilize BIM [18], [19], [8], [13]. However, there is still little knowledge on the interoperability of work and business practices that must complement technological interoperability to efficiently utilize BIM.

This paper is based on the results of the ECPIP (Engineering and Construction Project Information Platform) Finland research project. The project was started at a moment where the Finnish AECO industry saw that the new technologies for integrated design had reached maturity for industrial use and the industry was in great need for advanced ways of executing project business. The aim of the research was twofold: to develop the process so that the implementation of BIM would be possible in the best and most productive way, and to point out shortcomings in the software tools so that the tools could be in the future developed to be more usable and to better suit the working processes of the designers, consultants, and other actors (Figure 1). The research team consisted of researchers of both building ICT and business process development domain. Research scope was broad: the whole construction process and processes and point of views of all it's stakeholders.

In the paper we discuss the problems of process development and technology implementation in networked construction business. We present a list of challenges that were confronted in an example project using building information modeling (BIM) in inter-organisational operation and communication, and we present a classification of these challenges into categories. The detailed solutions to the problems are a matter of further research and development but the results act as foundations for the following work.

The aim of the paper is to help industry to understand why the implementation of IDS is slow. The studied research questions are: What are the challenges in

different process phases that the practitioners face when using advanced technology? Why does that happen? What true benefits there are present in the example case project? Are the predicted benefits experienced to realize?

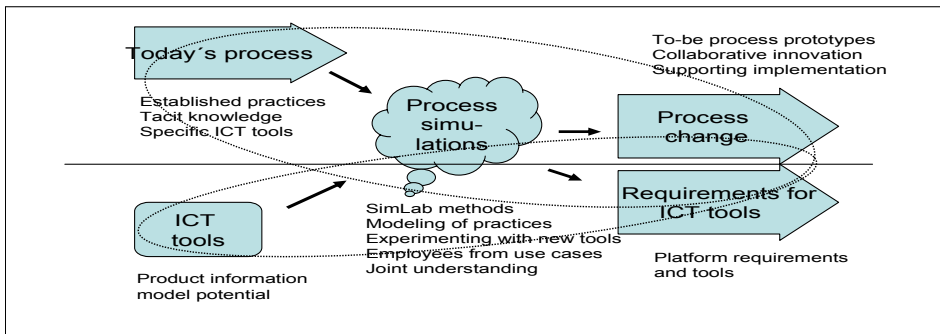


Figure 1. Describing the starting points, methods and targets of the research.

In this paper by integrated design it is meant using BIM and interoperable software solutions in construction projects in collaborative manner to assist tighter integration and better coordination and decision making within a networked team of stakeholders. During the research it was ever more emphasized that to really accomplish integrated design and construction a broader meaning than just using integrated tools should be used to integrated design.

## 2. Method

### 2.1 A case study

In order to understand the complex reality in the projects and to get into research questions we chose a case study method. [20]. This paper is based on a single case study of a project where IDS were applied in a very advanced way considering the time (completed 2006). The project involved some of the leading companies from the Finnish Real Estate and Construction Cluster (RECC). Involved in the research were also a couple of Finnish construction software developers.

The studied case was a public university building called Aurora 2 developed by a public building owner Senate Properties. The project is a one of a kind building where the architects were chosen by an architectural competition. The other designers were chosen according to their known pioneering skills and will

to develop further in using BIM and IDS. In Figure 2 the operations performed based on the building information models are presented compactly. The full description of the process flow can be found in the final report of the project [9].

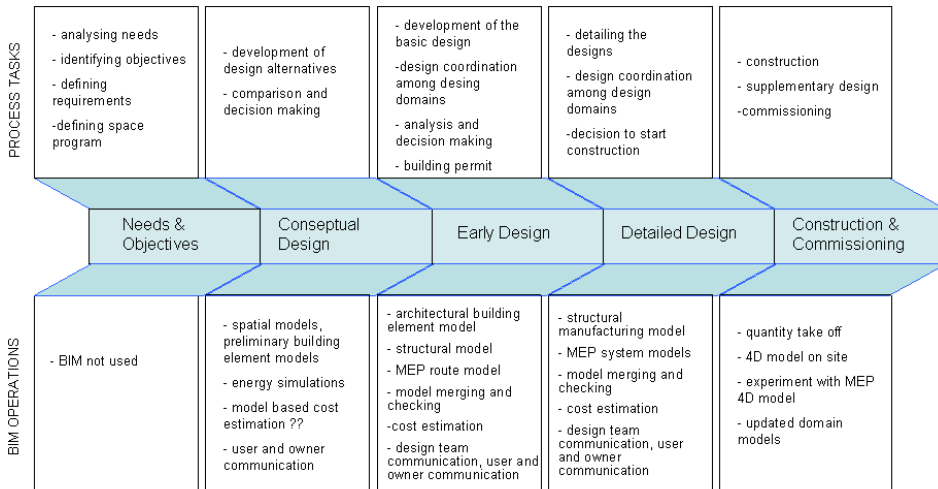


Figure 2. Case project phases and how the BIM was used in the project.

## 2.2 Research method

The research was qualitative research carried out as participative action research. We used a research method [15] that is a trade mark of Helsinki University of Technology Enterprise simulation laboratory Simlab. The SimLab<sup>(TM)</sup> method comprises of interviews, group discussion workshops called process simulations, in addition to background study of literature and case data.

In the case of developing business processes where many actors are involved simultaneously, the problem is not finding an optimal solution under certain conditions, but rather to find one solution that everybody could commit to as a basis for joint actions in a situation of change. Also in the case of complex process changes it is not always sure what the problems are in the first place. Therefore one crucial step in organizational development may be creating commitment towards what the joint problems are. Participative action research was chosen as a method for achieving this kind of goals, and was found out to be very effective in it.

Multiple data collection methods were used to increase the validity of the results. [21] The study consisted of the review of primary documentation of the

case project, single person and small group interviews with the project persons, and a whole day process simulation. The project documentation included project schedules, project development plan, minutes from meetings of the design team, and minutes from building site meetings. The project documentation was used to get an overall view to the construction project as well as retrieving important milestones and phases of the project, which could be used to help the interviewees to recall events within the project.

The interviews included both single and group interviews. All in all, 22 individuals representing the building owner, building user, architect, construction, MEP and electrical designers, contractor, project management consultant, and cost estimation consultant participated the interviews. When selecting the interviewees, the objective was to choose individuals who were the most involved in BIM or affected by it, and also to get a good representation of the whole project network. In addition to the interviews, a facilitated process workshop was held to further validate the results of the interviews. The process workshop was arranged as a facilitated group discussion [15] participated by 23 individuals, who had been involved in the project under study. In the workshop, the benefits and challenges related to BIM were discussed.

Before the process workshop the research team composed a visual process map of the studied project based on the interviews and project documents (Figure 3). Thus the gathered data was analysed and processed before the workshop to be able to focus on important points in the process. In order to get into the direction of future development, the challenges concerning the use of BIM faced in the project studied were pinpointed into the process map (Figure 3).

By this extension to the SimLab<sup>(TM)</sup> method the broad scope and complex nature of construction project were tackled. The discussion in the process workshop focused to the reasons and possible solutions of these challenges.

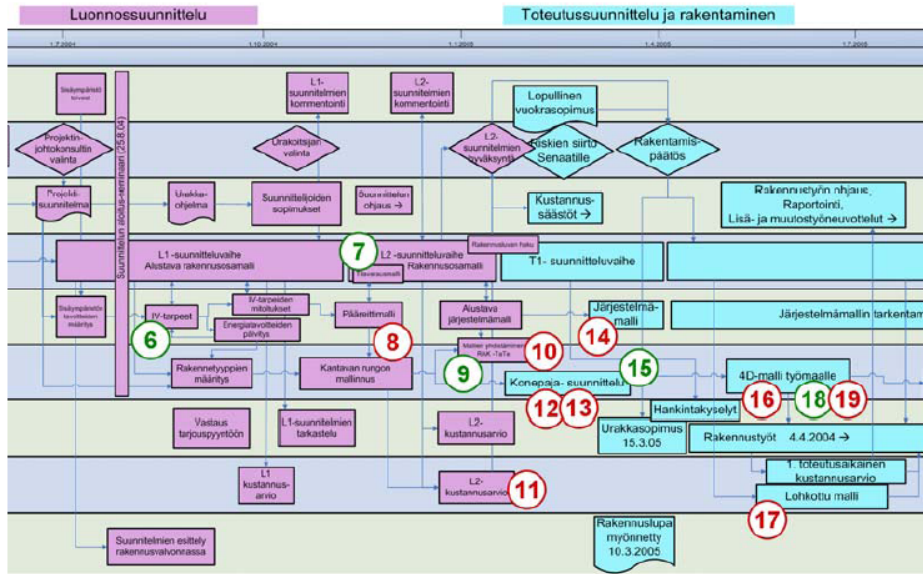


Figure 3. A process map describing the events, interactions and data flow in the project under study. The project stakeholders are listed along the rows and time runs to the right. The challenges (red) and benefits (green) of the technology numbered and pinpointed to the process context.

### 3. Results and industrial impact

The research generated great amounts of data about software shortcomings, problems in using software, problems in project coordination, skills and knowledge level of the project parties, lack of understanding of other parties aims and work processes etc. From the case data a paper has already been published about business process change in a project network from a point of view of business process development [11]. This paper concentrates on the development of design and construction process from the point of view of efficiently utilising BIM technology.

A crucial impact of the research was the involvement of the process actors themselves to the development. Because, in the end, the people carrying out the business must do the change, we suggest that the change is the faster the more the industry practitioners can be directly involved into and committed to the development. The used SimLab<sup>(TM)</sup> method [15] was found effective in creating mutual understanding of the ‘big picture’ of the process and reasons and needs for change on one’s own work. Many participants stated that the process

workshop was enlightening and contained also some surprises. Also the software companies were happy for the opportunity to follow the discussion and development process of the construction industry.

### **3.1 Problems and benefits in integrated design process**

As described already in the previous chapter within the method, we listed the faced problems and challenges and experienced benefits of the project and placed them into the process context and made them visible as numbered points also in the process map (Figure 3). We studied the work flow and modeled the process in as much detail as it ever was possible for such a broad scope that we had.

In the conceptual model of Hannus [7] companies' capabilities consist of information technology solutions, business processes and competencies. Comprehensive development should concern all these three elements [7]. Based on this division, we classified perceived problems and benefits into categories: Process, Technology and People. The problems and the categories are presented in Table 1.

Pinpointing the problems into process context and discussing them with the industry practitioners allowed us to see how the problems raise and what they are consisted of. After the thorough consideration most of the perceived problems were categorized into at least two of the chosen categories, sometimes even to them all. That shows the complex nature of the problems and hints that a trivial solution of just developing the technology or process or just training people will not be enough. Instead, the best results would be gained by developing all of these in parallel.

On the other hand, there are possible alternative approaches to solving the problems: for example technology can be developed to adopt to the process, process can be developed to adopt to the technology or people can be trained to work-arounds concerning to technology or process problem. Depending on the selected strategy the solutions would be for short or long term.



Table 1. Table of problems and their classification.

<b>Pinpointed benefits and problems with their aspects</b>		<b>Process</b>	<b>Technology</b>	<b>People</b>	<b>Benefit</b>
	<b>Conceptual Design phase</b>				
1	Visualisation of spatial group model for end user and client				X
2	Delays in modifications of spatial program and additions	X			
3	Energy simulations as basis for alternative solutions				X
4	Unusually early modelling of facades and window openings before actual design of facades	X	X	X	
5	Structural alternatives were not consulted in design of alternatives	X			
	<b>Early Design phase</b>				
6	Space specific MEP requirements on basis of space specific ambient condition goals				X
7	Architect's model for technical space reservation (for collision checking with MEP model)				X
8	Main MEP routes were modelled too late from structural designer's point of view	X	X	X	
9	Visual collision checking				X
10	Too many insignificant collisions reported in automatic collision checking		X	X	
11	Quantity take off problems	X	X		
	<b>Detailed design and construction phase</b>				
12	Penetrations were not possible to be communicated based on models		X		
13	During steel detailing structural designer had to make assumptions due to unavailability of some architectural details at the time	X			
14	MEP system model was available too late for structural design & detailing	X	X		
15	Integration of steel detailing and fabrication				X
16	Non-bearing steel structures were not modelled	X		X	
17	Phased model for quantity and cost calculations was isolated from design models	X	X		
18	4D structural frame model on site				X
19	4D structural frame model arrived too late for full utilization on site	X			
20	Quantities from MEP model were not utilized in procurement of mechanical equipment	X	X	X	
	<b>General problems</b>				
21	Team building, selection of designers and contractors	X			
22	Sharing and utilization of incomplete models / model views		X	X	
23	(Unsynchronized) Information in parallel sources	X	X		
24	IFC usability problems		X	X	
25	IFC translation problems		X		
26	Problems in model based costs calculations	X	X		

If one looks at the process map and pinpoints (Figure 3), one can see that there often is at a given point of the process one benefit and a couple of problem points. That can be interpreted so that there is a benefit considering the use of BIM at that phase of the construction, but the benefit is now not harvested fully because the raised problems cut it down. If we are able to solve these problems in systematic way that addresses typically multiple aspects, the predicted benefits can be reached.

## **3.2 Discussion**

Researchers argue that the modest productivity gains achieved from the increased investments in information technology, known as the productivity paradox, are due to neglecting process development when implementing new technologies [1], [4]. Our research is in line with this. Many of the problems listed were raised because the new technology was forced into the traditional process. For example, BIM makes it possible to integrate the work of the design team tighter than before. However, this change creates a need to better align the processes of different designers to be able to align their work in order to be able to coordinate the designs with model based methods. The situation in traditional process of different disciplines turned out not always to be that way (e.g. problems 4, 5, 8, 13, 14, 19 in Table 1).

To avoid just automating current activities, in general, processes should be designed first and after that the possibilities for supporting technology should be investigated [1]. However, technology may also open new opportunities for process design. By understanding and utilizing innovative ways of using technology, organizations can achieve breakthrough improvements [1], [6]. According to some examples in the case study (e.g. 4D MEP model and benefit 7, Table 1) these innovations are likely to rise bottom-up, so the people working in the projects should be motivated and encouraged to collaborate and experiment on the possibilities the technology may offer.

## **4. Conclusions**

The implementation of any large change is difficult, especially in a project-based environment such as the construction industry. The development of new processes and competencies requires the cumulative knowledge and experience from a number of sequential projects. There is a clear need to create mechanisms

that ensure the sharing of experiences between different projects, when more and more BIM projects are conducted. This would enable the creation of best practices that could be further standardized into improved guidelines, standardized processes, or both. This conclusion is also in line with [13]. Creating standards and guidelines, such as the BIM requirements by Senate Properties [23], Digital Construction of Denmark [25] and BIM Guide of GSA in the USA [24], is a way to help the utilization of BIM in construction processes, but also training is needed to aid practitioners in their work.

A further problem of cumulative learning is that the projects can be highly different: small scale, large scale, new building, renovation. This difficulty is present each time when a project differing from sequence of previous projects is started. Differences are also not just related to site or building itself, but also to stakeholders in project networks and at current state even individuals.

Utilizing BIM efficiently requires a tight integration of the project network to the project right from the beginning. It is especially beneficial to have the whole design team and the cost estimator participating early on, but also expertise from contractors might be needed. Hence, the owner needs to decide how to allocate these resources to the project. Apparently, this means inventing new bidding and contracting practices to get the participants involved early enough. In addition, the use of BIM needs to be acknowledged in contracts so that the responsibilities of different stakeholders are defined in the beginning of a project. More development emphasis should be focused to contractual issues.

Project management problems are perhaps one of the biggest barriers against reaching full benefits of information modelling enabled integrated design. According to the case studied, implementation of BIM creates challenges to the project management as there are no mechanisms, tools, or rules of thumb for selecting different BIM enabled options for improvements in communicating, analysing and coordinating designs in most beneficial and cost efficient way. Guidelines and education have been given for designers to create models and for building owners to see their advantages of modelling but the project managers have been left alone.

Although listings about benefits of BIM or IDS have been available for quite a while, and according to the study at least some of these benefits were real, the talk about benefits seems to be on a general level or on a project level. The individual benefits seem still to be confusing both on company level and on individual level. It should be emphasized that they are these individual people and companies who do the business. The benefits should be allocated and

disseminated to their level to make them motivated to make efforts to apply new technology and develop their work and skills.

Based on this research we state that the slow application of BIM and minor development and changes in construction process has followed from solving the detected problems one-sidedly by only developing technology, process or education of people alone without seeing that the technological issues, work and business process issues, knowledge, and human factors are interconnected in the bottleneck points. The thorough analysis of the questions why has been neglected or results of these analyses have not been transferred from the research scene to the industry.

In light of the previous paragraph the kind of mechanisms like the process development workshops of this research are needed and should be encouraged to increase the mutual understanding of the process and its problems and to raise collective will to change the current practices. We suggest that the change is the faster the more the industry practitioners can be directly involved into and committed to the development.

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# Intensive Collaboration between Architects and Construction Engineers in the Japanese Construction Industry

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## Abstract

This paper discusses the collaboration practice between architects and construction engineers in the Japanese construction industry. Contracts and management of construction projects in Japan are quite different from other countries, especially for big projects, in which many participants are expected to make their own decisions to cope with other participants. General contractors usually have great responsibilities for detailing plans and coordinating the drawings to realize the architects' design. General contractors also make construction plans before and while constructing a building. In the paper, the author, who belongs to one of the biggest general contractors and develops software tools, reports some of the past and current collaboration systems and discusses some issues. Then he proposes some ideas to translate architects' design to construction plans using construction planning knowledge, which will expedite use of information technology for collaboration in the construction industry.

**Keywords:** coordination, collaboration, construction engineering, construction planning, construction knowledge, building information modeling

# 1. Introduction

## 1.1 Background

Since computer aided design (CAD) was practically introduced in the architecture, engineering and construction (AEC) industry about 20 years ago, designers and construction engineers continuously challenged to apply the new technology to their real projects. Information processing tools have become necessary today and it is almost impossible to integrate project information without the information and communication technology (ICT) environment. The idea of Integrated Design Solutions (IDS) is also a part of the mainstream. However, most design tools, such as 3D CAD and building information modeling (BIM), are supposed for architectural use. There are some sophisticated CAD systems but they need more improvement for construction activities.

This may be correct only in the Japanese construction industry because the architects in Japan don't necessarily design buildings in detail before the construction planning phase. Construction engineers and architects solve the problems left in the design phase through collaboration in the construction planning and construction phases. Collaboration and integration are essential factors of the Japanese industry.

## 1.2 About the paper

This paper is written from a construction engineering viewpoint. A premise that the readers should be aware of is that the Japanese big general contractors, such as Shimizu, are not the same as contractors in other countries. The Japanese general contractors are more like composite enterprises having architects, structural engineers, mechanical engineers, construction engineers, researchers, and many other experts including IT engineers.

As for the relationship to the Integrated Design Solutions (IDS) visions, this paper introduces collaboration practice between architects and construction engineers in Japan and discusses how the IT tools are used to support it. Collaboration in the construction planning phase is very important to execute construction. The paper reports some systems for construction planning phase.

The features of the Japanese AEC industry is described in the first half of the paper. Relationship between architects and construction engineers, as well as past and current technologies used as IDS tools are reported. The other half



focuses on some software systems that are developed for the construction planning, such as a construction simulation system, a structural analysis system for under-construction structures, and a document search engine with BIM. Lastly, it discusses the reasons why the Japanese general contractors develop these kinds of system before closing the paper.

## **2. The features of the Japanese AEC industry**

### **2.1 The industry**

In Japan, construction engineers from general contractors are strongly connected to architects. Construction engineers support architects, and architects concentrate on architectural design. Legally, the architect has responsibility for his/her plans and quality. But the reality is the construction engineer is expected, and usually is responsible, to find mistakes that may result in serious problems. Therefore, construction engineers redraw detailed drawings to coordinate architectural, structural and mechanical drawings. When they find mistakes or inconsistencies, they send the architect requests for information (RFIs) to solve the problems. The construction engineers often give some proposals for architects to solve the problems easily.

There are about 520,000 licensed construction companies including subcontractors. Most of them are family businesses, but the five biggest companies, so-called the Big Five, each has about 10,000 employees. The big companies have any kind of engineers; architects, structural engineers, mechanical engineers, construction engineers, estimators, etc. They also have subsidiaries to lease cranes, temporary facilities, and even computers. Each Big Five also has a research institute, which promotes fundamental researches and supports job sites and any other divisions such as sales. The Japanese big general contractors offer comprehensive solutions to their clients.

Most contracts in Japan are categorized into two types; design-bid-build and design-build. But they are not exactly the same as in other countries. In any case, the general contractors guarantee the delivery date and price. Hence they need to make enormous efforts to save time and money. This is the biggest incentive to utilize new technology, or develop any if necessary.

Some technology development projects are very big. Technology development is sometimes done by groups of architects, construction engineers, and leasing companies or fabricators in some cases. The SMART (Shimizu Manufacturing

system by Advanced Robotics Technology) system (Figure 1) was one of the biggest projects. They also make concepts to show their possibilities. Although the *Green Float*, the gigantic oceanic artificial floating island where 1 million people live, seems not realistic at the moment, they show their ability to create new technology with the future images.

## 2.2 Collaboration between architects and construction engineers

General contractors are expected to find mistakes and inconsistencies hiding a bunch of design documents. If a general contractor overlooks some critical mistakes, they have to halt the operation of the job site until the architect solves the problems and issues change orders. And the bill probably goes to the general contractor. Therefore general contractors pay a lot of attention to consistency in detail.

One of the conventional tools is the “coordination drawing”. Architectural design, structural design, and mechanical design are usually done by different designers. These designers are not always intercommunicated that coordination is necessary afterwards. With coordination drawings, which general contractors make, construction engineers detect physical interferences, difficult connections, and many other undesirable things. When the coordination drawings are finally completed, subcontractors and fabricators design their products such as steel components, rebar, and formwork.

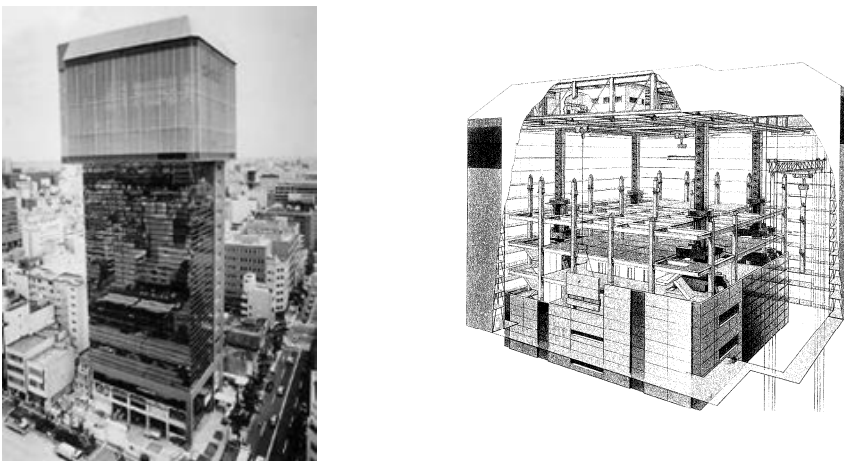


Figure 1. SMART System – computer integrated construction.

The coordination drawing is firstly used in 1980s and is widespread now. When the coordination drawing was becoming popular, an argument was who should make coordination drawings. Construction engineers said designers were responsible for consistency of their drawings. On the other hand, the Japanese Institute of Architects insisted coordination is a first process of construction planning. And recently, the design documentation sometimes requires the general contractors to make coordination drawings in advance of construction. This sounds interesting. The architect handed over some responsibilities to the construction engineers. Anyway, the coordination drawing is a collaborative interface between architectural design and more realistic detailed one.

### **3. Past and current attempts for integration**

#### **3.1 Computer integrated construction**

In the late 80s, the Japanese economy was growing fast. They invested in real estate, and the construction cost was going up. The construction industry was so busy that the labor was short. The labor cost was getting higher and higher. They presumed the labor cost would be much higher.

Big general contractors, who had ability to develop new technology, started to develop automated construction systems to use fewer workers. They made a big factory on top of a constructing building. Such a system included a roof, cranes or lifts, and assembly machinery. They were big construction systems integrated with robotics, prefabrication, information technology, and management systems [8]. (See Figure 1.)

Such a big sophisticated machinery system works if the labor cost is very high and there is room for machinery to be the replacement of the labor. After the bubble economy burst and the labor cost suddenly dropped, they stopped development of the automated construction systems. However, it was a good experience for the construction industry. The general contractors proved their ability to integrate technology and expertise.

#### **3.2 4D systems**

The 4D CAD is now very popular, and some software tools enable to make 4D models easily. The development of 4D software in Shimizu Corporation started

around 1991 [5]. The basic idea is the same as what we have today. The software linked 3D components and tasks to play the construction processes over time.

From the construction standpoint, there are some problems. One is based on the fundamental policy of the Japanese construction management. Project management software tools, such as Microsoft Project and Primavera, keep relationship between tasks, and when a task is delayed, its following tasks are also delayed. However, the Japanese construction contract doesn't usually allow postponing the delivery date. The construction period is not a target of simulation. Consequently, the 4D system was used only for demonstrating processes in animation.

### **3.3 On-site practice**

On the contrary to the unsuccessful challenges, the basic office software prevails at job sites to share information. Everyone got used to e-mail, a word processor and a spreadsheet. 2D CAD system is now very common. Most draftspersons use 2D CAD system, and construction engineers by themselves print them according to the site schedule to plan the following activities. Many job sites started to use application service providers to share electronic files among the project participants. Job sites sometimes have to report their progress via the web sites. The accounting system helps the managers concentrate on the job site management. The head office supervises job sites through their Intranet web site.

The Japanese construction job sites have a daily meeting in the afternoon. In the meeting, foremen report today's progress and reschedule tomorrow's jobs. The foremen then talk with the construction engineers and decide who has the priority to use resources such as cranes for the following activities. To expedite the meeting, they use a meeting system with a handwriting input device.

### **3.4 3D coordination**

There are some convenient software packages to assist 3D coordination. It became much easier to overlay 3D data to detect interferences. Since architects began to design curved structures, 3D coordination tools are necessary.

The technology development division developed a series of three-dimensionalization software by tracing 2D drawings manually and defining the component sections. After three-dimensionalization of architectural, structural, and mechanical drawings, they look through the model and find interferences.

The purpose of the system is to detect inconsistencies, which may hide behind the conventional 2D contract drawings. Tracing 2D drawings means checking the drawings as they were handed to the general contractor. Of course, 3D viewers such as Autodesk NavisWorks work well if the design is completed in 3D. But it is not likely to happen.

Because the 3D coordination tools are in-house software, the developers can add new functions when required by construction engineers. For example, they added functionality for quantity takeoff and animation. These functions are usually requested from construction needs. This is a good visible platform, on which designers and construction engineers discuss what and how to build a structure.

## **4. Tools for construction engineering**

BIM is getting popularity recently, especially since some successful users reported its values. The word 'BIM' spread out in the industry in 2008. However, construction engineers still question its practical benefit. This chapter discusses the reason and proposes some ideas for construction engineers to take advantage of the new technology.

### **4.1 Lack of viewpoints of construction engineering**

The major reason why construction engineers question BIM is that the viewpoints of designers and construction engineers are not the same. In most successful cases, they used BIM in the early phases such as schematic design. Some refer to usage of BIM for construction, but it is much more difficult to take advantage of BIM in the construction planning and documentation phase. It is not only because they have different level of detail, but also because they have different languages. The unit of components for construction is not the same as the unit for design. For example, a column in the architectural model is usually recognized as a rectangular prism between two floor levels. But, in reality, the length of a column depends on the structural system, the construction method, and some transport constraints. A steel column is positioned 1 meter above the floor level, and the length may be 2 or 3-storey long. It results in different quantity takeoffs.

Another serious problem is that it is impossible to tell what is determined and what is not. This type of problems occurs in the Japanese construction

environment. As mentioned before, architectural plans are not completed at handing over the drawings to general contractors. Therefore, general contractors interpret architects' drawings to receive their intension. Because the drawings are not complete, construction engineers have to judge the priority of information expressed in the drawings.

If there is a door on a wall (Figure 2), can you tell which of the following statements is correct? The door must be at the center of the wall for an aesthetic reason? Or the door must be 1 meter away from the side wall to avoid the door edge clashing it. If the draftsman draws it on a 2D paper drawing, he/she can express the difference by adding the measurement. The complete BIM data provide rich information, but assuming the model is not complete, it is very difficult to get the designer's ideas correctly.

The last thing is resources. Construction planning requires many types of resource; labor, machinery, temporary facilities, cost, time, and so on. Some types can be made visibly if they are really needed. Tower cranes and temporary jobsite offices may be added to animate the construction processes over time. However, labor, which contains productivity and cost, is not usually modeled in the design phase. The Japanese construction engineers always pay attention to time and cost because they guarantee the delivery date and price. The BIM and other tools need more improvement on construction engineering.

## **4.2 SPLIT system**

The SPLIT system is a computer program that enables what-if simulation in a short period of time for construction planning [4]. The 4D is supposed to be a construction simulation tool in many cases, but actually the 4D is just a result after building components and construction activities are defined. What construction engineers really need is the function to define building components and construction activities, which can be called a construction method. Construction engineers have many options to realize a building. The judgment is done by the project time and cost. Therefore, they need a simulation tool that returns time and cost when they assume a construction method.

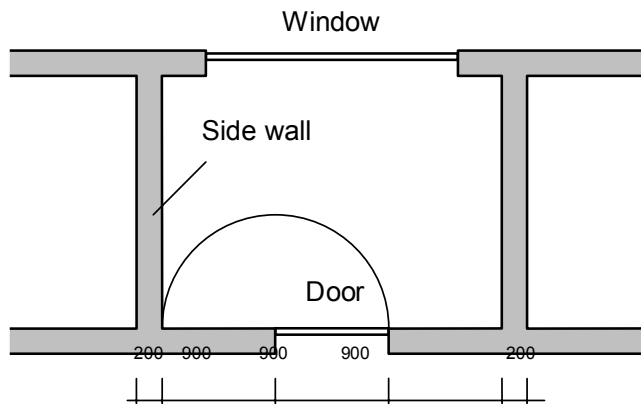
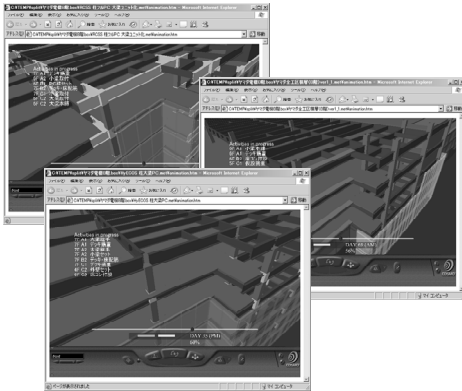


Figure 2. Architect's intension.

We have to define what is input and what is output to execute what-if simulation. Schedule is not a premise, but a result. Cost is calculated according to the schedule because cost of labor, machinery, and temporary facility depends on the length of construction. Production rate is used to calculate duration of activities. Production rate is usually collected beforehand at the past projects. Hence, the production rate is an input. The sequence of activities depends on the construction method. As a result, construction method is input, which defines activities and productivity. The building plan is an outcome of the design phase, that is, an input for construction planning. However, the building components may depend on construction methods. The building plan that is not related to construction method is the only input from the design drawings. After all, the input data for the system are schematic building plans and construction methods.

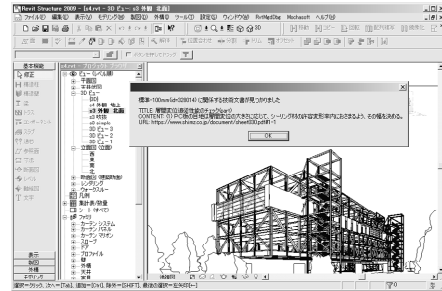
The SPLIT system accepts simple 3D data as a schematic building plan, and many construction methods to provide sequence and productivity of the activities. The system calculates duration of activities using production rates, summarize them to make a whole schedule, and accordingly calculate cost of labor, machinery and temporary facilities. The idea is quite similar to the human way to simulate a construction project.

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These 3 different construction models are automatically generated from the same 3D data.

Figure 3. SPLIT system.



The search engine found a relevant document and popped up a message box noticing the title, specification, URL, and other information.

Figure 4. Search engine using BIM.

### 4.3 Structural analysis during construction

Stress of a structure during construction is analyzed in bridge construction projects, but it is not common for building construction. But in some cases, the structures are not always stable or safe without adequate stiffeners or shoring under construction. To optimize such additional supporting elements, structural analysis during construction is important. [2].

To analyze structure step by step, construction engineers make half-done structure data and put them into an analysis program to detect elements in risks. To do this, construction method definition and accordingly a schedule of erection are needed to create half-done data of each step.

### 4.4 Search engine using BIM

Big companies have technical database as well as project records. It is very difficult to retrieve complete documents relevant to a given project. If the technical documents are written in some forms that enable computers to read and process, the search engine can be more sophisticated. An idea is that a technical document is written in a tree form, each node of which has contents and conditions. The conditions define that in what conditions the node of documents should be referred. Once the conditions are added, documents are automatically retrieved from the database matching BIM data. Figure 4 is a prototype system



of the search engine, implemented on Autodesk Revit. After a user makes a model and invokes a search program, the program scans the model and search for the parts of documents that are relevant to the model.

## **5. Discussions**

### **5.1 Why do the Japanese general contractors develop technologies?**

The Japanese general contractors usually guarantee the price at bidding. Therefore they need to save money to maximize their profit. Technology development means improvement of production efficiency, and accordingly raises their profit. They have improved production efficiency for long time by changing methods and developing tools. It seems that the room for the further improvement is getting smaller. Hardware technologies have been developed so far. The breakthrough will be software approaches. The information and communication technology contributes to management and decision making for construction processes. Construction engineers expect ICT's possibilities.

The Japanese general contractors are not only contractors but also total solution providers. They present many types of services to their clients. They believe that creating new value for clients is making profit in the future. The Japanese general contractors are always competing in proposals to clients and the society.

In the Japanese academy, the research on construction engineering is not so active. Universities usually focus on theory. Professors and students are not necessarily aware of construction in reality. They don't know much about what should be studied or developed for the future construction industry. On the other hand, private companies have the issues that they have to solve as soon as possible. The research institutes and technology departments of general contractors are always working on problems in hand. They have needs and some budget to solve them.

### **5.2 Does it work in other countries?**

The Japanese general contractors seem unique. In the Western countries, it is more popular to make a contract that restricts general contractors' arbitrary

decision making. General contractors are supposed to construct a building exactly as it is described in the design documents and specifications.

However, the situation seems to be changing. Big projects are complicated and need a lot of professional participants. Some clients prefer the design-build contract with guaranteed maximum price. In these cases, communication becomes more important. The Japanese way of managing construction projects will contribute to such projects.

### **5.3 How to achieve the IDS visions**

The first problem to solve is to distinguish design and construction responsibilities. In Japan, collaborative work processes are inevitably done by architects and construction engineers. However, the processes are not always well-managed. There is no fine line between the design and construction phases in the Japanese construction processes. In such environments, it is difficult to make decisions in the early stage of a construction project.

BIM tools for construction and construction planning should be taken into account. Currently, BIM and traditional 3D-CAD systems are often used in the design phase. Construction engineers and detailers do not necessarily use these systems to do their own jobs. From the practical viewpoint, information in the BIM data is not directly transferred to construction planning.

Both of these problems are very difficult to solve. The practitioners have long discussed the first problem and found that it was difficult to change the custom. The second problem may be solved in the future. The Japanese general contractors are now looking for effective way to apply new technologies for construction.

## **6. Conclusions**

In the Japanese construction industry, architects and construction engineers keep close relationship. General contractors have incentive and responsibility to rationalize construction processes. This is the reason why the Japanese general contractors make efforts to develop new technologies to save time and cost. To realize it, ICT recently plays a bigger role in operating construction projects.

Construction engineers expect BIM to be a fundamental environment to simulate a project and to make decisions for it. The most important issue is that the current BIM is not supposed for construction phases. It needs functions for construction planning and management. In this paper, I proposed some new

software tools; a system to simulate multiple construction methods, a structural analysis system during construction, and a BIM-based search engine of technical documents. They are implemented from the viewpoint of construction management.

I discussed the reason why the general contractors in Japan lead technology development. The contract and business custom are quite different from other countries. Once they make a contract, delivery date and cost are under the general contractor's control. They manage many types of resource not to exceed the guaranteed date and price.

Finally, the Japanese companies place importance on customer relationship. General contractors as well propose new ideas for customers' benefits. Technology development is necessary to keep up with customers' and society's needs. The companies hire many experts to enhance their skill and possibilities.

This paper described the Japanese construction industry. It may or may not be true for other countries, but if they want to form an intensive collaboration team, the Japanese architects and general contractors' experiences will help.

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# **Exchange of Relevant Information in BIM-objects Defined by the Life Cycle Information Model (LIM)**

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## **Abstract**

This paper focuses on the importance of exchanging relevant and reliable information in BIM (building information model) based software. The concept “Life cycle Information Model” (LIM) is a framework for information relevant to specified phases of the building’s life cycle, and is proposed in this paper. Software model objects / object libraries are proposed as the container for standardized professional information. Model objects with information are suggested to be named “BIM-objects”. The AEC-industry should take the initiative for achieving a broad consensus about the selections of information that should be standardized in the BIM-objects. A “BIM-object standard” can be based on the LIM framework. Content defined in BIM-objects can be included in development of IDM’s (Information Delivery Manual) within different professional purposes. Correct use of BIM-objects during the building projects life cycle should be supported by BIM manuals. Improved exchange of information in BIM based software will support use of integrated design solutions, (IDS).

**Keywords:** information exchange, standardization, BIM objects, BIM

## **1. Introduction – Problems addressed**

The exchange of relevant information in the AEC-industry (architects, engineers, contractors, operators and owners) is extensive. Use of IDS (integrated design solution) based building design processes, which normally is based on a team of different actors and disciplines performing together, is increasing the demand for exchange of *relevant* information at the right time.

The development of BIM (Building Information Model) based software for the transfer of information represents a change from the traditional design process. BIM integrates geometrical representation, which is directly visible, and information, which is not directly visible. In this paper focus is set on the information content, or lack of content in the model objects / object libraries, in this paper named BIM-objects. Today we observe that BIM generally contains very little relevant professional information, e.g. thermal transmittance, acoustics rating and/or fire rating. The variation between different software programs is large. The documentation of exported what information is usually absent, even if the software is marketed as BIM software, or profiled IFC-certified. A major challenge is therefore to remove the “black-box” information exchange which depends on the software developers’ priority, and instead move to a transparent information exchange where the user knows exactly what information is exported.

Standardization of professional information will have a positive influence in information exchange in the AEC-industry, and for increased use ICT tools in IDS. The AEC-industry should take initiative to develop a standard which set up the demands of reliable and valid professional information in BIM-objects.

## **2. Use of information in the AEC-industry**

### **2.1 Tradition for utilization of new information**

Because of the increasing complexity of buildings and the design process, the demand for information exchange in the AEC industry is increasing. Information exchange in previous times was based on a very small amount of formal exchange, and was more about the presence of the master-builder and his commands. There has been a development from the self-builder to the master-builder, and then to the period when the architects became a separate profession.

The AEC-industry of today is very fragmented, which reflects increased challenges in exchange of information.

Information exchange is today separated and handled by separate systems; drawings, technical documentation, procurement, legal documentation etc. A question is therefore if the ability to deliver information at the right time, in the right place and in the right quantity and quality has followed up. BIM is sometimes presented as the solution to the information flow. It is doubtful if this ICT technology itself will provide the relevant professional information. However, BIM – especially based on the IFC-format (ISO/PAS 16739:2005) is expected to have an impact on technical interoperability.

When we try to utilize information in BIM based systems, we should take into account the challenge of defining the relevant information. It is important that the AEC-industry control this process, not the software developers, even if it may be hard to reach consensus. A main purpose with information is to support the decision made in the design process. The possibility to carry through an interactive design process with multiple revisions is a central aspect of IDS projects. More *relevant* information should enable the possibility to make better decisions in an earlier phase than those made traditionally. In this way improved information exchange can be expected to have a high pay-off.

## 2.2 Information is a relation

The traditional sequence of: data – information – knowledge – wisdom, gives information a rank, but no definition. Bateson (1979) defines information as “a difference that makes a difference”, hence “*information is a relation*”. This perspective starts by defining what action you want to perform (method to use) – and then relates this to the information which is demanded. The result is a distillation of the *relevant* information. According to Sowa (2000) the information exchange must be as clear and transparent as possible to avoid struggling with the “Knowledge soup” vagueness, uncertainty, randomness and ignorance.

The common tendency to regard more information as better is well documented in studies by James G. March (1994) who finds that only selective information is used in practice. Managers spend much time in collecting information that is not used in the actual decision. An indication of the support for this view is that if all information is error free, it can be exported from a software application and then imported into another software application; the problems with information exchange are solved. The “quality” of information is

therefore context dependent. Some solutions for finding the relevant information are suggested in the next chapter.

### 2.3 Information exchange in IDS

Collaboration and exchange of information using IDS integrating different domains is much more demanding compared to the same within a single domain, such as structural engineering. The iterative process of information exchange to support goal review and decisions on the present information is illustrated in Figure 1.

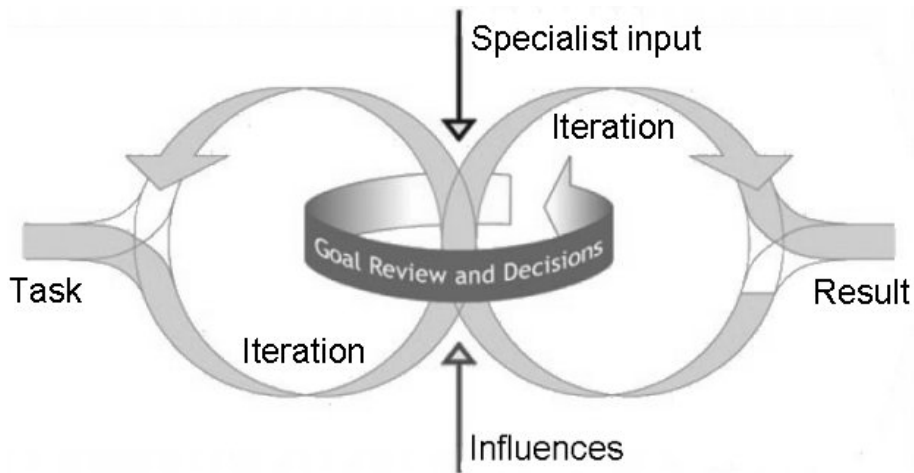


Figure 1. Iterations as a provider for problem- orientated analyses of design alternatives and optimisation (Löhnert et al. 2003).

The iterative process should contain relevant information and not only geometry (even if is in 3D and can be realistic visualised) for support understanding and make decisions. Today this is not is general principle possible, and the quality is depended on the software and use of it. Our suggested solution with BIM-objects will improve the information exchange process and as an extension lead to improvement of some parts of integrated design solutions.



## 2.4 Information Delivery Manual – IDM

The “IDM standard” is publicly available as ISO/DIS 29481. This is a “framework” standard describing a method for developing what information is required to whom and when in which form. It consists of three parts:

- *Process maps* (PM) is a description of the information flow and business processes. Because of the fragmented structure in the AECO-industry, this will itself be very demonstrative. This part is independent of software.
- *Exchange requirement* (ER) is documenting the professional relevant information needed. (it is this part we describe as professional information in this paper). This part is independent of software.
- *Functional parts* is mapping of ER against a technical schema (e.g. IFC 2x4).

The IFC schema (2x3/2x4) has achieved broad interest in several actors of the AECO-industry. Because of some limitation in the IFC schema this part has a cardinal focus. First of all – it is the information that is the major subject, and one must develop ICT systems according to this. One can sometimes get the impression that looking for IFC schema limitations is more important than finding the demand of information exchange among the actors.

Development of IDM’s within a defined topic and purpose (calculation method, use of a particular standard etc.) is recommended as a way of getting transparency in the information exchange. The professional information (ER) should be defined by selecting BIM-objects according to the Life cycle Information Model framework (Table 2) rather than being defined as single units. This will probably reduce time in the development of IDM’s, lower the level for participation, motivate for reuse and remodelling of IDM’s, making them more flexible over time.

## 2.5 BIM-manuals

BIM-manuals can be used as mandatory guidelines for correct handling of information in a project. The development of BIM-manuals is in rapid progress. At international standardization level has the ISO/TC 59/SC 13 has started the project ISO/TS 12911 Framework for BIM manuals (ISO, 2008). Governmental builders as GSA in USA (GSA, 2008), Senate Properties in Finland (Senate,

2007) and Statsbygg in Norway (Statsbygg, 2009) has developed their own BIM-manuals.

The BIM manuals can be developed to software related manuals, explaining how to set up the software (e.g. object libraries) and where to enter specific information. Use of defined BIM-objects and management of their information through the life cycle can be specified in BIM manuals.

### 3. Proposed solutions and frameworks

#### 3.1 New – need – nice – noise – nonsense

The common tendency to regard more information as better can lead to information obesity and more problems in practical use. The information that is needed for one purpose in an early phase can for other purposes and phases is directly misleading. To distinguish between different types of information we use the terms; New, Need, Nice, Noise and Nonsense as illustrated in Table 1.

Table 1. Types of information.

Information	Demands for use	Example
<b>New</b>	New methods	Use of environmental information in the pre-project phase. Most methods today are developed for detailed analysis in the construction phase.
<b>Need</b>	Defined methods, standards	Can be applied today and identified with relation to defined methods and standards. Can be too inflexible for changed used due to no “overhead”.
<b>Nice</b>	No defined methods (– most are good)	An extension “need” without defined purpose. Can give some flexibility for new combinations, but “nearly fit” can sometimes be hard to discover.
<b>Noise</b>	No defined methods (– all are good)	Undefined methods (“faulty goods”) Information can seem to fit. Can be counterproductive.
<b>Nonsense</b>	Nothing defined at all (– but can “fit all”)	Difficult to handle the model due to misleading info and large files. Definitely counterproductive.

- *New*: Information that has to be developed / determinate. Use of environmental information in the pre-project phase, stage 0–3 in Table 2, is an area that lacks proper information and methods. Use of EPD, environmental product declarations, has information in defined public databases (EPD, 2009). The information value is determined by ISO standards; ISO14025:2006 and ISO/FDIS 21930 and is primarily used for procurement in the pre-construction phase, stage 6 in Table 2.
- *Need*: This is information that is defined by its relation to specified methods, calculations, algorithms, analysis etc. Can be considered as the “relevant information”.
- *Nice*: This result in a larger amount of information than necessary because the methods are not defined, but only assumed. When used on a specific method it can be seen that information is still missing. Another aspect is that this motivates the use of approximate values, resulting in unreliable results.
- *Noise*: Too much irrelevant information in combination with some relevant information makes the analyses uncertain.
- *Nonsense*: Irrelevant information and duplicates, e.g. detailed and extensive information making wrong results and lead to computer slow down or fail.

Information content in both “New” and “Need” can be implemented in standards. This demands involvement from the AEC-industry.

### **3.2 The Life cycle Information Model – LIM**

The proposed framework “Life cycle Information Model” (LIM) is to be used for development of context related BIM-objects. The Life cycle Information Model uses 4 major phases for defining professional content:

- *Pre-project phase* (4 stages)
- *Pre-construction phase* (3 stages)
- *Construction phase* (3 stages)
- *Post-construction phase* (2 stages).

The information focuses on the object – building part or building function – and information is related to the building’s life cycle and the decisions relevant for specific stages. The LIM framework can be used as a template for developing standards for specification of professional information which model objects /

object libraries must contain to be defined as “BIM-objects”. The phases used in LIM correspond to the phases defined in ISO 22263:2008 “Framework for management of project information”, see table 2 for example of information. In addition to information about performance and status, can craftsmanship or other properties be included. The recommendation is to keep the list of mandatory properties as small as possible due to development cost and liability of information.

Table 2. Life cycle Information Model – LIM.

Stage phase	Stage number	Stage name	Description of information elements	Example /Case “Wall”
<b>Pre-project phase</b>				
Inception	0	Portfolio requirements	Establish the need for a project to satisfy the clients business requirement	<ul style="list-style-type: none"> <li>- Superior demands</li> <li>- Total geometry</li> <li>- Thickness of load-bearing core</li> <li>- Door type: single, double, swing</li> </ul>
Brief	1	Conception of need	Identify potential solutions to the need and plan for feasibility	<ul style="list-style-type: none"> <li>- Location: Internal / external</li> </ul>
	2	Outline feasibility	Examine the feasibility of options presented in phase 1 and decide which of these should be considered for substantive feasibility	<ul style="list-style-type: none"> <li>- Performance indicators, optional: thermal transmittance, acoustics rating and fire rating</li> </ul>
	3	Substantive feasibility	Gain financial approval	
<b>Pre-Construction phase</b>				
Design	4	Outline conceptual design	Identify major design elements based on the options presented	<ul style="list-style-type: none"> <li>- All layers in wall identified. (can interact with IFD)</li> </ul>
	5	Full conceptual design	Conceptual design and all deliverables ready for detailed planning approval	<ul style="list-style-type: none"> <li>- Performance indicators, mandatory: thermal transmittance, acoustics rating and fire rating</li> </ul>
	6	Coordinated design (and procurement)	Fix all major design elements to allow the project to proceed. Gain full financial approval for the project	<ul style="list-style-type: none"> <li>- Status, optional: Suggested / decided / built / replaced</li> </ul>

*To be continued...*

Table 2. Life cycle Information Model – LIM (continued).

Stage phase	Stage number	Stage name	Description of information elements	Example /Case “Wall”
<b>Construction phase</b>				
Production	7	Production Information	Finalize all major deliverables and proceed to construction.	- Status, mandatory: Suggested / decided / built / replaced
	8	Construction	Produce a product that satisfies all client requirements. Handover the building as planned.	- Reference to detail drawings and assembling descriptions
<b>Post-construction phase</b>				
Maintenance	9	Operation and maintenance	Operate and maintain the product effectively and efficiently.	- “As-built model” - Maintenance demand and interval: Last maintenance Next maintenance
Demolition	10	Disposal	Decommission, dismantle and dispose of the components of the project and the project itself according to environmental and health/safety rules	-Need for special actions: e.g. toxic components

In contradiction to the “enrichment of the model” where more information is synonymous with better – leading to information obesity, the LIM focuses on the relevance of information relation to purpose.

The LIM framework defines the mandatory information for a defined type of object for a defined stage in the building process according to Table 2. Case: Wall is used as object type and pre-construction as phase, stage 4–6 in Table 2, stage, this BIM-object should contain information about: total thickness, core thickness, and performance related information; thermal transmittance, acoustics rating and fire rating. This fundamental construction information is not present in most of available BIM software today. For post-construction, stage 9–10 in Table 2, the same BIM-object should have information about maintenance interval and other FM related information. The BIM-object can contain information for one or more stages.

*Status* – In design processes, and especially in IDS, it is important to know the formal status of the object. The design process is a decision process and knowing the status for all objects would be useful. The proposed status system has four categories:

- 1) *Proposed*: component, element, building part etc. This will be the native BIM-object status.
- 2) *Decided*; and should not be changed, e.g. placement of columns (but exact material, reinforcement does not need to).
- 3) *Built* indicates that the “object” has been assembled on the construction site
- 4) *Replaced* shows especially “historic” information, and will be useful in maintaining “as-built” models.

The LIM framework for BIM-object information should be developed by a standardization organization (as for instance ISO) or by a professional alliance. It is also possible to integrate LIM and IFD (International Framework for Dictionaries, ISO 12006-3:2007) in development of IDM’s or IDM modules. We consider LIM as a supplement to, and not as a replacement of, these standards.

### 3.3 Information in BIM-objects

The content of information should be defined by use of the LIM framework. By explicitly defining the content of information into each type of BIM-objects (such as walls, windows, doors, zones, electrical equipment, HVAC equipment, interior equipment, etc.) which can be used in all kinds of BIM based software. It does not demand connection to databases and use of other external systems. At present, there is no common definition of professional content in objects, even if they are supplied in BIM or IFC certified software. The main focus is on geometrical representation and visualizations.

Standard – The information in BIM-objects / object libraries should be defined in ISO or national standards. These standards should contain lists of both mandatory and optional information according to the LIM framework (table 2). For ensuring that the information is as relevant as possible, the standardisation work should be performed by experts from the AEC-industry, and with minor dominance from software industry. The BIM-object standard could be provided as a series of parts for covering all the different kinds of building objects and disciplines.

- Development – Development of the BIM-objects can still be performed by the same actors who provide model objects today. The only difference is that the providers now include professional information according to the BIM-object standard. They still maintain their visualization features and profiling of own products. The software developers could facilitate this by including a “BIM-

content” tab to the object property features. In addition to the generic models included in software, manufacturers of construction elements offer a wide range of objects for free use. It can be expected that manufacturers that offer “BIM certified objects” will be preferred, and this will gain a swift implementation of the information elements into their existing product objects.

- Certification – For some types of BIM-objects such as wall, window, doors etc. there is a close relation between properties such as thermal transmittance, acoustics rating and fire rating. A certification system can be established to ensure logical relevance and validity of information values.

### 3.4 BIM-library manager

BIM based design is primary assembling of a large numbers of different BIM-objects, as doors, windows, walls, electrical, HVAC components. The number of BIM-objects with variants will therefore be very large. Practical use of relevant BIM-objects can be supported by use of a BIM-library manager for collecting, organizing, presenting and selecting the right BIM-objects. This feature is available today for handling model objects, and is built on a simple “drag and drop” interface. Figure 3 illustrates a simpler way than table 2 to select BIM-object with necessary information. This can be used for both manufacturer and generic BIM-objects. A BIM-object can cover one or more indexes (stages).

Table 3. BIM-object Ordering System.

Index	Purpose	Description, relation to Table 2, the LIM-table
A	- Demand BIM	Information for stage 0 in LIM-table (Table 2). All defined predefined information. No values is predefined, but can be entered or “enriched” in later stages. The values will be project depended.
B	- Draft model	Information from stage 1 to stage 3 in LIM-table (2).
C	- Detail model	Information from stage 4 to stage 6 in LIM-table (2).
D	- As-built model	Information from stage 7 to stage 8 in LIM-table (2).
E	- Facility management	Information from stage 9 to stage 10 in LIM-table (2).

From a technical point of view, adding the program lines in the BIM-objects for relevant content of professional information is expected to consideration marginal extra cost. It should be expected that development and distribution of BIM-objects for different software will maintain the same pattern as for model objects / object libraries today. This indicates that the change for using objects without professional information to use BIM-objects should be possible to be implemented.

### **3.5 The “BIM-tab”**

In present BIM-based software one can double-click on an object and a dialogue box appear. We suggest supplementing this dialogue box with a “BIM-tab” for explicit viewing of professional information. For a BIM-object of a wall, the BIM-tab will in contain information according to the BIM standard. It will be possible to relate this to future IFD integration. From a software point of view this will only be presenting the content in the object attributes. The implementation of this feature is not expected to be difficult or expensive.

## **4. Discussions**

This paper started with focusing on the basic of information exchange, and ended up with a practical solution on something one should believe was solved a long time ago. BIM is after all about exchange of information. It can therefore appear strange that there are so few options for entering professional information in BIM based software: “Where is the I in BIM?”

One explanation can be that for the software user it seems like information is present and is being exchanged from the architecture software to the software for energy of fire-safety analysis. But the architectural software (and exported file) does not contain information about the thermal or fire index properties. These properties are processed in the analysis software on basis of the wall geometry (structure) – and for most walls is the 200 mm space in middle of the wall interpreted as insulation – with related properties and values. This gives a proprietary “black box” solution. The impression of information BIM results leads of course to low demand for real BIM-objects because one are not aware of the missing professional content.

The lack of I in the BIM can explained by constraint that the benefit of implementing professional information in BIM object require consensus about



what information should be implemented. Lack of standards can be a consequence of this. Limited use of IDS with its demand for information exchange can be another reason. A common interest to develop a BIM-object standard could be the first step. If, or when, the AEC-industry can put forward a defined demand for “BIM-objects” – expressed in a “BIM-object standard” – it is likely that the software developers will invest the marginal effort to implement these features. However, if no consensus in the AEC industry, it is likely that a lot of proprietary ad-hoc solutions will emerge, and the priority of a formal standardized solution will suffer.

## **5. Conclusions**

The lack of defined information in model objects in BIM based software limits the utilization of information in the design process in general and IDS in special. The limitation in software model objects has a connection to the absence of consensus about what type of information should be exchanged. The AEC-industry should take initiative to improve this situation and start a standardization process for defining relevant information to be exchanged.

The proposed “Life cycle Information Model” (LIM) should be used as a framework for defining the relevant information in BIM-objects according to its use in the life cycle. The “BIM-object standards” should be developed in series for covering the variation professional disciplines. The BIM standards should contain definitions over mandatory and optional information related to the different categories of model objects. These standards can be used for both development and for use of BIM-objects.

There are to day a lot of software developers and manufactures that offer model objects (often for free). The ICT technical effort to extend the model objects to BIM-objects is regarded as minor. With a standard on place and demand from the marked, is can be assumed that the transition to BIM-objects will be implemented.

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# **THEME: Sustainability**



# Environmental Assessment of Buildings

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## Abstract

This paper focuses on the environmental assessment of buildings, and is based on the doctoral thesis [1]. Currently, building environmental assessment tools are used towards the end of the design process to evaluate the environmental results. The later the assessment in the design process is done, the fewer possibilities it has to influence the design itself.

The existing methods and tools should not be underestimated. However, they cannot be considered the sole possibilities. All the important aspects may not be considered in the environmental assessments of buildings. Therefore it is important to analyse the current environmental assessment methods and criteria. Moreover, the role of the building environmental assessment tools in the integrated model has to be analysed.

**Keywords:** environmental assessment, service life, sustainability, life cycle

## 1. Introduction

The environmental assessments of buildings are based on assessment methods, and on criteria. The assessment methods are techniques for evaluations, and the criteria are the basis for evaluations. The buildings are assessed according to these criteria which have been defined by a smallish group of people. However, the criteria or their selection have not been included in the social or political discussions. Consequently, the viewpoint of environmental assessments of buildings is narrow and the conclusions are limited.

Currently, most building environmental assessment tools are used towards the end of the design process to evaluate the environmental results. The later the assessment in the design process is done, the fewer possibilities it has to influence the design itself.

Are all the important aspects considered in the environmental assessment of buildings, and is the focus on the most important issues? Is the development of the environmental assessment heading in the right directions? If the new aspects are neglected, there is a possibility that “the high quality building” of today will be “the low quality building” of the future.

## **2. Building environmental assessment tools**

Numerous tools have been developed for the building sector to help decision making and improve the environmental performance of buildings and building stocks. The variety of the tools is wide; LCA based tools, rating systems, technical guidelines, assessment frameworks, checklists and certificates [e.g. 2, 3]. Over the past decade, the development of the tools has been active, and the tools have gained considerable success. Cole [4], however, suspects the success of the tools has dwarfed all other mechanisms for instilling environmental awareness.

Most of the research institutes and universities have been involved in developing building environmental assessment tools at some level. Unfortunately, they have excessively been focusing on their own work neglecting possible collaboration in interdisciplinary fields.

Building environmental assessment tools are not all commensurable. The comparison of the tools and their results is difficult, if not impossible. Different tools have been developed to assess new and existing buildings, residential building, office buildings and other types of buildings.

### **2.1 Manipulation of the results**

The tools emphasise the life cycle of the building differently; some tools cover the whole life cycle whereas other tools are more focused on the maintenance and use of the building. Even if the tools cover the same phase of the life cycle in the assessment, they may cover the phases differently. One tool uses several criteria for a phase while the other uses only a few criteria for the same phase in question. Moreover, the tools may use the same criteria, but different indicators to correspond to these criteria. The key questions are: what are the most

important criteria for environmental assessment of building, and what indicators correspond to these criteria best? [1].

Currently, it is possible to manipulate the results of environmental assessment. The results give a different picture depending on the used units; concrete construction waste, for example, has high mass and low volume compared to wood [5]. As an example given by Haapio and Viitaniemi [6],  $10 \text{ m}^3$  of concrete construction waste is  $\sim 24000 \text{ kg}$  in weight, and  $10 \text{ m}^3$  of wood construction waste is  $\sim 5300 \text{ kg}$  in weight. On the other hand, the volume of  $1000 \text{ kg}$  of concrete construction waste is  $\sim 0,4 \text{ m}^3$ , and the volume of  $1000 \text{ kg}$  of wood construction waste is  $\sim 1,9 \text{ m}^3$ . It is all about the image. Concrete construction waste benefits if the amount of waste is expressed in unit of volume ( $\text{m}^3$ ), and wood construction waste benefits from using the unit of mass (kg). [6]. It is possible that one may benefit at the expense of the other. And it is all because of the image.

The surface area ( $\text{m}^2$ ) of the building can be measured from the outside (including the walls) or from the inside (excluding the walls). See Figure 1. For example, energy consumption is often expressed as joules (J) per unit area of surface ( $\text{m}^2$ ). The energy consumption is smaller if the surface area of the building is measured from the outside, and bigger if the surface is measured from the inside. And yet – the building is the same. [3]. Moreover, the results presented per surface area ( $\text{m}^2$ ) do not always tell the whole truth. The volume ( $\text{m}^3$ ) should also be considered, because the height of the space may vary [7]. If the used units and definitions are not fully understood, the results are most probably interpreted incorrectly. The user's skills and knowledge are fundamental in avoiding errors during the assessment and interpretation of the results. [3].

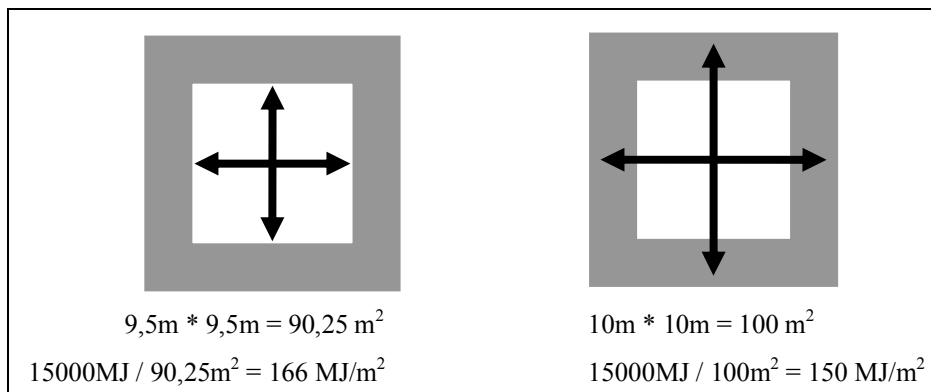


Figure 1. Measuring the surface area.

In the near future, the environmental assessment of buildings will probably become mandatory. Therefore, a thorough analysis of the assessment tools is needed immediately. The environmental assessment cannot be based on evaluations which provide a possibility to manipulate the results, intentionally or unintentionally. Otherwise, some building materials can benefit from the situation at the expense of the others.

## 2.2 Service life planning

Many of the building environmental assessment tools require an estimation of the building's lifetime. The service life of the building, however, has not been emphasised within the building environmental assessment tools. Rather, the service life is taken as given without further analysis. [3, 8]. And yet a single building may comprise over 60 basic materials and 2000 separate products. Their service lives are different, and they have unique production/repair/disposal processes. [9].

During the building's service life, the building needs to be maintained, and some components need to be replaced. The service lives of the components are different. The service life of the inaccessible parts should be the same as the service life of the building [10]. In other words, the service life of the accessible parts can be shorter than the service life of the building. If the service life of a component is shorter than the building's service life, the component needs replacement. [11]. As an example, if the design life (intended service life) of a building is 150 years, the suggested design lives are [10]:

- 150 years for inaccessible or structural components
- 100 years for components where replacement is expensive or difficult
- 40 years for major replaceable components
- 25 years for building services
- (easy-to-replace components may have design lives of 3 or 6 years).

Maintenance and replacements have environmental impacts. The maintenance can be proactive or reactive. In proactive maintenance, the action is taken in advance – before the damage occurs. In reactive maintenance, the action is taken afterwards – after the damage has occurred. There is a possibility the remaining service life of the components is lost, if the replacement is done proactively. If the replacement of the component is done reactively, the component may have



damaged its surroundings. The maintenance of these damaged surroundings has economical and environmental consequences. [11].

The time between the needed maintenance and replacements differs between different components, and also, the demands for the maintenances are different. In addition, the quality of the maintenance, i.e. workmanship, influences the forthcoming maintenances and may reduce the remaining service life. Poor maintenance, or disregarded maintenance, may cause damage elsewhere, and thus influence the whole building. For example, as a consequence of missing out the oil change of a car, the engine of the car may seize up. The repair of the engine is far more expensive than the oil change would have been. Also, wide repair is always more challenging, and exposed to further damages. [11].

The maintenance and the renovations of the existing buildings are critical issues for sustainable building, especially in Europe [12]. The service life of a building can be decades or even centuries. Moreover, the length of the service life is different in different countries. For example, the service lives of building seem to be shorter in the U.S. than in Finland. How the length of the service life affects the design of the building? Which alternative is better; a building with a service life of 50 years or 150 years? It is difficult, if not impossible to predict the development of building products and processes. Moreover, what are the needs and requirements of the tenants in the future?

## 2.3 Obsolescence

Although service life and obsolescence are related issues, they need to be differentiated. Obsolescence should be distinguished from the replacement due to defective performance [10]. Obsolescence is a condition of being antiquated, old-fashioned, or out-of-date. An obsolete item does not meet a condition of the current requirements or expectations. [10, 13]. However, this does not indicate the item is broken or dysfunctional. In other words, the service life of the item is not necessarily over, even if the item is obsolete.

Reliable data for forecasting obsolescence are rarely available. “Estimation of the time to obsolescence should be based on the designer’s and client’s experience and if possible documented feedback from practice” [10]. However, during the building’s long service life, manufacturing processes and products are developed. What was modern ten years ago is probably old fashioned today. This causes problems in the maintenance; matching old and new techniques and products might be challenging. The focus has been on the development of the

techniques, processes and products. The importance of the implementation of the techniques has been underestimated. [11].

Issues related to obsolescence should be taken into consideration already in the design phase. The focus should be on the development of easily replaceable components since the needs and requirements of the tenants grow and change constantly and there is no end in sight. Currently, service life planning and obsolescence are not emphasised within the building environmental assessment tools. However, these issues and their environmental impact should be studied thoroughly. Which criteria should be taken into consideration in the environmental assessment of buildings? Do they support “the green values” or “the consumerism”?

### **3. Resulting effects**

Currently, most building environmental assessment tools are used towards the end of the design process to evaluate the environmental results. Depending on the tool, the assessment can be done during the design phase or after the completion of the building. The building environmental assessment tools are not used simultaneously with the design tools. Consequently, the later the assessment in the design process is done, the fewer possibilities it has to influence the design itself. If the assessment is done after the completion of the building, it is done to calculate the realised environmental impact or the reached goals.

Often, these assessment tools are used by an external user [14], such as AEC professionals (architects, engineers, and constructors), producers, investors, consultants, tenants, authorities, and researchers [2]. The design of the building is largely specified by different regulations, building codes and standards. In addition, different actors in the building sector have different requirements for the buildings. Different building components and structural solutions can meet these regulations and requirements, but optimising and comparing these different solutions is challenging.

Optimising one solution may not be the ideal solution for the whole building; changing a building product in one place may cause changes elsewhere. A window with the best U-value, for example, is not always the best solution in northern Europe. In cold weather, water may condense on the surface of the window's glass, causing problems if the condensed water stays there for too long or is absorbed into the structures. [1]. However, the environmental assessment tools do not guide the user to choose “environmentally friendlier” solutions. The

user's skills and knowledge play an important role. Learning from experience is the best way to identify how the different solutions affect the results.

The integration of the assessment tools and design tools would facilitate the situation. Lützkendorf and Lorenz [14] are expecting it to happen in the future. However, the integration of the tools is challenging. The variety of the building environmental assessment tools is wide; LCA based tools, rating systems, technical guidelines, assessment frameworks, checklists and certificates. The tools cover different phases of the building's life cycle and take different environmental issues into account. Where the LCA based tools use databases, the environmental assessment frameworks rely more on guidelines and questionnaires. [1].

Before the integration of the assessment tools and design tools is possible and beneficial, the assessment methods and criteria need to be analysed thoroughly. The common goals in the development of environmental assessment of buildings have to be agreed on and accepted by the different actors in the building sector. Otherwise, the significance of the environmental assessment will stay minor, and conclusions and speculations meaningless.

Which are the most important aspects in the environmental assessment of buildings? How different definitions of the assessment methods and criteria affect the results have been underestimated. The interest lies excessively with the end results, without further clarification. Is the focus on the right issues? Is the development of the environmental assessment heading in the right directions?

## 4. Conclusions

A partly neglected aspect is the utilisation of the results of the building's environmental assessment. Could the utilisation of the results be more efficient? How the tool and its results have affected the decision making? To be able to critically analyse the benefits of the tools, these issues need further clarification. The development of the tools would also benefit from it. Furthermore, it would be beneficial to carry out research on what kinds of buildings are assessed, and compare the quality of assessed buildings to the existing building stock. There is a risk that "low quality buildings" will not be assessed at all when the assessment is not mandatory. [3].

Currently, the problem is the amount of information; there is too much of it. The essential information is swamped with the information available. The challenge is to identify the fundamental information, and moreover, to utilise

that information beneficially. [1]. The existing methods and tools should not be underestimated. However, they cannot be considered the sole possibilities. All the important aspects may not be considered in the environmental assessments of buildings. Therefore it is important to analyse the current environmental assessment methods and criteria.

There has been a shift from green building towards sustainable building. In addition to the environmental aspect, economical and social aspects are considered in sustainable building. The economical aspect has been very dominating, especially in service life planning. If the environmental aspect is to reinforce its current position, it cannot be done at the expense of the economical aspect. In the development of environmental assessment, economical aspects have to be included in the process; otherwise the building sector and the investors will not be interested. The whole process of the environmental assessment of the buildings needs to be attractive and beneficial for the financiers. [1].

Often teams working for the same project do not share information. There is a need for strengthening the collaboration between the actors within the building sector. According to Krygiel and Nies [15], the trend toward concentrated areas of expertise has led to a growing movement to combine the owner, designer, contractor, consultants, and key subcontractors into an integrated design team. Integrated design is founded on the ability to share knowledge across disciplines. *“When the entire design team is able to actively share one another’s work on the whole building, true integration becomes more real and compelling.”* [15].

The role of the building environmental assessment tools in the integrated model has to be analysed thoroughly. The needs and expectations of the integrated design team should be clarified, and taken into consideration in the development of the building environmental assessment tools.

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# Human Thermal Responses in Energy-efficient Buildings

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## Abstract

Quite wide global consensus seems to be achieved in a desire to improve energy-efficiency of both new and existing buildings when fulfilling international commitments and agreements in urgent environmental issues. However, this desire puts more pressure on both design and construction processes. This is because successful energy-efficient building concepts require verified guidelines for structural design and building service system dimensioning. This paper describes new possibilities to evaluate true thermal behaviour and interactions between indoor environment and occupants. The key-issue is to integrate sophisticated buildings energy simulation and detailed human thermal modelling. Such approach allows physically solid estimation of true impacts of alternative technical solutions on human thermal sensation and comfort.

**Keywords:** human thermal modelling, energy-efficient buildings, thermal sensation, thermal comfort

## 1. Introduction

Improving energy-efficiency in the future buildings will bring unavoidable changes in structural and building service system design practices. Most likely

indoor surface temperature levels of better insulating envelope components will increase during heating periods. At the same time surface temperature levels of at least traditional heating devices tend to decrease due to heating demand reduction. Therefore, there is an obvious need to evaluate the future design and dimensioning criteria of structural and building service systems – especially from an occupant’s point of view.

That the internal human body temperature should be maintained at around 37°C dictates that there is a heat balance between the body and its environment. That is, on average, heat transfer into the body and heat generation within the body must be balanced by heat outputs from the body. That is not to say that a steady-state occurs, since a steady-state involves unchanging temperatures and temperatures within the body and avenues of heat exchange will vary; the point is that for a constant temperature there will be a dynamic balance. [1].

If heat generation and inputs were greater than the outputs, the body temperature would rise and if heat outputs were greater the body temperature would fall. The heat balance equation for the human body can be represented in many forms. However, all equations have the same underlying concept and involve three types of terms: those for heat generation in the body, heat transfer, and heat storage. The metabolic rate of the body ( $M$ ) provides energy to enable the body to do mechanical work ( $W$ ) and the remainder is released as heat (i.e.  $M - W$ ). Heat transfer can be by conduction ( $K$ ), convection ( $C$ ), radiation ( $R$ ), and evaporation ( $E$ ). When combined together all of the rates of heat production and loss provide a rate of heat storage ( $S$ ). For the body to be in heat balance (i.e. constant temperature), the rate of heat storage is zero ( $S = 0$ ). [1].

## 2. Method

The widely accepted **conceptual heat balance equation** for the human body is

$$M - W = E + R + C + K + S, \quad (1)$$

where  $M - W$  is always positive.  $E$ ,  $R$ ,  $C$  and  $K$  are rates of heat loss from the body (i.e. positive value is heat loss, negative value is heat gain). For an analysis of heat exchange between the body and the environment, Fanger [2] uses the heat balance equation

$$H - E_{dif} - E_{sw} - E_{res} - C_{res} = R + C, \quad (2)$$

where  $H$  is metabolic heat production [ $\text{W m}^{-2}$ ],  $E_{dif}$  is heat loss by vapour diffusion through skin [ $\text{Wm}^{-2}$ ],  $E_{sw}$  is heat loss by evaporation of sweat [ $\text{W m}^{-2}$ ],



$E_{res}$  is latent respiration heat loss [ $\text{W m}^{-2}$ ],  $C_{res}$  is dry respiration heat loss [ $\text{W m}^{-2}$ ],  $R$  [ $\text{W m}^{-2}$ ] and  $C$  [ $\text{W m}^{-2}$ ] are net radiation and convection heat loss from the body, respectively.

ASHRAE (1997) gives equation for total evaporative heat loss from the skin

$$E_{sk} = E_{dif} + E_{sw} = \frac{w(P_{sk,s} - P_a)}{\left[ R_{e,cl} + \frac{1}{f_{cl}h_e} \right]}, \quad (3)$$

where  $w$  is skin wettedness (having values between 0.06 and 1.0) [-],  $P_{sk,s}$  is water vapour pressure at skin (normally assumed to be that of saturated water vapour at skin temperature) [Pa],  $R_{e,cl}$  is evaporative heat transfer resistance of the clothing layer [ $\text{m}^2 \text{ Pa W}^{-1}$ ],  $f_{cl}$  is clothing area factor (the surface of the clothed body divided by the area of the nude body), and  $h_e$  is evaporative heat transfer coefficient [ $\text{W m}^{-2} \text{ Pa}^{-1}$ ].

For **total respiratory heat loss** ASHRAE (1997) gives the equation

$$C_{res} + E_{res} = [0.0014 M (34 - t_a) + 0.0173 M (5.87 - P_a)], \quad (4)$$

where  $t_a$  is indoor air temperature [ $^{\circ}\text{C}$ ], and  $P_a$  is vapour pressure at air temperature [kPa].

Dry **convective heat transfer** to and from the human body is most commonly calculated using equation

$$C = f_{cl} h_c (t_s - t_a), \quad (5)$$

where  $h_c$  [ $\text{W m}^{-2} \text{ K}^{-1}$ ] is convective heat transfer coefficient, and  $t_s$  [ $^{\circ}\text{C}$ ] is either skin or clothing surface temperature exposed to room air. This convective heat transfer from skin or clothing results from an airstream perturbing the insulating boundary layer of air clinging to the surface of the body [3].

According to the well-known Stefan-Boltzmann law each surface emits **thermal radiation** power per unit area as

$$E_i = \varepsilon_i \sigma T_i^4, \quad (6)$$

where  $E_i$  is thermal radiation power per unit of area [ $\text{W m}^{-2}$ ],  $\varepsilon_i$  is emissivity of surface  $i$  [-],  $\sigma$  is the Stefan-Boltzmann constant  $5.670 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ , and  $T_i$  is surface temperature [K]. Total radiant energy leaving surface, called its *radiosity*, is the sum of the rates at which the surface emits energy and reflects or transmits it between itself and other surfaces. Imagine breaking up the surfaces of a room into a number ( $n$ ) of discrete patches, each of which is assumed to be of finite size,

emitting and reflecting heat uniformly over its entire area. If we consider each patch to be an opaque gray diffuse emitter and reflector, then, for surface  $i$  [4]

$$J_i = E_i + \rho_i \sum_{1 \leq j \leq n} J_j F_{j-i} \frac{A_j}{A_i}. \quad (7)$$

$J_i$  and  $J_j$  are the radiosities [ $\text{W m}^{-2}$ ] of patches  $i$  and  $j$ ,  $E_i$  is the rate at which heat is emitted from patch  $i$ ,  $\rho_i$  is the reflectivity of patch  $i$  [-],  $F_{j-i}$  is the view factor, which specifies the fraction of energy leaving the entirety of patch  $j$  that arrives at the entirety of patch  $i$ . taking into account the shape and relative orientation of both patches and the presence of any obstructing patches [-].  $A_i$  and  $A_j$  are the areas of patches  $i$  and  $j$  [ $\text{m}^2$ ]. A simple reciprocity relationship holds between view factors in diffuse environments [5]:

$$A_i F_{i-j} = A_j F_{j-i} \quad (8)$$

Thus, Eq. (7) can be simplified, yielding

$$J_i = E_i + \rho_i \sum_{1 \leq j \leq n} J_j F_{i-j} \quad (9)$$

Rearranging terms,

$$J_i - \rho_i \sum_{1 \leq j \leq n} J_j F_{i-j} = E_i \quad (10)$$

After solving these surface radiosities  $J_i$  simultaneously for each individual surface of a space, the net radiation exchange at a surface can be evaluated. The net rate at which radiation leaves surface  $i$  may also be expressed as:

$$-q_i = \frac{E_{bi} - J_i}{(1 - \varepsilon_i) / \varepsilon_i A_i}. \quad (11)$$

Equation 11 provides a convenient representation for the net radiative heat transfer rate from a surface, where  $(E_{bi} - J_i)$  represents the driving potential and  $(1 - \varepsilon_i) / \varepsilon_i A_i$  represents the surface radiative resistance. Therefore, there is net radiation heat loss from the surface if the emissive power that the black surface would have, exceeds its radiosity. In the opposite case, the surface will be the net absorber. [6, 7]

## 2.1 Detailed human thermal modelling

At rest, approximately 56% of total metabolic heat production is produced by internal organs, about 18% in the muscles and skin, 10% in the brain and 16%

within the other organs [8]. Heat produced in the body should be absorbed by the bloodstream and conveyed to the body surface because of poor heat conductivity of the all body tissues. Therefore, the convective flow of blood throughout the body is very important in internal heat transfer. About 50–80% of the heat flow in the tissue is carried in or out of the tissue by the blood flow [9].

As core temperature of the human body rises above its neutral value, vasodilation occurs and cardiac output increases dramatically. Nearly 100% of this increase goes to the skin tissue. For this development, a state of maximum vasodilation is achieved when core temperature reaches 37.2°C. At this state, the total skin blood flow rate may be as much as seven times its basal value. As mean skin temperature falls below its neutral value, vasoconstriction occurs. Skin blood flow, and therefore, cardiac output, decreases. At a state of maximum vasoconstriction, assumed to occur when mean skin temperature falls to 10.7°C, the total skin blood flow rate may be as low as one eighth of its basal value [10].

The transport of thermal energy by the blood flow in the micro-circular system, also called blood perfusion, is more important to heat transfer throughout the tissue than that in the macro-circulation. The blood-tissue interface area varies tremendously through the circulation system. For example, the approximate total cross section area of arteries in the body is 20 cm<sup>2</sup> while that of capillaries is 4500 cm<sup>2</sup>. Therefore, the capillary forms the major site for exchange of mass and energy between the blood stream and surrounding tissue. The energy exchange between this micro circulation and tissue is further dependent upon the tissue and blood temperature distribution, the blood perfusion rate, and the thermo-physical properties of the tissue. Detailed description of the local distribution of blood perfusion to energy exchange is an intricate task. Thus, a modelling compromise is required in order to facilitate the analysis of the important effect of microcirculation on the tissue energy balance. An approach commonly employed for this compromise, which accounts the heat transfer behaviour between microvasculature and tissue collectively, is based on the application of energy conservation, which is stated as the amount of heat taken up by tissue (or control volume) per unit time is equal to the arterial temperature minus the venous temperature times the rate of perfusion [11]

$$q_b = \rho_b \dot{V}_b c_{p,b} (T_a - T_v). \quad (12)$$

where  $q_b$  is heat transfer from perfusion blood flow to tissue [W],  $\rho_b$  is density on blood [kg m<sup>-3</sup>],  $\dot{V}_b$  volumetric blood flow rate [m<sup>3</sup> s<sup>-1</sup>],  $c_{p,b}$  is specific heat of

blood [ $\text{J kg}^{-1} \text{K}^{-1}$ ],  $T_a$  is the temperature of arterial blood coming into tissue [K], and  $T_v$  is the temperature of the venous blood flow leaving the tissue [K]. In many scientific papers people think it is reasonable to assume an almost complete thermal equilibrium between the exiting bloodstream and the surrounding tissue because of the condition of very slow blood flow in the capillary bed. [11].

## 2.2 Heat transfer to the extremities of the human body

Pennes was the first to formulate the heat balance resulting in the bioheat equation, and he did it for the analysis of heat transfer in the forearm [12]. He measured longitudinal and radial temperature profiles in the forearms of volunteer subjects under steady state conditions. He demonstrated the importance of convection of heat by the blood by comparing temperature distributions with and without proximal occlusion of blood flow. Based on these experiments he assumed that the forearm could be modelled as a right circular cylinder with steady state heat production and heat convection. Ignoring axial and tangential heat conduction, and assuming that thermal properties, blood flow, and metabolic heat generation are constant in the forearm. Pennes' heat balance reduced to

$$\rho c \frac{\partial T}{\partial t} = k \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \rho_b c_b w_b (T_a - T_v) + q_m, \quad (13)$$

where  $T$  is tissue temperature,  $k$  is thermal conductivity of the tissue,  $\rho c$  and  $\rho_b c_b$  are heat capacities of tissue and blood, respectively.  $w_b$  is the volumetric blood flow of blood in tissue,  $q_m$  is the metabolic heating rate, and  $T_a$  and  $T_v$  are the temperatures of the entering arterial and the exiting venous blood. Pennes made the assumption that the venous blood equilibrated with the surrounding tissue prior to exiting the control volume, i.e.,  $T_v = T$ .

Several interesting studies related to modelling human body has been conducted in the field of medicine (e.g., presurgical cooling of legs, and rewarming of the digits of the hands and the feet following cardiac surgery, Eberhard 1985). One aim of those studies was the exploitation of the basis of the sudden postoperative rewarming of the digits which has long been observed clinically, and its correlation with the degree of recovery of cardiac function. It was found that a strong vasodilation takes place when core temperature reaches the thermoregulatory set point (approximately 38 °C), at which time warm blood

flows rapidly to the digits, and skin temperature rises significantly (3–10 °C). The analytical model selected to describe heat transfer processes in the digits consisted of circular cylinder with homogenous property values, in which bone and nails were neglected. Also axial conduction and convection were neglected. Heat was rejected at the surface of digit by convection, using surface heat transfer coefficients derived from standard natural convection data. At the skin surface,  $r = r_0$ .

At time  $t = 0$ , skin temperature begins to rise above its initial value,  $T_i$ . Dimensionless temperatures and other variables were obtained by the following transformations [13]:

$$T_0 = T_b + q_m / \rho_b c_b w_b \quad (14a)$$

$$V = T - T_i \quad (14b)$$

$$V_0 = T_o - T_i \quad (14c)$$

$$R = r / r_0 \quad (14d)$$

so that

$$\frac{1}{R} \frac{\partial}{\partial R} \left( R \frac{\partial V}{\partial R} \right) - \frac{r_0^2}{\alpha} \frac{\partial V}{\partial t} - \beta (V - V_0) = 0 \quad (14e)$$

where  $\beta = r_0^2 \rho_b c_b w_b / k$  is the blood flow parameter. Assuming symmetry of the temperature profile at  $R = 0$ , and convective heat transfer at the surface.

$$\text{at } R = 0: \quad \frac{\partial V}{\partial R} = 0 \quad (14f)$$

$$\text{at } R = 1: \quad \frac{\partial V}{\partial R} = -\text{Bi } V \quad \text{Bi} = hr_0 / k \quad (14g)$$

The solution is

$$\frac{V}{V_0} = 1 - \frac{\text{Bi } I_0(\sqrt{\beta} R)}{\sqrt{\beta} I_1(\sqrt{\beta}) + \text{Bi } I_0(\sqrt{\beta})} - 2\beta \text{Bi} \sum_{n=1}^{\infty} \frac{J_0(u_n R) \exp\left[-\left(\alpha t / r_0^2\right)(u_n^2 + \beta)\right]}{(u_n^2 + \beta)(u_n^2 + \text{Bi}^2) J_0(u_n)} \quad (15)$$

where  $u_n$  is given by

$$u_n J_1(u_n) - \text{Bi} J_0(u_n) = 0. \quad (16)$$

$I_0$  and  $I_1$  are modified Bessel functions of the first kind of zeroth and first order, respectively. Similarly,  $J_0$  and  $J_1$  are Bessel functions of the first kind of zeroth and first order. The solution of Eq. (15) is valid for all  $R$ , but the surface is of principal interest. After defining the thermal properties of the tissue, the heat transfer coefficient value at the surface of the digit, and the temperature and flow rate of the incoming blood,  $T_b$  and  $w_b$ , transient tissue temperature values can be calculated. [13].

### 3. Results and discussions

Importance of different human body related heat transfer mechanisms, presented above, naturally depend on individual sets of input parameters and boundary conditions. For example, evaporative and convection respiratory heat losses, when estimated by Eq. 4 (Metabolic rate is  $100 \text{ W m}^{-2}$ , total skin area  $1.87 \text{ m}^2$ , and relative humidity 50%), depend on indoor air temperature and humidity. Typically, heat loss from the human body by this mechanism varies around  $15 \text{ W}$ , and evaporative respiration heat loss becoming dominant with higher indoor air temperature levels (Figure 1).

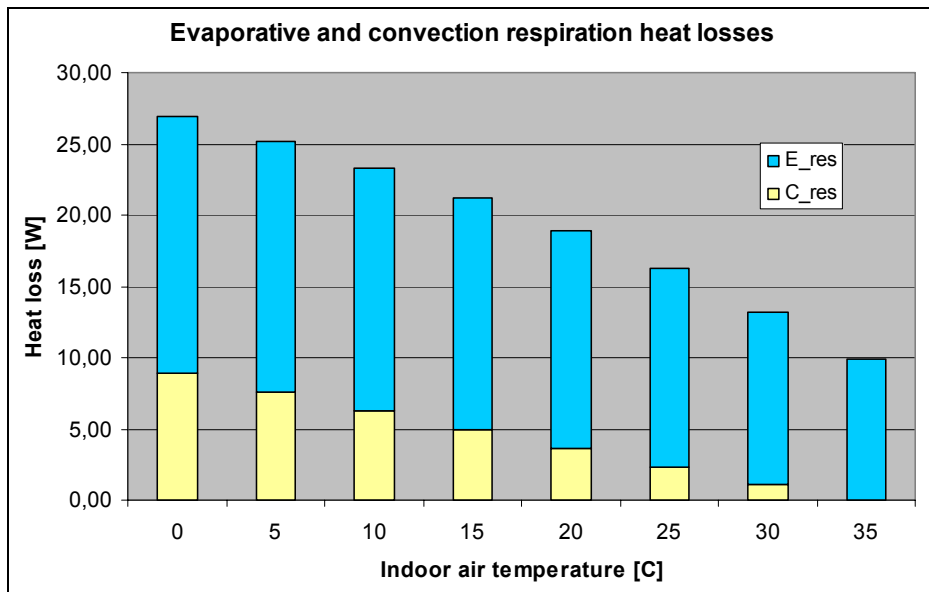


Figure 1. Human respiration heat losses depending on ambient air temperature.

Table 1 shows heat transfer interaction between a human body and a test environment. Convective heat loss is evaluated by assuming uniform skin temperature of 33.7 °C and a constant indoor air temperature of 22 °C. The results show rather significant differences between various body parts even in this test case of a nude human. If a more realistic clothed human was simulated, obvious surface temperature deviations would have occurred, especially with partly clothed and partly bare skin sections. Such deviations would have caused even more net heat transfer variations between different body parts. Therefore, it is highly important to fully understand local net heat transfer between body parts and a surrounding environment.

Table 1. A typical set of net convection and radiation heat transfer between a human and indoor environment.

Body part	Net heat transfer between an occupant and her/his surrounding environment [W]		
	Convection heat transfer	Radiation heat transfer	Total heat transfer
Head	6.9	4.2	11.0
Chest	12.4	6.2	18.5
Back	11.2	5.4	16.7
Pelvis	25.5	13.9	39.4
Upper arm	5.9	2.8	8.7
Forearm	3.6	2.2	5.7
Hand	1.7	1.2	2.8
Thigh	10.4	7.1	17.5
Lower leg	5.8	4.2	10.0
Foot	1.4	1.6	3.0
<b>Whole body</b>	<b>104</b>	<b>64</b>	<b>168</b>

Evaporative heat loss from skin typically varies between 10 and 30 W with skin wettedness value 0.06 describing moisture content of dry (non-sweating) skin. However, moisture evaporation from skin has a true potential of becoming a dominant heat transfer mechanism. By the skin wettedness index value of a unity, evaporative heat loss from the skin can increase up to level of 250 W or more (Figure 2).

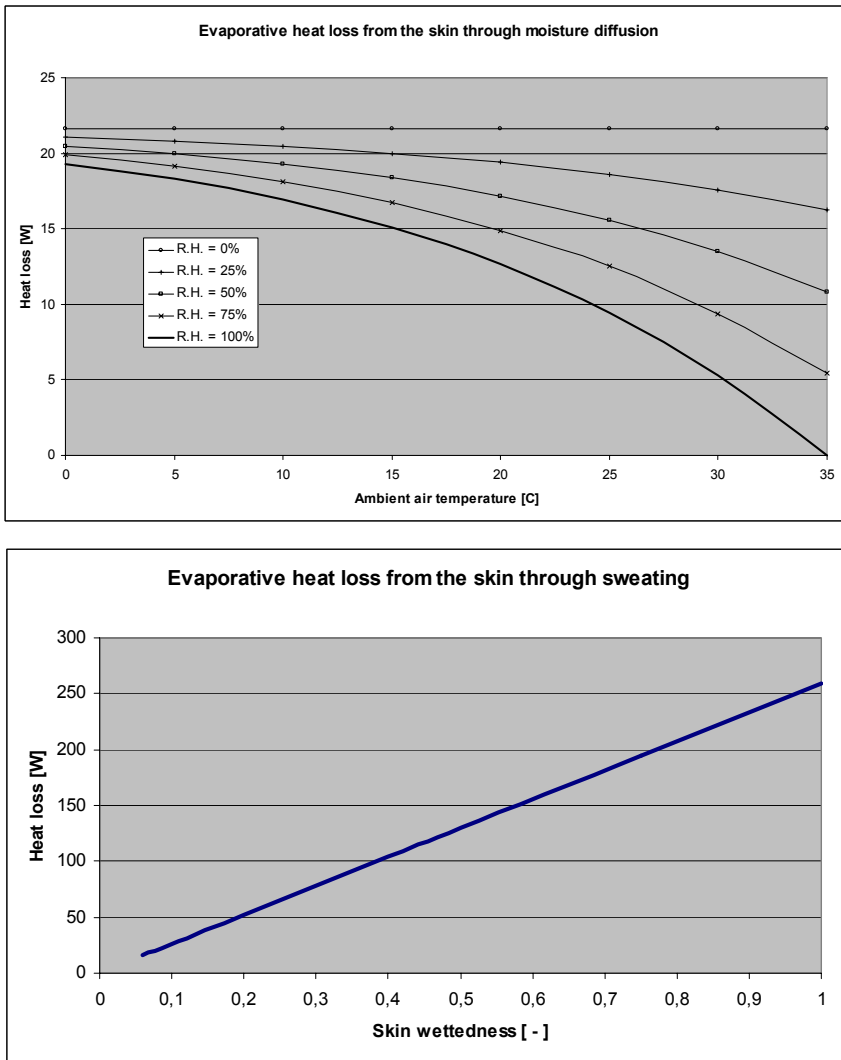


Figure 2. Evaporative heat losses from skin through moisture diffusion (above) and sweating (below, relative humidity 50%) with nude body and skin temperature 35 °C.

Another essential heat transfer mechanism having a huge potential is related to blood flow inside and between the body parts. For example, with 1 K temperature difference between entering dilate skin blood flow and torso's skin tissue layer, the net heat transfer due to this mechanism is 65 W. As an extreme, if there is a temperature difference of 1 K between all tissue layers of the torso and entering blood flow, heat transfer between blood perfusion and the tissue layers due to this mechanism in maximum blood flow conditions is almost 300 W.



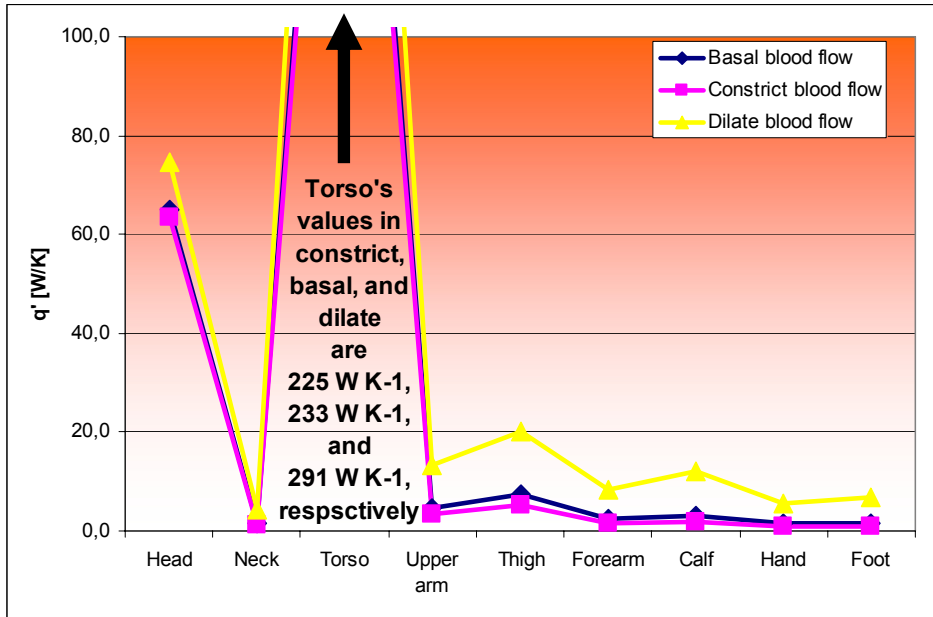


Figure 4. Specific heat transfer potentials of blood perfusion [ $\text{W K}^{-1}$ ] in different body parts – all tissue layers included (in Watts per difference between arterial blood and tissue temperature levels).

Adopting the following boundary condition values for the analytical solution of the cylinder and homogenous tissue parameters (Eq. 14 and 15):  $r_0 = 0.0553 \text{ m}$ ,  $h = 8.0 \text{ W m}^{-2} \text{ K}^{-1}$ ,  $k = 0.42 \text{ W m}^{-1} \text{ K}^{-1}$ ,  $c_p = 3768 \text{ J kg}^{-1} \text{ K}^{-1}$ , and  $\rho = 1085 \text{ kg m}^{-3}$ ; and the blood flow parameters:  $w_b = 0.001 \text{ s}^{-1}$ ,  $c_{p,b} = 3768 \text{ J kg}^{-1} \text{ K}^{-1}$ ,  $\rho_b = 1085 \text{ kg m}^{-3}$  and  $T_b = 37 \text{ }^\circ\text{C}$  gives  $\text{Bi} = 1.053333$ ,  $\beta = 28.41002$  and  $\alpha = 1.027327\text{e-}7$ . When adopting these boundary conditions, the eight first roots of Eq. 16 are  $u_1 = 1.2811905$ ,  $u_2 = 4.0917565$ ,  $u_3 = 7.163098$ ,  $u_4 = 10.276125$ ,  $u_5 = 13.402354$ ,  $u_6 = 16.534372$ ,  $u_7 = 19.669432$ , and  $u_8 = 22.806289$ . Adopting the initial tissue temperature value  $T_i = 25 \text{ }^\circ\text{C}$  gives  $T_0 = 37.153773 \text{ }^\circ\text{C}$  (Eq. 14a). Table 2 shows transient tissue temperature values given by the analytical solution and the VTT Human Thermal Model simulation. According to these results there seems to be excellent agreement with the results when adopting a number of 10 thermal calculation nodes for the simulation. Average deviations between analytically calculated and simulated were  $0.0432 \text{ K}$  and  $0.0014 \text{ K}$  on the surface (skin) and in the centre point of the cylinder, respectively.

Table 2. Analytical solutions and simulation results of surface skin and center muscle temperatures of a homogenous cylinder during the first 3600 s after a step change.

Time [s]	Analytical solution		Simulated results		Difference ( $T_{sim} - T_{analytic}$ )	
	$T_{skin}$	$T_{center}$	$T_{skin}$	$T_{center}$	Skin	Center
0	25.0000	25.00000	25.00000	25.00000	0.00000000	0.00000000
60	25.6536	25.67804	25.66371	25.67665	0.01014890	0.00138820
120	26.2514	26.31563	26.27134	26.31571	0.01995052	0.00007882
180	26.8054	26.91853	26.83195	26.91918	0.02650098	0.00064968
240	27.3205	27.4881	27.35163	27.48905	0.03110642	0.00095588
300	27.80032	28.02602	27.83483	28.0272	0.03450657	0.00117247
360	28.2479	28.53402	28.28501	28.53537	0.03712393	0.00134801
420	28.6658	29.01376	28.70502	29.01525	0.03920613	0.00149671
480	29.0564	29.46679	29.09729	29.46842	0.04090392	0.00162355
540	29.4216	29.89461	29.46394	29.89634	0.04231340	0.00173088
600	29.7634	30.29862	29.80687	30.30044	0.04349884	0.00182020
660	30.0833	30.68015	30.12777	30.68204	0.04450528	0.00189253
720	30.3828	31.04044	30.42819	31.04239	0.04536560	0.00194859
780	30.6634	31.38067	30.70954	31.38266	0.04610472	0.00198885
840	30.92638	31.70197	30.97312	31.70399	0.04674201	0.00201363
900	31.17283	32.00539	31.22012	32.00741	0.04729289	0.00202326
960	31.40388	32.29191	31.45165	32.29393	0.04776994	0.00201803
1020	31.62053	32.56248	31.66872	32.56448	0.04818346	0.00199835
1080	31.82373	32.81798	31.87227	32.81994	0.04854206	0.00196479
1140	32.01433	33.05925	32.06319	33.06116	0.04885300	0.00191805
1200	32.19316	33.28707	32.24228	33.28892	0.04912243	0.00185894
1260	32.36096	33.50218	32.41032	33.50397	0.04935561	0.00178847
1320	32.51844	33.7053	32.56800	33.70701	0.04955706	0.00170772
1380	32.66624	33.89709	32.71598	33.89871	0.04973070	0.00161786
1440	32.80499	34.07816	32.85487	34.07968	0.04987991	0.00152009
1500	32.93525	34.24912	32.98526	34.25053	0.05000763	0.00141564
1560	33.05755	34.41051	33.10766	34.41182	0.05011648	0.00130570
1620	33.17239	34.56288	33.22260	34.56407	0.05020869	0.00119145
1680	33.28023	34.70671	33.33052	34.70778	0.05028628	0.00107398
1740	33.38152	34.84248	33.43187	34.84343	0.05035097	0.00095434
1800	33.47665	34.97063	33.52705	34.97146	0.05040432	0.00083349
2100	33.87252	35.51107	33.92306	35.51131	0.05054359	0.00023793
2400	34.16248	35.91532	34.21303	35.91502	0.05054962	0.00029594
2700	34.37514	36.21726	34.42563	36.21652	0.05049076	0.00073847
3000	34.53129	36.44246	34.58169	36.44138	0.05040476	0.00108796
3300	34.64604	36.61023	34.69635	36.60887	0.05031211	0.00135578
3600	34.73044	36.73506	34.78066	36.7335	0.05022342	0.00155732
				Average deviation	0.04324765	0.00136680
				Maximum deviation	0.05054962	0.00202326

Integrated design solutions provide that there exists true linkage between different simulation and data management disciplines. Figure 5 shows *VTT House* simulation environment as one example of such integration. Namely, *Space Model* and *Human Thermal Model* of this environment are linked to each others producing holistic estimations of thermal behaviour of both building and the human – and thermal interactions between them. After transient tissue temperatures of the human have been simulated, this data can be used as input data for predicting thermal comfort and thermal sensation. This information, in turn, needs to be integrated with visualization and other post-processing features available.

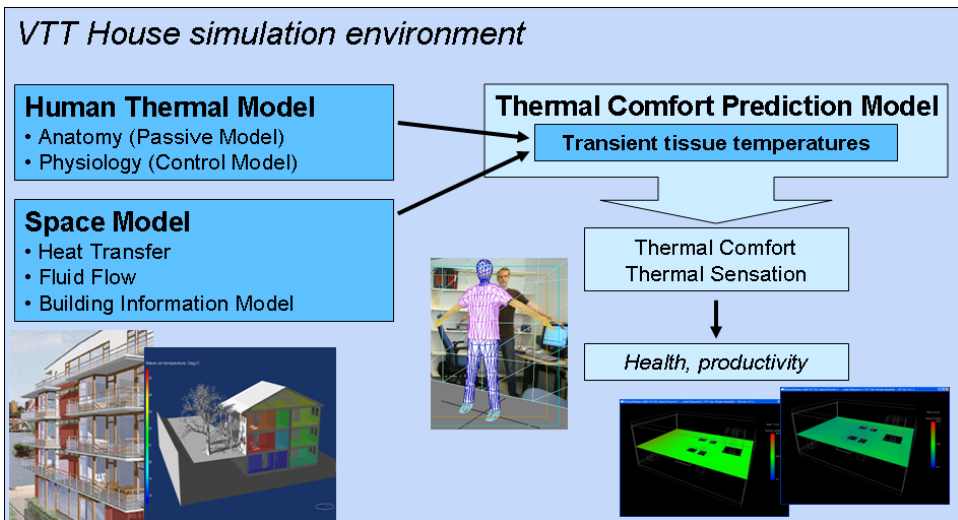


Figure 5. VTT House simulation environment as an example of an integrated simulation and data management platform.

## 4. Conclusions

Improving energy-efficiency of buildings will evidently require better thermal insulation in the future buildings. This, in turn, will change typical indoor surface temperatures of building envelopes, and therefore dimensioning principles and conventional operative temperature levels of building service systems (radiators, convectors, thermally active building structures, etc) need to be evaluated. At the same time, the results of a detailed human thermal modelling clearly indicate dominant heat transfer phenomena (both heat

generation due to metabolism and heat transfer by blood perfusion) into torso region. This suggests to sub-dividing the human body into body parts and to conduct a more realistic simulation of human body thermal behaviour (both anatomy and physiology) to fully understand thermal interactions between the human body and the surrounding environment.

This study indicates that there certainly are methods and possibilities available to evaluate thermal behaviour of the human body. This fact offers new opportunities to design both energy-efficient and thermally pleasant buildings. However, such professional design should be based on thorough understanding of thermal interaction both within the human body, and between the body and surrounding space. Otherwise, inadequate structural and building service system design will either reduce energy-efficiency of the future buildings or cause problems with thermal sensation and comfort. Modelling and evaluation of building end-user's thermal sensation and comfort is therefore recommended to be integrated to more holistic design solutions. Namely, both structural design and building service system dimensioning will put boundaries for occupant's thermal comfort (i.e. health and productivity).

Probably the most important practical benefit of human thermal modelling would be improving quality of the building design process. Namely, such more holistic approach would offer unique possibilities for optimizing alternative technical solutions – based on occupants' true physiological reactions, and health and productivity estimations. The crucial challenges of this opportunity will be implementation and validation of the human thermal model, and integration of this tool into integrated design solutions.

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# Improved Building Design by Joint Calculating Building Costs and Environmental Costs?

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## Abstract

In order to meet today's environmental and sustainability challenges, the building and construction industry needs to integrate environmental qualities' within their projects to a further extent. To achieve this, efforts must be put in the development of tools for integrated design solutions (IDS) that make possible optimized building processes for the actors involved. Further registration of environmental input data to support informed decisions is also necessary. The developed tools must be able to communicate with a BIM on open standards, such as IFC. Joint calculation of building costs and environmental cost through the entire building process from idea to detailed design, present a new perspective in decision making. This is one of the principle objectives in the Norwegian project GLITNE, by applying the tool Calcus, a tool for calculating building costs. Calcus is developed to import an IFC-based BIM.

**Keywords:** design, environmental, cost, assessment, building cost, EPD, building processes, BIM, IFC

# 1. Introduction

## 1.1 Background

Ensuring environmental qualities in design of new and rehabilitation of existing buildings is an important challenge in the building and construction industry. This requires optimal design processes, best available technology solutions and sufficient environmental input data as basis for different assessments. Considerable work has been done in developing environmental labelling, rating and classification systems for building products and whole buildings. More recently, international standards for environmental declaration of building products and assessment of buildings have been developed. At the same time, computerized tools for design of buildings (CAD software) and the use of Building Information Modeling (3D) have emerged. The introduction and use of open standards in the industry give new and more effective ways to exchange information between different ICT tools and a BIM.

The ongoing research project GLITNE (2006–2009) is a joint project of major actors from the Norwegian building sector. The main target is to produce knowledge on how environmentally effective buildings can be made more attractive and financially competitive. A method based on Life Cycle Assessment (LCA) and economic weighting of environmental effects [1] is being developed. The method will be integrated in a computerized tool that is supposed to calculate building costs and environmental costs together.

## 1.2 Scope

This paper focuses in particular on the following issues:

- Outline the drivers and restraints in calculating environmental qualities in buildings due to today's situation, especially founded in the lack of environmental input data such as Environmental Product Declarations (EPDs and EPD databases), but also due to existing ICT tools.
- Discuss how today's technology regarding the exchange of information between ICT tools and BIMs on open standards, may improve environmental design and the interaction between the actors in the building process (such as clients, architects and technical consultants).

- Demonstrate how an existing calculation tool for building costs may take environmental costs into account as well.

These issues will be discussed through specific cases (building projects), based on the GLITNE project. The paper addresses the following aspects of IDS; reuse of integrated data, a tool to make possible integrated building design and more informed decisions, all contributing to enhanced value during design.

## **2. Drivers and restraints in calculating environmental qualities in buildings**

The overall environmental and climate challenges will continue to increase the need for the building and construction industry to take its actions considering the implementation of environmental building qualities. Due to legislations, the Directive on the Energy Performance of Buildings (EPBD) has introduced a mandatory performance certificate for all buildings. Most likely, environmental certificate or similar regulations for buildings will be introduced as well, forcing the owners and managers to take the needed actions. This will to a wider extent, also make environmental qualities a factor for competition and business. Other incentives, such as taxes and user responsibility, may also be introduced to ensuring that energy and environmental considerations are made.

Another important driving force in calculating environmental qualities in near future seems to be the increasing use of digital building information modeling. This opens up for the use of a wide range of model-based tools, overcoming the practical problems related to e.g. life cycle assessments (LCAs), such as time needed to perform an assessment. It also opens up for increased integration in design processes, so that joint calculation and assessment of several aspects is more likely to happen.

[2] states that a number of economic, technological, and societal factors are likely to drive the future development of BIM tools and workflows. It also addresses the major technical barrier to be the need for mature interoperability tools. This is also the case of environmental assessment tools. Only a few LCA and BIM-based tools exist on the open format IFC. The existing tools are not necessarily suitable for the actors in the building process. Further, the lack of environmental data on buildings products and elements on suitable formats, are a considerable barrier for LCA-based tools to be widely in use.



## 2.1 The need for EPD databases

Depending on the purpose of the environmental calculation and in which stage of the building process the calculation is performed, the amount and accuracy of the data will vary. Whole building life cycle aspects should be taken into account, including information regarding both product stage, design and construction stage, employment stage (operation and maintenance) and end of life stage (e.g. deconstruction, re-use, disposal). The basic principles and presentation formats of environmental assessment in terms of Life Cycle Inventory (LCI) or Life Cycle Assessment (LCA) have been agreed upon due to international standardization processes.

There are an increasing number of manufacturers of building products that prepare environmental product declarations (EPD) for their products due to the International Standard Organization (ISO) 21930:2007 Environmental declaration of building products. An EPD is intended to provide information for planning, design and assessment of buildings, by giving verifiable and accurate information and ensure that any environmental impact is completely accounted for. The EPDs are based on the LCA standards, but an EPD may also include only a certain life cycle stage. In Norway, these EPDs are available as PDF-files on the Norwegian website of building products EPDs, owned by the Norwegian foundation for Environmental Product Declarations ([www.epd-norge.no](http://www.epd-norge.no)). A number of EPD programmes exist on a worldwide basis, covering several product categories ([www.gednet.org](http://www.gednet.org)).

Despite the growing interest for environmental declarations in the international building industry, so far only a few has been produced and are available worldwide as well as in Norway [3]. As a result of this, there is little knowledge of the environmental consequence of different design alternatives in buildings. No doubly, one major challenge yet to be overcome is the lack of relevant environmental data composed in available databases to be used in software applications.

## 2.2 ICT tools and BIM in environmental design

The largest influence on building qualities is probably in the early stages of the building process, in the building design phases. A major part of the information about a building project is defined in the design phases, and the ability to impact cost and functional capabilities will only decrease at later stages of the building process.

There is a need for integrated design, taking environmental analysis into account, to give the architects, engineers, managers etc a better foundation for informed decisions. In order to achieve this, several aspects have to be present, including:

- The necessary environmental information, given to the relevant building actor in order to obtain adequately informed decisions
- Suitable environmental assessment tools, adjusted to the building actors needs and preferable integrated with the design process and existing tools.

The introduction of Building Information Modeling (BIM) and exchange and sharing of data on international open standards, such as Industry Foundation Classes (IFC), make these key aspects possible. The benefits of building information modeling for e.g. owners, managers, architects, engineers and contractors are several. The use of BIM makes it possible to insert, extract, update or modify information on different stages in the building process, and directly see the consequences of ones choices of e.g. alternative building design due to building cost, calculated energy demand etc. No doubt, enabling the different actors to work together in the building process may lead to considerable savings in time and cost, and making sure that the best solutions are chosen.

In [2], the BIM use in design processes is discussed, including environmental analysis tools. Traditionally, environmental analysis (such as early assessment on energy demand, estimating operating costs etc), are relied mainly on experiences and rules of thumb. Existing environmental analysis tools, to be used by architects in early design, are only limited compatible with BIM design tools. As the building design develops, more information is available, and the analysis and simulations tools become more complex and are often used by domain specialists (e.g. engineers).

Early environmental analysis requires significant amounts of generic environmental data, describing the average performance. Further on in the building design stage, more information on materials and constructions, operation conditions etc is available, making it possible to make more detailed assessments with e.g. product specific environmental declarations (EPDs). In [4] it is stated that environmental assessment of a building can be integrated to a BIM similarly as cost calculations are already done today. Further, the potential of existing environmental building assessment or rating to support sustainable building design and refurbishment of buildings would be improved, if it the were integrated with BIM. This does not seem to be the case today.

In [5] it is stated that the use of BIM is not yet widespread, and that the most widely supported tool (application) was energy performance declaration. In [3], the interpretation of two existing LCA and IFC based tools are presented. This was BSLCA (Finland) and LCADesign (Australia). The interpretation revealed that both applications automatically import architectural models from 3D CAD system by using IFC. The objects are either automatically tagged given their environmental characteristics (BSLCA) or tagged manually (LCADesign). Further, both applications are using internationally known LCA methods and input based on national environmental data. Only LCADesign is using data from EPDs.

Given that the 'perfect' interoperable environmental assessment tool existed, fully suited to address the complexity of work, there would still be considerable barriers in implementing it. In [6], real-life projects are studied in order to investigate what happens when new technology, such as 3D based modelling or BIM, are implemented and used in architectural design. Both drivers and barriers were identified, one area being user skills and behaviour of actors. Some of the barriers identified, were related lack of resources for implementing and learning new technologies in ongoing project situations. This, including the lack of experience and a fully overview of what happens when the technology is used, lead to reduced implementation across all actors involved. Similarly, all of the skills needed for assessing joint calculations are not to be found in one person only. This forces the need for teams and integrated work in the building process.

### **3. Calculating environmental costs and building costs together**

#### **3.1 Environmental costs – the GLITNE methodology**

The ongoing research project GLITNE (2006–2009) is a joint project of major actors from the Norwegian building sector. The project is financed by The Research Council for Norway and the Norwegian Housing Bank. The Norwegian architect Snøhetta is the owner of the project, and contributes together with the partners. The main target is to produce knowledge on how environmentally effective buildings can be made more attractive and financially competitive. A method is being developed based on Life Cycle Assessment (LCA) and economic weighting of environmental effects [1]. The method will be integrated in a computerized tool that is supposed to join the calculation of building costs and environmental costs.

So far, economic values have been developed for three environmental effects; climate change (greenhouse gases), human and environmental toxicity (e.g. connected to the use of chemicals) and waste to disposal. In order to include the whole life cycle of the building, the intention of GLITNE is to rely on both whole life cycle environmental data from EPDs, but also the energy demand in the building's employment phase. The principles of the GLITNE method is shown in Figure 1.

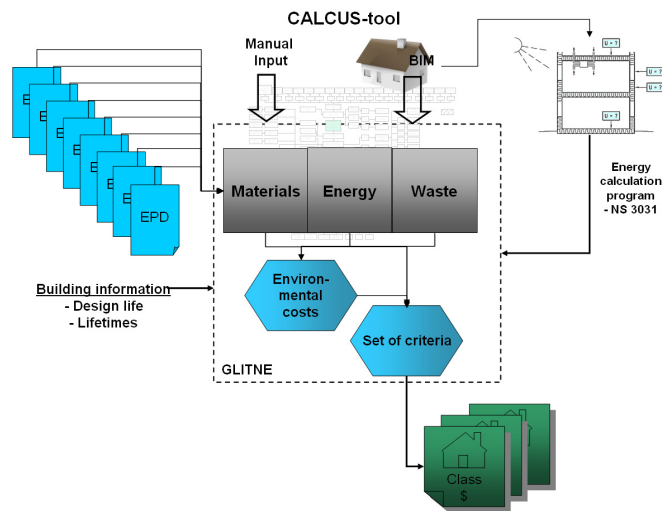


Figure 1. The GLITNE methodology. The input data is supposed to be based on EPDs and energy calculations program. Environmental costs are developed for climate change, dangerous substances and waste (based on [1]).

### 3.2 ISY Calcus – building costs and GHG emissions

The GLITNE idea is to give the actors the possibility to make informed decisions, taking environmental qualities into account. By using environmental valuing, it is possible to calculate the environmental costs together with e.g. building costs. In GLITNE this is to be done by integrating a GLITNE module in an already existing calculating tool, ISY Calcus. ISY Calcus is a tool for calculating building cost for early stage design. Even though it's not a CAD design tool, it makes it possible to work with a "living" building cost model from idea > schematic design > early design > detail design. The tool generates key quantity data from a building element database, containing approximately 1.500 predefined elements. Accordingly, 43 predefined model building projects

are available within the program. The element database is generated on the basis of costs from the underlying materials, based on historic record and experience of different materials, elements and construction solutions. The element database is organised according to the Norwegian standard (NS) of building elements, NS 3451. Calcus identifies the most important drivers for building costs, and make it possible to assess the building geometry due to the building costs. The tool is delivered by the Norwegian company Norconsult AS, and the methods and cost data within the program are developed in cooperation with another Norwegian company. Among 550 Norwegian companies are currently costumers of the calculation tool, among these e.g. architects, engineers, contractors, owners.

Already existing in a Calcus beta version (not yet released) is a greenhouse gas (GHG) emission accounting tool based on [7]. This tool, or calculation model, referred to as [www.klimagassregnskap.no](http://www.klimagassregnskap.no), is developed by Statsbygg. Statsbygg is Norway's largest property agency in the civil sector and their main clients are central government agencies such as colleges, universities, ministries and directorates. The calculation tool consists of four models; Module 1 Materials, Module 2 Transport of materials, site and construction, Module 3 Energy use in the operation phase and finally Module 4 Transport (of people, goods etc. back and forth to the building).

In Calcus, module 1 Materials is included. Accordingly, the data from Statsbygg's module 1 have been further developed by the tool producers. Thus, the GHG tool in Calcus consist of the emissions CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub>, recalculated to CO<sub>2</sub>-equivalents. The GHG emission data exists for both materials and building elements in the same way as for building costs.

### **3.3 GLITNE and Calcus**

By integrating the GLITNE module in Calcus, we are creating a decision support system which aims at improved building design by calculating building costs and environmental costs together. This addresses aspects of IDS in several ways. By using an already existing and widely used tool in the building process, the chance and possibilities for the building actors to take environmental aspects (costs) into account increases. No doubly, the overall most important aspect of a building project is the building costs. By introducing environmental costs and making an evaluation of these costs possible in the same stages of the building process, the decision makers will have the opportunity to see a whole new picture. This will increase integrated design processes and bring together

different domain experts. Further, it also makes it possible to reuse data about the building (type of material, building elements, building geometry e.g.). Today, Calcus have the possibility to import a BIM on IFC. The idea is that Calcus imports e.g. early design BIM, and by the predefined elements, makes it possible to calculate building costs. If EPD databases existed, the Calcus could be interoperable on the format IFC with this database, and calculate building qualities based on these life cycle assessment data. Then, by using economic weighting of environmental effects, these environmental qualities will be given the same value as building cost (in e.g. EURO).

Today's situation is however, that the lack of EPD databases makes it necessary to collect (both generic and specific) environmental information manually. In GLITNE, the needed environmental data will be collected only for the specific building cases within the projects, using the GLITNE method to calculate environmental cost. GLITNE will not create a EPD database. Further, as the GLITNE results are under development, the environmental cost will be exemplified as climate cost. The two other environmental aspects are not further looked into in this article.

Interesting aspects occur when the building design is changed, and the direct result of the building costs and (future) environmental costs are visualized. Such a process will of course have consequences for the architectural building design. It will also have consequences on e.g. calculated energy demand, making it necessary to recalculate in an energy simulation tool. By the use of BIM and open exchange formats, this process will be easier, involving architects, engineers, owners and contractors and their explicit tools (given that they are IFC/BIM compatible).

## **4. Results**

### **4.1 Three building projects and GHG emissions**

In the GLITNE project, several Norwegian building projects are supposed to be evaluated according to the GLITNE method during 2009. One project is under construction, the others are completed. The three cases presented in this paper are all office buildings, with or without basements for parking. One of the offices contains a public shopping area as well.

Office 1 is an interior rehabilitation project completed in 2005, originally built in 1972. Only the masses of the materials and elements used for the interior

rehabilitation is calculated costs. This means that the following is not included in office 1: ground and foundation, main load carrying system, exterior roof, stairs and balconies. Office 2 was completed in 2003. The building contains parking basement and office areas. Office 3 is under construction. The building will consist of parking, offices and public shopping areas.

The functions of the three office buildings are quite similar, and there are only smaller variations in construction and choice of materials. Different alternatives of the three office buildings were calculated by using predefined elements and model buildings in the Calcus tool. Further, none of the building cases were BIMs, thus the input in Calcus had to be done manually.

Table 1. An overview of the three building projects in GLITNE.

GLITNE-case	Year built	Total area (m <sup>2</sup> , BTA)	Description of cases and alternative design
Office 1: Reference case	1972 Rehab 2005	2500	As built case. Interior rehabilitation.
Office 1: Alternative A		2500	Cell offices changed to open landscape.
Office 1: Alternative B		2500	A Calcus model building is used to calculate all elements of the building (materials, elements) to illustrate office 1 as new built. Similar materials as for ref. case is used.
Office 2: Reference case	Built 2003	33 282	As built case. New.
Office 2: Alternative A		33 282	The outer walls are changed.
Office 2: Alternative B		33 282	A Calcus model building is used to calculate all elements of the building (materials, elements) to compare office 2. Similar materials as for ref. case is used.
Office 3: Reference case	Under construction	23 370	Based on information from the detailed design.
Office 3: Alternative A		23 370	The outer walls are changed. More insulation in the outer roof.

The precise materials used in the building projects are not presented, due to the fact that the choice of materials should not be done on the amount of the

embodied CO<sub>2</sub>-equivalents alone. The materials used in the building will have an impact on the operation conditions, and the ideal is to include this in the GHG emissions such as for the Statsbygg model (module 3). This is to be done in the GLITNE project as well. In Figure 2, the GHG emissions for the three building projects (and their alternative design) are presented in CO<sub>2</sub>-equivalents per m<sup>2</sup> gross area (the whole building area in all floors, above and below ground measured to the outside of the outer walls).

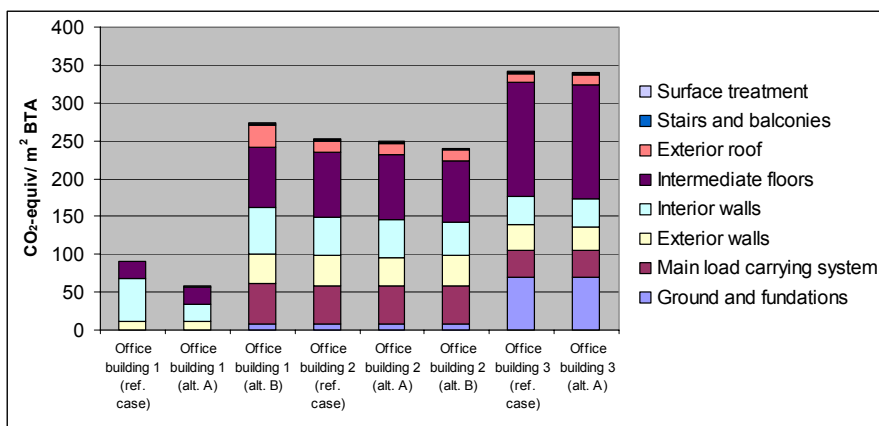


Figure 2. The GHG emissions for the building, presented in CO<sub>2</sub>-equiv per m<sup>2</sup>. The data is based on the calculation from the Calcus tool (beta version).

Office building 1, being the rehabilitation project, has the overall lowest CO<sub>2</sub>-equivalent per m<sup>2</sup>. Changing from cell offices to open landscape reduces the GHG emissions (e.g. reducing the values of interior walls). Alternative B for office building 1 is the Calcus model; representing the building if it was built as new (GHG emissions for demolition of already existing building is not included). Compared to office building 2 and 3, this might have been seen as a strong incentive for rehabilitation. The changes of outer walls done for office building 2 (alternative A) does not have an effect on the GHG emissions. Alternative B is a Calcus model building, built up by similar elements as the exact office 2. The difference in GHG emissions is small. Also for office building 3, the alternative A design, the changing of outer walls, had little effect on the amount of GHG emissions. More insulation in the outer roof leads to (naturally) higher amount of GHG emissions.



## 4.2 Building costs and environmental costs

As stated previous, the GLITNE and Calcus tool is under development, allowing only indications of the possibilities of the future tool. In the GLITNE method, economic values are under development for three environmental effects; climate change (greenhouse gases), human and environmental toxicity (e.g. connected to the use of chemicals) and waste to disposal. The details in the economic values are not presented in this article, and only the costs related to GHG emissions are illustrated. To calculate a so called ‘climate cost’ to the greenhouse gases, the assumption has been ‘no more than two degree Celsius rise in temperatures’, and economic values found in different (national and international) reports based on this assumption.

In Figure 3, joint building and climate costs are illustrated for the building cases (logarithmic scale, cost in EURO per m<sup>2</sup>).

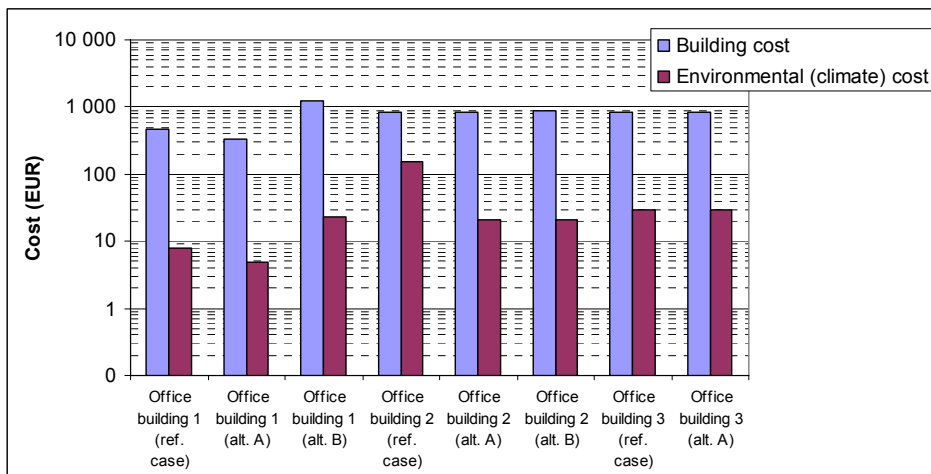


Figure 3. The building costs and ‘climate cost’ (based on part of GLITNE method) is illustrated together (EURO per m<sup>2</sup>). The scale is logarithmic.

The building costs are based on the predefined elements in Calcus. As the CO<sub>2</sub>-equiv per m<sup>2</sup> is calculated with the same cost factor, the climate cost will vary with the different designs alternatives in the same way as for Figure 2.

But the overall point is to illustrate how the different costs vary with different designs alternatives. The consequences are instantly presented; given the decision makers an opportunity to assess the direct building costs together with environmental qualities and environmental costs. Hopefully, this will be an

important driving force in taking environmental qualities into account. But, is it likely that changing concepts and assessing the total environmental and cost picture, is to be done by one person. No, this forces a team of experts working together in integrated processes, from idea, to early and detailed design.

## **5. Conclusions and implications**

Given the superior challenges of sustainability and climate adaptation, the building and construction industry needs to develop strategies and tools for integrated design solutions (IDS) that make possible optimized building processes for the actors involved. Internationally, work has been done in creating life cycle assessment (LCA) based tools to be used in environmental design of buildings, some of which also can communicate with a BIM on open standards. Little work has been done (both in Norway and internationally) in order to create tools, suitable for integrated environmental design of buildings that make it possible to consider environmental qualities in alternative building designs parallel to other aspects such as e.g. economy. The lack of environmental data and EPD databases on suitable formats are an important barrier for assessing environmental qualities in buildings, as well as contribute to more integrated design.

The use of BIM and exchange of data on open formats makes integrated design possible in a whole new way, and opens for a multidimensional attention of building quality assessment. One barrier for this to happen is our own user skills and capability to adjust to new tools and processes, and a not yet fully developed skill of multidimensional way of thinking. This point exactly, underlines the need for tools that may help the actors work together in integrated processes, different domain experts together.

In the GLITNE project, a method and a tool for calculating environmental qualities and cost, together with building costs, is under development. By using an already widely used tool for calculating building costs, the reuse of data is possible. It also makes it possible for the involved actors to take both building costs and environmental costs into consideration in the design process. The use of BIM and IFC is central. By the end of 2009, economic values for climate change (greenhouse gases), human and environmental toxicity (e.g. connected to the use of chemicals) and waste to disposal will be developed. In the future, the tool is ment to rely on both whole life cycle environmental data from EPDs as well as energy use in the operation. By introducing joint building costs and environmental costs assessments, a whole new picture is available for the actors involved.

## Acknowledgements

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# **THEME: Beyond BIM**



# Link between a Structural Model of Buildings and Classification Systems in Construction

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## Abstract

It is presumed that the classification systems will have a greater role in the construction process in the near future. They will support the communication between industry players while they will be dynamically formed by particular users based on common agreements. The existing international classification systems differ markedly in terms of the levels and details of specification. The internationally developed OmniClass and the Finnish Building 2000 differ in structure but both adequately serve the demands of the industry. With the available software intelligence, the most beneficial solution is to apply a mixed indirect and manually adjustable object classification system in a 4D modelling software. The present situation of information flow and 3D model usage is mapped in the construction industry in Finland. The information flow breaks several times in the process in the means of changing nomenclatures and switching from 2D drawings to 3D model, and back to 2D drawings. The recommendation is: utilizing the benefits of BIM by agreeing on the base classification system, and making it to follow the whole construction process. The changes in the plan are more easily handled with the use of BIM and the common classification system.

**Keywords:** Building information model (BIM), classification systems, construction, filtering, 3D, 4D

## 1. Introduction

This study is part of the on-going joint research project between Tekla Corporation and Construction Management and Economics Unit at the Helsinki University of Technology (TKK/CME).

The whole society will benefit from the changes happening in the construction industry, namely the shift to optimal utilization of Building information modeling. Owners will easier assess the cost of buildings and make better decision on the design and construction methods. One target for change is the format of information, to support the Integrated Design Solutions. In line with these development efforts the construction classification systems are in the focus of this study.

The classical intent for using classification systems is to support cost estimation, procurement, cost follow up and product manufacturing. It is predicted that classification systems will have a much greater role in the construction process in the near future. They will strongly support the communication between industry players while they will be dynamically formed by particular users based on common agreements. This study presents suggestions to the focal parties, describing the way of contributing to information flow jointly used by other parties in a particular building information model (BIM).

The direct and indirect classification methods are discussed and compared in the paper, taken into account is the software intelligence and the complexity of the built environment. The structure of the Finnish national classification system, *Building 2000* and the comprehensive internationally developed *OmniClass* are compared. In this paper the nationally accepted or widely used classification systems are called *base nomenclature* or base classification system.

Besides the theoretical recommendations, a technical tool is presented, which facilitates the implementation of the suggestions. Tekla Structures, a 4D structural design software, is used for demonstration of the theoretical and practical solutions. (By adding time to a 3D CAD application one forms 4D.) The Model Organizer is a new Tekla Open API (Application programming interface) application in Tekla Structures. The logic of the Model Organizer allows parties in construction projects to apply their own classification systems, and it can be utilized in many different ways for the benefit of all construction-related parties.



## **2. Method and critique of the study**

The research methods of this study involve literature review and expert interviews. The literature review targeted the relevant references about Finnish and international classification systems, standards, and the latest research results on Building Information Modeling. The interviews were conducted for gaining deeper knowledge of the information flow in the construction industry, and to test the suggested solution about the classification system utilization. The aim of the interviewee search was to find the representative interviewee(s) from within each of the six interviewee groups by branch type, i.e. owners, facility management companies, contractors, subcontractors, designers, and building products suppliers. Complementary interviewees were arranged with experts in the software industry, namely from Tekla Corporation. The second choice criterion implied that the interviewees would know Tekla Structures, and preferably already used it in their projects. Owners, architects and facility management companies' representatives are going to be interviewed later as the project continues.

As a critique of the study it is noted that the study describes only a part of the construction industry in Finland through the means of working and information exchange methods. In the opinion of the authors in the long run, as the technology develops, the classification systems will change its form and meaning. The present description of application is a step towards a more generally applicable solution. Therefore the presented approach can be considered as a temporary way of working to enhance the cooperation between construction industry players.

## **3. Functions and applications of classification systems**

The extent of application of classification systems differs greatly in different countries. Within single countries there can be several independent classification systems in the construction industry. Parties of the construction industry are seeking new ways of cooperation to reach more effective operation methods. The international standards are created to support these efforts between and within different countries. National classification systems have been changed and others could be changed to follow the directions of the international standard: International Organization for Standardization (ISO) 12006-2

Organization of Information about Construction Works – Part 2: Framework for Classification of Information (later ISO 12006-2). The common understanding of classification systems will help in international operations.

### **3.1 Classification systems used in Finland and internationally**

The basic process model of any construction classification system, stated in the ISO 12006-2 standard, is as follows: construction resources are used in or required for construction processes, the output which are construction results.

There are numerous construction nomenclatures used all around the world. *OmniClass* Construction Classification System (*OmniClass*<sup>TM</sup>) is presented here as an example. *OmniClass* is a strategy for classifying the entire building environment. It incorporates other extant systems as the basis of its Tables – Master Format<sup>TM</sup> for work results, UniFormat for elements and EPIC (Electronic Product Information Cooperation) form products. *OmniClass* is designed to provide a standardized basis for classifying information created and used by the North American architectural, engineering and construction (AEC) industry, throughout the full life cycle of buildings. *OmniClass* follows the international framework set out in the ISO 12006-2. Table 1 lists the table titles of *OmniClass*.

In Finland there is a long history of applying national construction classification systems like *Building 70*, *Building 80*, *Building 90* and *Building 2000*. Benefits have been realized but there is need for further adjustment of activities to fully utilize the inherent opportunities. The two commonly used nomenclatures at this time are the *Building 2000* (by architects) and *Building 80* (by constructor companies). Despite the widespread use of national nomenclature, several brakes can be recognized in the digital information flow in Finland due to the slow change towards 3D modeling. Strong efforts are currently being taken to tackle the problem with the involvement of several construction related companies. *Building 2000* is the favorable choice of classification systems for the future because it supports BIM.

Table titles of *Building 2000*: Building Elements, Construction Resources, Work Sections, Premises and Spaces, Project Classification, Worksite Equipment. When applying the *Building 2000* nomenclature, the Building Element and Project Classification table is used during the design and construction phase. For the preliminary specification of elements, the tables of

elemental bill and estimates and tender cost estimates are used. The tender cost estimation is based on an elemental bill, which may be itemized by activities when needed. The target estimation is based on a schedule of work sections.

Table 1. Relation between the tables of OmniClass and Building 2000.

<b>OmniClass tables</b>	<b>Basic dimensions of general classification</b>	<b>Building 2000 tables</b>
Table 11 – Construction Entities by Function	Construction Results	In Premises and Spaces Classification
Table 12 – Construction Entities by Form		--
Table 13 – Spaces by Function		In Premises and Spaces Classification
Table 14 – Spaces by Form		--
Table 21 – Elements		In Building Element and Project Classification
Table 22 – Work Results		In Construction Work Section Classification and in Building Resources Classification
Table 31 – Phases	Construction Processes	--
Table 32 – Services		In Building Element and Project Classification
Table 23 – Products		In Construction Product Classification
Table 33 – Disciplines	Construction Resources	--
Table 34 – Organizational Roles		--
Table 35 – Tools		Worksite Equipment Classification
Table 36 – Information		--
Table 41 – Materials		--
Table 49 – Properties		--

Table 1 organizes the table titles of Building 2000 and OmniClass in three groups based on the standard ISO 12006-2. The groups describe the basic dimensions of classification systems, like Construction Results, Construction Processes and Construction Resources. The Building 2000 tables are organized differently than the OmniClass tables. The content of Building 2000 tables can be paired with one or more similar OmniClass tables. The extent of Building

2000 is narrower than the extent of OmniClass. Building 2000 does not cover the classification for infrastructure, and as visible from the table titles, the Construction Entities by Form, Spaces by Form, Phases, Disciplines and Organizational Roles; while OmniClass does cover the whole built environment. Also the depth of Building 2000 stays at a more general level with its 4 digit code within the tables, while OmniClass has the maximum of 8 digit code within the tables.

### **3.2 Extent and depth of a classification system**

The extent and depth of a classification system is adequate if it serves the needs of the users. In the case of national nomenclature the goal is to cover the whole built environment and the structure of the classification system must support the BIM applications. The question is, how precise or deep should a classification system be in order to enable its wide applicability within and between several parties? Based on the interviews there is no need for very detailed base nomenclature, because the constructor and subcontractor companies' organizational structure and working practices widely differ. They see the adequately refined classification system as their competitive advantage. They can further refine the national nomenclature and still they can communicate to other companies through the base nomenclature or through the commonly agreed refined classification system. As a comparison base, OmniClass is the deepest nomenclature to be used when architects or structural engineers implement the classification.

### **3.3 Predefined and dynamic classification system**

Present CAD software are capable of storing classification information about the model objects in different ways. The Tekla Structures Model Organizer can store predefined classification groups, but the user is free to create any number of new groups that the project requires. The model objects are filtered and linked to the corresponding classes in the Model Organizer. The predefined part of the classification system is the base nomenclature in the Model Organizer. Structural engineers and architects deal with the predefined part. The dynamic part is the further refined nomenclature serving the needs of the contractor, subcontractors and other users of the 4D model. There is a possibility to agree on specific use of

the nomenclature, and on the method of extending or refining it project by project. Contractual forms must reflect these project needs.

Figure 1 shows an example of classification with OmniClass in Tekla Structures Model Organizer. OmniClass can be the basic nomenclature in an international project implemented in Finland. Civil Defense Shelter is an obligatory part in most of a multistory block house in Finland. OmniClass does not contain the category Civil Defense Shelter therefore a User Defined Class is added to the Element categories in this project. The parts comprised by the Civil Defense Shelter are listed with their product classification code within the element, because this can support the cost calculations.

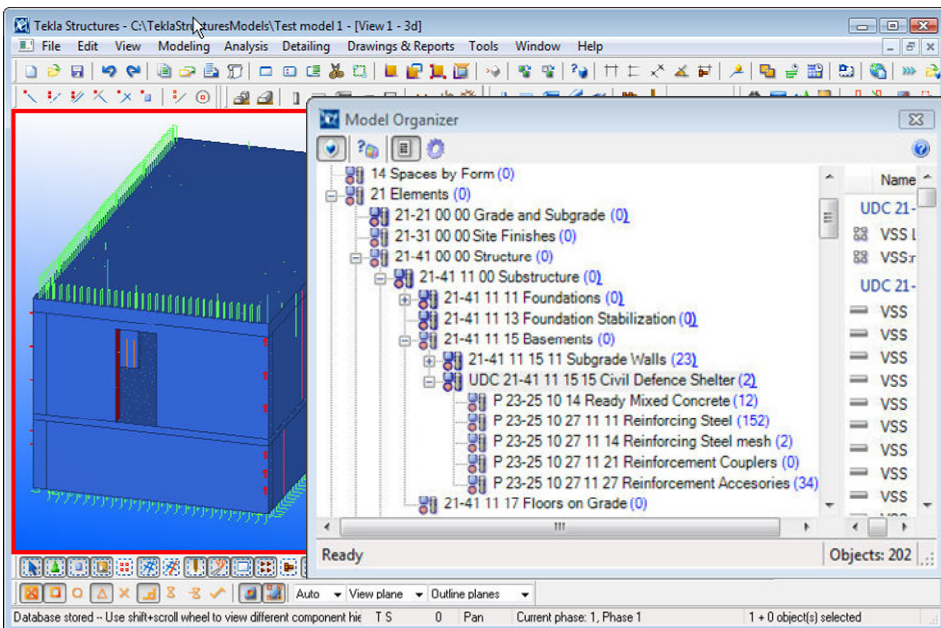


Figure 1. Example of classification with OmniClass and a user defined refinement.

### 3.4 Linking objects to classification system

The automation of the direct linking of the 3D model to the classification brings a great benefit to the creators and users of classification information. There are several theories and implemented applications for solving this technical challenge. This paper aims to present the major differences between the methods.

**Object property:** In this paper the property of an object is understood as the minimal definitive property of the object and it is created when the object is created.

**Attribute:** In this paper the attribute is understood as an additional property of the object, which is linked to it after creation.

In general means, depending on the properties of the objects they can be classified to different classes:

- All red beams greater than size 10, belong to class 1.
- A red beams smaller than or equal to size 10, belongs to class 2.

Once defining the classifier rules, the assignment of the object to a class can be done automatically by a CAD program. The program is able to handle any changes in the model by rerunning the assignments to classes or by redefining the classes. In order to use this system in practice the user has to be able to overwrite the rule and assign the object to any class.

There are two principal methods for connecting classification information to model objects.

- **Direct classification method:** the classification information is stored as an attribute to each object. The nature of this connection is one-to-one.
- **Indirect classification method:** the model objects and classes are connected to each other with a dependency. Dependency is typically a condition. If properties of an object match with the condition, it belongs to the class. The nature of this connection is one-to-many.

In the **direct** classification method, the object class is defined as an attribute of the object. Attributes and the way of linking it to the objects can be divided to two main categories:

- **Geometrical** attributes are created to define the geometrical appearance of the object.
- **Non-geometrical** attributes are additional information tagged to the objects.

Both main attribute categories can be used for storing the classification information.

**Geometrical attributes** are either linked to the objects in product libraries, or define the physical appearance of the objects otherwise. If geometrical attributes are used with **direct** classification, the geometrical appearance of the object is

directly connected to its class. This means that the size of the object library becomes needlessly big in normal buildings having a lot of variation. All the changes in geometric appearance are reflected in the class and vice versa. Management of the library and classification becomes laborious. However this method is well-suited for situations where minimal or no variation is needed in either the object library or classification (pre-engineered buildings made of standard components). A basic example is shown in Figure 2.

If **non-geometrical attributes** are used with **direct** classification, the geometry of the object is not directly dependent on the classification. The class is tagged to the object. However the automation for connecting the objects with classification system is difficult to arrange due to the one-to-one nature of the connection. The implementation possibilities of one-to-many connections are limited. Deficiencies in automation capabilities in practice easily lead to situations where the end user has to manually take care of the classification validity. The link between an object and its non-geometrical attributes created with the direct classification method is demonstrated in Figure 3.

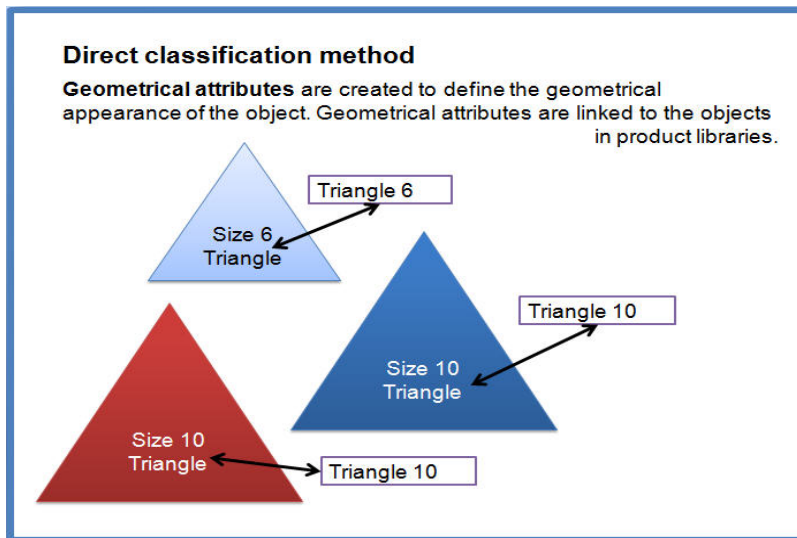


Figure 2. Direct Classification method with geometrical attributes.

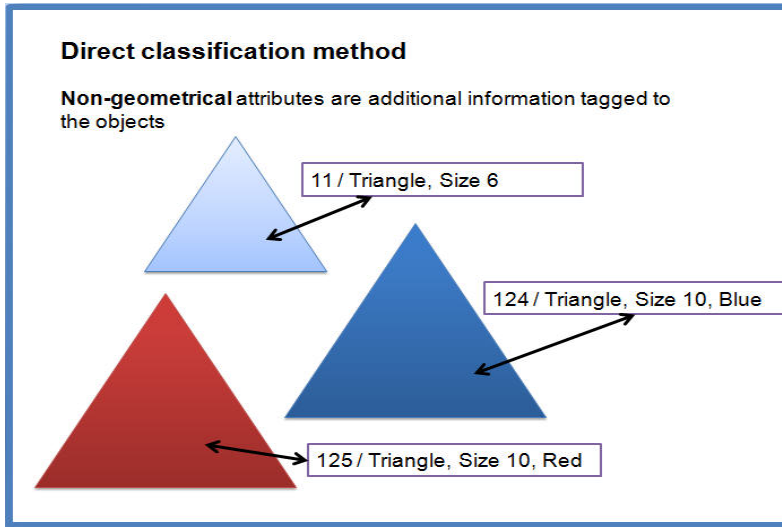


Figure 3. Direct Classification method with non-geometrical attribute.

The **Indirect** classification method has several benefits over the direct one. With the indirect classification method the automation is easy to arrange. Objects are automatically linked to classes and automatically switched to the correct class when changes occur in the model. Objects belong to as many classes as needed, there are no theoretical limitations. The way of object filtering with the indirect classification method and the manual adjustment is shown in Figure 4.

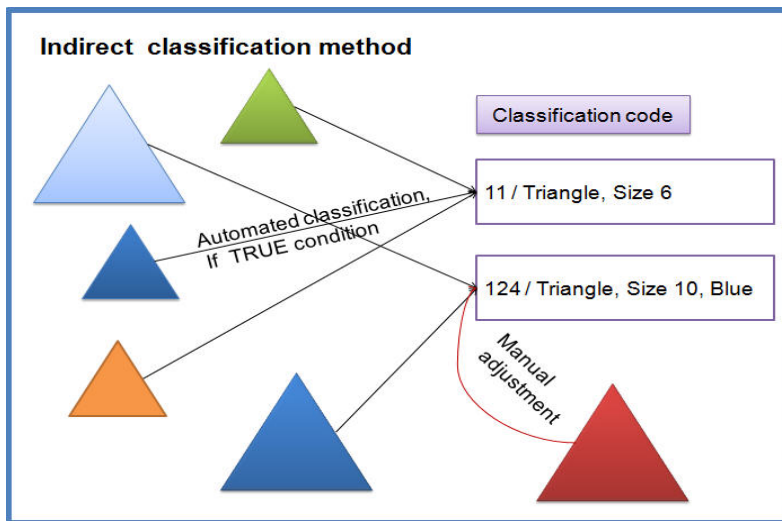


Figure 4. Indirect classification method.



In practice automation seldom provides a 100 percent precise classification result as there is a great variation of needs, therefore the **semi-automated method** is suggested. Satisfactory classification functionality is reached by the **combination of automatic indirect classification** and the possibility of **manual adjustment**. The one-to-many nature of the classification does not change when manually comprehending to the process.

### 3.5 User groups of classification systems in the construction industry in Finland

The interviewees described their contribution to the information flow and the way of utilizing different nomenclatures at the present time. The following working methods are derived from the result of the interviews; they are only examples and not exclusive methods in the industry.

#### 1. Architects

- use 2D CAD application and provide the drawings on paper
- use 3D software for the design. There can be a certain level of classification in the model, and possibly also the Building 2000 classification number of the object in the attributes.

#### 2. Structural engineer – creates the structural 3D model based on the 2D drawings in most cases, or imports the architectural model as a reference model and creates the structural model based on it. Based on RT (Rakennustieto, Finnish Building Information Group) recommendations, the structural engineer uses prefixes as object attributes. The structural engineer creates filters to the objects for the following purposes:

- owner requirements (for repeated project types)
- phases (layers) for self purpose: used with prefixes for drawing creation and reports.

It is up to the designer whether the Building 2000 classes are entered as attributes or not.

#### 3. Mechanical and electrical designer – can use the 3D model created by the structural engineer as a reference model for the design. They utilize the classification created by the structural engineer e.g. the Building 90 in

the model and complete it with RYL 2002, the classification system for mechanical engineering.

4. **Project Management Company** – usually uses Building 80 as the base of bid packaging, cost estimation and other purposes. The classification is added to the objects in the 3D model. Without 3D model and precise bid package preparation for subcontractors, the received tenders are estimative and they have great deviation in pricing.
5. **Contractor** – use Building 80 nomenclature for quantity survey, pricing and cost estimation. They are done by manual calculation or software is used. The 3D model is recreated in a chosen “quantity take off” software, and direct classification is used to support filtering. For construction scheduling and implementation monitoring, separate project management software is used, where the building objects are entered manually. In some company several separate internally developed coding systems are used. For example one coding system is based on Building 80 and the other is based on Building 2000, and they are used parallel to each other in the cost estimation and purchasing.
6. **Subcontractor**
  - **Subcontractor** – for implementation work receives 2D drawings or rarely 3D model, which is used for bid offer creation. The organization of implementation work is done manually and is paper-based.
  - **Steel fabricators and precast manufacturers** – mostly 3D model elements and project management software is used when the subcontractor is the product manufacturer at the same time. They also receive 2D drawings or a 3D model. When 2D drawings are received, the 3D element model for production is created. When the 3D model is received the elements are ready for production. They use an internal product classification system. Steel fabricators and precast manufacturers frequently use other subcontractors for the erection process.
7. **Product manufacturer** – receive orders and offers from the contractor.

8. **Mechanical (HVAC) subcontractor** – receives 2D drawings, sometimes a 3D model. As the received model is getting more and more reliable they are producing more prefabricated parts.
9. **Authorities** – require 2D drawings and do not accept 3D model.

### 3.6 Recommended use of nomenclatures in the construction industry

To support the information flow in the construction industry the following actions are recommended. Examples are taken from the Finnish Building 2000 classification system.

1. **Software vendor** – provides the classifier tool e.g. Tekla Structures Model Organizer and the base nomenclature (Building 2000) included.
2. **Owner** – Agrees in the contracts with the architect and the structural designer:
  - a. The architectural model contains object filtering using all four digits of the Building 2000 Elements table.
  - b. The structural model contains the classification of objects to the level of Building 2000, four digits.
3. **Architect** – classifies the objects with Building 2000 Elements to full depth (four digits). The classification information is transferred to the structural model through IFC model transfer.
4. **Structural engineer** – opens the imported reference model, and creates the structural model based on it. Classifies the structural and non-structural elements with the use of the Model Organizer. The base nomenclature with its search conditions (Building 2000 Elements to full depth) is already provided with the Model Organizer, so the engineer only runs the search functions of the Model Organizer. Model Organizer uses the classification in the object attributes to identify the non-structural reference model objects. Drawings are created based on the Model Organizer classes. The structural designer creates the combined model in Tekla Structures based on the architectural, structural and mechanical model. Spaces imported with the reference model are also entered into the Model Organizer. Reporting is done based on the classes in the Model

Organizer. When changes are made to the model, the classification with Model Organizer is easily redefined.

5. **Mechanical and electrical designer** – They have attributes in their model which can be used as a classification base, and can utilize a similar classification tool as the other parties. They utilize the classification created by the structural engineer e.g. the Building 90 in the model and complete it with RYL 2002, the classification system for mechanical engineering.
6. **Contractor** – Receives the model with a model sharing method. Refines Building 2000 to the level of needs in the Model Organizer. In the following points there is an example for the Contractor's process order.
  - a. Quantity list, cost estimation, project budget creation, project schedule creation – Building 2000 Elements depth can be enough, but checking and refinement is probably needed.
  - b. Bid package creation – Building 2000 Elements depth is enough for this purpose.
  - c. 4D work schedule e.g. in Tekla Structures Task Manager, or other software – easy to create tasks based on the Tekla Structures Model Organizer classes.
  - d. Subcontractor tendering – get the precise, time and work package schedule created with the help of the Model Organizer.
  - e. Budget comparison and acceptance.
  - f. Combining models of the contractor and subcontractor if needed.
  - g. Control of implementation – Tekla Structures Task Manager and Model Organizer is utilized, utilizing the 3D model for surveying and for measurement of object positions in the field.
7. **Subcontractor**
  - **Subcontractor** – for implementation work receives 3D model. Refines Building 2000 to the level of needs in the Model Organizer. The organization of implementation work is done digitally.
  - **Steel fabricators and precast manufacturers** – 3D model elements and project management software is used when the

subcontractor is the product manufacturer at the same time. They receive 3D model. When the 3D model is received the elements are ready for production. The internal product classification is a refinement of the Building 2000, so the communication is supported with the other parties. Steel fabricators and precast manufacturers frequently use other subcontractors for the erection process.

8. **Product manufacturer** – receive orders and offers from the contractor. The product numbers or classes correspond to the base classification.
9. **Mechanical (HVAC) subcontractor** – receives 3D model from the mechanical designer, there are no clashes in the model, so there is no need for onsite changes of the plan.
10. **Authority** – Classification system with the 3D model will serve the building acceptance and the building inspection.
11. **Facility manager** – utilizes the combined architectural, structural and mechanical model for maintenance. Facility managers have a special need for the spatial classification.

### 3.7 Industrial impact of the new solution

The compatibility of construction-related information is increased when working on common ground within the classification systems. One of the greatest benefits of the suggested working method is that the changes in the plan are more easily handled with the use of BIM and the common classification system. Construction time can be reduced, costs can be reduced; therefore owners and developers can gain competitive advantage and give their organizations a better return on their capital investments.

## 4. Conclusions and recommendation for future research

The existing international classification systems differ markedly in terms of the levels and details of specification. There are major differences between their uses by construction industry players in particular countries. OmniClass and the Finnish Building 2000 differ in structure but both adequately serve the demands of the industry, and can serve as a base for further project specific refinements.

As a comparison base, OmniClass is the most detailed nomenclature to be used as a base nomenclature.

The initial guidelines are suggested to construction industry players to reach common agreement on the applied classification system with utilizing the benefits of Building Information Modeling. With the available software intelligence, the most beneficial solution is to apply a mixed indirect and manually adjustable object classification system in a 4D modeling software. Tekla Structures Model Organizer is a commercially available tool to implement the suggested working method. After defining the classifier rules once, the assignment of objects to classes is done automatically by the program. The program is capable of handling any changes in the model by rerunning the assignments to classes or by redefining the classes. In order to use this system in practice the user is able to overwrite the rule and to assign the object to any class.

Based on the interviews, the interviewees seem to be convinced about the need for change in the information process in the construction industry, and are committed to the use of 3D modeling and common base nomenclature. The construction industry is slowly changing and still follows traditional methods, but given the right hardware, software tools and applications, people will change their working methods.

The working-out of correct contractual forms supporting the BIM process and requiring the common language of information exchange is inevitable for the success. The present study discusses only the Finnish construction process. In each country, all the different construction methods and processes should be analyzed and developed. In many of the cases the shift from one classification system to another will be necessary towards the optimal information flow. More detailed analyses and formation of public recommendations for certain types of construction processes would help the company managers to formulate the right steps for smoothly shifting the tools and language of information exchange.

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# The Use of Six Sigma and Lean Construction for Assessing the Production Planning Process of Sustainable Building Projects?

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## Abstract

Sustainable buildings have gained an increasing importance in recent years. This has represented many challenges for the current building practice. The complexities involved in the execution of these projects are related to the inadequacy of traditional management systems. However, few are the research works oriented to the identification of the potential areas for improvement. This paper presents an integration approach of assessment performance methods for assessing the production planning process in sustainable building projects. It also rationalizes the relationships between six sigma and lean construction. The aim is to identify and analyze critical factors causing plan variations which can lead to the identification of potential areas of improvement in the current practice. Performance measures are standardized to allow and facilitate the benchmarking between those activities related to the sustainability performance of buildings and the ordinary ones. Finally, a framework is proposed presenting the sequenced processes for implementing this integrated approach.

**Keywords:** sustainable building, six sigma, lean construction, production planning process



## 1. Introduction

Sustainable construction represents many challenges, especially for the building sector's ongoing activities. Buildings are complex entities that involve the consumption of large amount of various types of natural resources mainly during construction and operation stages. Consequently, sustainable buildings emerged as high performance properties that are expected to reduce their impacts on the environment and human health. Sustainable buildings represent a dynamic, rapidly growing and evolving field, driven by a confluence of rising public concerns about global climate change, cost and availability of energy sources. In particular, the topic of sustainable building has received tremendous interest in recent years and is gradually becoming a part of mainstream in the construction industry. However, the attainment of all requirements for accomplishing a sustainable performance in a building has led to a more complex planning by the increment of specialized processes involved.

As sustainable building projects become increasingly complex, dynamic, and pressed for time, the number of specialized parties involved in each project has increase. Although specialization within a project may offer flexibility and benefits to the industry, it has at the same time resulted in tremendous cost in the form of fragmented decision-making [14]. To make matters more complicated, some general contractors have adopted a contract-brokering role rather than the role of coordinating the project [35]. This has exacerbated the fragmentation among parties. Moreover, as involvement of specialized parties increase, the project organizations are becoming larger both vertically as well as horizontally. Therefore, coordinating the efforts of these parties to successfully complete a sustainable project today is a difficult challenge.

The complexities associated to sustainable building projects are deemed to be related to the different needs these represent and that current management systems used in construction are failing to meet. According to Eid [8] successful exponents of sustainable construction will be those that possess the organizational culture and management expertise and have developed the ability to assess and maximize the sustainable potential of any proposed project. Thinking and acting sustainability requires not only incremental change but also a revolution in approach, a shift of perspective, which will need to be reflected in a future generation of management techniques. The need to improve the efficiency and effectiveness of the total construction process through the greater interaction of the different phases is a key challenge. Specifically, the production

planning process (PPP) during construction stage in sustainable building projects is not an easy task. Nevertheless, none of previous research works have focused on understanding the PPP for its improvement. Thus, the assessment and improvement of the PPP is the main focus of this paper. For this specific purpose, it is proposed the use of Six Sigma and Lean Construction as an Integrated Design Solution (IDS) leading to a methodology that assesses the PPP in sustainable building projects and helps to identify critical factors for its improvement.

## 2. Production planning process

In recent years, project management has become one of the essential tools for a successful project completion. The main functions of project management are planning, organizing, staffing, coordinating, directing and controlling [30]. Planning is the first of the many steps involved in project management. If planning were not done meticulously, then the project control and execution would become very difficult. Of equal importance is the process of production planning, which is basically the planning of day-to-day production activities and controlling them to accomplish project objectives. Thus, a good and reliable plan decides the success of all the following functions.

Construction planning and production planning must account for the unique aspects of sustainable building projects. Requirements that differentiate sustainable buildings from ordinary buildings need to be addressed in the construction plan and must be included in the schedule. In particular, these specific requirements will impact the procurement, construction, project closeout and commissioning [11]. Resources procurement for sustainable building projects (e.g. green materials, specialized human resources, equipment) impacts the sequencing of construction activities as well as activity timing. The contractor needs to make sure that resources are capable of meeting the planned production schedule; otherwise, sustainable requirements and constraints can impact construction sequencing and timing. Tommelein [35] emphasizes that a big problem field workers face is that the schedule reflects only anticipated resource availability, but actual resource availability can differ substantially from it, so crews are obligated to deviate from original schedule.

According to Smith et al. [32] tools to support production planning must

1. be able to efficiently generate schedules that reflect the actual constraints and objectives of the construction environment

2. allow these schedules to be incrementally revised over time in response to unexpected execution circumstances.

In addition, Koskela [23] established that a production planning and control system should follow three principles, as follows:

1. Assignments should be sound regarding the prerequisites.
2. Realization of assignments is measured and monitored.
3. Causes for non-realization are investigated and those causes are removed.

Based on these reasons, the PPP in sustainable building projects is considered of vital importance. Thus, its performance assessment and the identification of factors affecting it are necessary to increase the plan reliability of the execution process and consequently the attainment of indicators that define the sustainable performance.

### **3. Performance assessment in construction industry**

Performance assessment is the process of determining how successful organizations or individuals have been in attaining their objectives and strategies [9]. In the manufacturing and construction industries, performance assessment is used as a systematic way of judging project performance by evaluating the inputs, outputs and the final project outcomes [33]. Manufacturing industry has been a source of innovations in construction industry for many decades. This has led to the introduction of well-known methods and techniques used in manufacturing to construction by shifting traditional paradigms. For instance, construction industry has adopted methods such as concurrent engineering/construction, lean production/construction and many others such as Just in Time (JIT), Total Quality Management (TQM), etc.

In the construction industry, performance assessment is the regular collecting and reporting of information about the inputs, efficiency and effectiveness of construction projects. This is normally approach in two different ways: (a) in relation to the product as a facility, and (b) in relation to the creation of the product as a process. Ward et al. [38] suggested that a common approach is to evaluate performance on the extent to which client objectives like cost, time and quality were achieved. However, these are more commonly used at the end of the project and report on decisions made in the past and therefore are of little use in improving current performance.

Emerging techniques and philosophies to assess and manage performance, such as TQM, benchmarking, lean construction, business process re-engineering, business process management, and six sigma have shifted their approach by assessing not only what the performance of an organization was, but the how that performance was achieved in on-going basis.

### **3.1 Production planning performance assessment and improvement**

Productivity is the same as efficiency, which is defined as the ratio, output energy divided by input energy. The key to raising productivity level lies in improving the performance and proportional balance of the input factors, when it comes to the improvement purposes, the objects are to eliminate excess labour and other resources, identify back-end operations more suited to subcontracting/outsourcing and shorten construction.

However, when we use the term “reliable planning” for improving productivity in the construction industry this is still a relative new one. Kaplan and Norton [18] pointed out that the existing construction project performance measurements are based on financial measures. Kartam et al. [19] indicated that available models and performance criteria are insufficient for analyzing and improving the performance of a construction planning system. They also add that many project managers use project performance criteria to control and punish poor performers rather than to improve project performance. Lantelme and Formoso [25] assert that managers regard measurement only as a tool for controlling project participants’ behaviours and that it should be used to communicate goals, share responsibilities, and promote learning in organization. Therefore, in order to promote reliable planning, adequate measurements are necessary.

In the manufacturing industry the use of lean production and six sigma philosophies has led to the better understanding of the “how” the performance was and the acquisition of more information regarding to the improvement of processes. The principles of lean production have been adopted in the construction industry creating the concept of lean construction and companies have repeated the benefits. Six Sigma is not widely applied in the construction industry but some approaches can be found where the advantages of using this method in construction projects have been proved. The following section will discuss Lean

Construction and Six Sigma philosophies, for their integration with sustainable building projects in assessing and improving its PPP.

## **4. Lean Construction and Six Sigma**

### **4.1 Lean Construction**

Lean production has had enormous success in the manufacturing industry [39, 40]. This has led to the exploration and then the development of a lean theory in construction, known as Lean Construction. Lean Construction introduced the production system as a new way to view construction projects with two important recognitions (1) dependences and variations along supply and assembly chains in construction projects and (2) managing product and process uncertainties [15]. Project management which is widely used in the construction industry generally identifies activities only as transformation activities especially in construction projects. This is argued by Koskela [21] who proposed to classified activities in two categories (i.e. transformation and flow). Later, Koskela [22] included the perspective of value-creation, defining the classification as transformation, flow and value activities.

Thus, Lean Construction has the aim to better meet the customer needs while using less of everything based on production management principles. The result is a new project delivery system that can be applied to any kind of construction but is particularly suited for complex, uncertain, and quick projects [15]. The implementation of lean principles in construction may represent differences from the common practice and the following ones can account as the most representative ones: there is a clear set of objectives for the delivery process, it focus at maximizing performance for the customer at project level, activities and processes are designed and it uses production control throughout the life of the project.

Contrarily, in the current form of production management in construction is assumed that the customer value has been identified and therefore the process is activity centered with more focus on optimizing the project activity by activity. Production is managed during a project by first breaking the project into pieces (i.e. design and construction), resources are estimated for each task and these are grouped in activities. These activities are therefore ordered in a logical sequence and assigned to crew leaders or foremen. Finally, these activities are monitored against their schedule and assigned resources.

## 4.2 Six Sigma

Six Sigma was developed by Motorola in 1985 as a system that would help them achieve near-perfect products [6]. The system has as main goal to reduce variability and in order to do it, it uses various statistical methods and tools to identify and reduce variability and thus achieve a 'closest to zero-defect' product. Linderman et al. [26] stated that six sigma is a statistics-based methodology that relies on the scientific method to make significant reductions in customer-defined defect rates in an effort to eliminate defects from every product, process, and transaction. Sigma ( $\sigma$ ) is the symbol for standard deviation in statistics. Thus a six sigma level means having all the products produced within six standard deviations of the mean (average). Thus a process having a six sigma yield level will have 99.99966% of its products produced without defect. The methodology used to achieve six sigma goals is known as DMAIC (Define, Measure, Analyze, Improve, and Control).

The aim of adopting Six Sigma is to bring the defect rate of a process or a product as low as 3.4 defects per million opportunities, which is expressed as  $6\sigma$  level. For example,  $6\sigma$  level represents one misspelled word in all the books in a small library, while  $2\sigma$  represents approximately 25 misspelled words in a book [6]. However,  $6\sigma$  level can be considered an inappropriate goal for construction operations. In the construction industry instead of looking to use six sigma as a way to achieve 'a close zero-defects' or  $6\sigma$  level, its use should be related to evaluate the project's performance improvement as an extension of the traditional approaches for achieving a high level of process quality.

The use of Six Sigma in the construction industry is relatively new and some of the first approaches encountered in the literatures particularly aimed at high quality and variability control [7]. Later, Kroslid [24] proposed the combined use of Six Sigma and lean principles as a way to achieve an outstanding performance. More specifically, Abdelhamid [1] looked at reducing the variability in lean construction by using six sigma principles. However, few are the cases where research has been conducted considering the defect rate involved in specific construction operations in order to define quantitative goals for performance improvement.

## 5. The integration

Even when Lean Construction and Six Sigma have brought benefits to the construction industry, these still have limitations. For example, Lean Construction does not clearly show the underlying mechanism of how to measure the level of defects in work processes. Lean construction also cannot set a quantitative goal to improve this workflow by removing the critical causes of defects in process variability. This is a very sensitive issue in the construction industry due to the fact that defect rates in construction processes is largely caused by unreliable workflow when sources of process variability are involved [13, 34]. Thus, Lean Construction is able to address the effect of variability, but do not help to eliminate or reduce variability by removing the root causes of the whole [1]. On the other hand, Six Sigma is focused on reducing variation and improving process. However, Six Sigma does not always address the way process flow is to be optimized. Thus, Six Sigma is suited to problems that are hard to find but easy to fix, while Lean Construction can work better with problems that are easy to find but hard to fix [12].

Therefore, for the PPP performance assessment and the identification of factors affecting it, the integration of six sigma and lean construction is proposed. In order to graphically introduce the proposed integration, the conceptual model is shown in Figure 1.

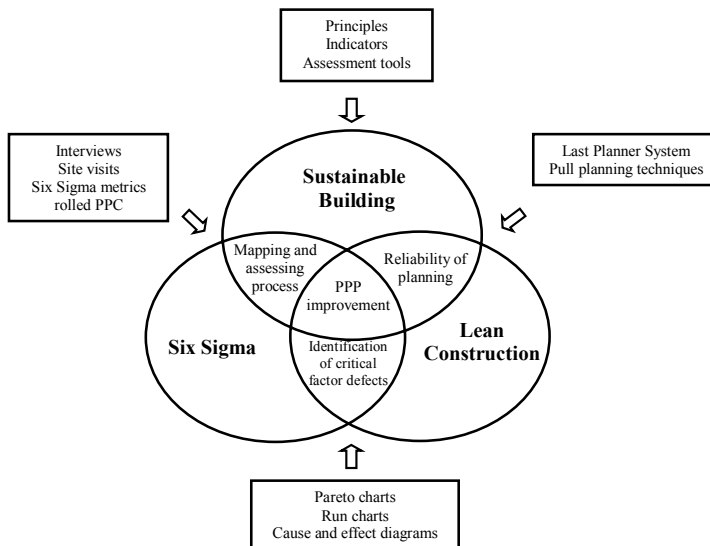


Figure 1. Conceptual model.

## 5.1 Sustainable building performance

In order to define a sustainable building and what determines its sustainable performance, indicators and their respective benchmarks must be identified for defining those activities that are related to sustainable deliverables which as a whole define the sustainable performance of a building. For the purposes of this research, these activities are denominated as “S activities”. The importance related to the identification of “S activities” lies on the aim to differentiate the performance of these activities from ordinary ones which can lead us to better understand the causes affecting their performance and the management needs related to them.

However, in the process of achieving higher sustainable performance standards, different verifiable sets of criteria have emerged. Separate indicators, or benchmarks based on a single criterion, have been developed to monitor specific aspects of sustainable building performance such as energy and water use. Several literatures provide valuable references of these indicators. These include BEES [27], Simapro [31], EcoQuantum [20], LCExplorer [28], DOE2 [3]. According to the classification of assessment tools provided by ATHENA [36], ‘whole building assessment frameworks or systems’ such as BREEAM [4], GBTool [16] and LEED [37] contain the suitable indicators that assist to define the desire objectives and strict performance criteria of an entire building. Particularly, these assessment tools have contributed enormously in the achievement of sustainable building projects and their indicators ensures that the evidence of sustainability can be obtained in the assessment process, and that performance criteria and sustainability level can be defined. Each indicator own a certain number of credits and this are awarded according to the level of compliancy with the benchmarks established. The way of selecting the indicators and the allocation of credits varies depending on national, regional or local contexts and conditions [17]. Thus, these tools are considered suitable for the identification “S activities”.

## 5.2 Mapping process

For defining the PPP in sustainable building projects it is important to recognize that it is different from one contractor to the other. Therefore, it is appropriate to use mapping techniques from Six Sigma that can assist to define this process. Mapping of a process involves determining the process inputs and outputs, the sustainability adding sub-processes, the involvement of any other process, flow



of information and all cross functional activities. Once these are determined, it is easier to create a process map. A process map is similar to a basic flow chart with all functions shown in boxes and flow of data shown by arrows [29].

By mapping the PPP we can obtain the following advantages: give a clear big picture, define the key inputs and outputs of the process, facilitate the understanding of cross functional activities, show the interface between various contributors in the process, show how the process flows through the organization, and highlight the ‘sustainability adding sub-processes’ related to “S activities” in the overall process. In order to map the PPP, accurate information is needed which can be obtained firstly through structured interviews which can help us to have a first draft of the map. Later, site visits will help to develop a more detailed map and validate it with the personnel more closely related to the process. The importance of the mapping process lies on the definition of the process that is going to be assessed and improved.

### **5.3 The assessment process**

For the assessment process the use of Six Sigma and Lean Construction metrics are proposed (i.e., Six Sigma level and the Percent Plan Complete (PPC)). Six Sigma metrics provide a more detailed understanding of the process and communicates more accurately its performance. The performance measure is standardized by using this metric which can be used to compare the performance of various activities and processes. The advantage of finding the Six Sigma level is that it better reflects the magnitude of disability in the PPP to maintain a reliable workflow.

The metric know as a PPC comes from a system called Last Planner System (LPS) developed under the principles of Lean Construction which provides a framework to plan and control daily production assignments in a construction project [2]. This metric is represented as a percentage with a range from 0% to 100% and is calculated as a ratio of the number of activities completed to the total number of activities planned in a given period of time. Therefore, the higher the PPC, the more reliable the PPP is.

On the other hand, Six Sigma uses the rolled throughput yield ( $Y_{RT}$ ) which communicates the probability that a single unit can pass through a series of process steps free of defects [6]. Defects in the construction projects can be seen as the activities that were not completed as planned. Thus, PPC can be adopted in order to represent the  $Y_{RT}$ . Abdelhamid [1] suggested the use of a metric called ‘rolled PPC’ similar to the rolled throughput yield in a manufactured

homes factory. By using the ‘rolled PPC’ metric he exposed the hidden factory (rework performed to rectify defects during sub-processes). The ‘rolled PPC’ metric gives a better sense of magnitude of the process performance failure [1].

Therefore, the ‘rolled PPC’ metric is proposed to be used for assessing the efficiency and effectiveness of the PPP in sustainable building projects. This metric better communicates the deficiencies of the planning process. In contrast to calculation of PPC, the ‘rolled PPC’ will reflect the magnitude of the problem, and thus it is more realistic for performance assessment.

#### **5.4 Identification of critical factors causing defects**

The assessment and analysis of any process are necessary steps to identify the factors affecting it. Once the process performance is measured, it makes it easier to analyze and find out the shortcomings in the process. Then, the identified factors should be rectified or removed for improving the production planning performance.

For the identification of factors affecting the performance, Pande [29] proposed that the best way to do it is when these can be presented with visual tools. Visual presentation of information helps to better understand the process and to identify the source of the problem. Some common techniques used are: Pareto Charts, Frequency Plots, Run Charts, and Correlation Diagram [5, 10]. The Pareto Charts used in Lean Construction and the Run Charts used in Six Sigma are proposed as suitable for the identification and analysis of the critical factors affecting the PPP performance.

Pareto Charts will help to highlight the factors that cause most of the problems and therefore should be analyzed for eliminating their root causes. These factors can first be categorized in different areas and then each area analyzed separately. On the other hand, Run Charts will help to identify the variations and patterns in the process over time (e.g. daily, weekly). For understanding the PPP and its performance is important to analyze the behavior of its variations and how these are responding to a change. Moreover, in construction projects the number of activities (i.e. products or samples) is variable over time, thus p-charts which allow the variability in sample size are proposed.

The Pareto Chart and the P-Chart, as described, help to detect the problem area and specific problems. The next step is to find the root causes for the identified problems causing variations. Variations in a process performance in sustainable building projects can occur due to many reasons, such as materials, methods, measures, equipment, environment, and people [11]. The identification

of the causes of these problems in a specific project can be done by drawing a “cause and effect” diagram as used in Six Sigma. This diagram will help to visually display the potential causes of a specific problem causing plan variations.

## **5.5 Increase reliability of PPP**

Once the indicators that define a sustainable building are identified, the PPP is documented and mapped, its performance is measured and the factors affecting it are detected. These factors should be removed for improving the reliability in the PPP when executing sustainable building projects. It is expected that with the reduction of plan variability by eliminating the factors causing it, the efficiency and effectiveness in sustainable building projects will increase.

The root causes identified can help us to localize the areas and specific processes that bring more constraints to the execution of activities as these were planned. For increasing the reliability of the PPP, these constraints should be analyzed and eliminated. This process should be speed up by first analyzing the areas where critical factors have already been identified. Therefore, it is proposed to use a pull planning system where the activity constraints emerging from these sources are eliminated before activities are programmed for execution. The previously mentioned LPS is a lean based production planning and control system which promotes the pull planning system. Ballard [2] introduced the LPS as a system of production planning and control which can increase workflow reliability. Activities ready for execution in the Last Planner System are firstly subjected to a constraint analysis that ensures no obstacles will prevent execution. If the last planner finds a constraint which could not be eliminated on time, the activity would not be allowed to move forward. Moreover, the last planner should sustain a backlog of work ready to be performed; assuring that all the activities in the backlog can be executed [2].

## **6. The DMAIC framework**

In order to follow a sequenced order for the application of the methods and techniques previously presented, the DMAIC framework is adopted. DMAIC is used in Six Sigma as a guide to improve an existing process [29]. This framework includes five steps namely Define, Measure, Analysis, Improve and Control. In this section, the process is illustrated in Figure 2 where the DMAIC framework is described by presenting the inputs, processes and outputs for each step.

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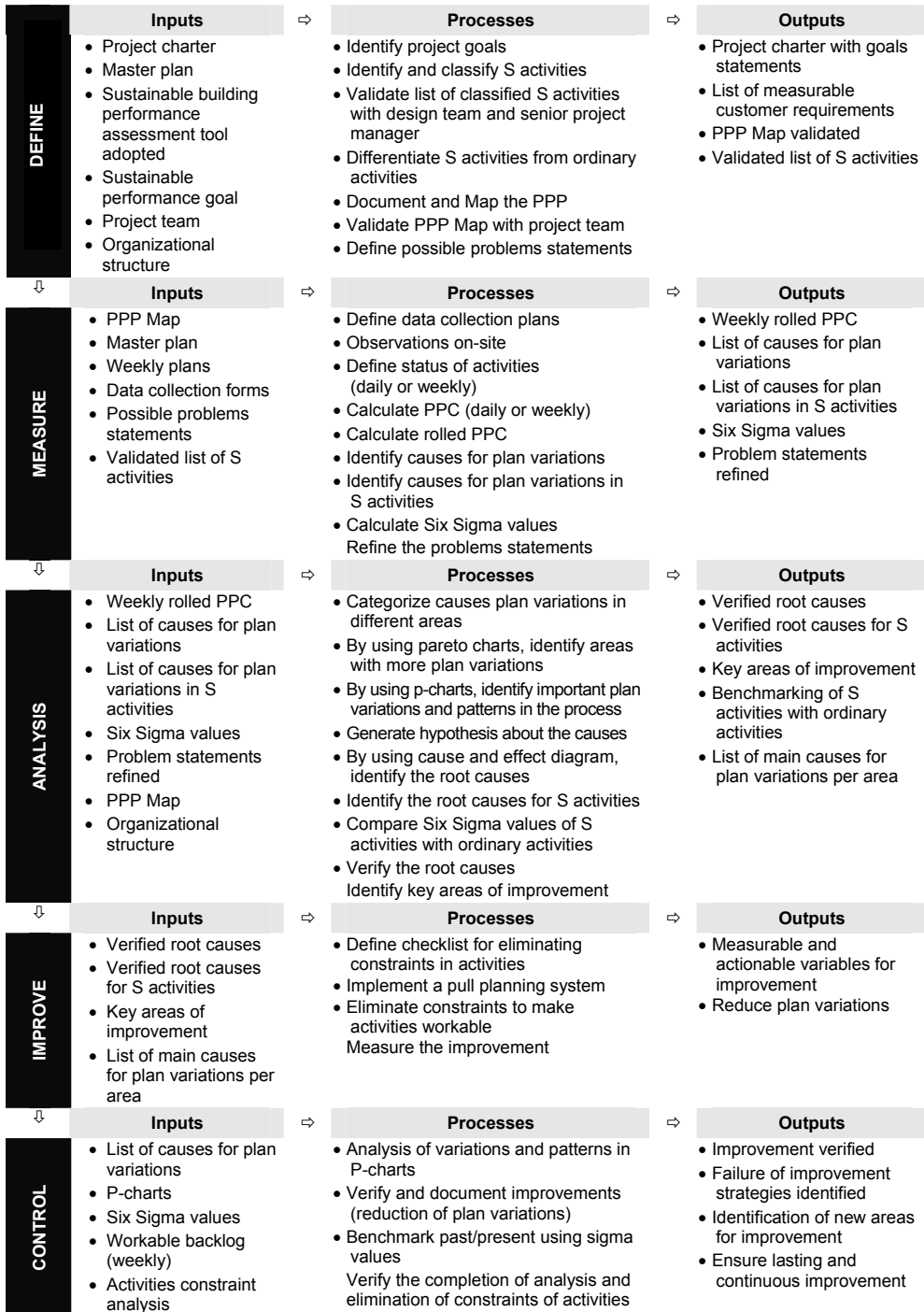


Figure 2. The DMAIC framework.

## 7. Conclusions

The improvement of traditional management systems to better achieve sustainable building projects is an imminent need. This paper proposed an Integrated Design Solution (IDS) to identify and evaluate the critical factors causing the plan variations in these projects which can lead to the detection of areas of improvement in the current practice. Moreover, performance measures are standardized which facilitates the benchmarking between those activities related to the sustainability performance of buildings and the ordinary ones.

The expected benefits derived from the implementation of this integration approach are considered of high importance to the building industry. The increasing demand for meeting sustainable performance in building projects is leading this industry to face important challenges that come from the emerging needs. In order to overcome these challenges in an effective and efficient way, they must accurately identify the areas that need to be improved, define strategies for improvement and be able to measure this improvement. This is also beneficial in the academic field, since it can provide evidence that demonstrates the areas of opportunity where new management systems are required to be developed for minimizing inefficiencies and enhance the value delivered during design, planning and construction.

The limitations of this integration approach are implicit in its conceptual nature, which lacks of validation from extensive empirical evidence. However, it is the intention of the authors to test it to derive its final form. It is believed that this approach can form the basis for effective management systems in the aim to better achieve sustainable building projects.

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# Optimizing Construction Planning and Scheduling through Combined Virtual Prototyping Technology and Building Information Models

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## Abstract

As the design of building has become more complex nowadays, it is very difficult for project managers to compute the time of construction planning and scheduling accurately. There is a pressing need of high level computer-assisted technologies to develop a comprehensive construction planning and schedule before a project is actually built. Currently, these computer-assisted technologies are often limited to the function for the examination of constructability or so. This paper introduces the use of combined virtual prototyping (VP) technology with Building Information Models (BIMs) to optimize the construction planning and scheduling. A real-life case study is adopted in the paper to show how the VP technology and the BIMs are used to conduct construction planning and scheduling, particularly focusing on arranging tower cranes to achieve the construction floor cycle.

**Keywords:** construction planning and schedule; virtual prototyping, building information models

## 1. Introduction

Currently, undertaking of a building project is similar to a gamble; contractors cannot predict the result at the beginning of a construction project owing to its characteristics (e.g. need for coordination of multidisciplinary teams, complex nature). This emphasizes the importance of project planning and scheduling. Project planning and scheduling is a critical process that determines the successful implementation and delivery of a project [1]. However, currently project planners are left without effective technologies to do the job, although planning approaches such as the critical path method (CPM) and bar charts are always employed. This in turn leads to the fact that in the construction sector design errors or imperfections are prevalent in construction plan and schedule; in practice, project planning and scheduling relies heavily on rules of thumb by experienced individuals. There is a pressing need calling for effective technology to conduct construction planning and scheduling.

Project planning and scheduling, by definition, is to involve the choice of construction technology, the definition, the estimation of required resources and durations and the estimation of costs [2]. It concerns the optimal configuration of construction process, activities, and available resources to achieve project goals such as time, cost, and quality. Traditional planning approaches such as CPM and bar charts have been devised and are still using in construction practices. With the increasing complexity of modern construction projects, computers were identified as an efficient tool to help project planner. However, the traditional approaches like bar charts and CPM cannot provide the spatial construction features, the resource and working space requirements [3, 4]. The traditional techniques of resource management have been classified into three categories: resource allocation, resource leveling and Time-cost trade-off analysis. Chan et al. [5], Hegazy [6], Leu and Yang [7] combined resource allocation and leveling using GAs. Li and Love [8] proposed GAs for the time-cost optimization problems. Hegazy and Kassab [9] combined a flowchart based simulation tool with GA technique. Wang et al. developed 4D Management for Construction Planning and Resource Utilization (4D-MCPRU) system which links 3D geometrical model with resource to compute the resource requirement [10].

All of the previous resource planning and allocation did not take the real productivity rate into account to analyze the resource. The application of VP technology should assist planner to identify construction method and prepare construction schedules [11]. Based on the present VP technology, adding real

productivity rate into the system can increase the objectivity of the construction planning and scheduling. The VP system furnishes the project planners a useful tool to plan the construction planning and scheduling. It allows them to consider objective productivity data to predict the potential constructability problem and analyze resource allocation including tower cranes to modify construction sequence to accomplish a comprehensive construction planning and scheduling.

The aim of this research is to introduce VP technology into the optimization of construction planning and scheduling. The research methodology taken was an “action research” approach. The paper first describes the framework of construction planning and scheduling through combined VP technology and BIMs. Next, a case study showing how the construction planning and scheduling is optimized through VP technology is presented. Finally, the future improvement on VP technology is discussed and concluded.

This idea achieves the vision for Integrated Design Solutions (IDS) as the construction planning and scheduling integrated two new technologies that are VP technology and BIMs to minimize the planning errors and mistakes. Also, this solution can be applied on different construction projects during the construction stage.

## **2. Method**

The research methodology taken was an “action research” approach where the researchers and developers were actively involved in the production of the virtual prototypes on behalf of the contractor thereby gaining consistent access to the decisions of the planning staff. The experiences from the case study were considered together with similar research on other construction projects.

## **3. The framework of construction planning and scheduling through combined VP technology and BIMs**

### **3.1 Definition of BIMs**

BIMs (Building Information Models) contain precise geometry and relevant data needed to support the construction [12]. However, in this paper, the BIMs are identified into two categories: construction model and resource model.

### Definition of construction model

There are two types of digital models for construction. The first type is same as BIMs which help evaluate performance by using information embedded in 3D models. The key function of BIMs on construction field allows the planners to view their static realistic images and check the design error and collision. However, the temporary works are the critical element in the whole construction planning [3]. This type of model is to develop the temporary work models generating by the parametric models. The details of temporary work model are available in Huang et al. [1].

The second type of digit models is similar to BIMs but this type of model is a detailed building component models which are related directly to construction activities. The purpose of these models is not only to be uses on the design check, but is also closely associated with the construction planning and scheduling. These types of models decompose serial assembly models developing a detailed construction activity. The decomposition of a product is the precondition of goal of simulation and assembly of parts is closely related to simulation process. As such, the purpose of the simulation is to display the sequence of pouring concrete. One floor of 3D concrete model will be decomposed into different assembly models (i.e. inner slab, half of outer slabs, outer wall, inner wall, each column) which are related to the sequence of the simulation (Figure 1).

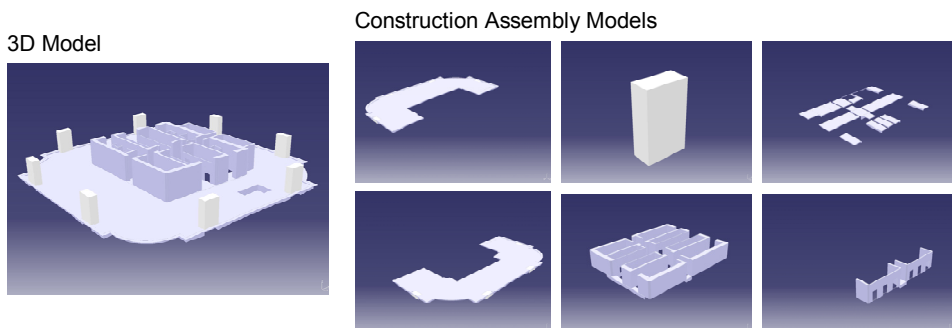


Figure 1. Decomposition of BIMs.

### Definition of resources model

Two resources models can be identified: equipment-based model and activity-based model.

**Equipment-based Model** – The characteristic of the equipment-based Model is a 3D-geometry equipment model linked with the productivity rate of equipment in database Excel library and physical capacity data. As such, tower crane contains the graphical information that is the exact geometry, shape and dimension for space analysis as well as the equipment capacity (i.e. maximum capacity, maximum lifting height and maximum radius) for testing the operating capacity.

**Activity-based Model** – The characteristic of the activity-based Model is a non-physical model linked with the productivity rate in database Excel library like the fixing reinforcement activity. Then, the activity-base model will be linked with construction model by users when generating the simulation process in virtual prototyping system to develop one process activity in the system.

## 3.2 Implementation

The database of the productivity rate and the construction planning and scheduling stores into Microsoft Excel format. The virtual prototyping system was implemented by using Visual Basic for Applications (VBA) in DELMIA V5 environment, and Microsoft Excel to develop the productivity database and the planning and scheduling linking with 3D Model. VBA is an object-oriented programming language to develop specific function. VBA provides a seamless link between the components of the model, supported by a powerful graphical user interface (GUI). The equipment-based model and the activity-based model will link with the productivity rate of equipment and the activity's productivity rate respectively.

## 3.3 Integrated construction planning and scheduling, site layout planning and all construction process activity

The 3D site layout model is developed based on the 2D site layout planning on VP system. Through the VP technology, a process activity is generated by linking a construction model and an activity-based model or by putting a construction model and an equipment-base model together. Combining each process activity with the construction planning and scheduling, along with the 3D site layout planning, a process simulation is developed (Figure 3).

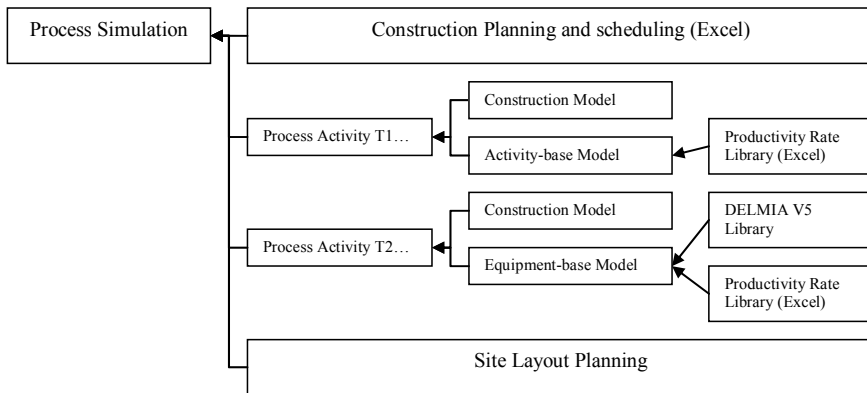


Figure 3. Structure of virtual prototyping.

### 3.4 Resource analysis

In construction field, all activity duration is based on the experience of the project managers. The duration of activities is therefore often uncertain. One major function of VP system utilizes the real productivity data from system database to verify and then adjust the resource allocation to optimize the construction planning and scheduling. Through the process simulation, resource can be analyzed. Most building construction projects rely on tower crane to perform lifting and hoisting activities [13]. Tower crane is the most critical factor of the construction planning and scheduling. Through 3D visualization and simulation on tower crane, the planner understands the planning in details and is able to predict the planning mistakes [14]. The following sections will describe how resource allocation analyzed by using a case study.

## 4. Case study

### 4.1 Introduction

The case study was about two residence buildings project in Hong Kong. At the time of our research, the foundation of the two building was already completed. The site layout planning had been done. During construction, the project managers encountered a critical problem while planning the construction typical cycle. They would like to have a visualization, digit and mathematical method to measure the constructability of construction planning and scheduling. They

provided us a preliminary construction planning and scheduling of typical floor construction which was a time slot – planning and scheduling on a 6-day cycle.

The building used the prefabricated concrete facades that were supported by in-situ concrete walls and lift core and half of in-situ slab. The two buildings were named No. 1 and No. 2 respectively. The project managers divided the buildings into two working bays in the middle. The bays of building No.1 were namely 1A and 1B. The bays of building No. 2 were namely 2A and 2B. The construction cycle of each bay was one day behind one another so as to fully utilize the tower crane.

A set of steel formwork panels was applied on all the concrete walls and concrete slab. Project managers planned to construct the two buildings at the same time but only one set of steel formwork was used. Two tower cranes were installed in the construction site for lifting the formwork panels, prefabricated concrete façade, reinforcement bars and concrete buckets. One Tower crane (T1) was installed between Bay 1A and Bay 1B while the other tower crane (T2) was installed in the middle of Bay 2A and Bay 2B (Figure 4). The two tower cranes were of different capacities. The maximum radius of T1 was long enough to reach Bay 2B whereas the maximum radius of T2 can only reach the temporary storage space. There were two ways to lifting the steel formwork. One was directly lifting the formwork from bay 1A to bay 2A by using T1. The second one was lifting the formwork from Bay 1A to the temporary storage space between the two buildings by T1 and then the formwork was lifted by T2 to Bay 2B. For pouring concrete, both Bay 1A and Bay 1B used the tower crane while a placing boom was used in Bay 2A and Bay 2B.

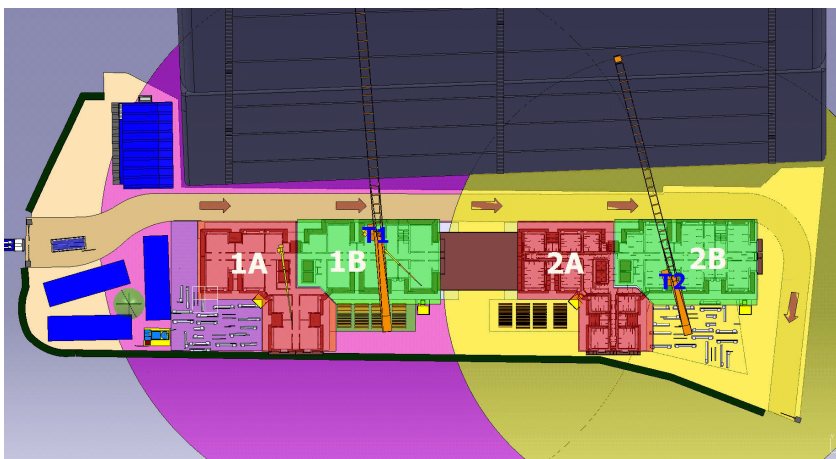


Figure 4. The location of the two tower crane and the four bays.



Project planners encountered a critical problem on the construction planning and scheduling. All preliminary planning duration of the activities were not computed by mathematical method. They wanted to use the real productivity rate data to verify the construction planning and scheduling especially for the cranes as they were the critical elements on the whole construction planning and scheduling.

## **4.2 Preparation of construction model and resource model**

A BIM of temporary work was developed based on the design drawings prepared by nominated subcontractor and that of building component was built based on the process activities to decompose the suitable assembly models. The equipment of two tower cranes and the placing boom were built to the equipment-based Model. Their capacities were based on their capacity catalogues to build. The activity-based Model was prepared from previous projects.

## **4.3 Start from preliminary construction planning and scheduling**

In this case, the main construction method was to use of one set of steel formwork for two buildings to reduce the cost of steel formwork. However, there was not enough space for storing the steel formwork. The schedule of the project was represented with simple time slot document. We generated a template of construction planning and scheduling in VP-Excel format for inputting the time slot planning data (Figure 5). The planning and scheduling was imported into the VP system. It can allow the users to link the process activities with their related Construction Models and Resource Models (Figure 6).

## **4.4 Build site layout environment**

The project planners had finished the site layout planning before we joined. We based on their 2D site layout planning to build the 3D site layout environment such as the location of two different types of tower cranes, site office, storage area, passenger and material hoists and access road. The 3D site layout could provide a virtual construction site for VP system to analyze the assignment of tower cranes.

# Optimizing Construction Planning and Scheduling through Combined Virtual Prototyping Technology and Building Information Models

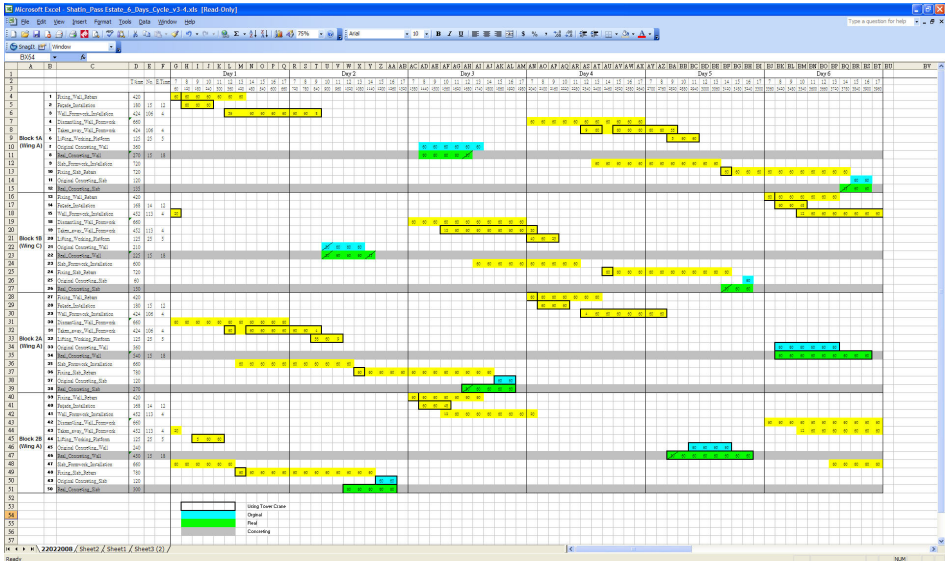


Figure 5. Construction planning and scheduling for VP-Excel Format.

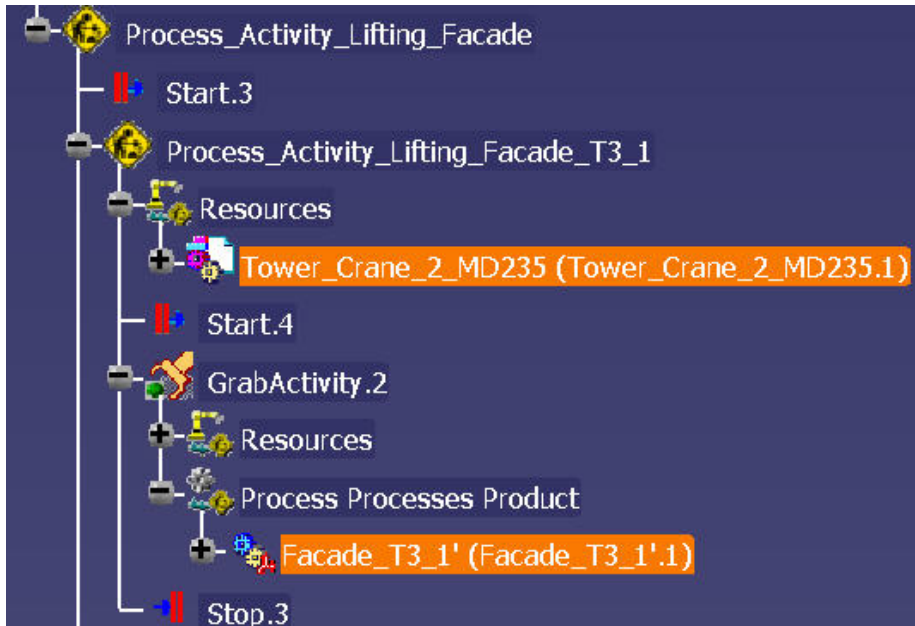


Figure 6. Assignment of the tower crane to lift the façade in one process activity.

## 4.5 Analysis the resource allocation

By integrating the preliminary construction planning and scheduling, site layout planning, construction models and resource models, the simulation of the construction process was developed to analyze the resource allocation. All productivity data of the activities were obtained from various previous projects. The data was thus objective. We would apply the tower crane into these activities. The data included the duration of delivery material as the material must be delivered to the site before the installation of this material to prevent delays to other work. There were different types of productivity rate related to the tower crane (Table 1). The user defined activities which are linked with tower cranes in order to analyze the accuracy of the construction planning and scheduling.

Table 1. Different type of productivity rates related to Tower crane.

	<b>Tower Crane</b>
The capacity of transit mixers	Yes
The speed of pouring by using tower crane	Yes
The lifting time of rebar	Yes
The lifting time of steel formwork from the building to temporary storage platform	Yes
The lifting time of steel formwork from 1B to 2B	Yes
The rising time of the working platform	Yes
The lifting time of rising and installation of facades	Yes

The planning of the usage of the tower cranes was crucial to timely and safe achievement of the 6 day floor planning and scheduling as cranes were involved in various activities across a construction site and a large number of building components were installed by using the cranes. Firstly, based on real productivity data, the VP system checked the duration of the construction planning and scheduling used by the tower cranes and then adjusted the activity duration. Secondly, based on the preliminary construction planning and scheduling, the VP system visualized and showed the clashed activity by using tower cranes on the display and Gantt Chart respectively (Figure 7). Through these two steps, users adjusted the construction planning and scheduling to achieve no-clash activity on the planning according to the clashed activities.

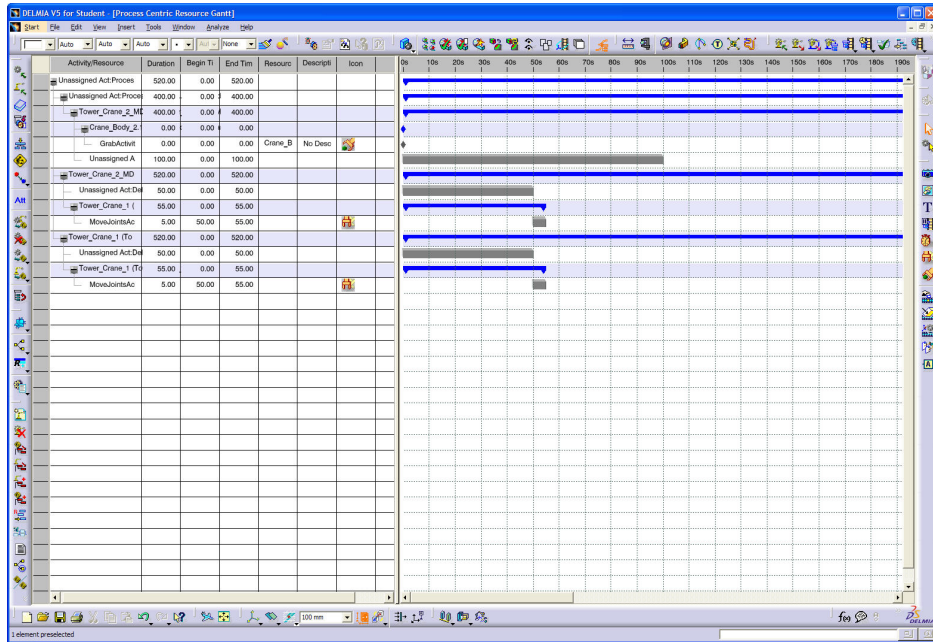


Figure 7. Assignment of two tower cranes in Gantt Chart.

## 5. Conclusion

It is believed that virtual prototyping will have strong potentials and will impose significant impact on the construction. In this paper, it illustrated how construction model and resource model can be prepared for the construction virtual prototyping. The purpose of using VP technology to construction simulation is to assist project planners to better understand construction planning process and predict the construction mistakes. The case study illustrated that VP system enabled the user to validate the proposed construction planning and scheduling. From the experience of the case study, access road is a key resource on construction planning and scheduling. The resource of access road should be analyzed in the VP system. This approach achieves the vision for Integrated Design Solutions (IDS) as the construction planning and scheduling integrated two new technologies that are VP technology and BIMs to minimize the planning errors and mistakes. Lastly, we are currently looking for other real projects to analyze critical more resources in order to optimize the construction planning and scheduling before building.

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# Location Tracking of Prefabricated Construction Assemblies

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## Abstract

This paper describes Internet based prototype tool for locating structural steel components at a construction site equipped with wireless Ethernet. The tool runs in a web browser on a notebook or on a Pocket PC and shows the location of an assembly on an aerial image or on a land survey. If the component being sought is not yet unloaded, it informs the user the trailer number and its location. This approach is based on the integration of location information with the component related information across the material handling process starting at the fabricators facility through the assembly of the building structure. Although the tool has been developed to assist the iron workers to locate structural steel, the concept is applicable to other prefabricated assemblies. The paper identifies the future research challenges and discusses different types of maps to assist users to help locate materials.

**Keywords:** prefabricated assemblies, tracking, integrated information flow, material handling, construction

## 1. Introduction

Construction of a large structure would typically require the handling of thousands of prefabricated construction assemblies at the fabricator's site and at the construction site. As the assemblies move through the various work steps of being fabricated, stored, transported and erected, there is a substantial re-entry of data required at each step. Finding these assemblies, such as structural steel beams and columns shown in Figure 1, can be time consuming in large material storage lay-down yards such as found either at the fabricator's site, or at the construction site. It can be especially so if assemblies are covered in the snow or hidden by vegetation. Time spent in searching for the assemblies and the related information is time wasted and has a negative impact on the construction workers productivity. This waste can be reduced if the latest information regarding the status of assemblies, its attributes, and location can be found at any work step and can be accessed from anywhere. This will not only help reduce the time to locate assemblies as they move through the work steps but will also support planning decisions that are location dependent.



Figure 1. Finding snow covered components could be very frustrating.



Most general contractors, sub-contractors, material suppliers, and sub-assembly manufacturers still rely on paper-based systems to track prefabricated assemblies. The lay-down yards are divided into zones and the location of materials is recorded in a paper notebook. There could be several people, each having a separate paper pad for recording the location information. Finding the location of a desired assembly by flipping through the pages of multiple paper notebooks is time consuming and could often be very frustrating. Not only is the current practice labor intensive and inefficient but it is also error prone due to incomplete information, illegible handwriting, and spelling mistakes. Moreover, the location data is not easy to update as in most lay-down yards the construction assemblies have to be moved from location to location multiple times before being finally erected.

Unfortunately, there is little academic research data available on the economic impact of applying material tracking. Torrent and Caldas [6] note that craft labour hours are increased by 16–18% due to material not being ready and that, based on other published works, workers can waste up to a third of their working time searching for materials. More colloquial evidence can be found in industry periodicals. An article by Sawyer [4] on a recent case study notes the cost benefits involving two similar industrial construction projects comparing the use of an automated material tracking system versus a manual system for a lay-down yard. The results were sufficiently compelling, after the initial stages, that the case study was stopped early to allow both projects to proceed using the material tracking technology. Times to manually track items were averaged about 36.8 minutes versus only 4.6 minutes using the automated system. Furthermore, almost 10% of the items sought manually “were not immediately found”, in comparison to only 0.54% using the automated system. In another article [3], Sawyer notes that the time saved as a result of knowing where precast members were and controlling the sequence of use saved about 10 days on a project equating to \$1 million.

Academic researchers have been interested in the problem of tracking construction materials for some time. One early example is the work done by Lundberg et al. [2]. They built a system where the user was presented with a CAD model of the lay-down yard and construction site with the location of the construction material. The system integrated radio networked hand-held bar code readers, a custom local multi-antenna radio transmission-based triangulation system which tracked beacon-equipped transport equipment, and a server computer to record material movement and other data. A significant amount of

manual work was required to scan and initiate location data recording during each material movement and the manual creation of the initial CAD representation of the site. Their solution depended on the use of a custom position tracking technology making adoption of their approach by others difficult and expensive.

A decade later, Stone et al. [5] developed a system capable of tracking material in lay-down sites including location and orientation of the material. Their approach made use of both RFID and bar code technologies for tagging the material being tracked and wireless communication with portable computers to communicate with workers in the field. By providing web-based access and updating of temporal databases recording material status and the recording of both position and orientation of the material after each transition, the system is capable of capturing data for as-built documentation. In order to capture the spatial orientation of each object, CAD models of all parts being tracked were required, and operators were required to gather accurate measurements of at least three “fiducial” position points (points defining the orientation of the material in 3D space) using specialized tracked equipment after each material movement. The authors’ note that usually this process takes only 30 seconds but this doesn’t take into account the time required for first unloading from the transport equipment and then long items, like beams, will also take significantly longer for the operator to walk around and measure each of them. This can be considered a major impediment to technology adoption even though the eventual pay off could be accurate as-built models.

Research work in this area remains very active for industrial construction applications [6] with current approaches making use of modern active RFID tags, networked GPS-equipped sensors mounted on mobile equipment and localization algorithms to refine position information based upon multiple remote material detections. Localization algorithms are required to extrapolate likely material positions based on multiple sensor readings by RFID readers installed on GPS-equipped vehicles that drive around the yard to scan and record the signals from the active tags. The broader the range, the more likely every material tag will have been sensed but the more difficult it is to narrow down the precise location. Thus, selection of RFID signal response strength limits requires making a trade-off. One draw-back to this approach is the use of active sensors costing about \$30 each, making this approach more likely in bigger capital projects.

Though the enabling technologies for tracking of materials such as bar codes, RFIDs, GPS, etc. have been around for some time, the adoption by the construction industry has been very slow. Tracking of components through

computer systems, with varying degree of automation, is very common in the manufacturing industry, whereas the same cannot be said for the construction industry. There are two major reasons; one is that, traditionally, the construction industry has been slow to adopt information technology solutions, and the second being that implementing tracking in the construction industry is much more challenging due to the harsh outdoor conditions and uncontrolled environment. Unlike in manufacturing and warehouse applications where the materials are stored indoor with components or pallets organized in racks, most construction materials are stored outdoors, on the ground. Tracking solutions very much depend on how the materials are tagged, handled and stored. Therefore, the solutions for the construction industry must work reliably and accurately in all types of weather, ranging from the hot summers to cold winters, from bright daylight to night illumination, and from rain to snow. The harsh outdoor conditions, combined with the storage scheme ranging from free form to pre-designated zones or grids on the ground, makes implementation of reliable and accurate material tracking a very difficult problem in construction industry.

The approach presented in this paper contributes to the Integrated Design Solutions (IDS) vision of CIB by showing that the problem of process inefficiencies in the materials management in construction industry can be addressed through the data integration and information management across the worksteps ranging from fabrication to installation of materials. The inefficiencies in tracking of materials arise as the latest and accurate information regarding the status of location of materials is not readily available. The economic benefits of materials tracking system can only be fully realised when it is integrated with the design, manufacturing, quality control, and materials handling work processes. The isolated development and deployment of just the material location tracking will only bring very limited economic benefits and may require manual re-entry of some data that may exist in some other system, for example weight of assembly, measurements, job number, etc to populate the database. Whereas a fully computer-assisted integrated tracking system will eliminate the manual data re-entry by integrating the data from other work units of the organization such as design, scheduling, manufacturing, quality control, and yard management. This integrated system will enable better coordination between the work processes leading to better planning of material handling operations culminating in higher efficiencies. The vision of IDS to achieve the integration between different phases of project throughout the whole life cycle when applied to the materials tracking would mean improving the communication

regarding the status and location of materials with all the parties in the supply chain including the fabricators, general contractor, and sub-contractor. A materials tracking system integrated across the supply chain would enable all parties to query the latest status and location of materials thus resulting in better planning across the project organization.

## 2. Integrated tracking tool

Finding the structural steel components at the lay-down yard of a large construction project can be time consuming. The current practice for the material handling of a steel framed building is that the structural steel components are received at the project site in trailers and unloaded to the ground as shown in Figure 2. The number of trailers that are simultaneously unloaded depends on multiple factors such as the size of the construction site, and the urgency to free up the loaded trailers for other projects, etc. After unloading, components are then quickly organized on the ground such that piece marks are visible to the iron workers. This step is known as the shakeout.

The foreman of the erection crew refers to the erection drawings and expects the arrival of the structural steel members in the order in which they are to be erected and he/she creates a list of piece marks on a paper notebook. The list is then used by the ground crew to search the steel members needed next. There are many instances when the search results *are* negative because the component has either not been shipped from the factory or has not been unloaded from one of trailers parked at the site. In such situations iron workers search more thoroughly on the ground and this can take several minutes depending on the size of the site. A material tracking tool that will help locate the components from the factory shipment to the storage yard will help increase efficiency by reducing the wasted search time.



Figure 2. Top left picture shows the steel assemblies received at a construction site on trailers. Bottom left shows the steel columns after unloading and shake out. The right picture shows the erection of a column.

The Centre for Computer Assisted Construction Technologies (CCCT), a part of the National Research Council's Institute for Research in Construction, is conducting research on how best to apply information technologies to address issues facing the construction industry. One of the key issues is construction sector productivity. Research is under way to develop tools for the tracking of prefabricated assemblies, for example, structural steel and precast concrete assemblies, to increase the efficiency of the material handling work process. A prototype tool has been developed to help a steel erection crew locate beams and columns quickly in the yard by integrating design and material handling processes with Geographical Information System (GIS) and GPS technologies. The tool runs on any standard Internet Browser, either on a desktop or mobile PC. Although the tool was developed for tracking of structural steel, the concept applies to other construction assemblies as well.

The conceptual architecture of the system is illustrated in Figure 3. The system is hosted on a web server and integrates the data from the design, bills of lading, and the actual location. The Assembly List shown in Figure 5 is exported

from the steel fabricator’s design model using NIST’s CIS/2 to VRML translator (<http://cic.nist.gov/vrml/cis2.html>). Most design tools for the steel framed buildings, e.g. SDS/2 from Design Data and Tekla Structures, support the export of design in CIMSteel Integration Standards version 2 (CIS/2) format which enables the seamless and integrated flow of information amongst all parties of the steel supply chain for the steel-framed buildings. The system takes Bill of Lading information as the second input and a geo-referenced map of the lay-down yard is used as the third input. The system uses Google Maps API and an aerial picture or a map (e.g. land survey) of the site to show the location of a steel assembly by displaying a marker like a balloon or a pin. If an aerial picture or a map has to be used, it needs to be geo-referenced by assigning corresponding geospatial coordinate values to all its pixels. This is achieved by using a GIS system and involves establishing control points for which the geospatial co-ordinates are already known. In most situations the property survey for the storage yard or the construction site should exist and could be geo-referenced for use in the system. The location information for steel assemblies is captured through a GPS camera.

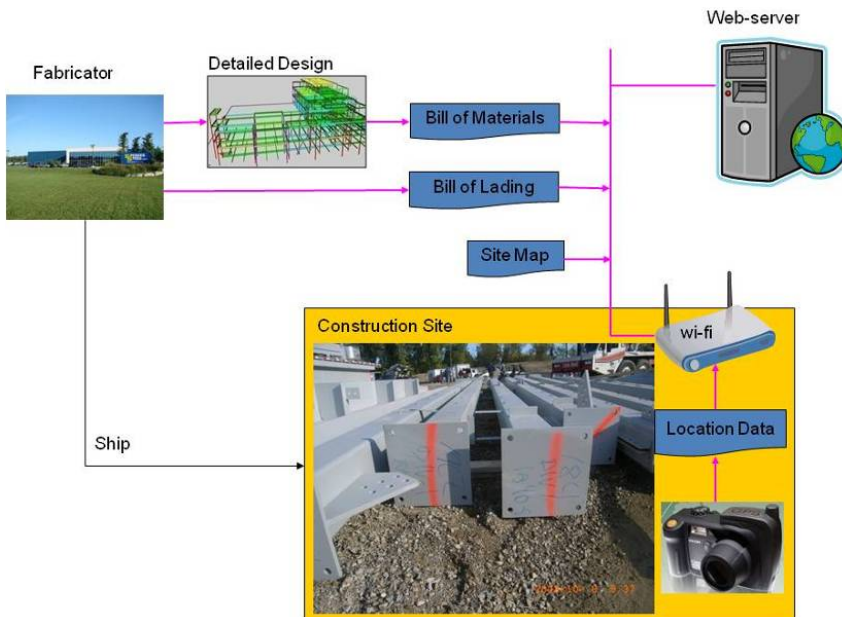


Figure 3. Conceptual Architecture showing the data integration from diverse sources such as bill of materials, bill of lading, site map, and location data.

The current industry practice is to identify the steel assemblies by marking the identification number on beams by either painting them with a handheld paint brush or with a marker pen. The columns are identified with engraved metal tags that are attached to the base plate as shown in Figure 4. The bar codes and RFIDs have still not found widespread use amongst steel fabricators. So that the tracking system is in conformance with the existing industry practice of painting the piece marks on steel assemblies, we have used a digital GPS camera (Ricoh 500SE has a GPS unit attachment that uses SiRFstar III chip) as a field data collection device to record the geo-coordinates of the location of the camera when the picture of the piece mark is taken. The camera embeds GPS coordinates in digital images by automatically storing the GPS coordinates in the image EXIF header. The GPS data can later be extracted from images using an application program capable of reading and parsing the EXIF data.



Figure 4. One of the steel beams on the left picture is marked as 6B4 for “DIV 2” erection sequence for the project identified as 10406. The right picture shows a column labeled with a circular disk tag with the identification number 22C1.

The usage of the system would require that the ground crew takes pictures of the piece marks on steel assemblies after the shake out. If the construction site or the storage yard has Wi-Fi connectivity, the pictures can be downloaded to the server immediately through the built in Wi-Fi in camera or else could be downloaded later. The user then uses GPS-Photo Link, an application program from [www.geospatialexperts.com](http://www.geospatialexperts.com), to associate piece marks to the corresponding geo-location. This is currently done manually as the user enumerates through the pictures, one at a time in the scrollable list, reads the piece mark, and types the piece mark in the text field. The process of enumerating over the pictures takes only a few minutes and results are saved in a file which is uploaded to the web

## Location Tracking of Prefabricated Construction Assemblies

server. The tracking application program on the server parses the assembly list, bill of lading, and the geo-location information and integrates the data to display the attributes of the component and its location on the ground.

	A	B	C	D	E
1	<b>Assembly List</b>				
2		Qty	Mark	Function	Unit Wgt* (Lbs)
3					
4					
5	1	5	1B1	Beam	1766
6	2	2	1B2	Beam	1797
7	3	2	1B3	Beam	1766
8	4	3	1B4	Beam	1700
9	5	1	1B5	Beam	1700
10	6	1	1B6	Beam	1766
11	7	1	1B7	Beam	1799
12	8	1	1B8	Beam	2026
13	9	1	1B9	Beam	2641
14	10	1	1B10	Beam	2641
15	11	2	2B2	Beam	2641

Figure 5. Partial view of the assembly list exported out into a spreadsheet from NIST's CIS/2 to VRML translator.

The user interface for the tracking tool consists of a table on the left side and the map to its right as shown in Figure 6. It runs on a standard Internet Browser. To find the location of an assembly the user scrolls through the table and selects its piece mark to see the location on the map. If the quantity of the assembly selected is more than one, then the location of all pieces is shown.

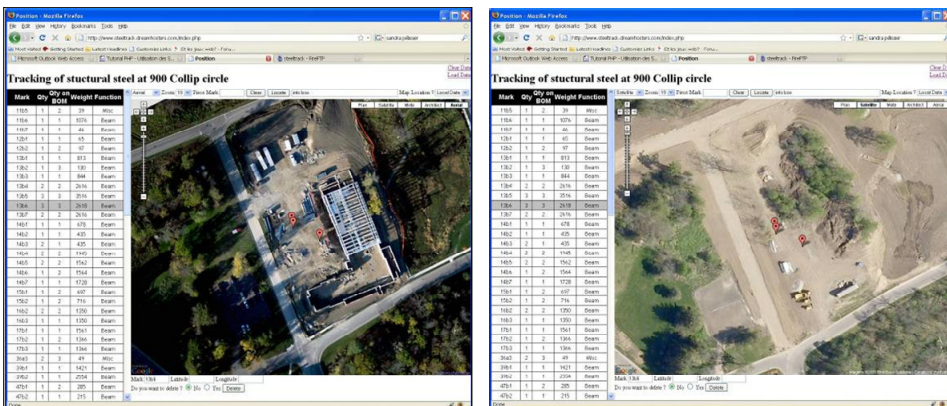


Figure 6. Tracking Tool for Prefabricated Assemblies. The left picture shows the location of the components in an aerial view and the right picture shows the locations on the Google Maps satellite view. The aerial picture is taken by an aircraft flying at a low altitude. Piece mark 13b6 is selected on the table on the left and the location of all corresponding three assemblies is shown on the map.



The ground crew can also choose to locate components on the site survey view as shown in Figure 7. Each construction site or a storage yard has a site survey and it can be geo-referenced and integrated to the tracking tool for helping visualize the location of components.

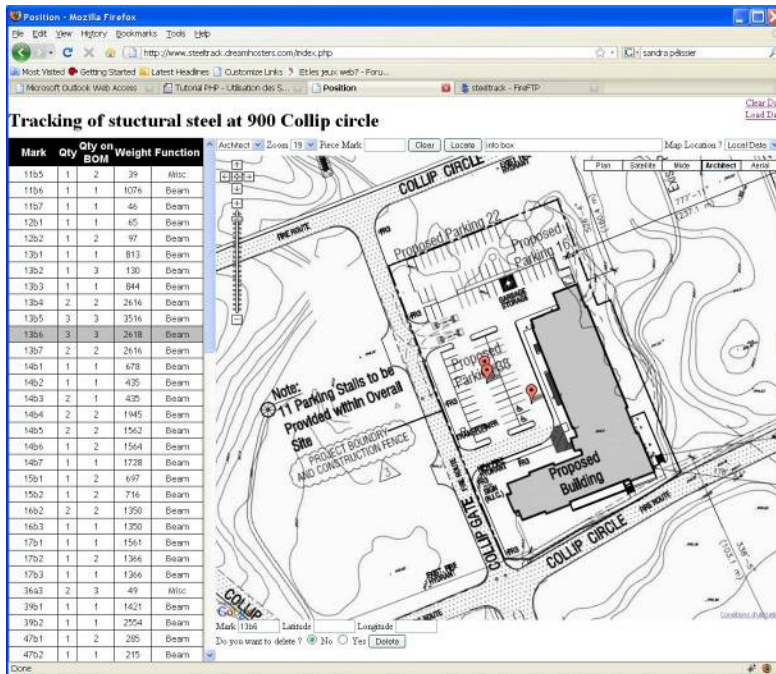


Figure 7. Locating assemblies on a site survey.

Apart from assisting in finding the location of an assembly on ground, the tracking tool informs the user if the assembly is still in the trailer and has not been unloaded to the ground. This way the user knows that the desired assembly is still on the trailer, including the trailer number, and does not have to waste time searching for it in the yard.

### 3. Conclusions

This paper has demonstrated the integration of design data and the bill of ladings within the framework of location tracking. The integration with the design data helps the field crew to know the major attributes such as weight, length, and width, etc. This awareness helps in identifying the desired parts quickly from a distance as the field crew gets closer to the indicated location. Integration with

upstream applications such as scheduling and fabrication will help in finding the manufacturing status of a part. Moreover, the performance of the whole materials handling system can be optimized by integrating the location data to other decision support systems such as crane dispatching, routing, materials storage layout [1], etc.

The initial testing of the tool by the researchers at a 60,000 sq. ft. green building construction project at the University of Western Ontario Research Park, shown in Figure 8, has shown that assemblies are quickly located by looking at the location markers on the map. When the foreman of the iron workers was shown the three alternatives maps of the site, the preference was shown for the aerial view and the site survey. The satellite view was not found to be very useful due to the outdated picture as the ground features no longer correspond to the satellite picture. During the early phases of the construction project, the ground features at the site undergo dramatic change as the foundation walls are poured and the security fence is installed around the site. Trailers for temporary project offices make other important landmarks at the site. These important landmarks are used by ground crew as mental reference points to locate assemblies whose location is shown on the map. Aerial pictures, when taken after the foundations are completed, can be useful, possibly until the completion of the project. The land surveys, an example shown in Figure 7, are equally useful since they show the footprint of the building. One added advantage of land survey documents is that landmarks can be added or removed by editing the CAD file. This way, the map can be kept current with the site conditions as the project progresses. Initial feedback, from the trades at the construction project, indicates acceptance of the site surveys and puts it at par with the aerial pictures in terms of its usefulness. The most important factor in selecting a map should be whether it shows a sufficient number of highly visible land marks. On a small construction site the footprint of a building and the trailers may be enough but a large lay down yard or a storage yard would need a sufficient number of highly visible landmarks or zones to help the field crew in locating the item with the help of maps.

Since the structural steel assemblies are large and the piece marks are visible from a distance, the maximum rated accuracy of 5 meters obtained from most consumer grade high sensitivity GPS chips such as SiRFstar III is mostly sufficient to locate large structural steel pieces. Since the piece marks on the structural steel components are large and can be read from a distance, very high location accuracy was not essential. In case, if only bar codes were to be used

instead of highly visible painted piece marks, sub meter level accuracy location devices would be highly desirable to quickly find the piece. We observed that the usefulness of the tool in quickly getting to the desired steel assembly is dependent on the number of factors such as, size of the yard, numbers of assemblies in the yard and its spread density, and size of individual assemblies. The larger the search space and number of items to be searched, the greater the time savings.



Figure 8. Erection of a 60,000 square feet office steel framed building.

We also found that the ability of computing hardware to withstand the rugged outdoor conditions such as bright sunlight, rain, snow, very cold temperatures and dust will govern whether tracking technologies actually get used at the construction work sites and storage yards. One of the major challenges in using the computers outdoors is the ability to read the screens in bright daylight. Notebook computers for home and office use have transmissive display screens that have a luminance of 250 nits or less which is sufficient for indoor use, whereas outdoor screens must have a much higher luminance value of 500 nits or more. Most notebooks that have outdoor displays are also ruggedized, made to military specifications to withstand shocks and harsh environmental conditions. These are therefore not only many times more expensive than their indoor counterparts but are heavier and not easy to carry, whereas, mobile computing

hardware, such as mobile computers and smart phones, can be used outdoors and are rapidly advancing in computing power, ease of use, while becoming affordable at the same time. Their small size makes them easy to hold in the palm of the hand and with when used with ruggedized casings make them good for outdoor use. Though not work horses for computing, smart phones are beginning to offer good functionality for inputting and receiving small chunks of data over the Wi-Fi or wide-area cellular telephone networks such as 3G. The blue tooth connectivity enables integration with other devices such as GPS, bar code readers, RFID readers and with relative ease. More smart phones are coming out with touch screen interfaces such as Samsung Omnia and some with both touch screen and keyboard such as Google Android. With newer and faster processors, larger memory, user friendly interfaces, integrated GPS, Wi-Fi, blue tooth, and 3G, the future smart phones have the strong potential for use in construction industry.

Though the location data collection through a GPS camera works well with the structural steel assemblies as these have hand painted piece marks, it is more suitable for slow moving inventory. The construction sites and storage yards are dynamic in nature, with materials continuously arriving and leaving. Moreover, the materials may also get moved around in the yard to approach and retrieve those that may be surrounded by others. For example, in order to get to the desired assembly, the parts that are either stacked on top or lie in very close proximity have to be relocated. Therefore, a computer-based tracking system will find wide acceptance by the field crew if the location data is not only accurate but is kept current at all times. This necessitates that the location data is collected in an automated way as the parts and assemblies arrive, leave, or are relocated in the yard.



Figure 9. Precast concrete elements stacked in layers.

Though large structural steel assemblies are not stacked in layers at the project site, there are other types of assemblies such as precast concrete elements that are stacked in layers at storage yards as shown in Figure 9. Finding the vertical position of a piece in a stack through automation is a challenge through current localization technologies as the accuracy needs for determining the vertical position are higher as compared to that of the horizontal. A fully automated materials tracking system must have the capability to find the exact layer in which the assembly is stored.



Figure 10. Tracking of prefabricated assemblies indoors, either at a fabricators warehouse or at a construction site, poses difficult challenges. Left picture shows structural steel assemblies at the fabricators warehouse awaiting shipment. The picture on the right shows the doors and windows assemblies at a construction project.

Not all the construction materials, even large assemblies, are stored in outdoor environment. For example, structural steel assemblies after fabrication and painting could be stored indoors awaiting shipping as shown in Figure 10. There are much greater practical challenges for tracking construction materials in indoor environments as indoor localization technologies for are not very accurate.

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# Construction Automation for Modular Assembly Operation

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## Abstract

Construction projects are divided into a number of major stages of development. For many years, exploit construction concept idea, procured by the architects, have been introduced in the form of 2D paper layouts or CAD models. Then, construction engineers apply management tools such as CPM and PM software, which assist in project control and integration. Today, we rely solely upon the ability of project participants to interpret discipline-specific models and their unique functions in order to form a mental picture of the proposed design and its corresponding construction approach. Using advanced computer tools, engineers create designs that integrate all discipline-specific models to coordinate the cross-disciplinary tools used for design, construction, and to facilitate management decision.

This paper presents an example of discipline-specific model integration for modular construction, proposing a step-by-step methodology of the crane selection operation process. The proposed methodology is illustrated through a case study which involved the construction of five student dorm buildings of three stores each. Each dormitory in the case contains three types of modules and a total of 18 separate units. The modules vary from 39,000 lb to 72,000 lb in

weight and from 22' to 51' in length. Fully habitable units are delivered securely on flatbed trailers to the site in advance. An all-terrain mobile hydraulic crane is placed in the centre of the construction site which lifts each module to its predefined destination.

The optimization of the crane position and detailed analyses of every lift prior to actual construction operations allow engineers to anticipate and envision almost any possible problem and direct the attention of the crew involved in the particular task. The detailed design/modelling of products and assistive equipment allows engineers, management personnel, and crews to contribute collaboratively to the decision making process in order to ensure a safe and successful assembly. Collected data and corporate “know-how” also assist the contractor in developing procedures and standards for similar projects in the future.

**Keywords:** 3D solid modelling, dormitory, modular construction, optimization

## 1. Introduction

The term modular or manufactured unit has been evolving in the construction industry for many years. Industry practitioners have used it to describe objects that are compact, well structured, and easy to handle for transportation purposes. These units can be either temporarily or permanently assembled. The advantage of developing such technique has come mostly in terms of total cost savings and delivery time. Completed (or near completed) products delivered to the site can be assembled in a few days.

Although, the term, modular usually refers to a single unit, authors have shown that low-rise multi-family residences and high-rise facilities can be a perfect fit for modular construction [9]. Automation of a developmental model process and extensive implementation of robotic technologies have been the subjects of discussion for two authors Nasereddin [18] and Bock [5]. Modular construction has evolved to include schools, hospitals and hotels, where repetitive space layout allows for the easy and efficient modularization of available shapes [12, 8]. Some other examples of successful applications related to modular technology include construction of specialty health care units, pharmacy centers, single-patient check-up rooms, and operating theatres [22]. These units can be customized to the specifications of patients with restricted mobility as well as to geographical requirements at just the click of a computer button over the



Internet. The purchaser can make the individual or collaborative decision as to the modular layout from anywhere on the globe [6].

Modularization as a concept lends itself well to off-site construction. Modules can be prepared at predefined sizes (transportation constraints) and totally finished at a fabrication facility. With the fabrication facilities being protected from weather, and isolated from areas of undeveloped land, and with easy access to necessary utilities modular construction has the competitive advantage over the traditional stick-build approach. Furthermore, activities at the construction site are limited to placing ready modules in a predefined sequence. However, some modular construction developers have used traditional methods during construction site preparation as well. It should also be noted that pre-assembled concrete panels have been used for the foundations of some structures in this project.

Digital layouts have been assisting engineers since computers were first introduced over 20 years ago. The industry has been in evolution in the role of computers from introducing simple 2D digital sketches of specific plans to rendering full 3D drawings in which mannequins mimicking humans simulate the relocation of objects and take predefined positions of each of the crew members. Such detailed visualization outputs require powerful hardware configurations, however, which depend heavily on operator inputs, knowledge and possible equipment displacement. In respect to construction site assembly operations, cranes are the critical tools by which to place components and handle materials. Some construction sites have limited space availability so the location and, swing space reserved for crane maneuverability are the main factors which lift engineers must consider. With the increasing complexity of crane layout, industry is developing tools to assist practitioners in the selection and optimum utilization of cranes [14]. Furthermore, the complexity of the lifts varies based on the type of construction site, some lifts could be simple and straight forward operations which do not require special attention, while others consume a fair amount of time in preparation and detailed lift analysis. The approach described by Tam [20] analyzes a particular area and uses a genetic algorithm (GA) to optimize tower crane operations, whereas Matsuo [16] and Sivakumar [19] have concentrated on developing a path planner for two cranes lifts. Deen [10] as well as Mashood [15] have continued with this topic of research, employing GA in order to solve the problem. On the other hand, Al-Hussein [2] and Moselhi [17] have introduced an algorithm by which to choose the optimal crane with respect to lift capacity while utilizing 3D animation for visualization techniques. In this case mathematical algorithms have been integrated with a data-base of

commercially available cranes. The minimization of transportation travel time [3] and [7] with respect both to the storage system and to inter-modal transportation networks is another important application of the algorithms. The same issues of minimization of travel time, walking cost, and connection between these two factors have constituted the subject of research conducted by Ahuja [1], who developed a polynomial time algorithm in order to control these issues. Control algorithms for the reduction of material handling cost, utilization of resources [21], and analysis of crane operations in warehouse systems [4] have also been explored. The optimization and analysis of crane lifts have achieved greater recognition in the sphere of 3D technology and spatial optimization algorithms in conjunction with more advanced capabilities of hardware and software for simulation algorithms [14]. Del Rio-Cidoncha [11] and ElGanainy [13] have analyzed floor plan layout design and the critical steps involved in the design process, as well as the various benefits, techniques, and interactions among these. This approach has led to significant improvements to the layout optimization method. Research exploring similar issues, but in a larger scale for site layout and floor level planning in construction, has also contributed a fair amount of knowledge to the industry.

## **2. System process**

The combination of the proposed technology, know-how, advanced computer tools and resources allocation requires significant planning. The development of a properly mapped methodology is an essential task at the beginning of any construction project. Some project managers use pre-tested methods with proportionally predefined outcomes for cost and time. They are reluctant to test the new approach especially considering that advanced computing technology has been introduced. The presented methodology can be utilized for any project with no restrictions to the site layout. It accommodates easily accessible construction sites as well as difficult ones with constraints or significant elevation differences.

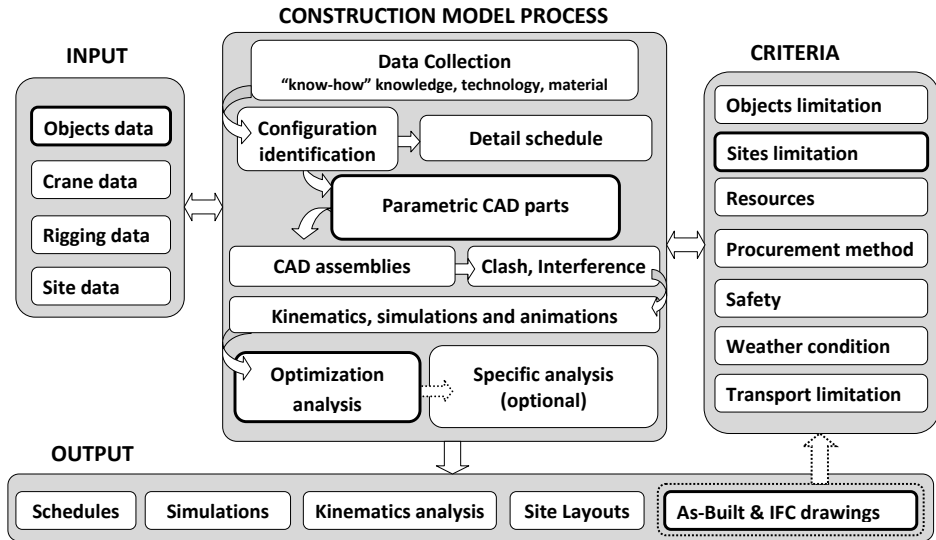


Figure 1. System process Methodology.

Figure 1 shows the system process methodology. The “Construction model process” contains several activity blocks, and refers to the preparation in a CAD model of virtual data of construction site operations. This “heart” of system methodology includes the “Data Collection” task, which describes unique know-how knowledge, material, and exclusive intellectual property information. “Configuration identification” determines the available crane configuration, including how it can be changed or remodeled during different lifts. The “Detailed schedule” box is an expansion of the client proposed time line; it is specific with respect to information included in the “Data Collection” box, and in some cases it could account for micro-detailing operations. This may be beneficial to the part of the schedule where “expensive” tasks are critical to the project. The “Parametric CAD parts” box is a collection of objects, equipment, and site and obstruction models. Models include material properties and full size shapes to fully mimic real objects. “CAD assemblies” are collections of separate models which are then tested for clash or interference checks. Assemblies can be part of a kinematics analysis. Simulation or animation outputs can be performed independently at any time if the operator needs to analyze object displacement.

### 3. Case study

In early 2006, Muhlenberg College management in Allentown, Pennsylvania made a decision to replace its outdated (1981) and inadequate single-level dormitory, which accommodated only 56 students. The new three-storey, 8,300 square-foot buildings, designed by local architects, fit perfectly with the brick walls of the surrounding neighborhoods and were able to house 145 college students. Each of the buildings has six apartments, most with one double bedroom and three singles. Each unit has a full kitchen separated by a bar from the living areas, which includes sofas and chairs. These solid-looking attractive buildings were manufactured in Lebanon, N.J. by Kullman Building Corporation. Each building consists of 18 modules, which must meet specific restriction related to size and weight. The modules not only had to fit under highway bridges and conform to the weight constraints of the crane for lifts (the largest modules were designed to be 13 feet wide by 57 feet long, weighting 72,000 lb.), but also must stand up to the rigors of being transported to the site., Overall, these fabricated units are structurally superior to stick-built units. Figure 2 shows an exploded view of a dormitory unit and Figure 3 shows typical floor layout configuration.



Figure 2. Dormitory exploded view.



Figure 3. Typical floor layout.

At the stage of architectural planning and dormitory shape development, all building components were modularized (divided) into manageable units for transportation, including the roof units. During the preliminary site assembly logistics preparation, the university team suggested the utilization of a nearby tennis court to pre-assemble the roof trusses and lift the entire unit to the top of the assembled modules. This proposal allowed planners to redefine the entire

schedule and attenuate it significantly. The tennis courts were already fenced and so the project manager had excluded that portion of the land from any planned construction activities. With college authority approval we excluded roof construction assembly from the critical path of the main dormitory construction activity, and this allowed for the establishment of a roof assembly schedule concurrent to the main assembly operation. From the originally planned 21 days assembly duration, setting the roof placement tasks as concurrent operations reduced the main schedule to only 10 days. Reducing the assembly time by 50% created suspicions among some key management personnel but a logical explanation of the proposed process garnered immediate approval. The team knew that a 10-day assembly process would be achievable if no major obstruction were encountered. The major treat to a smooth construction process was the weather. In the summer, Allentown typically experiences warm, sunny, weather but occasionally heavy rains can develop which can last up to a few days. The nature of modular construction allowed for units to be finished in fine detail, with painted walls and wooden components attached. Transported units had to be properly protected and assembly operation could only take place if the moisture level in the air was less than the allowable rate for gypsum panels. Figure 4 shows the CAD model for the roof, complete with rigging configuration, and Figure 5 gives an aerial view of the construction site with the tennis court and assembled roofs.

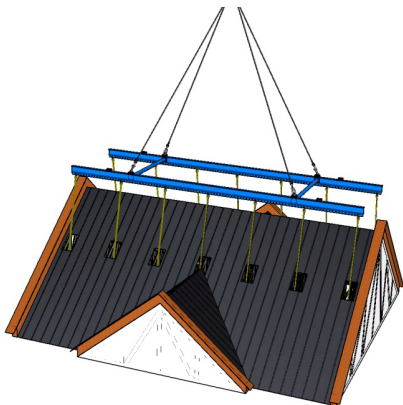


Figure 4. Roof CAD model with rigging.



Figure 5. Site aerial view.

The construction site was modeled in CATIA software for simulation, lift analysis and sequence development. In the middle of the process of developing lifts and incorporating predefined crane pick points for delivered modules, the Pennsylvania Department of Environmental Protection unexpectedly moved a retention pond onto an area reserved for one of the modules reserved. In a matter of hours we were able to rerun the simulation, change the sequence of lifted modules and utilize only one lift spot for all modules (Figure 6).

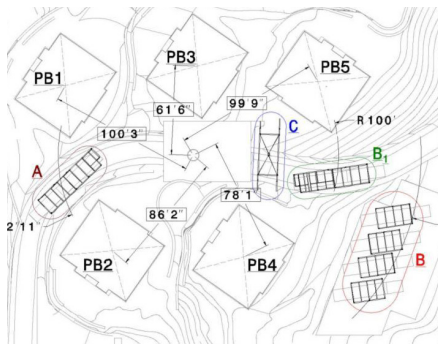


Figure 6. Staging area elimination.

oper code	activity/operation	module	place	start	crew	workers/crane time			place finish	
						p	ml	o		
						(min)	(min)	(min)		
<b>13 Jun 07</b>										
1	K1	unwrapping module	113	B1	4	25	20	15	B1	
2	K1	hooking module	113	B1	4	20	17	15	B1	
3	K1	folding tarp for next module	B1	4	25	15	10	B1		
4	T1	removing empty trailer	B1	7	5	3	-	-		
5	C-sb	load hoisting up	113	B1						
6	C-sb	load booming up	113			10	7	5		
7	C-sb	load swing	113							
8	C-sb	load hoisting down	113						PB1-1	
9	K2	securing-lining up	113	PB1-1	1	30	20	15	PB1-1	
10	K2	securing-bolting together	113	PB1-1	2	30	22	15	PB1-1	
11	K2	unhooking-remove lift lugs	113	PB1-1	2	25	22	15	PB1-1	
12	K3	welding bottom - one side	113	PB1-1	1	30	20	15	PB1-1	
13	K3	welding bottom - other side	113	PB1-1	1	30	20	15	PB1-1	
14	C-sb	return to next position	PB1-1	3	2	1			B1	
15	T2	placing trailer module for lifting	114	-		7	5	3	B1	
16	K1	unwrapping module	114	B1	4	25	20	15	B1	
17	K1	hooking module	114	B1	4	20	17	15	B1	
18	K1	folding tarp for next module	B1	4	25	15	10	B1		
19	C-sb	load hoisting up	114	B1						
20	C-sb	load booming up	114			10	7	5		
21	C-sb	load swing	114							
22	C-sb	load hoisting down	114						PB1-1	

Figure 7. Detailed assembly schedule.

Construction schedule development was the first task of the project. It required a detailed description of each operation as well as the time factor associated with the given task. The knowledge of modular construction assembly “know-how” was spread among individuals having worked for many years building and assembling units for Kullman corporation. Capturing this knowledge was a challenging job which required an approach tailored to the individual. When questioning about the performed jobs, participants are generally reluctant to share techniques and experience with others unless they sensed benefits or an opportunity to learn something new about their profession. To motivate the Kullman crew members to share their ideas at the brain-storming sessions, we presented the option of harnessing new technology to assist in the development of a state-of-the-art construction schedule. The computer-generated 4D virtual construction operation stimulates an individual’s perception of their particular job sphere and the associated movements and looks for potential improvements. These interactive brain-storming sessions allow for the recording of three different time values for each assembly operation “p, ml, o” representing, pessimistic, most-likely and optimistic data (Figure 7).

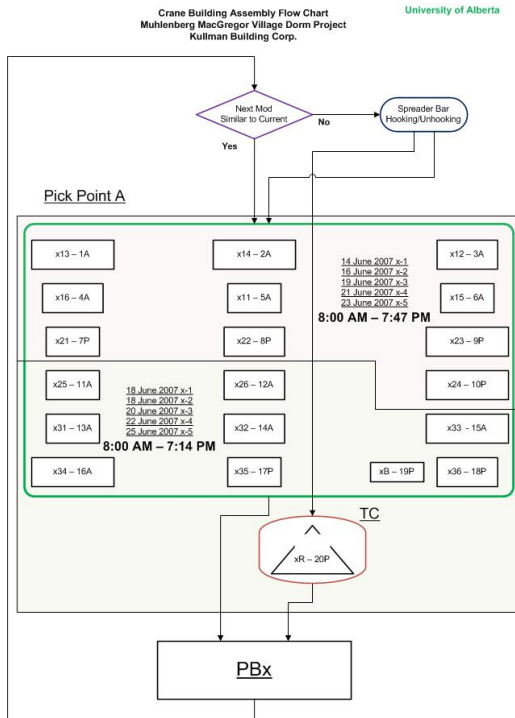


Figure 8. Operation Flow Chart.

June 22, 2007

01-412	7:00 am
02-415	7:27 am
03-416	8:58 am
04-424	11:01 am
05-423	12:02 am
06-425	1:44 pm
07-426	2:35 pm
08-421	3:26 pm
09-422	4:17 pm
10-434	6:20 pm
11-433	7:21 pm
12-431	8:18 pm

Figure 9. Daily "Minute-by-minute schedule."

Another important aspect of up-front preparation was the depiction of proper assembly operation through a flow chart of the sequence of tasks (Figure 8). The modified assembly flow chart shows rectangular blocks, which represents modules lifted from Pick Point A, and a middle division line two separate days of activities for one building. At the end of the first day of activity, assembled modules were covered with tarp. On the second day the remaining modules of the building with roof and concrete bridge were lifted. The roof (TC shape) was lifted from a different location than pick point A. The decision to be made before each lift refers to the task of either hooking or unhooking the spreader bar. Operations flow-chart development was supported by mathematical calculations of the best job series steps and the chart shows the scientific optimum advance (Figure 10). It shows that unwrapping and welding can only be part of the critical path when the corresponding times are positive. For instance, for unwrapping, the time  $I_u$  needs to be taken into account when

$$U_w > C_o + S_L + U + S_B.$$

In a similar manner, the welding time becomes part of the critical path only when it is taking longer than  $H + C_o + I_u + S_B$ . Based on the above described number, we can now setup a graph structure that will be used to explore various installation schemes the goal of which is to minimize the crane idle time. In fact crane idle time is the metric that is used to build the objective function to be minimized. In our case, this can be summarized as

$$\min[\sum(I_u + I_w + S_B)].$$

Clearly the time of unwrapping would affect the critical path only when the term

$$I_u = \max(U_w - (C_o + S_L + U + S_B), 0)$$

is different from 0. As can be seen, the time required to set up and remove the spreader bars is considered – wasted time. This immediately suggests that it would be optimal to install the largest possible number of similar modules before installing or removing the spreader bars.

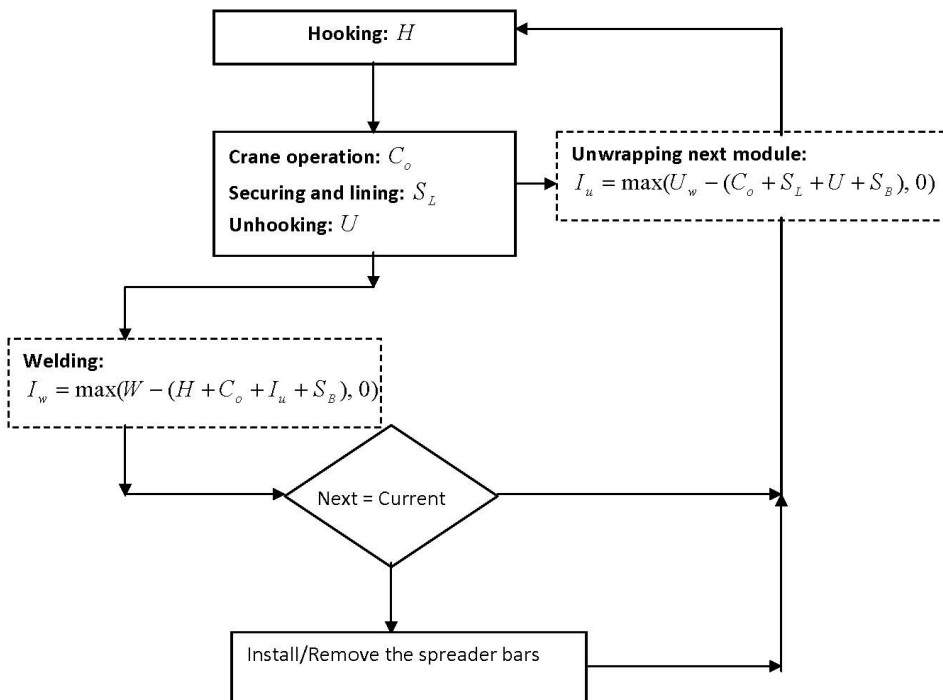


Figure 10. Operation Cycle.



## 4. Conclusions

Without adequate time, (which was given for preparation of the CAD model), set-up and run detailed lift analysis project may suffer delay or other problems related to resource allocation not included in the associated costs. Early discoveries of potential difficulties with roof assembly and placement onto the top of the buildings and relocation of the roof construction process to the nearby tennis court allowed planners to remove the entire operation from the main critical-path schedule. Dealing with the last-minute change of object pick point did not paralyze construction assembly, but instead had effect of making managers more willing to rely on computer-run simulation results. Major managerial decisions regarding lifting equipment utilization, replacing or moving tasks were first coordinated digitally on the computer CAD data, and then implemented in real scenarios. Successful assemblies simulation, animation, interference checks trajectory, and crane movements made decision makers more confident that downstream operations would succeed. Late-night questions about the crane entry site analysis were answered in a few hours several kilometers from the construction site and results were delivered for discussion the next morning. The benefits of implementing an automated process were countless since ALL questions regarding construction issues were answer immediately. We did not experience any unexpected site challenges during assembly operations. Despite the need to an additional extension to the main boom for the last roof lift, we allowed to the proposed step well ahead of the actual lift. In general, all interested parties recognize the benefits of preparing a construction automation assembly process.

In respect to IDS contribution; identifying the activities and their durations was the first essential step in data collection, and this process assisted both in building the simulation model and in allocating an adequate amount of time to building the CAD model and analyzing the lift sequences and locations; it also helped to lessen and prevent unpredicted errors. Taking into consideration all aspects and elements of the model and the components of the project at an early stage will ensure accurate results and proper management of resources such that delays in the delivery of the final product may be circumvented. An output analysis of the model shows that crane, fitting crew, and delivery space utilization were used effectively despite the time constraint which in some cases prevented the attainment of a higher level of utilization.

The advantage of proceeding quickly at the construction site was achieved with the help of the simulation model, which served to meet the constraints imposed on the project due to tight scheduling.

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# **THEME: User Value through Collaboration**



# **A Survey of Automation Technology for Realising As-built Models of Services**

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## **Abstract**

As-built documentation is a contractor's certified record to what was built and it is extremely important to the owners for the purpose of maintenance, major renovations, and demolition, especially for critical but typically hidden services infrastructure. Unfortunately, the value of the final delivered as-built documents are commonly limited significantly by leaving their creation, as an afterthought, to the end of a project. As-built documentation is also frequently left in the hands of inexperienced workers or apprentices to correlate original drawings, documented change requests and as-built input from the sub-contractors (when it exists). This often results in large un-correlated collections of in-accurate, incomplete information with limited utility for describing exactly what was built which is in direct contrast to the vision of Integrated Design Solutions (IDS). This approach also misses the opportunity of using continuously updated as-built documentation to manage on-going work, coordinate trades and catch deficiencies early enough to avoid expensive rework, another precept of IDS. Partially automating the maintenance of as-built documentation would make it feasible for construction management to use it as a tool during construction and deliver it in a useful form to the client upon completion. This paper reviews some past and current automation technologies used in realising as-built models of buildings with a focus on how they are applied to modelling building MEP (mechanical, electrical and plumbing) services, and includes some opinions on approaches and technologies that show promise in facilitating as-built model creation.

**Keywords:** as-built documentation, MEP, automation techniques, technology survey, BIM, CAD

## 1. Introduction

Most significant capital projects require the builder to provide as-built documentation to owner/operators as part of the contract. Currently, this task is usually left to juniors or apprentices and to the end of job. Furthermore, the documentation is often delivered as an uncorrelated collection of paper documents with different sub-contractor's as-built notes written on them combined with records of the change orders and sometimes the general contractors (GC) own observations notes. As-builts are also known as "redlines" due to the common practice of using red pencil to mark the changes on construction documents. Delivered in this way the documentation is not very useful. Pettee [25] does a good job of documenting these practices and makes the observation that significant effort and organisation is required with current practices and processes to create useful as-built documentation. Cheok et al. [17] note that on a typical \$100 million construction project approximately \$2 million goes to material tracking, monitoring progress of construction activity and creation of as-built documentation. Pettee [25] goes on to observe that unless these documents are constantly updated during construction the GC cannot benefit from them and that they are not a very closely reviewed deliverable, thus, to the GC, creating as-builts is not a value adding task.

Although "Measured Drawings" are also referred to as as-built drawings, the term is more applicable to recording existing conditions for existing structures for the purpose of renovations, re-modeling and historical restoration projects. Many older buildings or facilities lack accurate or any documentation of structural or service installations which are required before project plans are prepared.

Given floor plan drawings of a construction project, measured or from the architect, mechanical, electrical and plumbing services (MEP) consulting companies prepare the MEP drawings to show the 2D layout of building service endpoints such as the location of all HVAC equipment, thermostats, diffusers, air return grills, electrical fixtures, switches, panels, plumbing fixtures, and sprinklers. The drawings may not show the exact location of cable trays, electrical cable routings, drain pipes, etc. unless explicitly demanded in the contract document. The MEP drawings are then followed by general contractors, electrical, mechanical and plumbing contractors to do their work on a project.



Any changes from the proposed layout are to be recorded during the construction and the engineering drawings are red-lined to reflect the as-built conditions.

Since, several contractors usually work simultaneously to install the MEP services, the current common practice involves regular trade coordination meetings being held on site to identify and resolve problems so that the installation of one type of service does not interfere with another. Quantifying the costs of field conflicts is difficult due to the variations in projects but Riley et al. [26] note that ~80% of the costs are not recovered by the contractors and that simple coordination costs range from \$0.5 to \$2.0 a square foot. Pettee [25] points out that if up-to-date as-built documents existed during construction they could be used to coordinate trades on site and avoid late identification of clashes that can cause scheduled delays or worse, rework orders. Ideally, from the perspective of the GC, as-builts would track the current state of the building during the construction process and serve as the basic input for daily/weekly planning meetings.

From the perspective of the building owners and operators, final as-built drawings would show the net result of all change orders and show the dimensions, locations and assemblies/components actually installed. They would serve as basic documents for major renovations, large maintenance activities or use in facilities management.

Thus, all the stakeholders from the builders, to the owners and operators can benefit by having timely access to accurate as-built models but the high cost and effort currently required remains a significant barrier. As such, the focus of this work directly ties in to the CIB vision of Integrated Design Solutions (IDS) where information needs to be maintained, communicated and used to “minimize structural and process inefficiencies and to enhance the value delivered during design, build, and operation, and across projects”.

As the magnitude of the resources currently required to deliver good as-built documentation during a project is a major hurdle to their development and active use, the rest of this paper reviews and presents current technologies used to automate parts of the process of creating as-built models of services in constructions and makes suggestions for future tool development from a pragmatic usability perspective, hence describing paths towards the IDS vision. As mentioned earlier, this work will focus on ways to improve documenting as-built conditions of MEP services to support coordination during construction and a reduction in field conflict costs as well as later operations and maintenance.

The next section presents current, and some ongoing research into, processes and technologies used for creating as-built models. The final section looks at the future and how technologies can be used to reduce costs and time requirements to make as-build documentation and support construction activities.

## **2. Current process and technologies**

Before reviewing the technologies used to create as-built documentation, the two ends of the spectrum for delivering this documentation should be briefly described. Common today is the delivery of an un-correlated collection of documents (mostly paper) including change orders and red-line drawings from various contractors. This is the easiest to deliver, yet the least useful. The most advanced form is the use of Building Information Models (BIM) where the state of the construction is captured as semantically rich models (i.e. building elements can be identified as such and not just pure geometry) over time, hence as 4D models [20], and sometimes along with other relevant data such as serial numbers or operational characteristics of equipment for nD BIM models. These multi-dimensional models can support advanced applications like the simulation of the construction process and serve as a base repository for facility managers to operate and maintain the building.

### **2.1 Manual**

The manual approach for creating as-built drawings is inherently manual intensive and error prone. Workers on site use tape measures or hand-held laser range finders to measure critical distances and red-line them on drawings. In unusual cases these measurements might find their way back into electronic CAD drawings. Accuracy is limited by the manual nature of the data gathering. Technology has been harnessed to improve this approach by some solutions providers through the integration of a laser tracking system and a hand held computer to automatically record positional information in electronic models (e.g. BIM or CAD). The user uses a special pointer to indicate points to measure on installed construction elements [6] corresponding to elements selected in CAD using the handheld PC. Hardware setup of the laser tracker on a tripod is relatively quick including registration measurements against known installed features relative to a CAD model. As the process remains predominantly manual and user driven, the number of measurements possible remains low.

## 2.2 Video, time lapse photography & photography

Video, time lapse photography and photograph documentation of construction progress and activities are becoming more common in projects as the supporting technology has gone digital, and become more integrated and much cheaper to implement. These approaches are popular for big projects so stakeholders, the public or the owners, etc., can monitor progress over the web. Archives can be indexed by time and location, in the case of more than one camera, but they cannot provide actual spatial data on their own. If correlated with bills of materials, schedule information and reference locations or features in images it is possible to extrapolate some usually low quality dimensional data. Abeid et al. [10] integrated captured images with databases that contain schedule information to produce dynamic graphs showing planned versus actual schedules.

Though not yielding actual as-built documentation, the information is, by nature, up-to date and can be used to support the decision-making including planning and site meetings during construction. High quality digital pictures can show sufficient detail to serve as a reference for future facility modifications, repairs and inspections [13]. Other benefits shown include reductions in disputes and accidents, the possibility of remote real-time diagnostics, and enhanced communication between stakeholders regarding onsite activities.

Research in this area has looked at linking electronic copies of drawings, notes and sketches to imagery such as was done at Virginia Tech [24]. Their developed system builds on top of the computerized project schedule by electronically linking all drawings that are used in the project. As the construction process gets executed, the changes are redlined manually on the electronic copies of the drawings and stored.

Comparison of construction photographs and virtual reality (VR) images of construction has also been used to examine the difference between the actual situation in a job site and the 3D CAD design of the building [23], a form of gross visual inspection. However, in order to compare construction images to a VR model, the viewpoint and direction vector of both should be coincident as the report states that the “accuracy of objects for comparison highly depends on the correction of the deviation angle of camera in a horizontal plane and the 3D viewpoint of the construction photograph that has been presented”. Based on the authors’ experiences, it takes a fully trained person to map photographic images to the as-design models (or vice-versa in the case of augmented reality) and conduct the analysis. Manual mapping methods are time consuming and

erroneous and current computerized approaches are very dependent on good equipment setup, calibration and use of robust algorithms to register and combine the model and real view. In [11], pairs of point correspondence between models and images are used to eliminate the scaling, location and orientation problems for augmented reality applications.

## 2.3 Photogrammetry

Photogrammetry techniques have long been used to assist in realising CAD and virtual models of existing structures for architectural purposes. In fact there is at least one journal, ISPRS Journal of Photogrammetry & Remote Sensing, devoted to photogrammetry techniques where numerous articles on applications in architecture can be found. Photogrammetry uses two or more images taken from different locations and basic triangulation principles to locate points in the images in 3D space. It should not be confused with 3D photography where fish eyed lenses and stitched photographs allow the user to look in any direction from one point as mentioned in [21] or 360° panoramic imagery described in [16].

Again, the fact that digital cameras with relatively high resolutions, decent lenses (necessary for acceptable accuracy) and large memory capacities are nearly commodity items today is a strong incentive to revisit the use of photogrammetry based approaches to realising as-built documentation. In fact good quality cameras are now being built into mass market cell phones and digital stereo cameras are not uncommon even if a little more expensive. In terms of hardware, cameras are cheaper, more assessable, more portable and faster for capturing on site data than any other technology other than a simple tape measure (which is cheap but not fast). What is required is a computer and special software to get useful geometric data from the pictures.

On the whole, it is still very difficult to get computers to recognise general objects in images except for structured scenes with severe limits on objects so humans remain an integral part of the photogrammetric path to as-built models. Thus most approaches focus on a semi-automated or human directed approach. Furthermore, photogrammetry approaches rely on good images so lighting is an issue unlike many laser scanning implementations (discussed later).

Some consulting companies [19] specialise in using these techniques to create accurate as-built documentation for complex projects, and they tend to use more sophisticated equipment like high end stereo cameras and place registration markers in the scene to improve the quality of the data they gather and the

resultant models. They also will have significant expertise and software resources with which to process the data gathered and create the resulting models.

In essence, to extract spatial information using photogrammetry techniques requires knowledge of the camera locations and orientations (pose) for each picture and matching points in multiple photos of a feature to be measured. Given enough images and matching points it is possible to calculate where the cameras were. Software like *Microsoft Photosynth* [7] takes many images and automatically locates matching features to support determining the camera poses around a common 3D scene in the photos. With this information, Photosynth can place the images in the 3D space like billboards to give users the illusion of space. *Autodesk ImageModeler* [4] requires the user to manually identify matching features but gives you tools to build geometry directly from any measurements made. To then get geometric information from the pictures requires providing a scale based on a known length in the images and identification of feature points to be measured between in the images. Done this way the data yielded is not much more detailed than a series of manually acquired lengths or 3D locations that can be used to build or compare to CAD models. When using stereo cameras with known optical properties the results can be grids of depth information. Accurate measurements rely on accurate location of points in multiple images and thus the best results are achieved for edges and other distinguishable features and poor or no results are typical for surfaces, especially curved ones.

Research continues into improving the level of automation of identifying and matching important features. One older, but particularly interesting work, is the rather comprehensive effort made by Hirshberg and Streilein [22, 28] where the authors provided interpretive directions for the software in the form of pre-defined straight-edged profiles of features which they wish to have matched and measured in images from edge drawings or pre-processed semantic models of expected geometry found in the as designed CAD model. Their software iteratively matched the outlines to edges found in multiple images using edge-detection image processing techniques. Once the images were registered with each other the resultant geometry of 3D points, edges and loops was exported directly to CAD for comparison of as-built to as-designed.

In another sophisticated approach to automatically identifying construction objects from digital pictures, Brilakis [15] used photogrammetry to aid the inspection process by semi-automatically identifying where pictures are taken and what direction they are looking in relation to an existing CAD model and

pulling up that part of the model for inspection comparison by the user. A GPS enabled digital camera is used to capture images which are then filtered by attributes and clustered to narrow isolate key construction features. These features are analysed using Content Based Image Retrieval (CBIR) techniques with matches being limited to objects expected in that part of the construction site based on the CAD model.

Given that the objective in this work is to identify and document installed services, the capabilities of the approaches above suggest that a nearly automated system should be possible to capture straight runs as the geometry of the objects being sought is well understood and known in advance. However, the user will probably have to provide further description about the nature of each service found as there is little or no difference between air supply and return ducts, hot and cold pipes, conduit for electrical or phone or network and different types of waste plumbing.

## **2.4 Laser**

3D laser scanning (a.k.a. LADAR – Laser Distance And Ranging) is a newer approach than photogrammetry techniques. It requires much more expensive equipment in general, though prices continue to drop, and yields significantly higher levels of accuracy. The higher accuracy is often achieved through capturing much larger sets of data, typically clouds of 100's of thousands or millions of 3D points. Direct measurements and simple visualisation can be done directly from the un-processed data using the system supplier's software. Another advantage of laser scanning is that it is usually much less sensitive to ambient lighting conditions but the authors' own experience has shown that in some cases vegetative surfaces have been found to absorb the wavelength being used by the scanner. Unlike photogrammetry techniques laser scanners are good at getting dense measurements over even smooth surfaces.

One potential drawback of laser technology is that the operating field conditions of many construction sites, including extremes of temperature, humidity, and dirt, must be considered given the sensitivity of laser scanning equipment. Furthermore, current commercial options for post-processing are mostly manual or assisted manual and require powerful computers with lots of memory to handle the large datasets. The registration of multiple scans to a single coordinate system is usually a fairly quick though manually directed process, but generating models from the data is still intensively manual. The

application specific exception is in using high-end software, like *Innovx RealityLinx* [9], which is designed to support rapid matching of parametric CAD models to user selected sections of scans of industrial piping installations as found in factories, refineries and chemical industries.

Given the immense number of sites of historical, religious or architectural interest, a large number of publications document investigations of laser scanning technologies to accurately capture their shape and colouration. The resultant models were used for virtual tourists, educational purposes, simulations and academic study. For example, Shih et al. [27] use laser scans to digitally preserve a historic temple in Taiwan but the models were made manually and for the most part only represented net shape and not semantically separate construction elements as would be necessary for machine reasoning applications. Arayici [12] describes in decent detail a process involving manual steps using *PolyWorks* [8] to convert a laser scan into a faceted model suitable for use in visualisations, and ultimately into BIM models. Arayici's approach semi-automates the process of extracting profiles for use in CAD model development by aligning the scan with an XYZ axis and then using scripts to project points near user defined planes onto planes to create the desired profiles.

For inspection applications during construction, *Autodesk Navisworks* [5] supports overlaying "as-built" models, including information derived from laser scans on "as-designed" models for visual comparison and analysis. The software includes a point/line based interference detection module to assist in performing clash tests against specified geometry to identify discrepancies. Figure 1 illustrates the results of the in-house scenario of an as-design model as shown on the left side of the figure against an as-built model generated from the captured cloud of points using the Faro laser scanner.

Bosche et al. [14] have placed significant effort on automatically "retrieving" 3D CAD models of objects found in scanned images, a significant road-block to automated inspection or contextual as-built documentation. The scanned data are aligned with faceted versions of the planned CAD models and then scanned surfaces are compared with those expected. The result is a difference map which can indicate how well as-built circumstances match the plans at a semantic or object level. This approach remains under development and is sensitive to magnitude of the discrepancy between planned and actual construction and transient objects like unused construction material or debris in the scans.

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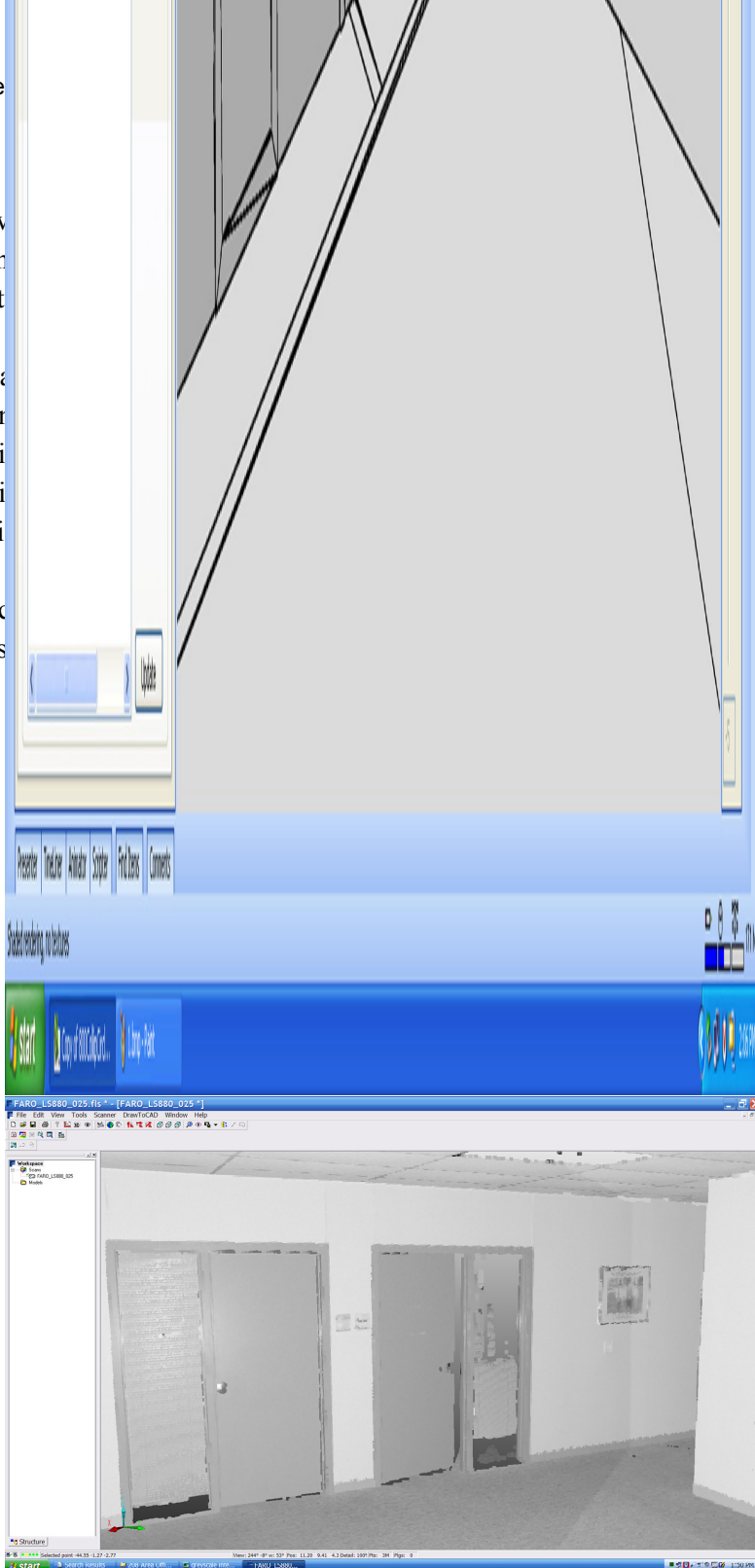


Figure 1. An example of as-designed (top) vs. as-built (bottom).



### 3. Observations and the future

Except for specialised applications, of all the methods for gathering the raw data for creating as-built documentation, the authors find the simple camera to have the most future potential due to its low cost, portability, availability and rapidity of data capture. In fact, for simpler construction jobs, the quality of today's digital images combined with the some correlated as-built documentation may prove to be sufficient to locate building services as required after construction. This would, however, require good photos be taken after each MEP element is installed with broadly identifiable features included in the images. If images are captured regularly, correlated with the designs, and made available immediately for planning or coordination sessions they could support effective construction management practices.

For more complicated jobs or installations or to update digital designs, sufficient information coming from fixed cameras, multiple photos or video data, combined with photogrammetric techniques should support creating as-built records of MEP element locations often within centimetres or better. If higher accuracies are needed then laser scans or other more advanced equipment may be required to gather the raw data. Unfortunately a significant bottleneck remains in having to manually updating existing CAD or BIM models with as-built dimensional information.

The authors see significant potential in a combination of photogrammetric software with CAD applications to support overlaying multiple camera views on 3D models for rapid visual identification of differences in design and implementation. Additional tools for the rapid re-alignment and positioning of components to match the photographed reality would greatly simplify recording as-built conditions in digital models. Further application of newer Content Based Image Retrieval (CBIR) technologies could then lead to automatic matching of as-built to as-designed components and ultimately to automatic updates of as-built models, subject to operator oversight. These goals should be realisable more quickly by narrowing the scope of automatic recognition to specific domains, like MEP for example. As mentioned earlier, some software like *Innovx RealityLinx* [9] and *Autodesk Navisworks* [5] are already taking steps towards these targets, however aligning as-built data with models remains an onerously manual task.

Though not the direct focus of this work, it is worth stating that if no electronic models exist, a common problem for many heritage and even modern

facilities, significantly more human effort is required to build models from scratch based on human knowledge of the individual components and the gathered dimensional data. For example, one of the authors used a *FARO* laser scanner [2] in 2006 to create as-built models for a manufacturing facility where no CAD data existed. In total the process **took about 3 person months** to complete. The following outlines the manual steps involved:

65 spherical and paper targets were strategically placed around the environment to facilitate registration of the 37 scans taken over a period of two days. As each scan was completed, the raw range data was sent to a PC for alignment and registration. With two skilled operators working in parallel, the scanner and PC were kept in constant utilization. In total, over 1 billion data points of X, Y, Z, location and R, G, B intensity values were captured. The size of the data set itself caused the computational time for many of the raw range data analysis and manipulation operations to be measured in minutes when processing with *FARO Scene* [1] software. Also only three or four scans could be loaded simultaneously before hitting 32-bit Windows maximum limit of 2GB of memory per application. The practical work around required manual swapping in and out of adjacent scan sets and repeating the registration process with a second pass through all the scans to align adjacent scans not aligned during the first pass. CAD models were then built manually from extracted dimensional data from the entire scan data set using dimensions directly measured using *FARO Scene* or through tracing in CAD imported tomography projections of a slice of data onto a plane (Figure 2).

To create visually realistic models (Figure 3a), *3ds max* [3] was used to load the CAD models and add textures based on pictures taken in the manufacturing facilities. The final result was CAD (Figure 3b) and 3d models suitable for CAD design or advanced visualisation applications like the ability to create still images, animated videos, and even environments for self-directed navigation through the space.

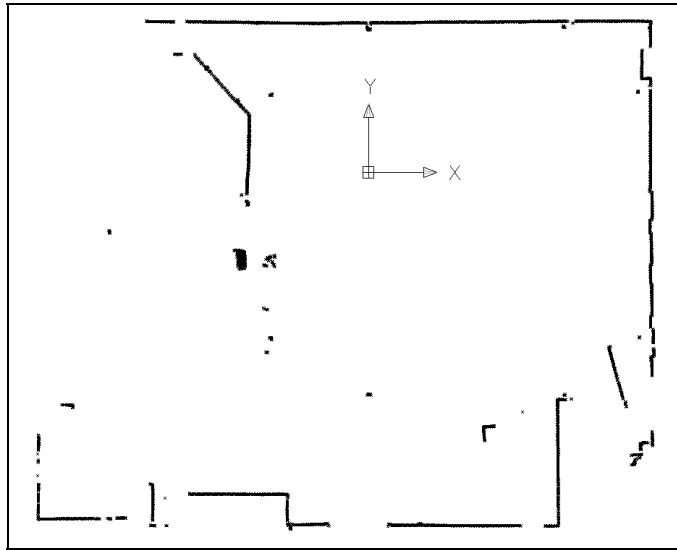


Figure 2. An example of a horizontal (plan-view) tomography based profile as viewed in AutoCAD.

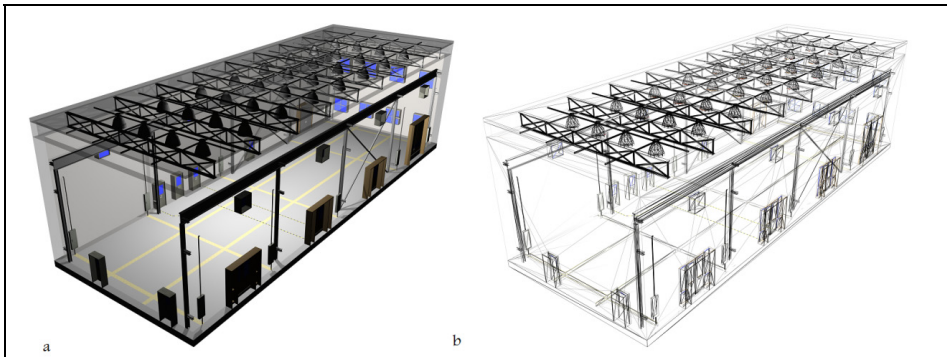


Figure 3. a) Example of a visual model of a high-bay facility based on CAD model b) Direct visualisation of geometry from a CAD model.

In terms of improving building models from raw data, it should be noted that although only 3 years have passed, new computers and operating systems should improve the speed of computations and number of scans that can be registered in one pass. Still, the identification of targets in each scan remains a manual process (for photogrammetry and laser scans) but new RFID or other technologies could be used to allow the software to identify targets and control the alignment process freeing the operator for other tasks. Such jobs could be

left to run overnight or over a weekend as required once all the scan data was captured. However, it is creating the model from the gathered data that remains the longest and most manual task. The better superposition of multiple full colour images into CAD environments, as mentioned above, could greatly ease adding and aligning library components to realise rapid model development. The further future would hopefully include more robust recognition of objects as-built, potentially based on tagged construction materials (e.g. RFID) that can be electronically queried for their identities or in the case of older constructions, more advanced object recognition technologies able to identify common elements from images.

## 4. Conclusion

The authors have presented an overview of traditional and newer technologies used in the creation of as-built documentation with a bias on their application to MEP services. Though robust solutions do exist they remain manually intensive and often require expensive equipment and trained personnel. However, new software technologies (i.e. image processing and image registration) and cheap digital cameras show significant promise for the creation of new tools that could greatly ease the manual work required to keep as-built documentation up to date and support on-going construction. In the further future as image processing and object recognition technologies improve there is hope for nearly fully automated as-built documentation for specific construction domains.

Although these technological approaches are still in their infancy they are rapidly becoming more practical to realise as the construction site and project documentation goes electronic. The solution does not lie in one technology but rather the integration of these technologies into simple tools for the industry to use.

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# Knowledge-based Design Integration using Bluethink Applications

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## Abstract

This paper describes how the construction value-chain can improve its design integration and operation by using knowledge-based tools as part of Integrated Design Solutions. The tools described support a continuous knowledge improvement cycle to obtain the best results and effects from an industrial approach across the phases of design, engineering, construction, and operations. The tools referred in this paper consist of three main components: *Experience*, focused on learning and knowledge management; *House Designer*, focused on building design and development; and *Supervisor*, focused on project configuration and information management.

We describe the collaboration processes and the integrated flow of knowledge and information through the various value-chain phases. We further discuss how all parts of the construction value chain can benefit from specific knowledge management and how product life-cycle efficiency is best assured by the combined use of knowledge management tools. Both experienced issues regarding technical integration and use cases are presented.

**Keywords:** design optimization, rule-based design, reuse, experience, collaboration, methods, IT-based tools, building information modeling, BIM, knowledge-based



engineering, knowledge management, industrialized, house building, construction operations, construction processes, quality, resources, automation, forward-looking technology

## 1. Introduction

Selvaag is a residential construction company that has produced 55000 housing units in the Oslo area since Second World War. The innovative company founder had to wrestle with the building authorities during the post war development in the 50s, when he claimed that quality housing could be provided with much less material and effort. By introducing new materials and construction methods in combination with volume production and tightly managed project logistics, Selvaag was able to provide improved standard housing units at a much lower cost. In essence, the good practices established was promoted as the industrial approach, defined as: *“The most intelligent way to convert material resources to finished products with necessary repetition and exploitation of local advantages to gain the best possible results in economy and quality”*, but in fact, the Selvaag approach was an Integrated Design Solution. The many Selvaag housing still in use today show how this approach created value both for home owners as well as for the company.

The base for the industrial approach in Selvaag was standard housing units and building types, used repetitively and continuously improved. Changes to existing standard products were consciously done based on feedback on project applicability of solutions and new knowledge, but typically applied when the product was used again in following projects.

In the 1980s, the challenge of achieving predictable, industrial performance, yet acceptable customized design homes, was evident and at the same time Selvaag experienced how knowledge on best practices and good product solutions faded away with the passing of time and attrition of individuals involved in specific tasks. As a result, Selvaag looked to information technology to find means to create a collective experience base that would be available for younger engineers or newcomers in the engineering work within Selvaag. With a high innovation rate of housing units, the goal was to still use standard solutions and/or always check possible new solutions versus the existing recorded experience. The Knowledge Based Engineering (KBE) technology was found promising in both recording corporate knowledge as well as a way to actively promote specific solutions.

The developed Selvaag Bluethink applications include tools (Figure1) for experience recording, coordination of experience and new knowledge, as well as tools for exploration of new design options and promotion of validated solutions in integrated design projects.

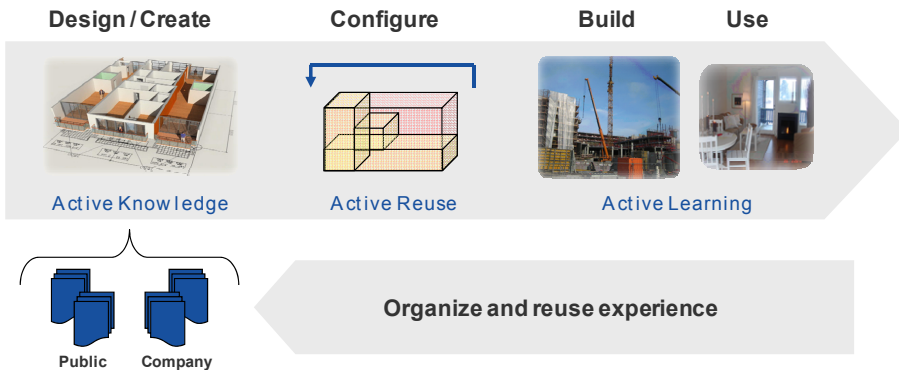


Figure 1. Bluethink approach to knowledge management.

## 2. Knowledge growth methodology

Building projects have a bad track record on efficiency [1], and has in recent years received attention specifically for its lack of productivity development in comparison with other industries. Most building projects are set-up and managed as a one-off project where the owner, architect, engineering resources and contractor are gathered for a (reasonable) short period of time to share information and knowledge to reach the specific project goals. Typically, little is done to research experiences made in previous projects or record experience for following projects. Risk management is partly handled by everyone looking to solve issues as close to their existing experience as possible and by setting up contracts that require strict bordering between the participants rather than promoting shared risks and rewards of good performance. This further leads to specific contract deliverables, often in the form of paper documentation, being the only information carrier between the participating parties.

Well, change is coming. Today, Building Information Modeling (BIM) [2] is rapidly becoming the approach in many building projects, in which Integrated Design Solutions and new risk schemas are implemented in new Integrated Project Delivery [8] methodologies. However, there is still a distance to go from

sharing information to sharing knowledge in order to fulfill the Integrated Design Solutions vision. Most of the information shared in BIMs is still created by the hands of individuals from different disciplines, and the solutions only meets the knowledge of others at a point where code validations, clash detections, and other tools are used to check if in fact a project can be realized. The many iterative cycles of creating information and checking it is still inefficient, and even when successful, the detailed engineering miss out on obvious construction process efficiency issues. And so, the next project starts without learning from the previous with iterative cycles and without achieving the expected results of Integrated Design Solutions.

## **2.1 Product, process, people – knowledge management**

Sharing knowledge between building project participants, let alone between projects, is difficult. Many obstacle questions arise as people are encouraged to reuse information or knowledge. When does knowledge apply? How does one find the appropriate knowledge? Where is the experience from previous projects recorded? Will we spend more time sorting out the records rather than just create the solutions over again? Is the knowledge outdated?

In order for a knowledge worker to reuse knowledge, the worker needs to trust it, find it, accept it, and then be able to contextualize it with the ongoing task. Many knowledge management software tools focus on providing relevant information from trustworthy and ranked sources based on the workers request. But, what if the knowledge worker doesn't ask? A conscious learning corporation considers knowledge an asset and wants the participants in various tasks to actively use the right version of its assets and also actively contribute to the improvement of the asset. This means that the knowledge should have an obvious and well defined presence in the production, and in order to improve the knowledge asset it needs acquisition, assembly with other components, innovation and maintenance. The handling needs a structured ordering of knowledge to provide accurate use.

In support of the industrial approach, the ordering for knowledge in Bluethink methodology follows the idea of production by recipe. Products (buildings) are prepared by a set of activities involving raw material, methods of transformation or assembly, made by personnel with appropriate skills and tools, and based on accurate instructions. Hence, the knowledge management for Integrated Design Solutions needs to encounter as many of such recipe considerations as possible.

Knowledge elements are therefore managed as separate data entities categorized by a range of category dimensions. Categorization has meaning both for recording in order to understand the reference of the experience or the knowledge content, as well as for retrieval and use in appropriate context. The dimensions used are

- project (location, season, crew, duration)
- phase (design, engineering, site logistics, construction, inspection, use),
- building type (families of repeatable combinations of building solutions)
- building part (apartment, room, internal, external, etc.)
- building element (door, window, shower, curtain wall, etc.)
- discipline (timber, concrete, mechanical, etc.)
- trade (carpenter, plumber, etc.)
- function (insulation, moist protection, etc.)
- issues (leak, moist, cracks, ventilation, etc.)
- means of dissemination (documents, software applications, physical tools)
- area of Application (context, applicable codes and regulations)
- activity
- skill.

All of these dimensions make parts of the information model that makes the skeleton for population of knowledge entities. All entities will be categorized by all applicable dimensions, although entities may have a mix of specific entry point in some of the categories, while having multiple entry points in other categories. Many BIM technology platforms support the Industry Foundation Classes (IFC) building information model defined in the ISO/PAS 16739 standard [3]. Bluethink refers to the same standard in its information model, providing the framework for Integrated Design Solutions by promotion and dissemination of knowledge with relevant referencing in tools supporting the IFC standard.

In order to manage knowledge elements, records include date, recording person, handling agents, discussions on cause, alternatives and effects, historical archive of previous versions of the knowledge element, and promotion method. This allows the organization to handle this as a stock similar to other assets.

## **2.2 Knowledge growth process**

Knowledge growth means the accumulation of relevant knowledge elements over time by both structured and unstructured means. However, the conscious

corporate knowledge asset management requires a formal handling procedure of all incoming experience elements and new knowledge (including public codes and regulations). The knowledge Growth Process allocates tasks, responsibilities, roles, authority, and formal process steps to move a knowledge element from recording entry to project dissemination. These steps can be described as

- discovery: the first notion of an experience or new knowledge arrival
- recording: the structured information input to define the element
- exploration: first evaluation of importance, relevance, need for handling, etc.
- elaboration: inclusion of additional information, the evaluation of alternatives, business analysis, preferences and consequences
- decision: selection of use of knowledge element, including activation, de-activation, and means of promotion or activation
- promotion: presentation of knowledge element with relevant reference and content for voluntary use
- activation: publishing knowledge element with relevant reference and content for forced use.

To provide trustworthy and traceable knowledge for all parties involved in Integrated Design Solutions efforts, each of the steps require tooling for information handling, involvement of the right resources, control of completeness of steps, authorizing the forwarding to next step and recording of all relevant information for the handled version of the knowledge element.

## **2.3 Knowledge dissemination – enhancing organizational skills**

Knowledge dissemination may be instrumented in several ways along a path from highly voluntary use, to complete disciplined activation of knowledge directly in a production process step. The means can be of many types, such as: available reference material for lookup; consciously transferred knowledge between colleagues in line or in teams; best practices notes; control system procedures; drawings; 3D models; production recipes; and physical manifestations in for instance prefabricated building elements.

Dissemination of knowledge has historically been achieved by project control procedures and discipline, but is well served by software tools. Bluethink supports three distinct levels of knowledge activation.

#### Promotion by Availability

First, when handling a knowledge element in Bluethink Experience, the categorization will give a lookup to other knowledge relevant by the selected categorization. This will promote the appropriate assembly of experience and new knowledge with relevant consequences, being product quality, process applicability, or human resources.

#### Activation by Integrated Design Automation

Secondly, the Bluethink House Designer uses knowledge based engineering technology to automatically generate design alternatives. It integrates functional intent, material and building element selection, constructability by production method, and compliance considerations, all based on activation of validated knowledge elements. In this context, the designers (collaborative effort by owners, architects and engineers) still explore a fairly open solution space where all knowledge elements' combinatorial effects can create new designs.

#### Activation by Product Configuration

The third level is supported by Bluethink Supervisor, and leaves only configuration of product options left to the designer. In this situation, all possible outcomes of the use of knowledge is known, similar to how one would order a car by configuration on the internet. The pre-existing integrated data and information include all necessary engineering details, documents and models, and the configuration leads to a selection inside the existing library. The production process is highly predictable and required engineering is reduced to a minimum.

## **2.4 Product lifecycle management – enhanced value delivery**

Using a highly enforcing knowledge activation tool, brings the handling of buildings, building information, and construction projects to the similar Product Lifecycle Management (PLM) [4] approach as can be observed in manufacturing industries. The conscious recording of information relevant to products, including division in sub-parts, use of strategic procurement, and sharing information over well defined data transfer protocols, enables a high frequency of innovation and new product releases. The product environment is well documented from inception to operating manuals, and changes are only made when impacts are

understood from the lab through the production facilities, through to operation and use.

The building lifecycle management [5] paradigm is now promoted within the AEC industry, often led by public owners [6] and authorities, but it still focuses on per project collaboration and best effort, along with using BIM for appropriate documentation for operation and maintenance, rather than the overall efficiency in providing the product – the building.

A PLM approach will provide the industry with the industrial predictability. It is still an open question though, if it can handle the market demand for customization.

### **3. Knowledge activation in integrated design solutions**

The NIST report [7] on “The Cost Of Inadequate Interoperability In The U.S. Capital Facilities Industry” is an example of several reports describing how the building industry suffer from inefficiencies due to lack of interoperability. The industry has realized that the inefficiencies are largely due to the conventional linear process, and both professional organizations and public owners are promoting and requesting new collaborative ways of working. The AIA has released their Integrated Project Delivery (IPD) [8] and public owners like US GSA [9], Norwegian Statsbygg [10] and Finnish Senaattii [11] have put out requirements on use of BIM in their projects. One goal is to share as much information as possible through digital information modeling means, but also adopting an integrated, collaborative work style where discussions on solutions and impacts are done as early as possible to avoid the need for iterative re-working cycles and corrective actions later in the project.

#### **3.1 Frontloading the building project**

Patrick Macleamy of AIA, in 2004, introduced the “Macleamy Curve” (Figure 2) [8], [12], illustrating the advantages making design decisions earlier in the project when opportunity to influence positive outcomes is maximized and the cost of changes minimized, especially as regards the designer and design consultant roles. This is now well accepted as a driver for sharing information and is commonly used as part of the argumentation for Integrated Design Solutions based on use of BIM.

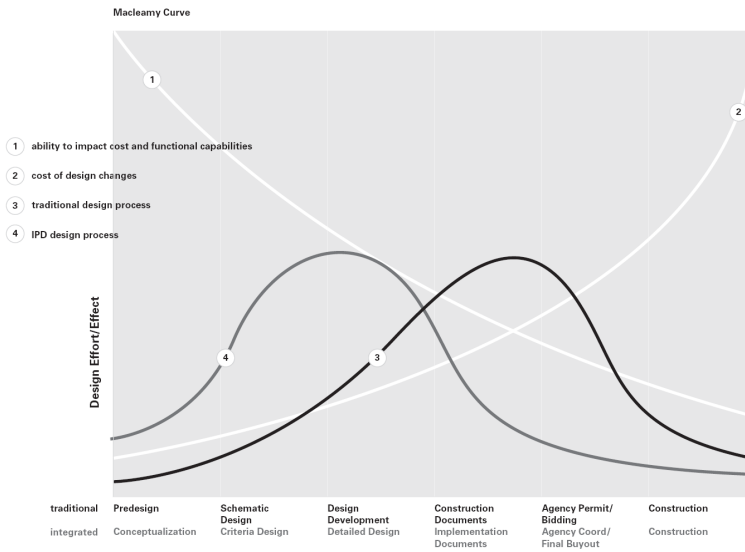


Figure 2. Macleamy Curve.

FIATECH [13] is another organization promoting use of digital information technology for improving efficiency in capital project delivery, and in the same manner as the buildingSMART [14] community’s promotion of IFC, looks to data standards as a means to improve collaboration and information flow. FIATECH’s “Vision of an Integrated and Automated Capital Projects Industry” is illustrated in (Figure 3), and shows how “Technical Plan, Target Cost and Schedule” together with “Supplier Designs/Capabilities/Products and Services” can allow for “Automated Design” based on the “Requirements and Conceptual Design” input from the scenarios required from the “Scenario-based Project Planning”.

Bluethink combines the intention of early design decisions in the Macleamy Curve with FIATECH’s vision of automated design by automatically activating integrated design knowledge. As described in 2.3, the automation levels can vary between creating new design as validated combination of known solutions, or by selecting among product configurations. “Frontloading” the building project includes setting up the project for best possible performance with a dramatically improved design processes. Projects starting from product oriented designs rather than emerging one-off designs will require less effort in each project as is illustrated in Figure 4. The benefits are many, but improvements will be found within the design process itself, seeing less need for arbitrating design details, and the construction process and end product will see the advantages of applying solutions and processes that have already been tested.



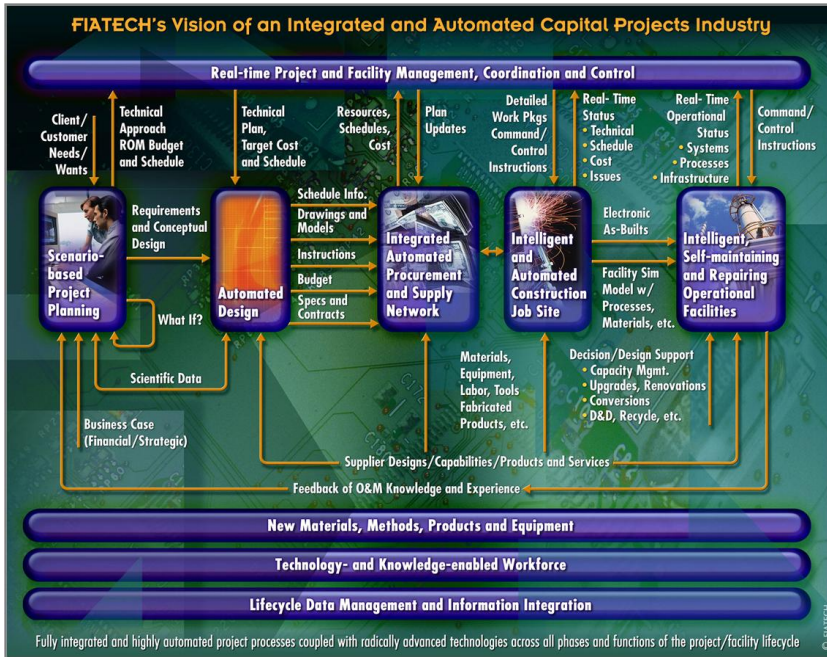


Figure 3. FIATECH “Vision of an Integrated and Automated Capital Projects Industry”.

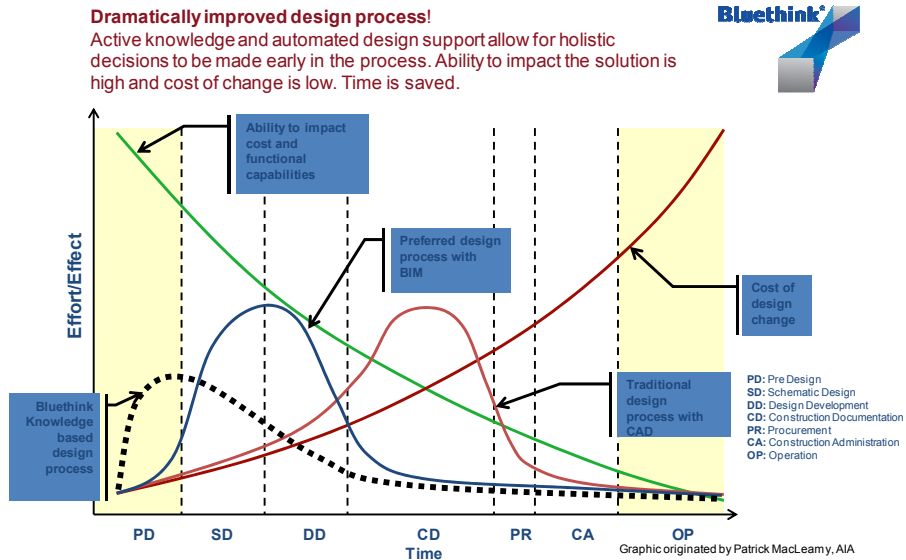


Figure 4. Bluethink’s “Dramatically improved design process”.

Frontloading of projects is especially attractive to enhance value to owners, operators and contractors who are involved with buildings of typical repetitive use patterns. Examples are

- residential
- public service buildings; schools, kindergartens, nursing homes, court houses
- hotels
- stores
- army facilities.

The participants in these projects typically delivers many similar projects and they often have the benefit of growing knowledge over time about product quality, inefficient logistics, construction processes, documentation inconsistencies, etc. This can all feed into a Product Lifecycle Management information system that allows considerate product innovation and reuse of well established design solutions.

### **3.2 Information flow in integrated design solutions**

Information Design Solutions benefits like project efficiency improvements, early design decisions, Building Lifecycle Management and Product Lifecycle Management, are all achievable only if, and when, information can be represented and shared in an efficient way. Digital information systems make it possible to store and retrieve data, but only make a difference in process efficiency when the data can be retrieved and used by other process participants. The CAD drawing-, planning-, procurement-, and other systems applied in the building industry over the last few decades have all led to local productivity gains, but have not solved the issues of lack of interoperability, re-entering of data based on paper prints, and the participant's need for risk avoidance.

“Frontloading” of a building project with shared integrated design decisions will only pay off when information is represented in a form so it can be well understood by all participating decision makers and available to be directly used in the following project phases. Only then will participants trust the information, continue to elaborate the detailed engineering based on the original data, and collaborate in risk and reward sharing schemas.

The IFC standard now can be used as a schema for data transfer between various software applications, and examples have shown how project phases starting with room programming and schematic designs, carrying on through the detailed engineering, procurement, and 4D (cost) and 5D (time) planning can

reuse the information. The ability of software and organizations to represent data to allow meaningful information to flow is strengthened by the efforts to create handbooks such as the US National Institute of Building Sciences (NIBS) National BIM Standard [15].

However, the IFC standard defines how to transfer data, but not what to transfer. This is now met with the development of standards such as the Information Delivery Manuals (IDM) [16] which map out business processes and exchange requirements for the information content to flow between process steps. IDMs can be used in generic form or as specific agreements in projects. In this way, information content, form, and transferability is assured between phases and participants in a project.

Given proper IDMs, design frontloading of projects create predictable conditions for the following project phases. Furthermore, if the design frontloading is based on product configuration, the IDM in fact constitutes the same information system that makes the PLM system found in other industries.

## **4. Use cases**

The use cases show two Integrated Design Solution examples achieved by frontloading the design process. The first example is a UK construction company targeting the “Affordable Housing” marked in UK, utilizing Knowledge Based Engineering early in the design process to mitigate the risk of not meeting public requirements in a highly regulated market. The second use case is a low cost modular home product delivered by Selvaag. The concept is based on an industrial prefabricated delivery process, where the delivered building is a result of a valid configuration of predefined modules and elements part of a PLM type of a product.

Both use cases will discuss effects and consequences in an Integrated Design Solutions perspective.

### **4.1 Mass CUSTOMIZATION by knowledge based engineering – affordable housing in UK**

Inspace Partnerships, a social and affordable housing developer in the UK (Figure 5), has deployed the Knowledge Based Engineering application Bluethink House Designer to improve their design of affordable housing. The affordable housing market is a highly regulated market with complex codes and regulations. The Inspace challenge is to improve designs and reduce cost by

integrating best practices, standard solutions, public rules and regulations, and constructions methods.



Figure 5. Example affordable housing units from Inspace Partnerships.

The Inspace solution supports and automates the early design phase by enabling use of standard layouts describing the functional intent of the layout instead of the physical solution. The best practices, building methods, and codes and regulations are modeled into the application which activates knowledge as generative functionality automatically creating the design, and validating functionality criticizing the design. The collaborative design team reaches an integrated and validated design at a very early stage.

From a business perspective Inspace is striving for, among others

- avoidance of historical and frequently recurring errors in design through knowledge capture and rule enforcement
- maximum objectivity and reduced subjectivity in: architect design; design co-ordination skills; technical compliance checking
- fewer defects because of more standardisation and more efficiency through rule enforcement on schemes.

#### **4.1.1 Automate knowledge at decision point, frontload the design process!**

Automatically applying knowledge early in the design phase, forces the designer to focus on functional intent and not schematic design. Inspace documents their best practices as layouts describing the functional intent. Using Bluethink House Designer the functional intent is described as apartments and buildings with

spaces where the spaces are assigned room types and functionality (Figure 6). Each room type comes with associated rules and reasoning capability. Thus, selecting a specific room type such as “Living Room” for a space automatically activates it all the rules associated with that type in the knowledge base.

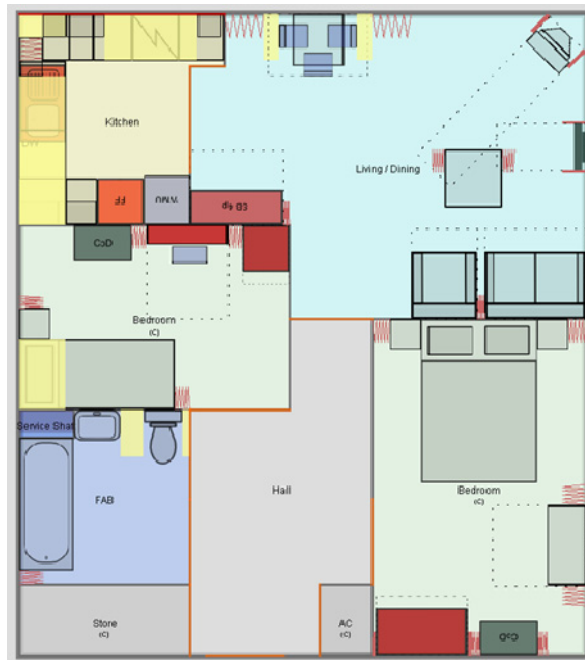


Figure 6. Bluethink House Designer screenshot of a functional intent layout.

To ensure that the correct rules are applied, the user selects the various Rule Sets. In this way the same layout can be the starting point for different resulting designs, allowing focused collaboration among design team members over different integrated design considerations. For Affordable Housing in UK, rule sets concerned with integrated design for Wheelchair, Life Time Homes, Care Homes, etc. will be applied.

Once the functional layout has been defined, a detailed information model is generated. The Preview mode shows detailed floor plan along with the conflict violations detected by checking the model against the active rule sets. For each conflict, rules that are violated are shown, along with recommended solutions to fix the problem, when available. (Figure 7) shows how the doors and windows have been automatically picked and positioned together with switches and some other electric components, all based on the generative rules embedded in the

system. In the right panel, the violations detected are shown. The description also includes reference to the Knowledge Base allowing skills to grow from experience and knowledge directly into new project designs.

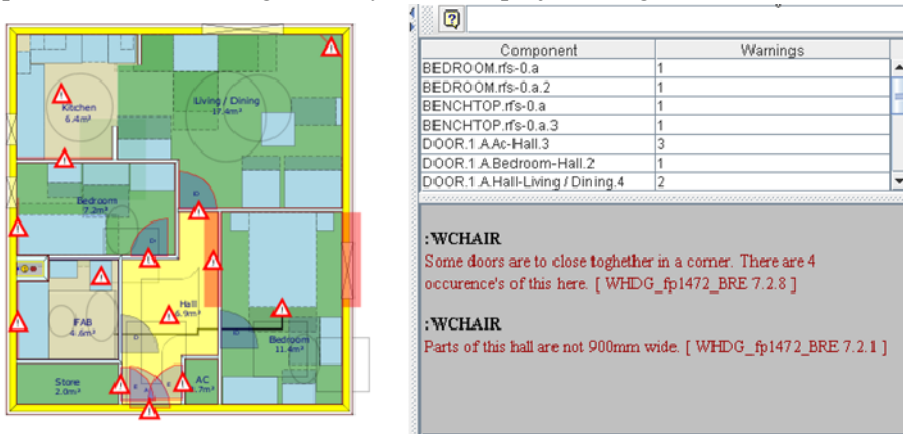


Figure 7. Generated layout in showing knowledge reference and rule validation.

When different apartments are integrated into a building with a fixed footprint and elevation, a complete Building Information Model is generated. The model is exported by use of IFC (Figure 8) as a starting point, bootstrapping and frontloading the remaining design process. The process constitutes a frontloaded Integrated Design Solution by which complete new buildings can be created from the validated knowledge within minutes and hours instead of days and weeks.

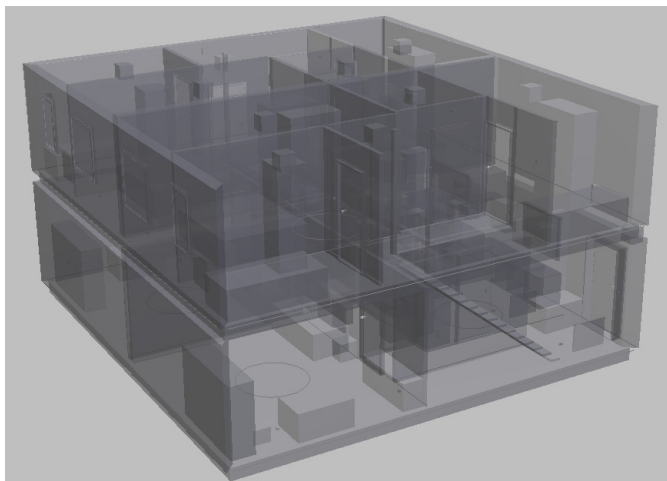


Figure 8. Example of an IFC export converted into 3D pdf.

#### **4.1.2 Findings and challenges related to Integrated Design Solution**

The Inspace system frontloads the design obtaining the Integrated Design Solutions goals of minimizing structural and process inefficiencies by automation, enhancing the value delivered during design, build and operation by providing guaranteed approved affordable housing units, and clearly bringing knowledge across projects by activating best practices. The remaining design process will still include some detailed engineering and creation of construction documentation which will look similar and face most of the same tasks as other projects. However, there are some unique positive effects and new challenges.

##### Automating information and use of standard components

Since the Knowledge based Design tool select all components used from a library (Equipment, wall types, doors, window etc), the information and component ID will always be aligned with the company standards eliminating designers and engineers “habit” of selecting a better but not standard component. This will lead to a higher percentage of standardized components and thereby better support the estimation and procurement processes. Further down the line, this will also lead to a higher percentage of repeated solutions (Process, material, competency) at building site.

##### Interactive use of IFC imported models

A frontloaded design from Bluethink House Designer populates its BIM based on known properties in the knowledge base. With today’s available technology, most use of IFC includes the operator of each application to “prepare” the property values included in exported data to match the needs of the receiving application, being energy analysis, estimation, etc. If the export is incomplete or requires an update, the data are typically changed by the operator in the originating application and then re-exported.

To accommodate for the lack of complete information standards, the IFC export from Bluethink House Designer sometimes still require the use of private property sets or other means to prepare its exported BIM for other Integrated Design Solution tools.

## 4.2 MASS customization by configuration – Low cost modular homes in Norway

The low cost modular homes initiative of Selvaag is aimed at maximizing the industrial potential of residential development. The goal is to deliver quality housing for low income families entering the residential market. The challenge is to allow enough customization to satisfy local municipalities, topographical factors on the site and the end customer. To be able to achieve this without reducing quality and keeping engineering to a minimum for each project, Selvaag has developed a modular product based on repeated use of prefabricated modules (approx. 4m x 12m) (Figure 9). The modules use standardized internal solutions like equipment groups, room clusters and functional associations. Integrated design considerations are all pre-engineered, and information technology is heavily used to control, conduct and automate where appropriate, in learning, engineering, configuration and documentation.

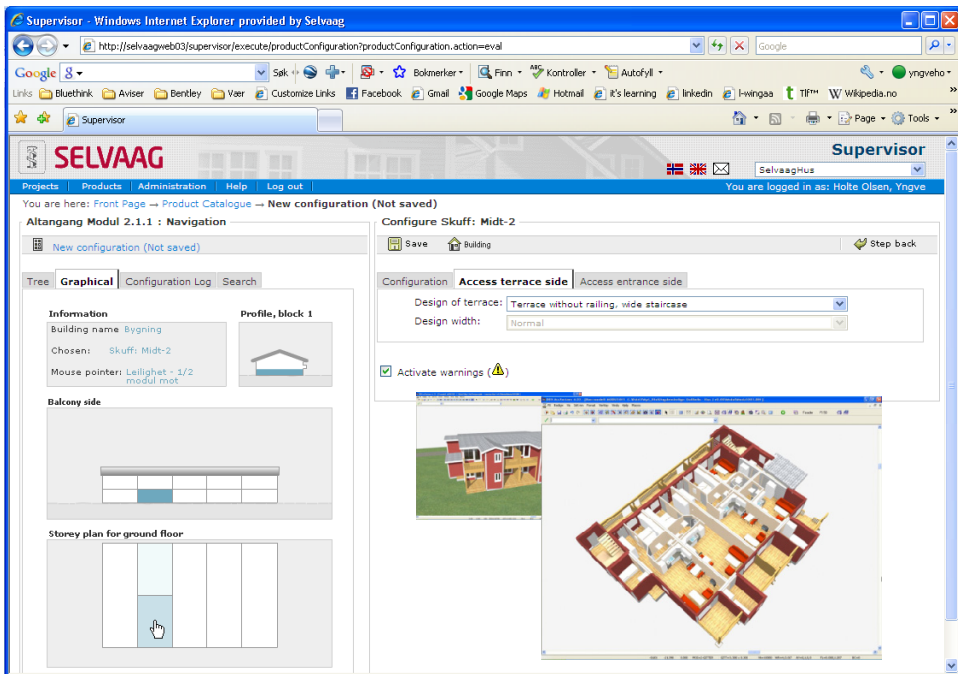


Figure 9. Web based product configuration including illustration and 3D models.



## 4.2.1 Levels of Product Management

### Building type elements and structure

The modular housing product (Product) is divided into building type elements. A typical single element is a repeated element like a set of kitchen equipments, wall elements etc. It is also possible to define more complex elements which combine single elements. Each building type element is logically defined and maintained in Bluethink Supervisor Developer and represented by a linked BIM object in a CAD/BIM tool (Figure 10).

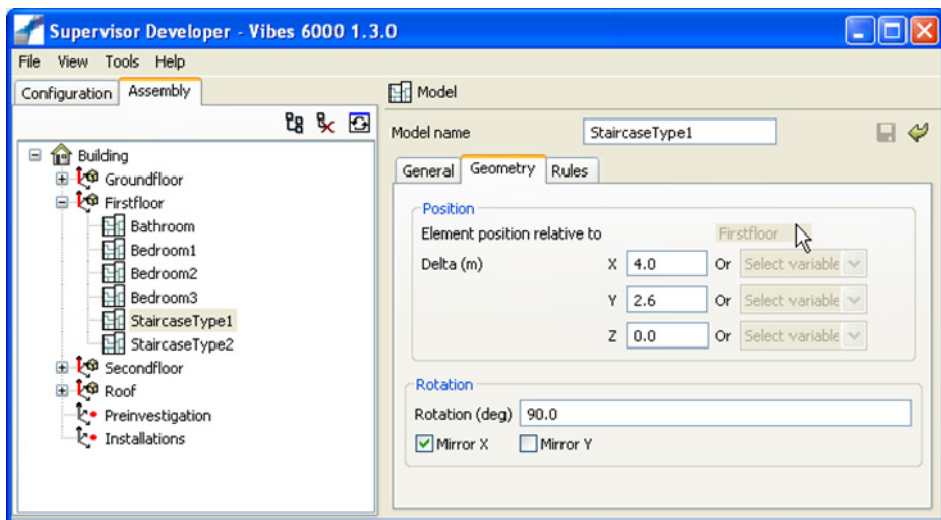


Figure 10. Supervisor Developer illustrating a product structure with linked BIM objects.

### Product model and options

To allow the collaboration between home buyers, project developer, and site engineers, to configure buildings providing the best match to functional and market requirements, and not based on product elements and structure alone, a parallel product model is defined. The product model consists of options with multiple predefined values like number axes, apartment types, façade concepts etc. The Option model is defined and maintained separately, and Supervisor Developer also holds functionality enabling and assuring the developer to obtain a consistent model including both Building Elements and Product Options (Figure 11).

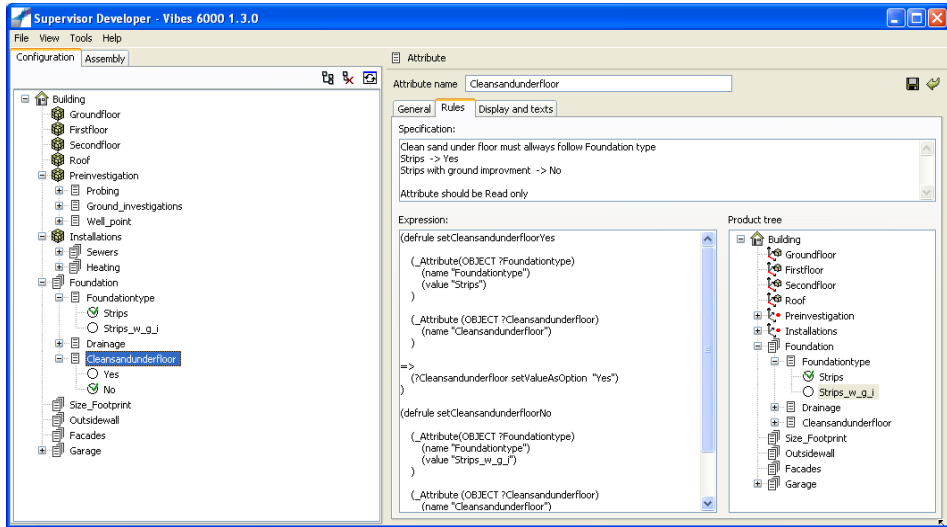


Figure 11. Supervisor Developer illustrating an option model with configuration rules.

Configurable buildings – a highly efficient design process

Configuration of the buildings is done by selecting the Product option. The Bluethink Supervisor then picks the corresponding Building Type Elements represented in the CAD/BIM library based on configuration rules and assembly rules, and automatically assembles a complete BIM (Figure 12).

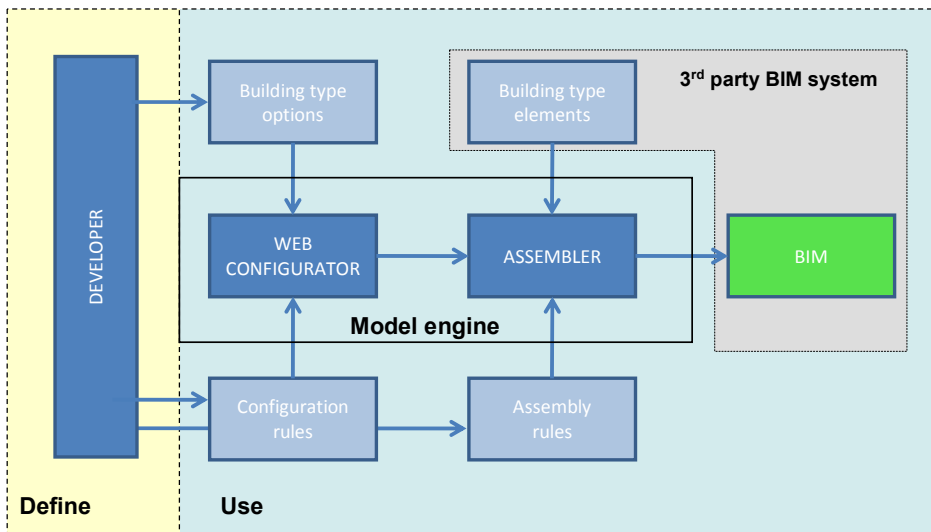


Figure 12. Supervisor Developer application modules (Patent pending).

Since the BIM is built up by the predefined Building Type Elements the resulting BIM will hold all integrated information to the level the individual BIM objects are modeled. Further use of the BIM is then enabled and dependent on the quality and information level in each BIM object. To achieve an efficient information flow in the project, the BIM objects are modeled according to the Selvaag BIM Manuals and Integrated Design Solutions requirements. This turns into a BIM structure targeted and streamlined for prefabricated module production, providing added value to the contracted builder.

#### **4.2.2 Findings and challenges related to Integrated design solution**

Due to the automated configuration and documentation process in each project, the quality of the end product relies on the quality of each Product element. This leads to a situation where the experience and knowledge must reflect the functional perception of the Product in addition to the engineering perspectives of building elements, disciplines, function, etc. Selvaag has experienced that the internal structure in the IFC model exported from the assembled BIM model lack the ability to represent the functional and configuration options perspectives. To allow collaboration between different process participants, the Integrated Design Solution must be able to handle multiple perspectives of the same product.

- Production structure; how the product is modularized and produced.
- Product Option structure; how the product is logically structured, reflecting how the market perceives the product and its options, and how it is partitioned to be flexible enough to meet changes in market demands.
- Building structure; how the end product is documented and defined using IFC.

On the other hand, the Selvaag approach reduces challenges met by most one-off projects when applying Integrated Design Solutions. The design, engineering and documentation process is set up for the Product, not the project. This means that the specific challenges present at each integration point are met one time only, and the process is established and reused across projects.

With Selvaag's ability to repeat their modular product, they have maximized process efficiency and managed to deliver high quality housing units at low cost. With an Integrated Design Solutions that has project by project variation within predictable

configuration options, they have created a process similar to other industrial PLM processes. Cost of design and engineering in each project is reduced to a minimum.

## 5. Conclusions

Bluethink has developed tools for automatic, integrated design in building projects. The development of the tools is based on the experience gained from Selvaag, a residential construction company in Norway, in its quest for industrial production of residential buildings. Selvaag has built some 55000 housing units in the Oslo area since the Second World War.

The Bluethink applications discussed add to Integrated Design Solutions with tools for knowledge capture, knowledge management and knowledge dissemination. Knowledge elements are handled as separate data entities which are categorized by a number of industry specific dimensions. Each knowledge entity is managed in a knowledge growth process including the steps of Discovery, Recording, Exploration, Elaboration, Decision and Promotion or Activation. Appropriate personnel with different roles and authority are involved in the process to establish corporate knowledge.

Knowledge dissemination by promotion by availability provides lookup to knowledge relevant to a theme and promotes the appropriate assembly of experience and new knowledge with relevant consequences.

Knowledge dissemination through activation by integrated design automation uses knowledge based engineering technology to automatically generate design alternatives. In this context, the designers still explores a fairly open solution space where all knowledge elements combinatorial effects can create new designs.

Knowledge dissemination through activation by product configuration leaves only configuration of product options left to the designer. All possible outcomes of the use of knowledge is known, similar to how one would order a car by configuration on the internet. The production process is highly predictable and required engineering per project is reduced to a minimum.

Using knowledge activation tool brings the handling of buildings, building information, and construction projects to the similar Product Lifecycle Management (PLM) approach as can be observed in manufacturing industries. Although a building lifecycle management paradigm is now promoted it still focuses on per project collaboration and best effort information use, rather than the overall efficiency in product management. A PLM approach will provide the

building industry with the industrial predictability, but it remains to be seen if it can match the market demand for customization.

Activated knowledge with Bluethink tools facilitates change towards the “Integrated Project Delivery” approach promoted by AIA and the FIATECH’s “Vision of an Integrated and Automated Capital Projects Industry” by “frontloading” the design process with validated designs either by new designs generated automatically from known knowledge elements, or by starting a project from well established configurable products.

Knowledge Based Tools offers enhanced Integrated Design Solutions by frontloading design efforts with automatically created designs using managed knowledge. However, knowledge elements need to be handled with tool support in a formal knowledge growth and dissemination process.

Use cases illustrating knowledge dissemination through activation by design automation and through activation by product configuration show how organizations use Bluethink tools to provide better quality housing at lower cost in two different countries.

Inspace Partnerships apply knowledge of allowed combinations of apartment layouts and public codes and regulations to automate the design of compliant affordable houses. The design process now can focus on functional intent, and it only takes minutes to design valid apartment layouts for buildings in a range of combinations.

The Inspace system frontloads the design obtaining the Integrated Design Solutions goals of minimizing structural and process inefficiencies by automation, enhancing the value delivered during design, build and operation by providing guaranteed approved affordable housing units, and clearly bringing knowledge across projects by activating best practices. The use of the generated building information models in the following process steps still encounters some issues with the IFC based information flow as many tools require “prepared” data to accept the imported IFC model.

Selvaag apply product knowledge in its modular low cost homes. The designs of new buildings are done by configuration of a product option model, and all possible combinations offered have already been engineered. The standard sized modules (4m x 12 m) are produced in factory surroundings and shipped to the building site, where they are merely assembled. This is a highly industrial approach, and the modular product is managed by a PLM approach. However, the IFC information models mainly focuses on physical building elements rather than product capabilities, and the product option model needs to be maintained in a different model.

With Selvaag's ability to repeat their modular product, they have maximized process efficiency and managed to deliver high quality housing units at low cost. With an Integrated Design Solutions that has project by project variation within predictable configuration options, they have created a process similar to other industrial PLM processes. Cost of design and engineering in each project is reduced to a minimum.

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Author(s) Kaisa Belloni, Jun Kojima & Isabel Pinto Seppä (eds.)		
Title <b>Improving Construction and Use through Integrated Design Solutions</b> <b>First International Conference on CIB IDS 2009</b>		
Abstract <p>Integrated Design Solutions (IDS) connect people, processes and technology in the construction industry, transforming it into a high performance sector. An integrated system incorporates building concepts, business processes, production technologies, information &amp; communications technologies support, and training. This enables future construction to act as a flexible, agile, value-driven and knowledge based industry and most of all to be highly customer-centric, efficient and competitive.</p> <p>The first international conference of CIB's new Priority Theme: Integrated Design Solutions (IDS) took place on 10–12 June, 2009 in Espoo, Finland. The conference attracted forty five experts from twelve countries worldwide. They represented the views and expertise of industry, academia, and research. They shared their research, ideas, and thoughts during themed sessions on:</p> <p><u>Utilisation of Building Information Models</u>: BIMs as vehicles for simulation and virtual prototyping; BIM for supporting safety process on construction sites; use of BIM for location tracking of construction components; use of BIM to generate design alternatives and construction process sets.</p> <p><u>Integrated Processes</u>: knowledge sharing processes to supported integrated design and construction; identification and classification of challenges in integrated design; need to share processes across disciplines; using BIMs to structure and manage tasks on construction projects.</p> <p><u>Sustainability</u>: improving building design through parallel building and environmental costing; human thermal responses in energy-efficient buildings; environmental assessment of buildings.</p> <p><u>Beyond Building Information Models</u>: connecting structural buildings models to different construction classification systems; optimisation of construction planning through virtual prototyping and BIMs; integrated design systems for homes; BIM as a service offering; IT-based innovation in construction; construction automation for modular assembly.</p> <p><u>User value trough collaboration</u>: knowledge based design integration; automation technology for realising as-build models of services.</p>		
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**Sustainability:** improving building design through parallel building and environmental costing; human thermal responses in energy-efficient buildings; environmental assessment of buildings.

**Beyond Building Information Models:** connecting structural buildings models to different construction classification systems; optimisation of construction planning through virtual prototyping and BIMs; integrated design systems for homes; BIM as a service offering; IT-based innovation in construction; construction automation for modular assembly.

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