COLLABORATIVE WHITEBOARD: TOWARDS REMOTE COLLABORATION AND INTERACTION IN CONSTRUCTION DESIGN

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ABSTRACT

The need for improved collaboration and interaction in construction projects has grown significantly in recent years, especially as projects have become ever more complex. The early design stage is of particular importance for the final results as most of the building's lifecycle characteristics are committed at this stage, and the opportunity to influence them decreases rapidly as the cost of making changes, or correcting design errors, increases dramatically. Recent advances in information technology offer methods and tools to meet this need. In view of this, a collaborative whiteboard (CollaBoard) for remote collaboration – is being developed to support mixed, geographically distributed teams. Interconnected via a network, two or more system setups allow users to interact and share information over a common, interactive vertical whiteboard, allowing experts from different disciplines access to databases through intuitive interfaces in order to integrate and optimize lifecycle-related parameters into a new product. Superimposing the live video of the remote partner – "people on content" – also allows the transfer of meta information, such as gestures, resulting in more intuitively distributed collaborative teamwork.

Keywords: design process, lifecycle, remote collaboration, visualization technology, whiteboard

1. INTRODUCTION

The construction industry is project-centered, complex, and highly fragmented, including a wide range of companies from small and medium-sized enterprises to multinational corporations. A typical construction project is characterized by short-term partnerships between multidisciplinary – and sometimes globally distributed – teams with varying levels of process maturity and information handling capability. It usually involves the planning, design, and erection of structures of all types, plus a number of stakeholders such as clients, designers, material and component suppliers, and contractors. Compared with other manufacturing industries, construction companies are accused of having low efficiency levels, relatively poor profit margins, and problems with quality (Woksepp, 2007); these shortcomings have been reported frequently (e.g. SOU, 2002).

This paper presents a new collaborative whiteboard system, CollaBoard, to facilitate collaboration and interaction in construction design.

1.1 Adoption of ICT in construction

Information and Communication Technology (ICT) has been widely applied across many sectors in order to increase competitiveness and reduce costs (Marsh et al., 2000), and is today seen as a vehicle to gain a competitive advantage. In recent years, a great number of researchers have shown the values of using ICT in construction projects (e.g. Woksepp, 2007; Dawood et al., 2005; Fischer et al., 2004; Björk, 2001) and the potential of ICT as a powerful driving force for productivity improvement, e.g., Christiansson et al. (2008), Molnár et al. (2007), and the e-Business w@tch EC report (2005).

In spite of this, many studies indicate that the percentage of ICT utilization is still relatively low in the construction industry (e.g. e-Business w@tch, 2005). A comprehensive study within the EU project InPro (Pfitzner et al., 2007) investigated the use of ICT tools in the European construction industry. The study revealed a lack of use of ICT tools in construction projects despite several good candidate solutions being available. Some plausible reasons for the limited adoption are deficient understanding and lack of knowledge about the potential of ICT, unsuccessful implementation in project organizations, and limitations of software functionality. The e-Business w@tch EC report (2005) also concludes that "there is still a limited perception of the full impact and importance of ICT". As a result, construction companies often find it difficult to justify new investments in an industry that suffers from low profit margins and instead regard this as a process of consumption rather than capital expenditure. Ugwu et al (2007) point out the deficiency of research that focuses on issues and factors related to the uptake of ICT in construction, and Dainty et al. (2006) blame the fragmentation of the industry and lack of integration between design and production processes. However, there is also evidence that the use of ICT in the construction industry has been growing over the past years, e.g. Samuelsson (2008). Samuelsson reports that "the situation has been changing over the past years but there are still differences between stakeholder groups".

Several years of research have been done in the field of visualization, and significant algorithmic and technological results have been achieved worldwide. However, only a few research results are currently applied industrially to boost collaboration and interaction in construction design. Two relevant reasons for this are:

- Visualization systems were not adapted to industrial needs, i.e., they are complicated to handle and not very well suited to other business processes
- Limited interaction capabilities constrain the functionality of the system, even where the visualization is of a high quality

In addition to this there is a lack of standardization, e.g. between interfaces of different tools. These aspects of the problem point to another likely reason for the slow progress: a large gap between research, development, and the current needs in the construction sector. This implies a lack of applied research and development activities where the use and impact of new tools, systems, and processes are empirically evaluated and tested in, for example, real-life construction projects. This would surely result in systems not adapted to user needs and limited compatibility with other systems. This insight into development needs provides some support for the statement by Zarli et al. (2007) that "the real adaptation and deployment of ICT in construction has indeed just started".

2. CONSTRUCTION DESIGN DEVELOPMENT PROCESS

Since construction projects are becoming ever more complex and involve increasing numbers of specialized experts – design actors – in design development, the possibilities for and commitment to collaboration and interaction has become proportionally more significant, especially when considering the whole life cycle of the building. Design actors in this context represent the professionals in the design team, particularly those involved in design idea generation, but also other stakeholders involved in design development, for example, the client who provides project guidelines in the form of design goals and requirements. The design development in this context is understood as design activities, including idea generation and requirement handling, performed collectively by the design actors; the design products are the results of this, as stated by Sebastian (2007).

2.1 Design as a social creative process

Essentially, the practice of design is a problem-solving activity, and as designing is the development of new products in a process of generating and realizing ideas with intermediate stages (Pahl, 1999), the social context plays an important role. Thus, we also have to see designing as a social creative process. The social aspects in designing are described by Badke-Schaub (2007) as a "complex human activity that is determined by a network of influences from several fields". Within a social and creative context it encompasses (Badke-Schaub, 2007) activities such as drawing, visualizing, talking; cognitive processes such as generating, comparing, reasoning; and motivational, emotional, and social processes.
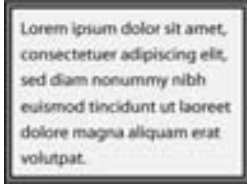
This scope implies a broader interrelated view on innovation and creativity. True innovation – leading to some kind of added-value for the client – comes from creativity. From this perspective, creativity is the ability to understand and develop connections and relationships where others have not. However, due to a common misunderstanding, creativity is equated with originality when, in fact, there are very few absolutely original "innovative" ideas. Most of what seems to be new is simply the reuse of existing concepts, not bringing together and merging (developing) previous experiences into a holistic approach. Besides facilitating creativity for a particular reason – developing a product – this holistic approach also facilitates developing collaborators' personal ability to think intuitively and creatively, which, in the long run, will change our view on how collaboration may benefit design practice.

However, much of the recent work undertaken on collaborative work has focused on the delivery of technological solutions with a focus on web and CAD applications (design and visualization) as well as knowledge management technologies. It is now recognized that good collaboration does not result from data handling alone, but must include the aspects of social creativity as well.

2.2 Remote group collaboration systems

There are existing systems that support having geographically distributed teams collaborating in a joint environment, but they are limited in their effectiveness. In addition to the common solutions including email, telephone meetings, et cetera, table 1 gives an overview of systems' working principles for remote group collaboration. Some of these systems are commercially available and some exist only as conceptual models. Systems on the market offer either remote communication with people only, content only, or with people and content on separate displays. Some systems, which exist only as prototypes, offer content on people. However, content on people has proven to be neither user-friendly nor efficient in supporting remote collaboration. The concept of people on content, on the other hand, could potentially become a highly efficient and user friendly way to support remote group collaboration.

Table 1: Different representations of people and/or content.

Representation	Description	Principle
People only	Only the live video image of the remote participants is shown.	
Content only	Only the content is transferred between team members. It can be transferred as a live video or by using a specific data transfer protocol such as ITU-T T.120.	

People and Content	A live video of the remote participants is transferred as well as the content. Both channels are displayed simultaneously next to each other.	
Content on People	A live video of the remote participants is transferred as well as the content. The transferred content is visible on top of the transferred video signal from the remote station (content overlay).	
People on Content	A live video of the remote participants is transferred as well as the content. The live video is on top of the transferred content (video overlay).	

This article argues that there is a need for a "People on Content" view for presentations and remote collaboration. However we have neither found an available device that provides the desired functionality in an intuitive, natural way nor any up-to-date publications from other research institutes regarding the support of a "People on Content" view for collaboration environments.

2.3 Life cycle design aspects

The life cycle is described by ISO 14040 (2006) as "consecutive and interlinked periods of time between a selected date and the cut off year or last year, over which criteria, e.g. cost, relating to a decision or alternative under study is assessed. This period may be determined by the client for the analysis (e.g. to match the period of ownership) or on the basis of the probable physical life cycle of the asset itself".

Olofsson et al. (2010) argues that, in general, literature about the life cycle design of buildings and sustainable buildings emphasize the need to focus on a wider range of parameters and considerations besides just the investment cost. To assure that the realized building will be a good technical solution for the occupants, owners, and the environment, decisions in the early design stages should be evaluated taking into account the consequences for the performance of the building and the total economy, as well as the environment impact. Sarja (2002) introduced the *integrated life cycle design* as an improved quality approach. This approach is known as life cycle quality and includes four aspects: human conditions, financial costs, culture, and ecology (figure 1).

Human conditions
Functionality in use
Convenience
Safety
Health

Financial costs
Investment costs
Construction costs
Running costs   WLC
End of life cycle

Integrated life cycle design
Life cycle quality
Life cycle performance

Culture
Building traditions
Business culture
Architectural styles and trends
Aesthetics

Ecology
Energy costs
Raw materials costs
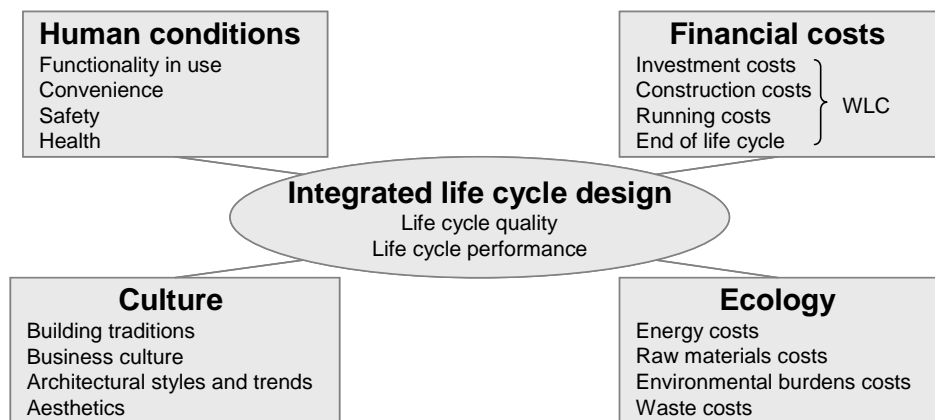Environmental burdens costs
Waste costs

Figure 1: Main aspects of integrated life cycle design, adopted from Sarja (2002).

2.4 Design parameter flexibility through product development processes

As known from product development research, many product life-cycle characteristics and the major part of the overall costs are already committed at the early product development stages. This means that after these early stages, the possibility of influencing the final design of a product and its characteristics is relatively small and the cost of making changes dramatically increases. Given that the design development, especially the early phase, is so important for the final result, it is crucial to involve experts from all potentially important disciplines in a creative process as early as possible. The early stages should also be used to generate a common understanding of the [life cycle-related] challenges in relation to envisioned product concepts, and how they would fit with the client business goals as well as other stakeholders' business goals. This is particularly important in order to attract suitable organizations, expertise, and people to the product development process.

It is clear that modern design development must support "life cycle thinking", as decisions during early design development greatly affect the impact of products throughout their life cycles. Thus, a key question is how life cycle characteristics could be integrated into these decisions in a systematic and collaborative way.

2.5 Existing data support for early life cycle related design development and assessment

Recently, much useful data has been gathered into enormous databases, and some methods have been developed to use these data in order to design from a life cycle perspective. However, a key problem is how to make these databases more operative since few or no graphical user interfaces exist that allow intuitive access to the complex information.

Some initial approaches to such interfaces exist for later product development stages. This includes CAD systems for designing product geometry. Though, at such late product development stages, only some parameters of the life cycle related databases are relevant. Also, only experts of one field, i.e. design engineers, are involved. Since multiple disciplines with unique 'languages' are typically involved here, common denominators such as an easy-to-use graphical interface become crucial. Life cycle-related design parameters are not defined by a single expert, but rather, are the result of interdisciplinary discussion within a team. Each team member typically has his/her own point of view and is an expert in some of the sustainability related design parameters, which might also affect parameters from other experts in the team. During the discussion, the varying of all relevant parameters should be possible and the life cycle related implications of any changes should be visualized for all participating experts. However, few solutions to support this early and multi-disciplinary design development currently exist.

2.6 Initiatives from EU

Numerous EU-funded construction-related initiatives have accepted the challenge of investigating and introducing new ICT platforms, tools, and collaborative methods, including human aspects, to support product development in construction, for example, the InPro, Manubuild, and I3CON projects. Some, such as the InPro project, focus on the early design phase. The European Construction Technology Platform (ECTP) has identified important research themes in the domain of "processes and ICT in construction" addressing four key aspects of construction: process, products, projects, and enterprises. One of the identified themes is collaborative support, for which ECTP has identified some key business drivers [for success]: *rapid and easy connectivity*, leading to *robust team interaction*, which in turn results in *seamless inter-enterprise integration*. And as ICT is recognized as a key enabling technology (also by e.g. Benning et al. 2010), ECTP has defined key corresponding research topics in ICT tools for information sharing, project steering, decision support, et cetera, as well as the aspects of interoperability (ICT infrastructure).

3. TOWARDS A COLLABORATIVE SOLUTION

The current paper presents an effort to respond to the need of collaborative support and propose a system with the following characteristics regarding collaboration support in design development (starting point is the vision of ECTP):

- Support on-line, distributed, and simultaneous teamwork throughout the design process (see figure 2)
  - Cover design, especially early design (but also including construction sites)
  - Bridge over to client business processes (requirements)
- Support engagement, social cohesion, and trust among geographically distributed, cross-organizational teams with multidisciplinary skills, multiple cultures, and multiple languages
  - Natural meeting point and meeting facilities, e.g.
    - Virtual meeting spaces enable synchronous and asynchronous communication
    - "People on Content" view for presentations and remote collaboration
- Data support for creative product assessment – decision support in an integrated design process
  - Access to a large database through intuitive interfaces
  - Allow experts from different disciplines to collectively integrate and optimize design parameters into a new product (though not a model manager) from a life cycle perspective
  - Allow stakeholders to adjust their own set of design parameters
  - A common display, shared by all participants, will allow visualization of the effects of each parameter set on the overall sustainability performance of a product
- International standards enable fast set-up of collaboration platforms for new project consortia.
  - Video and electronic whiteboard functionality
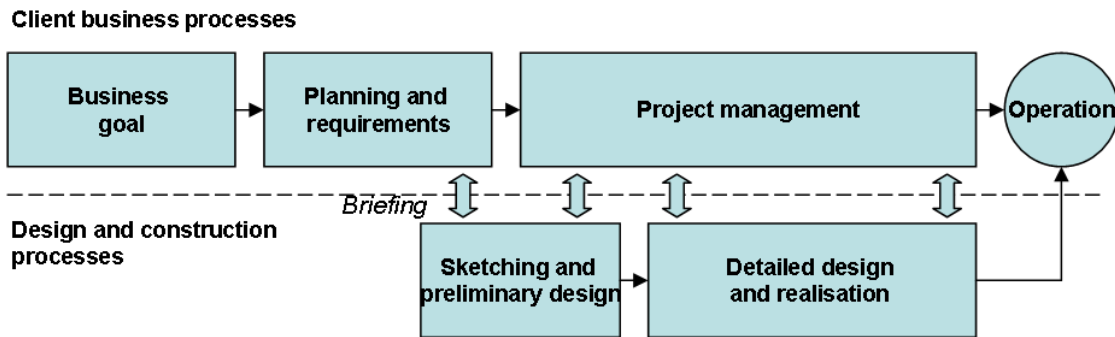 - Easy to use without system specific training

Figure 2: Proposed solution supporting early design processes (adapted from Olofsson et al., 2010).

3.1 Continuous adaption by iterative development steps

Commonly, product development extrapolates current knowledge and trends into the future (forecasting). The inherent danger in this is that while decisions may be correct according to current conditions, they may not be so if conditions fluctuate. It is more reasonable to take a given definition of a future sustainable society, try to find flexible target solutions in a step-by-step plan, and review this target solution regularly, i.e. adapt it to possible new conditions by making short-term predictions within the overall long-term plan of reaching the principled goal. A illustrative metaphor for this is the way a chess player plans and acts in order to reach the principled goal of a checkmate without knowing upfront the detailed outcome or how conditions will change during each game.

Over time, the product concept is optimized in several respects. Overall, the investments (decisions) should (i) strengthen the organization's platform for coming investments that are likely to take it towards success as defined by socio-ecological sustainability principles (SPs) and other goals set up by the organization. As a basic mindset, the organization should in each investment (ii) seek to move towards reducing its contribution to society's violation of the SPs and (iii) strive to be economical with resources so that the process is continuously reinforced by proper return on investment (ROI). In the decision regarding an individual investment, guiding principles "ii" and "iii" need to be assessed in a dynamic interplay between each other and the longer term plans, "i". This can be facilitated if engineers and other professionals can meet more frequently without having to travel. Thus, the system should not only provide a common workplace in which the elaborated optimization results will be visualized, but it should also support net-based team meetings by transferring multi-channel audio and video signals. By providing this, the experts will have data visualization at their disposal, and also the possibility to

intuitively interact in a new multi-modal system. Finding a path that supports sustainable development is a multi-faceted objective and, therefore, a multi-dimensional optimization problem. This multi-dimensionality must also be supported by a new system.

The suggested system aims at supporting on-line, distributed, and simultaneous teamwork for decision-making in the construction process with a particular focus on the early design stage. It provides a common overview for all participating experts on the optimization progress within a certain topic:

- Communication tools introduced with the purpose of imposing better control and coordination in the construction process.
- Both design and production in construction projects share a need for rapid access to information and communication in real time.
- Remote capabilities provided – Designing mobile ICT then takes on the purpose of giving people the same possibilities in the field as they would have at their bases. But mobility can also be a more fluid form of activity where there is no such thing as a base. In work places such as a construction site, mobility is an important component of the work itself. In these work environments people are mobile while the activities occur; they are not simply mobile in order to transport themselves to some place to perform the work.

This initiative focuses on facilitating integration of life cycle-related aspects into the construction design process. It is a highly interdisciplinary process requiring multiple areas of expertise from typically geographically distributed teams. Although huge databases containing relevant data exist, access to them is very limited due to missing visualization and interaction technologies. There are also significant amounts of data not being stored centrally but only existing on an individual basis. As a result, experts rely on their own experience and cannot utilize all the available information. Thus, there is an urgent need to bring together these different areas of expertise and use visualization technology for collocated and net-based teamwork and intuitive access to complex data. This is also why meta information is so important, since this is one way to exchange information, feelings, et cetera, which is not or can not be stored in any database.

This initiative aims to support the development of sustainable construction by means of visualization technology. Such a new visualization system will not only enable intuitive access to life-cycle related project data, but it also allows their fast and easy modification by experts from the different disciplines involved in the development process. The proposed application will strengthen partners' sustainable construction activities and combine it with the emerging field of visualization technology. One part of the suggested system has been realized, namely the collaborative whiteboard. Another part of the suggested system only exists in terms of stand-alone technology components. These components, called tangible and tabletop interactive systems, are yet to be integrated for the purpose of our project.

3.2 The collaborative whiteboard system CollaBoard

CollaBoard is a collaborative whiteboard system allowing expert users from different disciplines to integrate and optimize sustainability-related factors into a new product, see figure 3. The system will allow each expert to adjust his/her own set of parameters, giving access to a large database through intuitive interfaces. A common display, shared by all participants, will allow visualization of the effects of each parameter set on the overall sustainability performance of a product. This relates to the results on sustainable product development by Kunz et al. (2006). Since the optimization of a product is an outcome of intensive teamwork, the system should support net-based collaboration among the team members, allowing more frequent meetings over the network, and sparing the great and unsustainable effort of travelling.

CollaBoard provides an interactive vertical workspace within the collaborative environment (figure 3). In addition to standard electronic whiteboard functionality, a video from the scene in front of the interactive workspace is acquired. In stand-alone operation, the video allows documenting the constitution process of the information on the electronic whiteboard. If two CollaBoards are interconnected over a network, the displayed shared electronic content is enriched with a video stream from the remote station. This allows transferring meta information in addition to the regular shared content. The CollaBoard module allows the user to interact on a vertical workspace

and to simultaneously share it with a remote collaboration partner. Also, the video image of the person in front of the CollaBoard is acquired and transferred to the net-based collaboration partner. This allows transferring so-called meta information in addition to the regular content of the interaction space. However, it is important that both types of information are displayed on the same interaction space, but using two independent channels since they are separately acquired and transferred. This may assure that the content of the interaction space stays editable at both sites.
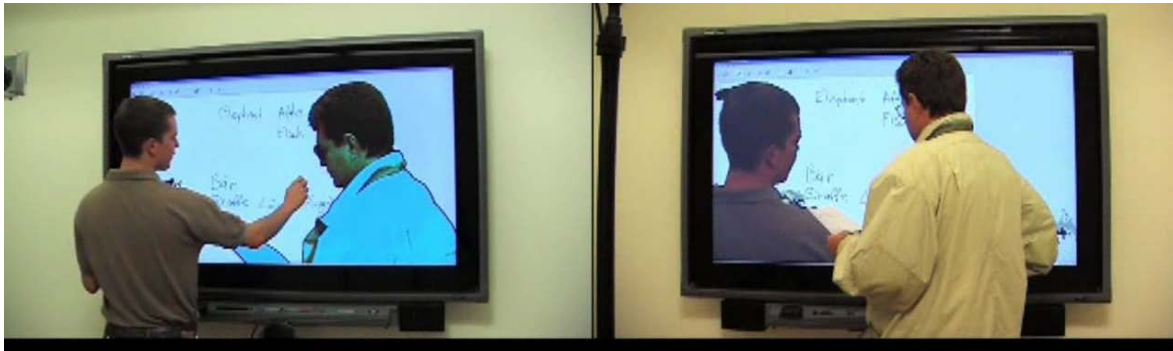

Figure 3: Collaborative whiteboard system for remote collaboration and sketching (CollaBoard),
a recent outcome of research activity at ETH Zurich in collaboration with Chalmers TH.

3.3 Advanced interaction devices: collaborative tangible and tabletop systems

Besides traditional data input devices such as PCs and interactive pens, Collaboard opens up for more advanced interaction for example so-called Tangible User Interfaces (TUIs). TUIs are intelligent physical devices offering users a more physical and direct control of complex digital information. Most often, TUIs will operate on interactive tabletops. Hence, complex information and parameters may be visually represented partly on TUIs, partly on the tabletop.

For a given life design topic, the experts attempt to optimize the product by varying the parameters in their field of expertise. In order to do so, they have their own tangible input devices, for example Personal Digital Assistants (PDAs). The objective behind TUIs is to allow users to interact with computers through familiar tangible objects, thereby taking advantage of the richness of the tactile world combined with the power of computer-based simulations. TUIs employ physical artifacts both as representations and controls for computational media. They lend themselves well to collaboration around intelligent tables, especially for the early design process. While involved in discussion, experts adjust the parameters in such a way that optimizes the product. The common visualization also provides a timeline that moves with a certain speed and limits the time of the optimization process for a certain topic.

However, since all of the optimization parameters are part of the envisioned final product (the construction), the optimization in one topic affects the optimization within others. After the optimization time for one topic is expired, the common view can be changed to another optimization topic. However, when switching to another topic, the past optimization aspects should still be visible, but since all visible layers must be accessible by the interaction device this cannot be done simply by modifying the alpha-channel of the visualization. In addition, a suitable visualization metaphor is required allowing the intuitive visualization of data available in databases. Thus, it should be possible to see how relevant properties change as a result of changes in the design parameters. In addition, the system should first, or in parallel, support the selection of the most relevant objectives and aspects.

The interaction devices allow easy access to the parameters of the related database while the common display shows how design parameter adjustments affect the overall life-cycle result. Depending on the chosen optimization topic, the visualization on the common display as well as the interactive device may change, allowing adjustment of the relevant parameters and thus intuitive access to the database.

A further extension of the system would also allow the optimization process to be carried out over the network by interconnecting participants via a multipoint videoconferencing system. Based on a shared scene-graph infrastructure, the system will allow users to easily address various applications and devices making it open to different setups. An additional challenge will be to design the software system in a platform-independent way in order to allow various input devices that might be based on different operating systems.

3.4 First user test of CollaBoard

A first user test was conducted on the CollaBoard system in December 2009 at ETH Zurich. The study involved 20 subjects: 18 males and 2 females, from 24 to 61 years of age. Most of the subjects were colleagues at the same department and were accustomed to working with computers on a daily basis. The user study was structured so that test subjects, working in pairs, had to solve three different tasks of the same nature while working under three different conditions. The conditions were: co- located (CO), Skype Video (SV), and CollaBoard (CB). In the co-located condition, both the subjects in a pair were located in the same room and used the electronic whiteboard to solve a task. In the Skype Video condition, tests subjects were separated into two different rooms. Each user had an electronic whiteboard and solved together with the remote partner a common task; on a separate screen to the side of the whiteboard they could see and hear their remote partner via Skype. In the CollaBoard condition, tests subjects were also placed into two separate rooms. Together with the remote partner, each subject used an electronic whiteboard to solve a common task, but overlaid with the content on the whiteboard was the upper torso of their partner.

The goal of the study was to determine how the CollaBoard performs and is perceived by the test subjects through a questionnaire comparing it with SV and CO. By doing so we aimed at evaluating which combination of video, content, and presence is most beneficial for remote team-based collaboration. Out of the 15 questions answered with regard to each of the three conditions (CO, SV, CB) the CollaBoard system was graded positively in 11. In 3 questions out of those 11 it is rated as good as the Skype Video condition. In 1 question out the 11 it is graded as the best condition. In 4 questions out of the 15 it is rated as inferior to the Skype Video condition.

3.5 Adapting to construction needs

First user tests of the system confirmed its usefulness in collaboration. Further tests will examine user-friendliness and functionality in construction design environments, e.g. decision-making and data support with regard to life cycle characteristics. The results from these tests, together with existing technical conditions, e.g. data handling, exchange formats, interaction devices, and aspects of a "typical" construction design environment, will support future work in developing the necessary characteristics of the system to ensure added value to construction design.

REFERENCES

Badke-Schaub, P. (2007) "Creativity and innovation in industrial design: wishful thinking?" J. Design Research, 5(3), pg. 353-367.

Benning, P. et al. (2010) "Framework for collaboration." EU project InPro public report of deliverable D16b. (http://www.inpro-project.eu/docs/InPro_FrameworkForCollaboration.pdf)

Björk, B.-C. (2001) "Document Management – a key IT technology for the construction industry." Proceedings of the ECCE ICT Symposium 2001 Association of Finnish Civil Engineers, Espoo, Finland.

Christiansson, P., Svidt, K. and Sørensen, K. B. (2008) "Future integrated design environments." Proceedings of the CIB W78 2008 International Conference on Information Technology in Construction in Santiago, Chile.

Dainty, A., Moore, D. and Murray, M. (2006) "Communication in construction: Theory and practice." Oxon: Taylor and Francis.

Dawood, N., Scott, D., Sriprasert, E. and Mallasi, Z. (2005) "The virtual construction site (VIRCON) tools: An industrial evaluation." ITcon, 10, Special Issue From 3D to nD modelling, pg. 43-54.

e-Business w@tch (2005) "ICT and Electronic Business in the Construction Sector – Key Issues and Case Studies." Sector Report No. 08-I, July 2005. (http://www.ebusiness-watch.org)

ECTP (The European Construction Technology Platform). http://www.ectp.org/ (last visited 10 June 2010)

Fischer, M. and Kunz, J. (2004) "The Scope and Role of Information Technology in Construction." CIFE Technical Report #156, Stanford University, USA.

I3CON – Industrialised, Integrated, Intelligent Construction (EU Project). (http://www.i3con.org/) (last visited 10 June 2010)

InPro - Open Information Environment for Knowledge-based Collaborative Processes throughout the Lifecycle of a Building (EU Project). (http://www.inpro-project.eu/docs/Inpro_overview.pdf) (last visited 10 June 2010)

ISO 14040:2006. "Environmental management – Life cycle assessment –Principles and framework." (http://www.iso.org)

Kunz, A., Fadel, G. and Taiber, J. (2006) "Towards Collaboration in Engineering of Tomorrow - Building highly interactive Virtual Collaboration Platforms". Proceedings of the SAE 2006 World Congress on Automotives, Detroit, Michigan, USA.

ManuBuild – Open Building Manufacturing (EU Project). (http://www.manubuild.org/) (last visited 10 June 2010)

Marsh, L. and Flanagan R. (2000) "Measuring the costs and benefits of information technology in construction." Engineering Construction and Architectural Management, 7(4), pg. 423-435.

Molnár, M., Anderson, R., and Ekholm, A. (2007) "Benefits of ICT in the construction industry – Characterization of the present situation the house building processes." Proceedings of the CIB W 78 conference, Maribor, Slovenia, pg. 423-428.

Olofsson, T. et al. (2010) "The InPro lifecycle design framework for buildings." EU project InPro public report of deliverable D37. (http://www.inpro-project.eu/docs/InPro_LifeCycleDesignFramework.pdf)

Pahl, G. (1999) "Thinking and Acting in the Engineering Design Process – Results of an Interdisciplinary Research Project". Konstruktion, 6, pg. 11–17.

Pfitzner, M., Neuberg, F., Tulke, J., Nummelin, O. and Benning, P. (2007) "Analysing of existing software tools for early design." EU project InPro public report of deliverable D5. (http://www.inpro-project.eu/docs/InPro_AnalysisExistingSoftware_Public.pdf)

Samuelsson, O. (2008) "The IT-barometer – a decade's development of IT use in the Swedish construction sector." ITcon, 13, pg. 1-19. (http://www.itcon.org/2008/1)

Sarja, A. (2002) "Integrated life cycle design of structures." London: Spon Press.

Sebastian, R. (2007) "Managing Collaborative Design." PhD Thesis, Faculty of Architecture / TNO Built Environment and Geosciences, Delft University of Technology, The Netherlands.

SOU (2002) "Skärpning gubbar! Om konkurrensen, kostnaderna, kvaliteten och kompetensen i byggsektorn (Wake up fellows! About competition, costs, quality and skills in the construction sector)." SOU 2002:115, Miljö- och Samhällsbyggnadsdepartementet, Byggkommissionen, Stockholm, Sweden. (in Swedish)

Ugwu, O. O. and Kumaraswamy, M. M. (2007) "Critical success factors for construction ICT projects – some empirical evidence and lessons for emerging economies." ITcon, 12, pg. 231-249. (http://itcon.org/2007/16)

Woksepp, S. (2007) "Virtual Reality in Construction – Tools, Methods and Processes." PhD Thesis, Division of Structural Engineering, Luleå University of Technology, Sweden.

Zarli A., Kazi A.S., Hannus M., Bourdeau M., Ekholm A. and Andersson R. (2007) "A strategic and comprehensive vision for future R&D in construction ICT." Proceedings of the CIB-W78 - IT in Construction conference, June 25-27, Maribor, Slovenia, pg. 263-270.