Can virtual workspaces enhance team communication and collaboration in Design Review Meetings?

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Abstract

The development of software to facilitate collaborative working among project teams has been an active research area for the last two decades. However, the recent impetus in deploying BIM in construction has brought teamwork to the forefront and, therefore, it is important to conduct an in-depth study as to how BIM could be complemented with advances in visualisation and interaction technology to enhance team communication and collaboration. Effective tools that bring critical data and stakeholders together to solve design challenges have the potential to produce optimised solutions, reduce the number of meetings, improve communication and, consequently, delivery times. This paper explores how virtual workspaces supported with advanced visualisation and interaction techniques can enhance team communication and collaboration. It explores the type of communication channels necessary for supporting team collaboration with the use of both public and private workspaces that are essential for supporting individual and team exploration. These features are then implemented and tested using a collaborative design scenario. This research shows that the implementation of direct and indirect communication channels within virtual workspaces can significantly enhance team communication and collaboration. Furthermore, it shows that the use of a private workspace can assist individuals to contribute creatively to team activities.

Keywords: communication, collaboration, 3D tools, co-located environment

Introduction

Since communication is the central activity of any project, whether it is verbal or visual, the majority of time is spent in some form of team interaction. Within the context of building construction, communicating architectural design through artefacts and visual representations of the design is crucial as complex design and engineering concepts are constructed through continuous interaction between multi-disciplinary actors (Perry, M. and Sanderson, D. 1998). This is because there is an amalgamation of direct and indirect stakeholders in any typical construction project, using different technical jargon, focusing on different specialisms (Wikforss, O. and Lofgren, A. 2007) and representing a diversity of cultures, skills and disciplines (Lu, S.L. and Sexton, M. 2006). Despite this diversity, these stakeholders need to work together to deliver the final product, the building, and, therefore, a tremendous amount of collaborative work is required to achieve shared thinking, shared planning and shared understanding (Montiel-Overall, P. 2005). Since communication is a core element in creating a collaborative culture (Gautier, G., Kubaski, S., Bassanino, M. and Fernando, T. 2009), it has become one of the on-going challenges that team members face, that is essential to the success of any project (Jackson, S.E. 1996) (Bassanino, M., Lawson, B., Worthington, J., Phiri, M., Blyth, A. and Haddon, C. 2001).

To facilitate communication, regular meetings are usually organised throughout the entire project life cycle to identify any potential issues among the various competencies (Gautier, G., Piddington, C., Bassanino, M., Fernando, T. and Skjærbæk, J. 2008). In order to understand how people can communicate and interact with each other during these meetings, it is important to study the conceptual model of the multi-user interface illustrated in Fig. 1 as presented by

Miles et al. (Miles, V.C., McCarthy, J.C., Dix, A.J., Harrison, M.D. and Monk, A.F. 1993). In this diagram, one can see that, in order to enable a shared understanding or shared goal (e), participants need to interact with each other either directly (a and d) or indirectly (b and c). Examples of direct communication are face-to-face speaking, hand gesturing and eye contact (a) or making a reference to the artefact (d). Indirect communications are those occurring interactively to or through the artefacts such as physical and virtual objects (b and c). A communication channel (c) implies that communication could take place when a participant is performing an operation such as direct manipulation or undertaking changes to the artefact which is directly visible to the others. A communication channel (b) implies that the participant can perform an interaction task independently and then communicate it to others by making the artefact available to them.

The implementation of these communication channels in design review meetings is a challenging task since it involves multi-disciplinary teams and complex artefacts. Typically, multi-disciplinary teams collaborate in four different modes as identified by Huifen et al. (Huifen, W., Youliang, Z., Jian, C., Lee, S. and Kwong, W. 2003): face-to-face (same place, same time), synchronous distributed (different places, same time), asynchronous (same place, different time) and asynchronous distributed (different places, different time). The approach for establishing these communication links in each mode can vary, each providing a different degree of "bandwidth" in conveying the intended message to others. For example, face-to-face meetings provide a high bandwidth for channel (a) since gestures, eye contact and body language could easily be communicated to others, whereas the synchronous distributed mode has a lower bandwidth in transmitting such human behaviour due to the limitations in current tele-immersive technologies.

This paper is focused on examining the role of visualisation and interaction technologies that could be used in establishing the above communication channels and evaluating their effectiveness in supporting communication and collaboration during design review meetings. Specifically, the authors focused on establishing these communication channels in face-to-face meetings which are referred to as co-located meetings. The authors planned to examine how channels (d), (c) and (b) could be established by using visualisation and interaction technology. Channel (a) is not considered in this research since this channel is already established as a high bandwidth channel within the context of a co-located meeting.

The establishment of channels (c) and (d) implies that these channels should be formed within a shared "public workspace" since any interaction with the design artefact by a participant should be directly visible to others. The purpose of channel (b) is to provide independent interaction with the design artefact and then to allow the possibility of transmitting changes made to the artefact by a participant to other participants. In this research the authors propose to examine the use of a "private workspace" to allow such independent interactions to take place and to use the shared "public space" to communicate any changes made to the artefact by an individual to the other participants.

The key research questions addressed by this paper are:

- What interaction features should be supported for establishing channels (b), (c) and (d) in order to conduct design review meetings?
- Could virtual workspaces that offer such channels enhance communication and collaboration among design review teams?

The work discussed here goes beyond the demonstration of the technical features required to improve collaboration in a co-located environment to actually validate their impact in enhancing communication and collaboration during design review meetings.

Background-Related work

The previous section recognised communication as an on-going challenge in supporting collaboration for multi-disciplinary project teams. This section moves the argument forward and puts it into context by providing some background work on how communication among multi-disciplinary project teams has been accomplished over the last few decades through CAD (Computer-Aided Design), BIM (Building Information Modelling) and virtual workspaces.

Since the 1970s, CAD systems have been extensively used by project teams to visualise the design through the manipulation of 2D and 3D graphic objects. In addition, the ability to walk through the proposed design, perform clash detection and demonstrate various solutions has increased collaboration among all project team members. This is because CAD systems have influenced how people communicate design (Gabriel, G.C. and Maher, M.L. 2002) as they have provided infinite possibilities for viewing objects (Lawson, B. 2005) and visualising them (Nahab Bassanino, M. 1999) in an interactive manner. They have also assisted the architect in conveying his/her design ideas to other members of the project team as well as to the client and to the public (Sasada, T. 1995). As a result, these systems have improved how project teams perceive design, interact with it and communicate their own perspectives to others, enabling fast and more effective design reviews (Autodesk 2006). Despite these benefits, CAD on its own is limited in facilitating multi-functional collaboration since additional support is needed to provide an integrated platform to support multi-disciplinary collaborative design (Safina, S., Leclercqa, P. and Decortisb, F. 2006). A typical CAD approach does not allow teams to combine their design data into a unified building model or to collaboratively explore various design options, design changes or design optimisations.

As a result, researchers (Rosenman, M.A. and Gero, J.S. 1996) (Chiu, M.L. and Lan, J.H. 2005) and (Saad, M. and Maher, M.L. 1996) have integrated CAD systems that are aimed at supporting various design representations integrating their discipline views and concepts of the 3D architectural model. For example, Saad et al. (Saad, M. and Maher, M.L. 1996) separated administrative data, semantic data and graphic data and linked them to a 3D architectural model in an attempt to support multiple views enabling each discipline to bring its own views to the design. Rosenman et al. (Rosenman, M.A., Smith, G., Maher, M.L., Ding, L. and Marchant, D. 2007) proposed a framework for multi-disciplinary collaborative design to represent the same design with various views from different disciplines. However, the lack of standards in these attempts resulted in a limitation of their use.

The increased demand to have a standard approach for capturing various design perspectives to create a unified building model and information exchange between partners led to the development of the Industrial Foundation Classes (IFC). IFC marked the birth of Building Information Models (BIM) that can be used to capture various design perspectives in a unified data model and provide data security, information exchange management, product life cycle management, etc. (Howard, R. and Björk, B. 2008). In comparison with conventional CAD systems where data is represented as mathematical surfaces and graphical entities, BIM models define objects as building elements and systems to carry all the information related to the building and its processes (Azhar, S., Nadeem, A., Mok, J.Y.N. and Leung, B.H.Y.

2008). As a result, BIM offers the opportunity for multi-disciplinary teams to work together to bring their design data into a single building model and identify design faults, simulate building performance (energy, acoustics, structural) and assess critical product life cycle issues during design. However, while BIM has brought impetus into information management which is a crucial factor in project team communication and collaboration, it lacks appropriate human-computer interfaces that can bring information into a team-centric environment that can support real-time collaboration among team members. As a result, current BIM platforms are ideal as collaborative platforms for information sharing rather than as user-centric platforms for collaborative tasks (Plume, J. and Mitchell, J. 2007) and (Grillo, A. and Jardim-Goncalves, R. 2010). However, BIM technology is currently experiencing a challenge in providing a common user interface for multi-functional teams during the synchronised collaboration (Singh, V., Gu, N. and Wang, X. 2010).

In contrast, digitally enabled virtual workspaces have demonstrated great potential for multi-user interaction for purposes such as product design (Shyamsundar, N. and Gadh, R. 2002), decision-making (Yao, J. 2010) and scientific exploration and analysis (Heer, J. and Agrawala, M. 2009). These workspaces explore how tasks conducted by two or more people using ICT tools in a collaborative environment can work together to realise the shared goal. In order to engage with the participating stakeholders, these working environments must support them with the ability to communicate and interact with each other's content intuitively and interactively (Woo, S., Lee, E. and Sasada, T. 2001).

However, BIM and virtual collaboration have several drawbacks. For example, BIM demands that a team model the entire building from various engineering viewpoints and therefore a considerable amount of effort and investment is required in achieving a complete model (Howard, R. and Björk, B. 2008) and (Yan, H. and Damian, P. 2008). Furthermore, each stakeholder's organisation needs to invest considerably in training and in digital technology platforms, as well as making sure that their models are interoperable with the models from other stakeholders, to create a complete integrated building model (Eastman, C., Teicholz, P., Sacks, R. and Liston, K. 2011). Another challenging problem that is faced in the creation of a complete BIM model is ensuring that the correct version of the design parts are maintained in the final model (Rosenman, M.A., Smith, G., Maher, M.L., Ding, L. and Marchant, D. 2007). Although BIM encourages teams to consider all different viewpoints, only a limited number of viewpoints are supported by current BIM solutions.

Although virtual collaboration is considered as important for teams in order to produce better quality products with reduced cost and time (Maj, P.S.C. and Issa, R.R.A. 2007), many human and organisational barriers exist that hinder successful collaboration among partners. As indicated by Patel and Pettitt et al. (Patel, H., Pettitt, M. and Wilson, J.R. 2012), the important factors that are essential for collaboration are culture, trust, interaction processes, teams and tasks. Furthermore, model ownership and responsibility for its data entry, accuracy and updating need to be managed to avoid complicated indemnities by BIM users and a change of contractual agreement between the participants (Eastman, C., Teicholz, P., Sacks, R. and Liston, K. 2011).

The study of computer mediated collaboration has been the main focus of the CSCW (Computer Supported Collaborative Working) for many years. This research has shown that a typical CSCW platform should support information sharing, information exchange, decision-making and control protocol (Schmidt, K. and Rodden, T. 1996) for both individual and cooperative work. Saad et al. (Saad, M. and Maher, M.L. 1996) argued that workspaces with the aim of providing space for exploration can enhance and support multi-perspective collaboration. Multi- perspectives' collaboration combining public with private spaces can allow for rearranging a task into subtasks for parallel execution (Stefik, M., Foster, G., Bobrow, D.G., Kahn, K., Lanning, S. and Suchman, L. 1987), providing privacy during cooperative sessions (Beaudouin-Lafon, M. 1990), and enables users to self-explore different interests and viewpoints (Sarin, S. and Greif, I. 1985). Building on previous CSCW research, this work explores how advanced visualisation and interaction could be brought into such private and public virtual workspaces to enhance collaboration among multi-functional design teams, giving due consideration to the various direct and indirect communication channels that should be established as specified by Miles et al. (Miles, V.C., McCarthy, J.C. et al. 1993).

Interaction Features for Design Review Meetings

This section examines the interaction features that are necessary within channels (b), (c) and (d) specified in Fig. 1. This was performed by conducting a literature survey and through a series of workshops with experts from the construction sector and the human factors' area. A two day workshop was organised to capture user requirements and build the construction team collaboration scenario discussed later. 15 experts with some experience of collaborative working and IT participated. The experts who participated in these workshops included project managers, design managers, architects, engineers (structural, electrical and mechanical), technical consultants, technology providers and material suppliers. Together, they brought the perspectives of clients, contractors, consultants, designers, SMEs, finance, and technology. Please note that the research methodology with regard to evaluating the 3D design review environment is discussed in detail in the 'Evaluation' section.

Concurrent design activities by each of a project's stakeholders usually take place through a series of regular design review meetings to evaluate the design against its requirements. Lawson sees design as a process that takes place through three main activities linked in an iterative cycle; these are: analysis, synthesis and evaluation (Lawson, B. 2005). Nevertheless, currently these design activities take place in between design review meetings because of the inability of these meetings to provide anything more than discussing and proposing changes with little support for design collaboration (Aspin, R. 2012). According to Aspin, this occurs because such meetings are limited in supporting cross discipline creativity since they are not supported with appropriate team interaction tools even though they are organised to facilitate communication among project team members. Therefore, in order to achieve multi-functional collaboration and efficient design review meetings, Aspin suggested that it is important to provide users with a number of tools to assist them in manipulating, navigating, exploring and analysing the design (Aspin, R. 2012). He went on to criticise traditional approaches for supporting single-users whereas, in fact, these systems should provide what he calls 'a more subjective form of interaction' enabling each stakeholder to interact, manipulate and modify the design.

Typical design review meetings involve key project team members such as the client, project manager, architect, structural engineer, electrical engineer, HVAC engineer, plumbing engineer, thermal and acoustic engineers, etc. Each team member is in the meeting to make sure the design fulfils the functional requirements from their own discipline viewpoint without conflicting with other design perspectives.

It is argued that advanced visualisation and interaction features in both private and public workspaces that support communication through channels (a, b, c and d) could substantially enhance team collaboration in such design review meetings. They will allow clients to discuss their requirements and make decisions; architects to explore new architectural solutions and assure uniformity; project managers to ensure everyone's view is clearly expressed and understood, validating constructability and controlling the cost; engineers to test structural integrity, energy efficiency, maintainability; users to test accessibility, intended function, comfort, etc.

However, although extensive work has been undertaken on the design process itself, little research has been carried out in relation to the detailed content of the meetings' activities (Huet, G., Culley, S.J. and Fortin, C. 2010) involving various team members. In order to provide a structured framework for capturing the interaction features necessary for multi-functional collaboration, the authors have used Lawson's design process activity (problem analysis, synthesis and evaluation) (Lawson, B. 2005) as the basis for task analysis and have introduced the workspace context, purpose of activity and interaction tasks to analyse the activities within a design review meeting as illustrated in Fig. 2. This framework was useful in defining the context (public workspace, private workspace), the objective of the activities and the interaction tasks for communication channels (c), (d) and (b).

Analysis Phase: Within the context of design review, the analysis phase is where the current design is presented to the participants and where any design changes or design errors that require a solution can be seen. This particular activity needs to take place in the public workspace since the idea of this phase is to communicate the design issues to the entire team and establish a common understanding of the problem and initiate a discussion towards a possible solution. This activity requires certain functionalities to provide direct and indirect communication channels as explained earlier on and is represented as (c and d) in the conceptual model of the multi-user interface by Miles et al. (Fig. 1). Channel (d) would require the availability of a visual model of the design and the ability to pass control to participants to point and select parts of the model. Channel (c) in this activity would require the participants to gain control in making their views known, in manipulating, navigating, and annotating the visual model (see the analysis phase of Fig. 2).

Synthesis Phase: Synthesis of the design is when users propose a possible solution to the design problem that has been presented during the analysis phase, which can potentially take place in both the public and private workspaces. Collective exploration of alternatives in the public workspace requires extra functionalities for channel (c) such as model editing, collision detection in response to a change, ability to switch on/off various design data layers (i.e. electrical, plumbing, furniture, building structure, etc), and undo. Furthermore, the interaction features identified as necessary for the analysis phase were considered to be necessary in the synthesis stage as well. The self-exploration of alternatives in the private workspace requires functionalities to support indirect communication between the participant and the artefact, represented as (b) in Fig. 1. Functionalities identified as necessary for the private workspace include all the functionalities identified for channel (c) for the public workspace as well as the ability for the stakeholder(s) to take a copy of the design into their private workspace, to access their own modelling tools, to have the ability to port new design parts from their own model databases into the private workspace and to upload their design proposals to the public workspace.

Evaluation Phase: The evaluation phase of the design is where a chosen set of design solutions are collectively assessed to choose the most sound solution that satisfies the concerns of all the stakeholders from different disciplines. The interaction features that are necessary for this activity were considered as similar to the synthesis phase in the public workspace and the private workspace. During the evaluation phase the participant can use the communication channels offered in the public workspace to evaluate the design solutions or take a copy of the proposed solution to their own private workspace to assess the impact of the design solution within their own domain. This would involve assessing any new clashes, new plumbing layouts to cater for the new design, etc.

These features were implemented in this research with a view to evaluating their importance in supporting team communication and collaboration during design reviews and also with a view to identifying the missing functionality. The following sections explain the evaluation of these workspaces and the communication channels through human factor experiments.

Team Collaboration Scenario

In order to bring realism into the above theoretical analysis, a real world design review scenario was developed in collaboration with the project partners: COWI (Denmark), Construct IT (UK) and TA-Net (UK), in order to provide a realistic context in developing and validating the potential of the above communication channels in enhancing team communication and collaboration during design reviews. A request for a design change was used as the basis for defining the scenario since this is common in many construction projects; such requests arise due to additional requirements from the client or unforeseen problems that arise during construction.

The design review scenario starts with a meeting which is required in order to discuss the layout of a disabled bathroom in a block of flats (Gautier, G., Piddington, C. et al.

2008). The addition of a separate installation shaft has impacted on the bathroom's space which is no longer accessible by wheelchair users. The most likely solution is to replace the bath with an accessible shower-unit but the layout should still include the same elements as previously planned: a close-coupled WC, a basin, a bath tub/shower, a wall-hung cupboard and a window, as illustrated in Fig. 3.

The scenario starts with the participants being invited to attend the design review meeting to solve the design problem. The participants had to go through the problem analysis phase, the synthesis phases and the solution evaluation phase as described above to find a satisfactory solution, using an interactive 3D collaborative platform. However, in order to test the principles of this research three types of team members were considered:

- Architect: owns the 3D architectural model. His/her role in the meeting is to propose and discuss the bathroom's new design with the other participants. He/she also takes the project manager's role in this instance.

- Mechanical Engineer: specialised in plumbing. His/her role in the meeting is to check the bathroom's plumbing.

- End-user representing the wheelchair user: his/her role in the meeting is to check the accessibility of the bathroom's new design for wheelchair users.

Experimental Platform

Fig. 4 shows the key technical components that were developed to create the interactive collaborative environment that offers interaction capabilities within channels (b), (c) and (d) to support the design analysis, the synthesis and evaluation, as summarised in Fig. 2. The overall technology platform comprised a model data server, a middleware layer that supports real-time data distribution among users and a multi-user interface that provides individual portals for various team members such as the architect, the MEP engineer and the client. Only a brief description of the experimental platform is presented in this paper due to space constraints. A detailed technical description of the interactive collaboration platform will be presented in a separate paper.

The function of the Model Server is to maintain different design layers from various disciplines and allow users to gain access to their user interface on demand. The Middleware layer is used to support the real-time model synchronisation between the pubic workspaces. The Design Management module maintains a copy of the 3D building model on each user's laptop and feeds into the private workspace and the public workspace that are embedded within the overall user interface. The 3D design tool was designed by targeting the end users' disciplines involved in the design review scenario. The 3D design tool provides a design space for the users to perform collaborative design during the design review process. The 3D design space comprises a number of various components to allow users to interact through a number of operations which are discussed in the following section.

Interaction Features for Supporting Communication Channels

The 3D design service module in the system offers a range of visualisation and interaction services for both private and public workspaces (Fig. 5), which were identified in the previous section and illustrated in Fig. 2. These features include a number of operators such as: freehand annotation, mark up operator, annotation textual operator, model editing operator, collision operator, measuring operator, multi-disciplinary structure operator and a model sectioning operator. Each one of these operators are provided in the framework to offer certain functionalities to support the direct and indirect communication channels and the task(s) the users undertake during the design review meetings. For example, it supports model manipulation, navigation, object delete/undo, porting models from local model databases, mark up functions, textual annotations, collision detection, etc. Furthermore, the multi-disciplinary structure operator allows users to browse and interact with the building structure of the model by making the layers visible and invisible.

Public and Private Workspaces

Fig. 6 shows the overall look and feel of the user interface and the embedded private (left graphical window) and public workspace (right graphical window). The public workspace is shared by all participants where they can all experience the same view of the 3D building model to support design discussions. This space is usually controlled by the meeting facilitator (chair), but the control could easily be passed onto other users, allowing them to express their own viewpoints. The private space which appears on each participant's desktop provides them the opportunity to take a copy of the model in the public workspace and explore the 3D building model independently.

Evaluation

In this research, human factor experiments were conducted to evaluate the interactive 3D design review environment that was designed to support team interaction via communication channels (b), (c) and (d). The purpose of this evaluation was to assess whether the virtual workspaces (both public and private) that offer team interaction via such communication channels enhance communication and collaboration among team members.

Four experiments/evaluation sessions with 12 participants in total (three participants in each session) were organised to evaluate the interactive 3D design review environment. Three evaluation sessions took place at the University of Salford, UK: the first session which was conducted as a pilot study was organised with a group of academic researchers (working within IT and project management domains). Other sessions included members of Construct IT for Business (an industry-led network to promote innovation and research in ICT in construction in the UK) and TANet (a university and industry network for the UK SME manufacturing sector). These three sessions were followed by another evaluation with a group of end-users at COWI (a leading international consulting group in engineering, environmental sciences and economics in Denmark). The selection criterion was based on the participants having some experience of collaborative working and use of IT systems such as BIM or virtual workspaces. It is worth mentioning here that although the participants' number was relatively small with 12 users taking part to evaluate the 3D design review environment, the results were very consistent throughout the evaluation which enabled the authors to draw conclusions.

In each one of the above mentioned evaluations, all the participants used their laptops with the system installed on each machine. In each session, three participants took the roles of an architect, engineer and end user (representing the wheelchair user in this case). A HD camcorder was used to record the experimental sessions.

All the participants entered the meeting room and each was handed a laptop with the system installed on it. First, a technical demonstration was delivered to the participants by the facilitator explaining the functionalities of editing, navigation, manipulation, collision detection, layering and undo.

Following the technology familiarisation phase, the facilitator explained the design problem associated with the bathroom scenario for the disabled client. Roles were assigned to each participant and they were asked to use the virtual workspaces available to them to solve the design problem. The meeting then started with the architect presenting the problem of the existing bathroom using the public workspace. During the discussion, each participant had a chance to study the new layout in their private workspace and discuss the new layout from their own perspective while using the advanced 3D visual and design tools to move objects, mark up objects or highlight any possible clashes. Following discussion and exchange of viewpoints, one possible solution was to replace the bath with an accessible shower-unit. Once the architect updated the design in his public workspace, all individual screens were automatically updated. The new design was then validated by all the meeting's participants with the end-user checking the bathroom's accessibility. During the meeting, participants were also given the chance to repeat the above exercise as many times as they wished to discuss alternative designs and layouts. As soon as an optimised solution was reached, accepted by all the participants and validated by the end user, the session was terminated.

Towards the end of the exercise, the participants were given a set of questionnaires to fill in. During the exercise, observation sheets were used to collect data, making use of the 'Verbal Protocol' where users vocalise thoughts, goals, perceptions, opinions, feelings and talk about their actions whilst performing tasks (Bainbridge, L. 1990). The participants were also asked to complete a questionnaire comprising a set of closed questions with semantic scales to test the usability of the system as well as the impact of the 3D visual and design tools on collaborative working, while open questions were used to further collect the participants' views during the co-located meeting.

Evaluation Results

Usability testing of the interaction features in the virtual workspaces

It is possible to hinder collaboration if the execution of interaction tasks is difficult for each individual user. Therefore, the initial set of questionnaire was designed to evaluate the usability of the interaction features to ensure that users did not encounter any difficulties in using the system functionality. The following statements were used to test the tools' usability:

1a: It was difficult to add 3D objects in the 3D design system.

1b: It was easy to delete 3D objects in the 3D design system.

1c: It was difficult to annotate the 3D object in the 3D design system.

1d: It was difficult to manipulate the 3D object from different viewpoints in the 3D design system.

1e: It was easy to detect collisions in the 3D design system.

1f: It was easy to undo my actions in the 3D design system.

1g: It was difficult to make the layers of each discipline visible and invisible in the 3D design system.

Fig. 7 represents the distribution of results on the usability of the interaction functions. The results show that nearly all subjects considered the use of the interaction functionality as "good" to "excellent" since they were well integrated and able to support their major design activities. The users were highly satisfied with the interaction functionality integrated within both the private and the public workspaces in assisting them in visualising the 3D model, moving objects, detecting collisions, undoing their actions and so on. The low mean results, which were less than 3 for questions 1c, 1d and 1g, reflect the users' positive response towards these functions because the actual statements were, in fact, negatively worded; these functions included annotation, viewing and layering.

Further examination highlights the fact that the distribution value of the usability of the interaction functions for each question was minor. This means that the users gave similar values throughout the 1st, 2nd, 3rd and 4th quartiles. However, a few differences have been detected as a result of examining the above data. With regard to the function of adding objects (1a), one subject indicated that the system should provide a "copy and paste" function for adding a 3D object. In addition, data was not distributed evenly in the case of the layering functionality, with the value from quartile 1 to 4 being less consistent for this statement than that for other statements. This could be explained by one of the user's suggestions for the provision of a quick access by using "hot keys" for commands to ease the process. All the above suggestions were added to a wish list for consideration for future release.

Testing Enhanced Communication and Collaboration

The main evaluation was carried out to test if the virtual workspaces that offer team interaction via channels (b), (c) and (d) can enhance communication and collaboration among the team members. Rather than testing individual channels, this research explored the overall view of the team in relation to team collaboration. The following statements were used to capture user feedback:

2a: The 3D collaborative workspaces did not facilitate discussion between users during the meeting.

2b: Using the 3D collaborative workspaces could help to facilitate problem-solving during the design phase.

2c: Design mistakes would be discovered earlier using the 3D collaborative workspaces.

2d: By using the 3D collaborative workspaces, we managed to explore more design alternatives during the meeting.

2e: Compared to the way I conventionally work, the 3D collaborative workspaces could help me to improve design work.

2f: The 3D collaborative workspaces facilitated decision-making during the meeting.

2g: Passing the master role on to someone else in the public team space assisted in highlighting multi-disciplinary views.

2h: I was not aware of what other people were doing in their private space.

2i: The private space allowed me to explore/check the design on my own if needed to.

2j: I could compare various designs using the private space.

Fig. 8 illustrates the distribution of the results of the overall impact of the virtual workspaces in enhancing communication and collaboration. It clearly indicates that the users were very much in favour of these workspaces. On the whole, the mean was nearly 4 or above for all the statements. (It was 1.67 for statement 2a, but that particular question was worded negatively). It is obvious that the provision of communication channels (b), (c) and (d) led to enhanced collaborative working in the co-located meeting. A participant from TANet commented, "*I like the ability to be able to review live feedback, comments and further modification visually by external* *parties in real-time"*. Another user from COWI referred to the system's ability to support multi-disciplinary teams by adding: *"a design team consists of several organisational levels divided in separate disciplines and sectors, each with a focus on his/her main subject and interests. The evaluated system helps cross-sector and cross-discipline communication while using the graphic model as a basis for discussion"*. Identification of mistakes and rectifying them from an early phase was another objective met through the provision of such technical features. This was pointed out by one the users *"The system would enable design problems/solutions to be resolved much more effectively"* [end user-CIT]. Furthermore, the ability to explore design alternatives among team members in the public space (questionnaire 2d) was very positive. It received a mean of 4.33 and a value of 4 for both 1st and 2nd quartiles and a maximum value of 5 for both the 3rd and 4th quartiles.

The availability of the private workspace to support communication channel (b) was also positively assessed as illustrated in Fig. 8 where the mean was nearly 4 or above for all the statements related to the private space including 2h, 2i and 2j. This confirmed the significant role of the private space in facilitating collaborative working, and in providing privacy and self-exploration for finding solutions. Moreover, the system is also capable of providing users with the possibility of comparing various designs using multiple private spaces (statement 2j). The following statements were expressed by the participants: "*It is useful for private confidential thought and for experimentation*" [end user-CIT] and "*The ability to redesign in the private space and upload to the public view is a beneficial function*" [TANet member].

Discussion and Further Development

Following on from presenting the full set of the evaluation data in the previous section, this section progresses to further reflect on these results. In order to understand how advanced 3D visual and design tools in a combination of public and private spaces enhanced multi-functional collaboration, a reference will be made to the conceptual model of the multi-user interface as presented by Miles et al in Fig. 1 as well as the framework for integrating the design process activities in a design review meeting presented in Fig. 2 .

As explained earlier on, analysing the design by team members in the public space requires supporting certain actions to allow multidisciplinary teams to discuss the order and structure of the design problem and its objectives through direct and indirect communication channels. The establishment of these channels (represented as d and c in Fig. 1) together with the advanced set of tools provided in the 3D collaborative workspace supported project teams as they visualised and navigated the 3D design through channel (d) by allowing them to pass control and to select specific parts of the artefact. Extra functions were provided through channel (c) to support users to manipulate and annotate the design. This enabled team members to better communicate their views and reach a shared understanding about the design.

Once the participants have analysed the design, they move forward to the synthesis phase to explore alternatives and solutions to the design problem that were discussed during the analysis phase. This stage is recognised as a critical one where members of multidisciplinary teams interact with the artefact and, therefore, systems should be able to support intuitive interaction and fluid information sharing (Leicht, R.M., Messner, J.I. and Anumba, C.J. 2009). For this reason, the advanced set of tools are provided in the public space to support both direct and indirect communication channels (represented as d and c by Miles et al in Fig. 1) as users interact with the artefact and with one another through the artefact in the public space. Thus, the functionalities of navigation, manipulation, editing, annotating and layering enabled users to explore design alternatives and exchange views as they could take turns to pass the control and detect collision, enabling multidisciplinary teams to have their input into the design (Fischer, M. 2008). This way, interactive workspaces can increase the possibility of more effective collaboration as Leicht et al. (Leicht, R.M., Messner, J.I. and Anumba, C.J. 2009) realised through their work in combining physical, virtual and human elements in one framework. The reason behind this, as explained by Oviatt et al. (Oviatt, S., Coulston, R. and Lunsford, R. 2004) is that the combination of various tools in a single framework provides the possibility of increasing the interaction among team members because, as individuals switch from one mode to another, it will spread someone's cognition to other areas of the brain leading them to focus more effectively on the problem.

In addition to the public space where users share their views of the design and generate alternatives as a group to enhance cross discipline collaboration, another added aspect of the 3D collaborative platform was the users' ability to self-explore solutions for the design problem (presented as channel b in Fig.1). This way, users could access their own data in the private workspace for personal exploration of any design issues while using similar functions to those provided in the public spaces such as navigation, manipulation, annotation and so on.

Evaluation, which is the critical appraisal of the various solutions, takes place in the public/private workspace and requires certain functionalities to support both direct and indirect communication between the users as they interact through the artefact to validate the design. The same interaction features provided in the synthesis phase through channels (c) and (d) for the public workspace and channel (b) for the private workspace are provided in the evaluation phase to support users' interaction.

It is apparent from the above discussion that the intuitive design and annotation tools available in the 3D collaborative framework undoubtedly provided support for the participants during the evaluation sessions in a design review meeting by offering the possibility of navigating, manipulating and modifying design. This coupled with the possibility of team and self-exploration of design alternatives as well as comparing the various options improved the group's performance and supported the decision-making process (Fig. 8). The fact that the participants were able to visualise and discuss a variety of options enabled them to better communicate/discuss their viewpoints and provided instant feedback to support the iterative process of design including the activities of analysis-synthesis-evaluate until a solution was agreed.

In this context, it is worth noting a number of issues brought up by the users during the evaluation sessions. The first one deals with the system's ability to keep track of changes and to record decisions, previously raised as a drawback by Rosenman et al. (Rosenman, M.A., Smith, G., Maher, M.L., Ding, L. and Marchant, D. 2007). Although the current prototype enables participants to view the various versions of design solutions/alternatives, a suggestion was made to add an automatic revision control with a digital signature of the decisions as a way of keeping track of changes and recording decisions since it is important to integrate decision support tools within the framework (Khosrowshahi, F. and Howes, R. 2005) as part of supporting cross-disciplines' collaboration. Another possibility worth exploring and adding as a future development is the option of capturing the whole activity in a multi model form that utilises audio, video and text describing the complete session.

In addition to accommodating the above development, future work can look into the impact of multi-functional teams beyond Co-located meetings to support distributed environments, thus including other modes of interaction: synchronous distributed interaction, asynchronous interaction and asynchronous distributed interaction.

Conclusion

This paper explored how communication and collaboration among project team members could be enhanced through collaborative workspaces that offer direct and indirect communication channels, as defined by Miles et al. (Miles, V.C., McCarthy, J.C. et al. 1993). These direct and indirect channels were established through a private workspace and a public workspace that utilise visualisation and interaction techniques. In order to provide a structured framework for capturing interaction features necessary for multi-functional collaboration, Lawson's design process activity (problem analysis, synthesis and evaluation) (Lawson, B. 2005) was used as the basis for task analysis. This framework was useful in defining the context (public workspace, private workspace), the objective of activities and the interaction tasks for the direct and indirect communication channels specified by Miles et al (Miles, V.C., McCarthy, J.C. et al. 1993). This theoretical work was useful in establishing a sound foundation for developing interaction and visualisation features for face-to-face design review meetings.

In order to validate whether collaborative workspaces that offer these communication channels indeed enhance team communication and collaboration, this research implemented a collaboration platform based on these principles and conducted human factors' experiments. A scenario that required design changes for a disabled bathroom was used as the context for testing the team collaboration involving an architect, engineer and end-user. This collaborative design task was repeated four times, each involving three different team members. The result showed that collaborative workspaces with direct and indirect communication channels indeed enhanced the communication and collaboration among team members. Team members felt that they were able to explore more design alternatives, were supported for their design discussions, were able to solve design problems and discover design mistakes earlier. On the whole, the mean was high as 4 (out of 5) or above for all these features. Participants also felt that the private workspace played a significant role in facilitating collaborative working, providing privacy and self-exploration for finding solutions.

While the construction industry is now undertaking significant investment in implementing BIM for supporting collaboration, this research shows that, by integrating real-time collaborative workspaces, the power of BIM could be further utilised to enhance team communication and collaboration during design review meetings. This will make design review meetings more productive, hence reducing time and cost and increasing the quality of the final product.

Although, this research has used co-located meetings as the physical context of the design review meeting, the findings of this research could be applied to distributed meetings. However, channel (a) that supports direct communication (gestures, eye contact, face-to-face speaking) between team members needs to somehow be successfully established through video conferencing or tele-immersive software in order to achieve similar results comparable to the co-located meeting settings.

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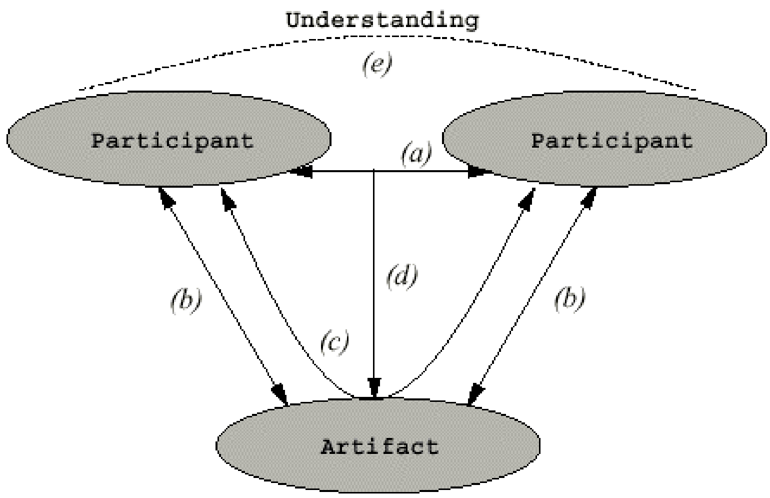


Fig. 1- Conceptual model of multi-user interface as represented by Miles et al. (Miles, V.C., McCarthy, J.C. et al. 1993) “With kind permission from Springer

Science+Business Media: Computer Supported Collaborative Writing, Conceptual Model of Cooperative Work, 1993, page 137, Miles, V. C. M., J.C.; Dix, A.J.; Harrison, M.D. and Monk, A.F.,”. (author: May Bassanino)

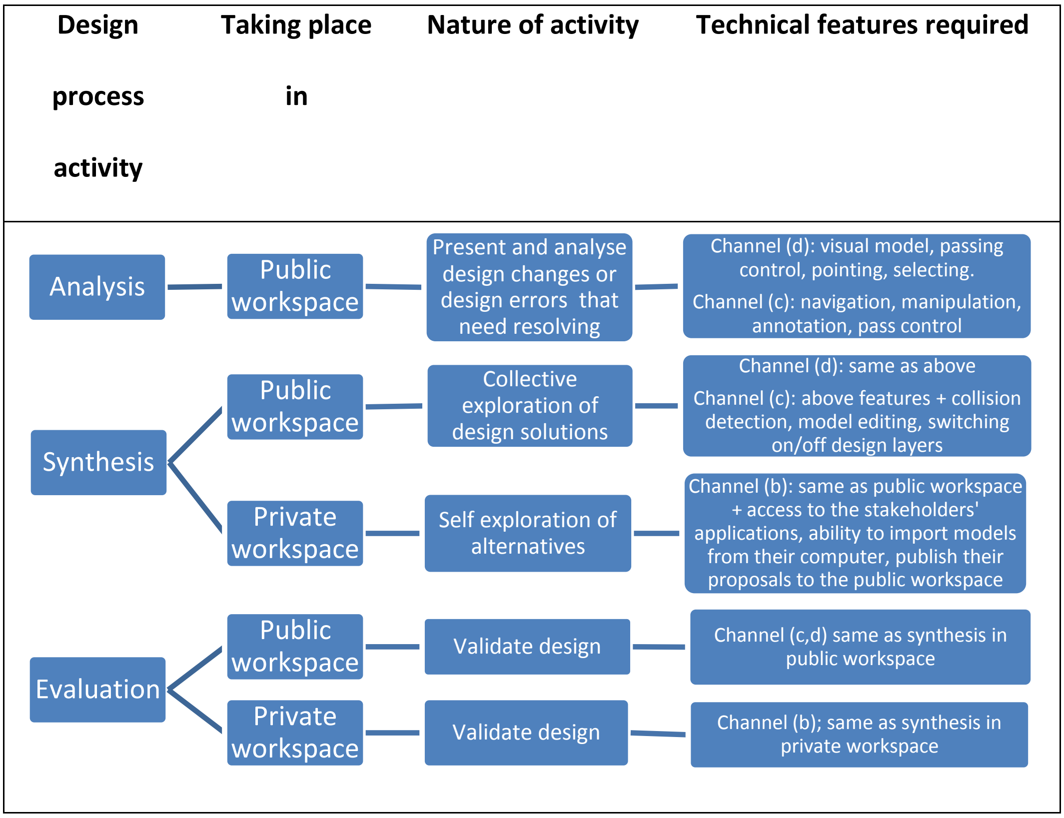


Fig. 2 - A framework illustrating the integration of the design process activities in a design review meeting (author: May Bassanino)

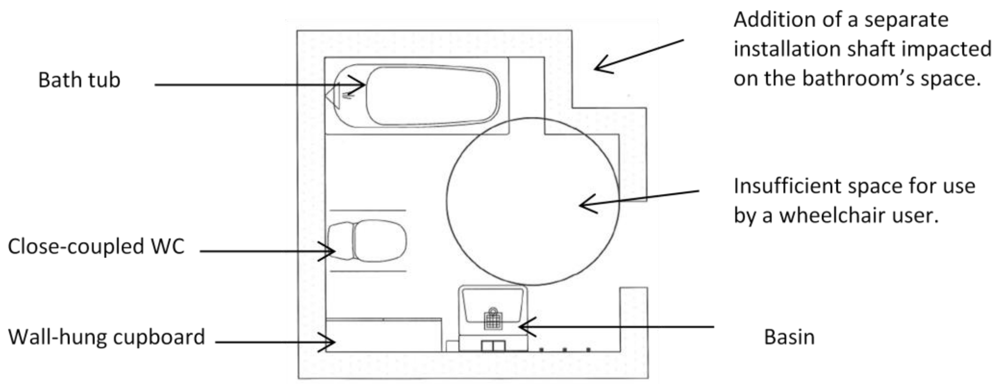


Fig. 3 - Current setting for the disabled bathroom illustrating insufficient circulation space due to the addition of a separate installation shaft (author: May Bassanino)

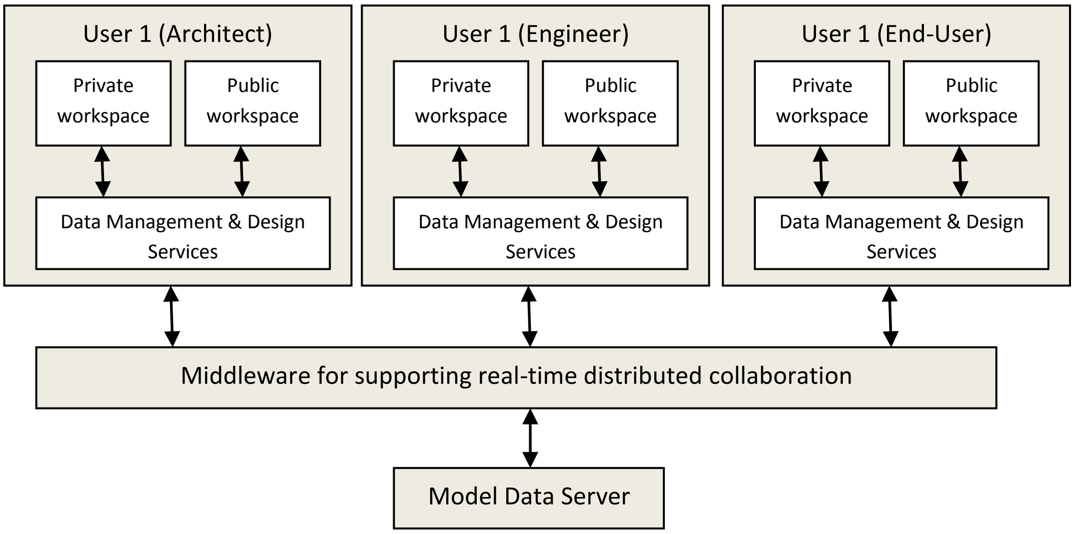


Fig. 4 - The core system components (author: May Bassanino)

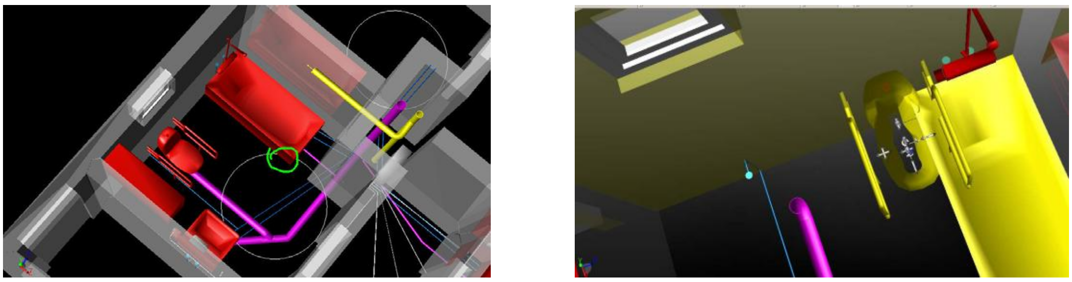


Fig. 5 - Representation of some of the 3D design services such as the freehand and annotation mark up operator (left) and the collision operator (right) (author: May Bassanino)

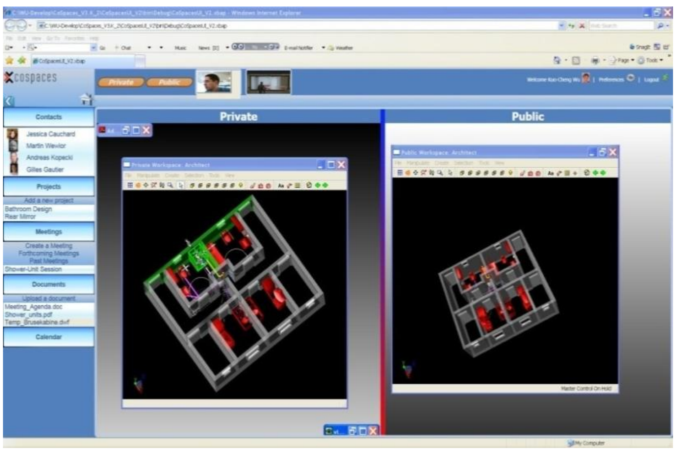
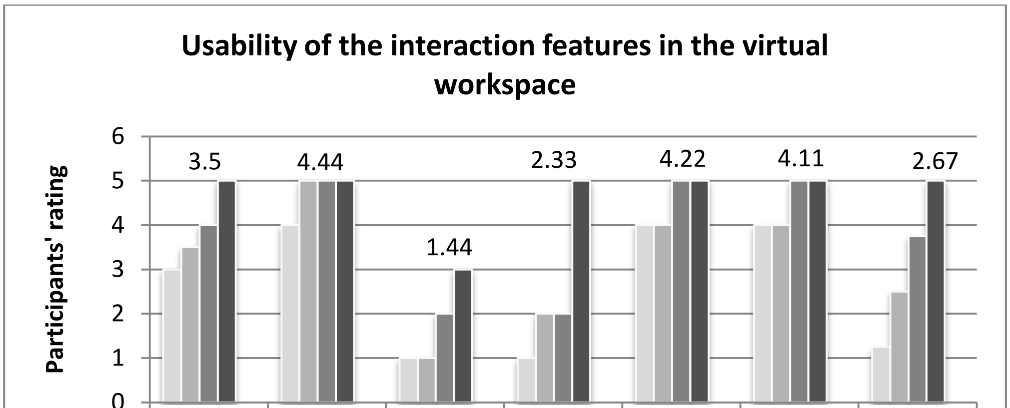
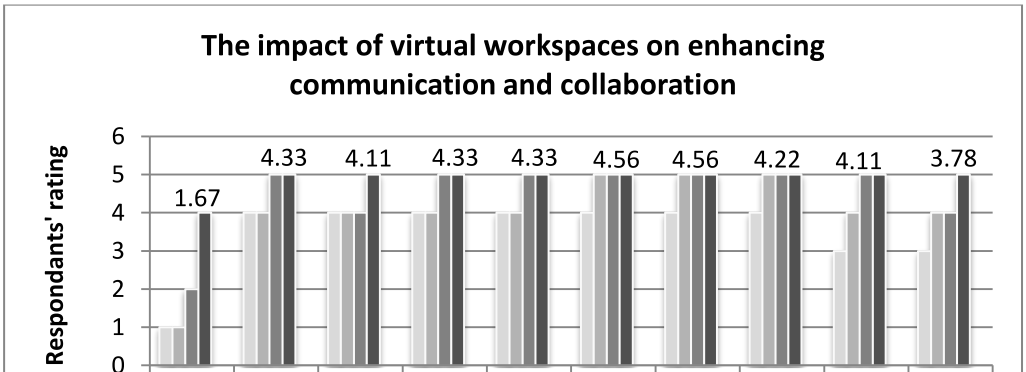


Fig. 6 - Collaborative workspaces including the Public Team Space and the Private Space (author: May Bassanino)



	1a	1b	1c	1d	1e	1f	1g
QTR1	3	4	1	1	4	4	1.25
QTR2	3.5	5	1	2	4	4	2.5
QTR3	4	5	2	2	5	5	3.75
QTR4	5	5	3	5	5	5	5
Mean	3.5	4.44	1.44	2.33	4.22	4.11	2.67

Figure 7 - Clustered columns showing the distribution of the results on the usability of the interaction features (author: May Bassanino)



	2a	2b	2c	2d	2e	2f	2g	2h	2i	2j
QTR1	1	4	4	4	4	4	4	4	3	3
QTR2	1	4	4	4	4	5	5	5	4	4
QTR3	2	5	4	5	5	5	5	5	5	4
QTR4	4	5	5	5	5	5	5	5	5	5
Mean	1.67	4.33	4.11	4.33	4.33	4.56	4.56	4.22	4.11	3.78

Fig. 8 - Clustered columns showing the impact of 3D visual and design tools on collaboration (author: May Bassanino)