A DISTRIBUTED VIRTUAL REALITY APPLICATION FRAMEWORK FOR COLLABORATIVE CONSTRUCTION PLANNING USING BIMSERVER[1]

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ABSTRACT: *As the architecture/engineering/construction (AEC) industry proceeds in the direction of digitalisation, computer supported collaborative work (CSCW) enhanced by building information modelling (BIM) becomes realistic for multidisciplinary collaboration in construction. Networked virtual reality (VR) supported by BIM servers, though showing great potentials in connecting multidisciplinary teamwork, is still less clarified for geographically dispersed construction teams to achieve collaboration. Taking the advantages of networked VR through the BIM server connection, this paper discusses a BIMserver-based VR application framework for distributed teams to perform real-time collaborative 4D construction planning and simulation. Through the analysis of current 4D modelling approaches, BIMserver adoption for collaborative 4D planning, as well as enabled VR platform technologies, the paper highlights availabilities of the interactive definition method for collaborative 4D planning underpinned by BIMserver. This method supports CSCW activities like co-navigate, so-sort, co-plan, co-simulate and co-talk for the 4D planning teamwork, together with power wall based semi-immersive VR platform for accommodating group users. On the basis of these discussions, a BIM-VR groupware system named Co-Studio is depicted from system architecture and application features. These discussions lay a foundation to develop a full functioned Co-Studio system as a next step. The system's applicability will be verified and validated in its subsequent implementation and industry projects.*

KEYWORDS: *BIMserver, collaborative 4D planning, groupware, virtual reality*

1. INTRODUCTION

A construction plan plays a fundamental role in construction management. A rigorous construction plan is the basis for developing the budget and the schedule for work. Depending on this function, the construction plan can further help formulate correct strategies for coordinating different construction activities. Thus the on-site conditions are foreseeable in the light of the conceived construction panorama. In view of its complicated nature, creating a construction plan, especially a robust plan, is a critical task in construction management. A useful approach in forming a construction plan is to simulate the construction process either in the imagination of the planner or with a formal computer based simulation technique (Hendrickson, 1989). However, the planner's imagination for construction planning is dependent on individual's experience and knowledge. A concern over skill shortages in this field is increased because junior staff usually has insufficient on-site experience to play this role like retired planners (Winch, 2002). With the advancement of information communication technologies (ICT), the computer based simulation is the more dependable approach to a robust plan.

4D (3D plus time) CAD is the one of computer based methods to generate construction simulations (Collier and Fischer, 1996). By linking a construction schedule with a 3D model, 4D can generate a dynamic construction sequence. This kind of simulation allows the user to preview a construction process so that potential conflicts in the schedule can be disclosed before the project delivery. The research interests of this technology have become

[1] Citation: Zhou, W., Heesom, D. & Tah, J. (2013). A distributed Virtual Reality application framework for collaborative construction planning using BIMserver. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

increasingly active due to its great potentials. In order to explore more benefits for the Architecture / Engineering / Construction (AEC) industry, substantial efforts have been invested into different facets of 4D CAD in product and process modelling (Heesom and Mahdjoubi, 2004). Being further extended, the use of 3D building model had been considered to connect multiple dimensions to investigate more AEC issues like health-safety, energy, cost, etc. An example is the nD modelling project conducted by the University of Salford in the United Kingdom. This kind of 3D based building information modelling (BIM) technology has led to the more extensive discussion for effective application in the AEC field (Succar, 2009).

Although having reached the stage of advanced BIM application, the construction industry still faces up a challenge in applying 4D CAD technologies for distributed collaboration. One of the weaknesses of 4D CAD lies in its insufficient support for geographically dispersed subcontractors. In the industry, the Critical Path Method (CPM) is popular in making a construction plan (InJongbeling et al, 2006). The CPM-based 4D CAD creation mainly relies on experienced engineers' imagination in accordance with blueprints (Chau et al, 2005). Moreover, subcontractors in a project specialise in their own fields, and concentrate on their own project planning in different locations. It is apparent that their static, abstract, and isolated schedules are incapable to deal with dynamic on-site situations. Although 4D technologies are helpful to disclose hidden contradictions in a project plan, prevailing stand-alone 4D tools have modest capabilities to support true distributed collaboration. Targeting this limitation, virtual reality (VR) based 4D groupware was envisaged as a viable approach to involving subcontractors into a unified 3D virtual environment for collaborative planning (Zhou et al, 2006). In spite of being successfully deployed in diverse fields, VR technologies are unbalanced in utilisation in the AEC industry. Most VR applications focus on the design phase but not the more complex and dynamic construction phase.

It was reported that (semi-) immersive VR systems are used for constructing interactive workspaces, such as CIFE iRoom at Stanford University, Interactive Collaboration Laboratory (ICL) at the University of New Brunswick in Canada, the Immersive Environment Laboratory (IEL) at Pennsylvania State University, etc. Recent reports (Issa, 2007; Muramoto, 2007) show that (semi-) immersive VR systems as a part of infrastructure are closely combined with the high bandwidth network to build a tele-collaborative environment. This inception intends to enhance information communication for rich modes of creative activity and collaboration. Compounded with these VR systems, extra equipments include interactive tabletop display, audio/video conferencing systems, and interactive board with touch-screen capability, special digital pen and eraser, etc. Users can interact with these devices using wireless mouse or even their fingers. These sorts of interactive workspaces are dedicated to creating a tele-collaborative educational environment in the AEC sector for general design and education purposes. The success from these reports prompts that a tele-collaborative VR environment can be a feasible platform for collaborative 4D construction planning in the condition of running suitable 4D groupware for a group of geographically dispersed planners.

The use of BIM models in the server end can enhance the network infrastructure of a tele-collaborative VR environment, and hence positively improve the productivity of collaborative 4D planning performed in it. Applying BIM models, particularly the industry foundation classes (IFC), for 4D planning is verified to be an effective way to integrate both 3D building entity information and plan data into a unique database (Tanyer and Aouad, 2005). However, the reported successful case was about individual planning using IFC data files rather than networked collaborative work applying IFC model servers. The latter is recommended for wide adoption to reduce disparity for data presentation and decrease incompatibility in data exchange among clients (Kam et al, 2003). Given an IFC-compliant BIM server, geographically dispersed planners are able to share the same project information and more effectively and efficiently manage their work. This possibility becomes realistic with the advent of open source building information model server – the BIMserver (BIMserver, 2013). Since it applies IFC for creating a building project information repository, the server can thus synthesise all project-related information provided from the client ends, update related IFC objects in the database, and then dispatch it to every client in real time. It can minimise BIM interoperability problems among different clients accessing the same IFC database to achieve integrated project delivery.

The objective of this paper is to discuss a 4D-VR groupware application framework applying the open source BIM model server – BIMserver for distributed collaborative construction planning. Through the review of the state-of-the-art of construction simulation technology, it highlights the viability of the interactive definition method for collaborative 4D planning by applying the BIM model server. From technological and constructional perspectives, it further discusses IFC-compliant BIM model server and enabled VR platform technologies respectively. Based on these discussions, a power wall based semi-immersive IFC-compliant 4D/VR groupware framework named Co-Studio is proposed from a constructional perspective.

2. CONSTUCTION PLANNING AND COLLABORATIVE 4D MODELLING

Using computer to simulate a construction process is helpful to generate a robust construction plan. According to the level of detail in the project control, related simulation approaches are classified to be product modeling and operation modeling. Product modeling at a project level can be applied for visually examining a developed construction plan; and operation modeling at an operational level can create a construction plan after the simulation (Kamat, 2003). Taking geographically dispersed condition into account, a construction plan can be also achieved through a collaborative 4D approach (Zhou et al, 2009). This section discusses and analyses existing investigations in these areas.

2.1 Modeling based construction planning

Current modeling based construction planning can be performed via both macro and micro approaches. From a macro perspective, the product modeling, which can be further developed into process modeling, follows the top-down approach to visualizing a created project plan (Figure 1). Its basic mechanism is to decompose a 3D model and link its elements (Product Breakdown Structure, PBS) with specific schedule activities (Work Breakdown Structure, WBS) to be a visualized construction sequence. Along with time progress, 3D elements appear in their last spatial locations, thus their corresponding schedule activities can be visually examined for contradiction identification. This dynamic product presentation provides planners with visual insights for controlling construction at the project level (Koo and Fisher, 2001). Compared with traditional Gantt chart based schedule, using final product to disclose potential logical, spatial and temporal problems in the schedule can lead to a relevantly robust construction plan.

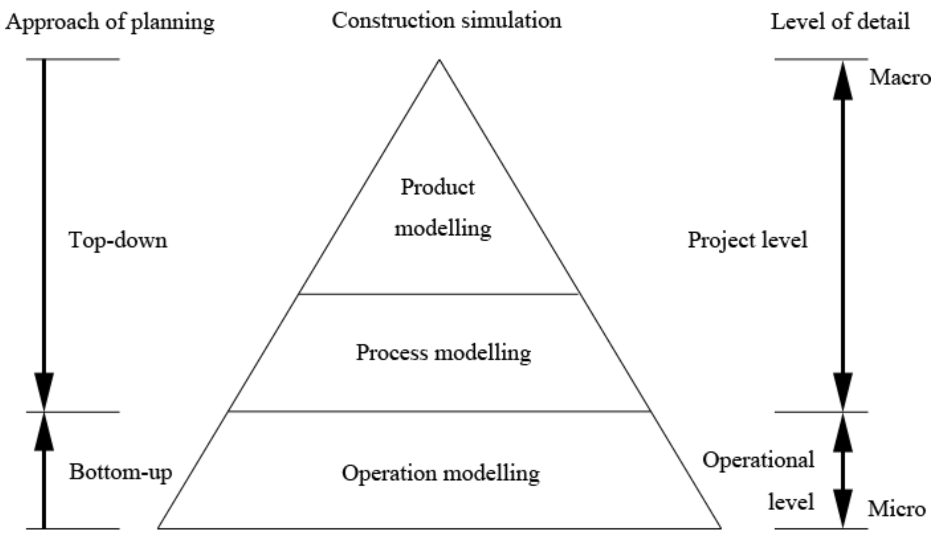

Fig. 1: Modelling based construction planning

The CPM-based 4D CAD is a typical top-down product modelling. In its creation, the project schedule needs to be generated using bar chart in advance. Afterwards, it can be visually checked and enhanced by linking the 3D elements (Collier and Fischer 1996). Normally, the linking → checking → updating procedure needs to be repeated several times to incrementally guarantee a conflict-free plan. For assisting conflict identification, relevant research concentrates on its visualisation, e.g. CIFE 4D Annotator (McKinney-Liston, 1998). The top-down approach is also applied in process modelling. On the basis of product modelling, process modelling emphasises analytical information such as cost, space usage, site layout etc. (Heesom and Mahdjoubi, 2004). Different methods are demonstrated for seeking more reliable plans in these areas, e.g. multi-constraint planning (Sriperate and Dawood, 2003), critical space analysis (CSA) (Dawood, 2004), location-based (or line-of-balance, LOB) 4D simulation (InJongbeling, 2006), etc. Because of separate 3D model and schedule creation, more feasible ways are needed in the top-down approach to automating the connection of 3D model with the schedule.

From a micro perspective, operation modelling can generate a project plan following the bottom-up approach. In contrast to product and process modelling, operation modelling deals with the dynamic motion of resources and facilities used during operations. It can visualise not only project level activities, but also motion of resources used by construction activities (Tantisevi, 2007). As 4D CAD only depicts the evolution of the construction product rather than the interaction of its consumed resources, operation modelling focusing on work at the field or operational level can naturally achieve the evolving product as its by-product (Kamat, 2003). Accordingly, its construction plan can be derived from this by-product. Li (2003) indicated this approach applying a knowledge-based VR system, the Virtual Construction Laboratory (VCL). The VCL can support construction planners to simulate construction activities in order to evaluate construction operations. In its operational level simulation, the planner's activities performed in the VCL can be recorded, and become the base for automating construction schedule generation. In such an approach, the system produces construction schedule according to the planner's activities.

In general, the top-down approach in product and process modelling is the prevailing way to obtain a robust construction plan. The application of 4D technologies mainly adopts this approach in the industry. The bottom-up approach, on the other hand, is mainly discussed in the research field. Compared the top-down approach with the bottom-up approach, the former is straightforward and explicit whilst the latter is indirect and implicit. Besides these differences, the top-down approach features iteration and inflexibility in modelling creation while the bottom-up approach bears accuracy with extra workload for the resources and facilities simulation.

2.2 Collaborative 4D planning

Collaborative 4D planning enables planners to create and integrate WBS based on their shared PBS in a geographically dispersed condition. It is different from stand-alone 4D modelling, which require individual's work on a created 3D building model without sharing PBS-WBS information with collaborators. Since the 4D CAD initiation nearly two decades ago, reported 4D creation methods and construction planning ways mainly concentrate on stand-alone applications for product modelling. Targeting this pitfall, the interactive definition method follows a top-down modelling approach to distributed collaborative 4D planning (Zhou et al, 2009). It emphasises an inputted 3D model to be accessible across the Internet. The PBS of the 3D model can be obtained by geographically dispersed planners via the network, and hence they are able to create WBS in their local places concurrently. Its related 4D simulation is also developed along with the WBS creation. The outcome of this collaborative planning has an integrated WBS - the construction plan, and completed 4D simulation.

The interactive definition method specifies a distributed real-time collaborative working context, in which a collaborative community and collaborators' behaviours are defined by CSCW dimensions, such as time, space, group size, interaction style, etc.(Mills, 2003). Applying this method, 4D collaborative planning work can be achieved by a geographically dispersed planning team. Every team member specialises in different fields such as structure, HVAC, electricity, etc to perform their own work individually and collaboratively. In the offline condition, planners can perform their individual work like other stand-alone 4D applications. In the online condition for collaboration, they can interact with each other for concurrent planning using their local devices like wired or cordless PC, mobile, etc. The planners can fully control their own information and obtain other planners' information synchronously. Basically, they can perform five types of work in their collaboration including co-navigate, co-sort, co-plan, co-simulate, and co-talk.

A prototype named 4DX implemented full features of the interactive definition method (Zhou et al, 2012) based on the desktop platform. In its collaborative functions, co-navigate and co-sort were created for analysing spatial structure of 3D building model. As every defined plan task in 4D planning is based on specific 3D model entities, these co-navigate and co-sort operations allowed planners to manually filter out their domain-related entities for plan data creation. Co-plan and co-simulate played a dominant role in the group planning. Co-plan was designed to support planners to access PBS from different locations, distribute local planners' schedule information, as well as receive other schedule information from remote planners. During the co-plan process, co-simulate across the network was positive for multiple planners to co-discover potential conflicts from a co-created plan (Kang et al. 2007). Multidisciplinary planners hence could focus on not only their own but also integrated whole plan's simulation. Co-talk could make use of audio and videoconferencing to achieve human-human interaction to facilitate collaboration during the planning.

3. BIMSERVER AND VR TECHNOLOGIES

The interactive definition method indicates a possibility of adopting advanced BIM model server and VR technologies into distributed real-time collaborative 4D planning groupware. It will be positive to connect geographically dispersed planners across time and place for communication, collaboration and integration. This section discusses the adoption of BIMserver and enabled VR technologies for the 4D groupware investigation.

3.1 BIMserver adoption

BIMserver is an open source project dedicated to the AEC industry to apply IFC as model server (BIMserver, 2013). It allows users to easily customise the server environment to suit their own needs, such as reuse, modify and adapt implementations of low-level tasks like underlying EXPRESS schema and instance parsing, persistency management and visualization. Besides the low-level operations, it provides developers with service interfaces of SOAP (Simple Object Access Protocol), JSON (JavaScript Object Notation), etc. to communicate with the server though a large collection of created methods. Developers thus can create their own client applications to fully take the advantage of BIMserver using any programming languages.

The freely accessible BIMserver provides excellent opportunities to create sophisticated 4D planning groupware. One of benefits is to enhance server management. The reported 4DX planning groupware took a server-client mode to create related functionalities. It applied entity-based 3D building models and separate plan data storage in the server end so that planners in the client ends can download the whole model and data, and then identify their domain-related entities for 4D planning. The building entities and plan data were loosely managed in the server since they were not synthesised into building models. However, BIMserver can significantly improve the server functions to integrate both entity and plan information in the database. Because IFC models contain both graphical and semantic information, which can be presented by product models like building entities and non-product models like cost, plan, energy, etc.(Froese, 2003), BIMserver therefore can simplify the server management by using IFC models only to restore both graphical and semantic information into a central project repository.

Applying BIMserver in the 4D planning groupware will also provide convenience for planners to perform their individual and collaborative work. In the entity-based 4D planning groupware, planners need manually pick out their domain-related entities for plan task definition. It costs amount of time to prepare a 4D planning context if the building model is complex and mixed with multiple domain information. Using the BIMserver, however, planners can focus on their interested entities to define plan tasks by automatically retrieving related parts from IFC model server. This effective and efficient working approach can be easily achieved in the client ends by developing related IFC-compliant features to identify smart objects and related project plan information in IFC models. Because IFC data structure has defined data types like IfcWall, IfcRoof, IfcDoor, etc. (BuildingSmart, 2013), the identification of related smart objects and project plan information from the BIMserver has no barriers to be realised. The adoption of BIMserver into the 4D planning groupware will also get rid of the server development burden with few efforts to update original functions in the clients. The entity-based 4D planning groupware still can preserve existing functions and further create IFC-compliant features by using SOAP interfaces provided by the server.

3.2 Enabled VR technologies

VR technology wins wide acclamations in the AEC industry (Dawood et al, 2006; Woodard et al, 2009; etc.). It provides computer applications with added values such as improved HCI, better information visualization, sense of 'presence', improved simulation, etc. (AIG, 1994). Besides these benefits, it also has potentials to facilitate collaboration in the 4D planning process. Adopting these excellent features, a distributed 4D-VR environment is able to empower a collaborative planning team to create a robust construction plan. This section discusses available technologies for VR-enabled 4D groupware creation.

A range of software tools and packages are available for 4D-VR application development. Following the interactive definition method, a created 3D building model is needed as input to foster a shared planning context. In terms of 3D building modelling, CAD systems such as 3D Studio MAX, AutoCAD, MicroStation, CATIA, etc. can be applied for 3D modelling. Latest BIM systems like Revit, Tekla, ArchiCAD, Digital Project, etc. provide even more powerful features to reach this aim. High level real-time graphics packages such as Multigen Creator, VEGA, EON, etc., are reported in both product modelling (Kim, 2001) and operational modelling (Li, 2003). Some popular low level computer graphics development kits like OpenGL and Direct3D have already widely applied in not only the AEC field but also other graphical intensive industries like mechanical engineering, gaming, etc. Recent research showed success using Direct3D in distributed 4D CAD creation based on the desktop platform (Zhou et al, 2009; 2012). Mainstream graphics cards like NVIDIA GeForce can support these 3D graphical technologies to create immersive effect based on an active stereo VR system (Belleman et al, 2001).

4D CAD studies are reported using different VR platforms. In accordance with the capability of producing immersive effect, VR platforms generally consist of three types: non-immersive VR (desktop VR), immersive VR, and semi-immersive VR (Woksepp and Tullberg, 2002). Correspondingly, their equipments are desktop PC, head mounted display (HMD) or cave automatic virtual environment (CAVE), and projector-based power wall. Almost all current 4D studies are based on desktop systems and can be considered desktop VR solutions suitable for individual applications. It was also acclaimed that the value of a CAVE in 4D construction planning lies in 'a tool to foster collaborative planning with improved communication among the various project planners' (Yerrapathruni, 2003). In view of limited space of CAVE system, it is still mainly suitable for individual work. At the same time, it is seen that projector-based power walls have the capacity to enable a group of audience working collaboratively. A good example is Construction Management Simulation Centre (BMSC) (Vries, 2004), which is dedicated to construction on-site training for collocated students in the VR environment. Given a network condition, the power wall based VR system can be applicable for both distributed and collocated collaboration in 4D planning.

Summarising these software and hardware utilities, it can be feasible to develop a distributed collaborative 4D-VR groupware system based on a semi-immersive power wall platform using active stereo projector and BIMserver connection. Commercially available BIM authoring tools can provide object-based IFC models inputted in the system, whilst low level graphics development kits can be applied for the 4D groupware development incorporating the depicted 4D CSCW design. The latter can also apply existing 4D systems, e.g Autodesk Navisworks since it fully supports VR configurations and functional extensions. Because of the requirements of IFC models from BIMserver, entity-based CAD models need to be converted into IFC models for the server application. Conversion methods can refer to relevant documents from CAD vendors, such as AutoCAD Architecture from Autodesk (Solihin, 2010). The network infrastructure can underpin the groupware for communication. The BIMserver-based 4D-VR groupware system can be applied for both collocated and distributed collaboration depending on planners' availabilities.

4. CO-STUDIO FRAMEWORK

On the basis of the foregoing discussions of 4D planning groupware, BIMserver and enabled VR technologies, the application framework of 4D-VR groupware system can be constituted by connecting a few of stand-alone 4D-VR systems as clients, which is named Interactive Studio (iStudio), with BIMserver through the Internet. A group of networked iStudio systems create Collaborative Studio (Co-Studio). Every single iStudio as a node in the Co-Studio network can support local planners for individual work or collocated collaboration whilst Co-Studio links geographically dispersed planners (in iStudio) for distributed collaboration. Co-Studio system architecture and its groupware application features are discussed as follows.

4.1 System architecture

Co-Studio can apply the server-client mode in its 4D groupware architecture. Accordingly, the groupware applications encompass a server-side application using the open source BIMserver and a few of client-side applications. The server-side application takes the responsibility of connecting the client-side applications for communication via the network. The client-side application provides planners with related functions to perform planning work and communicate with other online collaborators. Some third party utilities like MS Project can also run in the client side to support the groupware performance. Using Microsoft Windows as operating system, the Co-Studio system can be based on networked PCs with the extensibility of becoming networked semi-immersive VR systems. Each independent PC running the client-side application creates an iStudio system. Underpinned by the BIMserver connection, a few of iStudio systems can be connected into Co-Studio. The overall system architecture is illustrated in Figure 2.

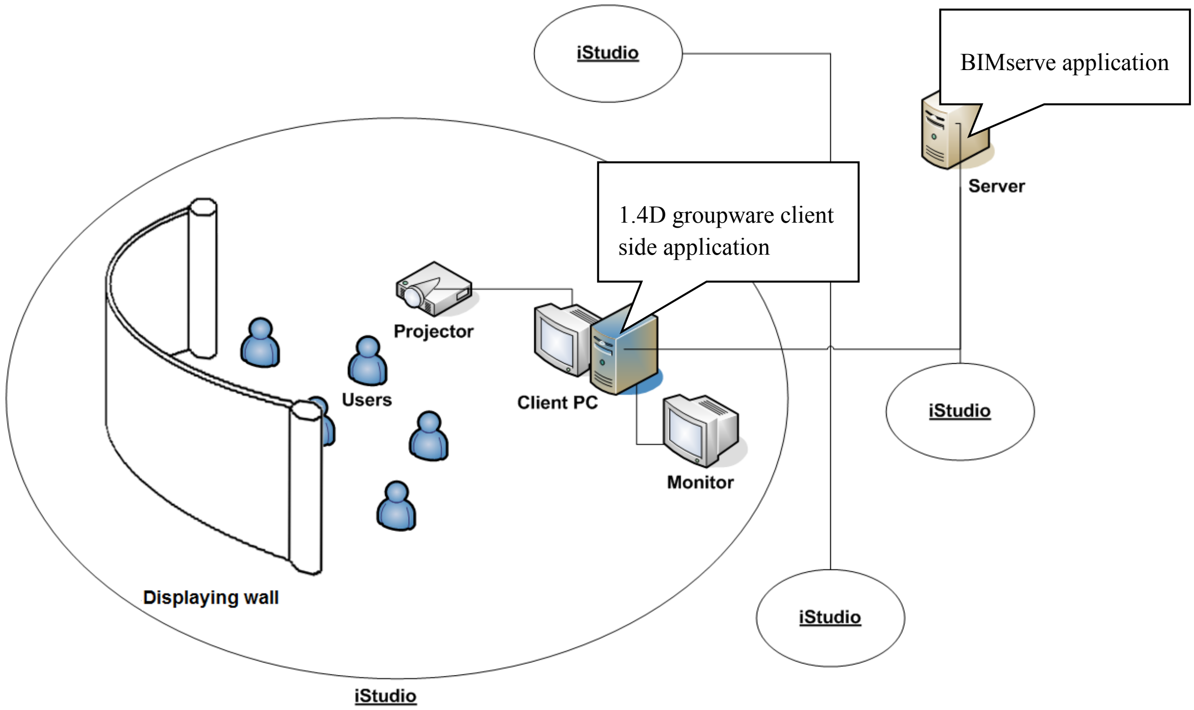

Fig. 2: iStudio and Co-Studio system architecture

Besides 4D groupware client-side application, the software in iStudio can adopt MS Office utilities like MS Project, MS Excel, etc. as well as third party video conferencing system. The 4D client-side application can support planning work while the MS Office tools are applied for recording planning and other nD modelling analytical results synchronously. Its basic hardware configuration is a standard PC connecting with multiple monitors. The multi-monitor in the system can provide planners with specific user interfaces of the 4D client-side application, MS Office, and videoconference. This hardware configuration can be further extended to a power wall based 4D-VR system using suitable projectors and graphics cards. Therefore, the user interface of 4D client-side application is possible to be projected onto a displaying wall to generate immersive effect. Based on seamless interoperability of Windows messages and object linking and embedding (OLE) technology in the Windows system, the 4D client-side application can exchange information with MS Office utilities synchronously during planning and simulation process. In the network condition, online iStudio systems can communicate with each other for exchanging and integrating plan information, and conduct 4D simulation across the network for creating a robust construction plan.

4.2 Application feature

Application features are different between stand-alone iStudio and networked iStudio – the Co-Studio based on different platforms (Table 1). On the desktop PC platform, iStudio is suitable for individual planning work. The existing CSCW design of co-navigate, co-sort, co-plan and co-simulate can be only performed by individuals without collaborators. In this circumstance, individual planners can conduct navigate, sort, plan, and simulate in their local iStudio for planning. The outcome of this individual planning is a finished plan and simulation without integration from other planners. The finished plan can still be outputted synchronously during planning and simulation process using Windows OLE technology. Co-Studio on the networked desktop PC platform can be applicable for distributed collaboration among individual planners. Online collaborators can fully conduct the designed CSCW activities to co-navigate, co-sort, co-plan and co-simulate for real-time collaborative planning.

Table 1: Application Matrix of iStudio and Co-Studio

Type	Desktop PC	Power wall
iStudio	Individual application	Collocated group collaboration
Co-Studio	Distributed individual collaboration	Distributed group collaboration

Taking the advantage of power wall, the application of iStudio and Co-Studio can be available for a group of people. In the offline condition, iStudio can accommodate collocated planners and other stakeholders in the same place for collaboration. Its similar application example is reported in live projects such as Walt Disney Concert Hall (Goldstain, 2001). Nevertheless, this kind of collaboration only exists in oral communication among stakeholders. Planners still need to perform their own work separately without involving CSCW and data integration. In the online condition, positively, Co-Studio can enable planners to fully make use of designed CSCW for communication and data integration among geographically dispersed planners and stakeholders.

Compared with CIFE iRoom (Fischer et al, 2002), the proposed Co-Studio has unique features in both system architecture and application. Besides the significant differences of 4D groupware application and Internet availability using BIMserver, another difference between Co-Studio and iRoom lies in iStudio. The iRoom applies Local Area Network (LAN) to achieve data exchange among 4D CAD and other MS Office utilities supported by several computers, whilst iStudio can utilise Windows OLE technology to realise synchronous data transfer between the groupware and MS Office in the same computer. Apparently, the former needs more financial investment on multiple computers whilst the latter only utilise one computer to achieve the same aim, and thus be lightweight and affordable. In terms of application feature, iRoom is applicable for individual application and collocated group collaboration, whilst Co-Studio is more flexible that can be any of applications listed in the application matrix.

5. CONCLUSION AND FUTURE WORK

The Co-Studio framework has potentials to create a distributed 4D-VR environment for real-time collaborative construction planning underpinned by BIMserver. Through the methodology analysis of current construction simulation, the paper highlighted applicable collaborative 4D planning approach – the interactive definition method with BIMserver to be adopted into the Co-Studio groupware development. From application and constructional perspectives, it discussed BIMserver adoption and relevant VR technologies as well as a power wall based semi-immersive VR platform for the Co-Studio creation. On the basis of these discussions, the framework of Co-Studio and iStudio was proposed and analysed from system architecture and application features. Co-Studio and iStudio as networked and stand-alone 4D-VR systems are able to accommodate both individual and group as well as collocated and distributed users for advanced collaborative 4D planning though BIMserver connection. This convenience also implicates unique excellence in low cost, lightweight, and flexible system configuration compared with CIFE iRoom. Their prototype implementations will be conducted to verify its effectiveness and usability. Moreover, their industry project validation is anticipated being available in the near future.

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