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AN INTERACTIVE APPROACH TO COLLABORATIVE 4D CONSTRUCTION PLANNING

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SUMMARY*: The use of 4D simulations within the construction field is growing, however, its application when carrying out true collaborative planning has not yet been fully realised. It is postulated that 4D models are currently utilised as a planning review tool, rather than integral to the initial construction planning process and do not fully support multidisciplinary collaborative construction planning by the various teams involved. Targeting this problem, a novel approach of interactive definition through a distributed environment is proposed, thus allowing interactive collaboration to create the construction plan and the subsequent 4D simulation directly from the unique 3D model. Based on a review of current approaches, a detailed comparison of current 4D creation methods and recent research initiatives, the interactive definition method is proposed and developed. This approach supports the planning process by providing a unique 3D model input, which can be manipulated using effective user-system interaction leading to comprehensive simulation item definition. The provision of this capability through a local and wide area network provides a collaborative planning workflow thus supporting collaboration and social interaction. Incorporating this rationale, a prototype system named 4DX has been developed as a distributed collaborative 4D based planning environment and used for the verification testing of the method. The findings of the preliminary testing shows the proposed approach and prototype achieves distributed real-time collaborative 4D construction planning, and can subsequently achieve a robust plan and full 4D CAD simulation.*

KEYWORDS*: 4D CAD, distributed collaboration, construction plan, interactive definition*

1. INTRODUCTION

Construction planning can be interpreted from different angles. From a professional point of view, Hendrickson (1998) specifies that construction planning is a fundamental activity involving the choice of technology, the definition of work tasks, the estimation of the required resources and durations for individual tasks, and the identification of any interactions among the different work tasks. From a cognitive point of view, this activity is the reflection of a planner's mental process for problem solving. Using the introspection method of psychology (Titchener, 1899), this mental process can be clarified as three continuous procedures when defining a basic plan task. Firstly it is represented by the planner's workplace identification based on design illustration. Secondly the planner decides task and time associated with the identified workplace and finally a logical task sequence is arranged. This mental process of the task definition is related to spatial information for workplace identification, temporal information for task time control, and logical information for sequence generation. In most cases, construction projects are a collaborative effort, and the development of a construction plan is no exception to this approach. This requires social creativity including contributions from multiple planners'.

Fischer et al. (2005) states that much human creativity arises from activities that take place in a social context in which interactions with other people and the artefacts that embody group knowledge are important contributors to the process. In order to support social creativity, the context needs to be open-ended and complex (Schön, 1983). These statements highlight that collaborative construction planning ought to own a shared, open-ended social context to motivate social creativity. In the meantime, social interaction and user-system interaction are key activities for collaboration. Moreover, these conditions need to be supportive of an individual's mental process in workplace identification, task time control, and logical sequence generation. This complex context builds a fundamental social-technical environment for multiple planners to carry out collaboration.

Construction planning is increasingly being supported through the application of 4D CAD. This is seen as a natural progression to 3D models, as it adds a further dimension (time) (Phair, 2000). The interest in the area of 4D CAD has grown rapidly in recent years and Staub-French and Khanzode (2007) highlight that the significant increase in research efforts demonstrate that 4D approaches are now being applied to address the complex challenges of construction. Work carried out by Coles and Reinschmidt (1994) demonstrated that creating a 3D model over time assisted in the planning process, whilst Webb (2000) envisaged that the use of 4D simulations could assist in halving the waste costs associated with a construction project. The use of 4D technology has the potential to present ideas to clients in order to promote collaborative working (Fischer, 2001; Kähkönen and Leinonen, 2001), and to assist in the problems associated with site logistics and site layout (Chau et al., 2005). Moreover, it can be used to improve site logistics, such as work execution space (Akinci et al., 2003; Heesom, 2004; Mallasi, 2005) and to analyse the construction schedule to assess its executability (Koo and Fischer, 2000). Additionally, 4D simulations have proven useful as a medium for the evaluation of alternative construction schedules (Vaugn, 1996). Work undertaken by Dawood and Sikka (2007) and Songer et al. (2001) demonstrate that understanding of building information is greater when utilising 4D models in comparison to the more tradition approach of 2D media, whilst the application of 4D simulations has also been advocated as a training tool for inexperienced planners (Jaafari, 2001; Clayton et al., 2002).

Although 4D CAD has demonstrated feasibility for construction (Koo and Fischer, 2000), it is still less incorporated into a complete planning process. Given the planner's mental process, current commercially available project planning toolkits, such as Microsoft Project and Primavera Project Planner (P3), can well support individual planners for task specification but not workplace identification and robust logical sequence generation. Many 4D CAD studies (Collier and Fischer, 1996, Kim et al., 2001, Dawood 2002, Chau et al., 2005, Jongeling and Olofsson, 2006) have proven that the use of the 3D geometric element within 4D models assists in the area of task-workplace recognition and logic sequence visual representation. However, the 3D geometric model receives attention for a review purpose within the 4D simulation instead of assisting planning from the beginning. Moreover, few studies clarify the potential of the 3D design model for creating a shared social-technical environment, and providing effective interaction between project planners. Seeking an applicable 4D approach in these aspects can provide a breakthrough for multidisciplinary collaborative construction planning.

The use of 4D tools to assist in collaboration is documented in several research efforts (Fischer et al., 2002; Koseoglu et al., 2007; Rad and Khosrowshahi, 1997). However a phenomenon within the construction industry is very often the fragmented approach and geographical distribution between contractors and subcontractors within the project team, with each having a focus on their own fields to arrange construction activities. These independent schedules then give rise to potential conflicts (both in terms of logistics and spatial constraints) during the project delivery. In order to overcome this barrier and achieve a complete and robust construction plan, communication and collaboration can be combined with 4D CAD principle for true collaborative planning

(Heesom and Mahdjoubi, 2004). Nevertheless, truly collaborative 4D based construction planning involves more than pure technical issues and includes a substantial number of social-technical concerns.

The implementation of new ICT approaches has seen some penetration into the area of improving communication and collaboration within the construction team. Muramoto et al. (2007) discuss the use of tele-collaborative tools, specifically within the context of design projects. Whilst this does not incorporate 4D specifically, the approach does demonstrate the potential for using a wide range of 3D software tools (including real time stereographic virtual reality) across a wide area network. A similar approach was proposed by Issa et al. (2007) who suggest that the use of an interactive workspace can improve the decision making process. Kähkönen et al. (2007) enhance the concept of 4D through the implementation of augmented reality using live video streams. This approach provides the ability for multiple angle video streamed over the internet to be overlaid with the 4D model to provide a live picture of progress against the proposed 4D simulation.

Whilst there is significant research effort being focused on 4D CAD, the application in industry in still uncommon when compared with other emerging tools (Bansal and Pal, 2008) and some postulate that one reason for this includes the difficulty and inflexibility of current 4D tools (Issa et al., 2003). Some other observers have highlighted that some of the technical aspects of 4D modelling hinder the collaboration of parties involved in a construction project (Poku and Arditi, 2006) whilst Zhou et al. (2007) suggest that in its current form 4D approaches act as a planning review tools rather than being integral to the construction planning process.

An effective collaborative 4D approach needs to support not only individuals but a group of multidisciplinary planners to generate a complete and robust plan. However, existing 4D CAD creation methods are dedicated to a stand-alone system for individual planners (Poku and Arditi, 2006). Generally when developing 4D applications, a Gantt chart is generated and used for the creation of a 4D model, however the development of the schedule still relies on experienced individuals' imagination according to the blueprints (Chau et al., 2005). Songer et al. (2001) concluded that using 3D models during the development of a project plan improved comprehension of the tasks required during the construction process. Subsequently, the ability for multidisciplinary planners to access a complete 3D model of a project whilst engaging in tele-collaborative interaction and user-system interaction, will support the mental processes to generate a more complete construction plan. Most importantly, a unified 3D model within a networked planning environment is able to provide multidisciplinary planners with a shared social context, in which it can promote planners' individual creativities and their social creativities for collaboration and thus formulate a robust plan. In such an interdisciplinary field, three aspects are worth consideration including 4D creation methodology, computer-supported collaborative work (CSCW), and networked computing. Particularly, a suitable 4D creation method fundamentally affects the other two aspects to achieve collaborative 4D construction planning.

2. CURRENT 4D PLANNING APPROACHES

4D CAD creation is known as the connection of 3D model elements – the Product Breakdown Structure (PBS), with construction activities – the Work Breakdown Structure (WBS). In terms of the PBS and WBS relationship and linkage, there are three types of methods applied in the creation of 4D CAD and construction planning: manual linking, (semi-)automation, and manual assembly. In order to formulate a suitable 4D-based planning method for collaboration, this section provides a blended discussion of these methods and analysis about their capabilities for collaborative working approaches.

2.1 Manual Linking

A 4D simulation is traditionally created by manually linking a critical path method (CPM) based schedule with its 3D model elements through a third party software tool (Collier and Fischer, 1996). Some off-the-shelf tools like AutoCAD or MicroStation are used to develop the 3D model, whilst project planning tools such as Microsoft Project or P3 are used by project planners to develop a schedule of activities. The linking of these elements is made using third party 4D software, although some CAD based toolkits now offer the ability as an integral part. This approach is widely applied and almost all the commercial 4D solutions adopt this technique for 4D modelling, such as Autodesk Navisworks Simulate and Common Point Project 4D. The significant feature of this method is its independent process of 3D modelling, planning, and PBS-WBS linking. When applying this method, 4D simulation is used for a post-planning review of an existing project schedule rather than supporting the initial planning process. It can be seen that this 4D approach provides a construction planner with limited support during the schedule development phase as the development of the tasks still require a significant and coherent mental process (Heesom and Mahdjoubi, 2004). Whilst functional, this approach lacks a shared social context for social interaction and collaboration, i.e. planners can only interact with their independent systems based on existing information. The diverse creativity of the planner in undertaking the scheduling operation may result in a conflict plan when integrated with other plans developed for a project.

2.2 Automation

Automating PBS and WBS connection is an efficient method for linking a separate 3D model and project schedule for 4D simulation generation. Dawood et al. (2002) applied a Unified Classification (Uniclass) database to semi-automate the linkage of the WBS and PBS within the VIRCON project (Dawood, 2005). A central database defined the relationship for PBS and WBS according to the Uniclass specification. Accordingly, an internal 4D simulation was created in an AutoCAD environment through retrieving data from the central database. In a similar approach to the manual linking method, this method needs a predefined plan and a 3D model as inputs, but their connection is automated. PBS and WBS automation is also applied in construction planning. In order to fully generate the project schedule automatically, de Vries et al. (2007) attempted another approach such that a 3D model was the only input whilst project plan was the output. An algorithm was implemented to analyse the inputted 3D model topology. In this full automation process, the inputted PBS was detected in an AutoCAD based prototype and by applying VBA code, the WBS was derived from the PBS. A log file was used to record the relationship of PBS and WBS during the analysis process. Afterwards, this log file was exported into MS Project to create a schedule of activities.

Both the semi-automation and full automation methods concentrate on the efficient creation of a 4D simulation and plan so to relieve the manual burden for PBS-WBS connection and the attributed mental workload. The former focuses on a partial mental process such as the manual linking for task-workplace recognition. The later, though considering a whole planning process, eliminates the possibility of user-system interaction. Moreover, a fully automated process without shared social context makes planning a close-ended operation. In this condition, planners have few chances to interact with both systems and humans for creative problem solving.

2.3 Manual Assembly

Frohlich (1997) sought an interactive approach of sequence assembly to create a schedule of activities. Applying a 'Responsive Workbench' system to support multiple input devices and two-handed manipulations, the user could conduct assembly and disassembly operations in a virtual space. This system demonstrated that 4D principles could be integrated to the actual planning process, rather than acting as a tool for planning review. Comparably, Thabet (1999) and Waly (2003) proposed a strategy to automate the scheduling process aiming at the design phase. The Virtual Construction Environment (VCE) allowed a prepared 3D architectural model to be re-assembled by drag and drop operation (Fig.1). Simultaneously, the construction plan and management decisions could be made by database support. It was argued that thinking about construction activities in the design phase is able to translate design information for sequencing project activities. This concern is consistent with the Construction Design and Management (CDM) Regulations 2007 of the U.K., which stipulates the designer's duties of "take all reasonable steps to provide with his design sufficient information about aspects of the design of the structure or its construction or maintenance as will adequately assist clients, other designers, and contractors to comply with their duties" (Statutory Instrument, 2007 No. 320).

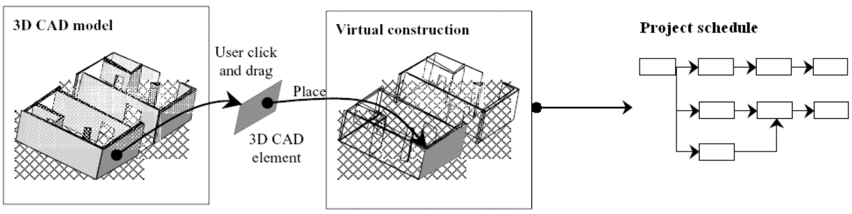

FIG 1: VCE Model (Adapted from Thabet et al. 1999)

As an alternative approach to manual assembly, Bansal and Pal (2008) propose a novel application of GIS within the realms of manual assembly of 4D models. This approach implements a GIS framework that allows the user to develop a schedule from the graphical elements of a 2D or 3D model thus providing a dynamic link between product and process.

The manual assembly approach to 4D development shows an interactive approach to generating a construction plan from an inputted 3D model. Through analysing the user's manipulation of the 3D model's reposition within the virtual construction site, it is able to formulate the construction sequence. It partially caters for the planner's mental process from the beginning of workplace identification. However, the remainder of the plan realisation relies on a set of complex peripheral modules to interpret the user's behaviour rather than explicit social and user-system interaction. This becomes its major limitation of being a close-ended system to gain external information from multidisciplinary collaborators who are usually involved in the planning process at the same time.

2.4 Current Limitations Proposed Solution

Based on the above discussion, it can be seen that current 4D planning approaches are inadequate to support a fully distributed and collaborative process for construction planners'. Both the manual linking and semi-automation methods can meet the partial needs of task time specification and logical sequence visual representation but not workplace identification. On the contrary, the manual assembly method can support the planner in identifying workplace but be moderate in another two aspects. Subsequently, these limitations confine their user-system interaction only within supported aspects but not available in the whole planning process. Because of the close-ended nature of these mechanisms, the planners' creativity and knowledge are hard to be incorporated in their corresponding processes. Although the artificial intelligence theory for construction planning is highlighted (Levitt, 1988) to adopt a planner's knowledge and proposed in 4D planning (Aalami, 1998), such a computerised cognition rationale in general deviates from a social and cognitive perspective to consider collaborative construction planning. Moreover, the reported methods are dedicated to a stand-alone system. None of them provides a shared social context for possible collaboration during the planning process. Social interaction is thus also excluded in these methods. Leicht et al. (2007) suggest key components for a socially interactive and collaborative workspace as including a digital virtual environment, interaction devices, physical artefacts and a display system. Whilst this postulation is based on a single location collaborative environment, the underlying requirements and concepts can be expanded to map onto multiple-location collaborative workspaces.

Current limitations of the 4D planning methods highlight the directions of possible solutions for collaborative 4D planning. It is practical to combine the advantages of existing approaches to formulate an applicable approach for the application of 4D methodologies for collaborative work in the initial planning stages. Among the discussed methods, the advantage of the manual assembly lies in its interactive 3D model which allows planners to consider possible solutions from the initial planning phase. It can also be used to build a shared social context for fostering collaboration. On the other hand, the task specification can refer to popular off-the-shelf project planning toolkits. As for logical task conflict detection, the manual linking method demonstrates the original essence of 4D CAD for visually checking a construction sequence. Incorporating these merits, a new 4D planning method can satisfy the full process undertaken by the construction planner. It is noted that automated mechanisms within these methods can not take the place of the planners' creative work but can however assist in formalising the link made between PBS and WBS, and thus result in a more close-ended system. Effective user-system interaction and CSCW are important contributions for open-ended planning work in a new solution. They form the basis of the proposed interactive definition approach to collaborative planning through 4D methodologies. This new approach is detailed in the following sections.

3. INTERACTIVE DEFINITION METHOD

The 'interactive definition' method is proposed to provide a platform for collaborative construction planning and seeks to adopt the merits of the previously discussed methods. Interactive definition allows multidisciplinary planners to collaboratively conduct planning work in an open social-technical setting, in which planners can not only perform their own planning but also interact with each other for real-time collaboration. The strategy of this method is to focus on a distributed and shared 3D environment, and interactively define simulation items. The interactive collaboration is supported by plan data exchange and incorporation, user-system interaction, and CSCW. The defined simulation items, which wrap PBS elements and WBS items together, are transferred via a network and synthesised to be integrated for the final plan and simulation output. Leveraging this user-system interaction, CSCW, and comprehensive information expression, this method can support distributed planners to generate a robust construction plan and simulation. The following sections specify the principle components and theories of the proposed approach.

3.1 Interactive collaboration principle

The interactive definition method emphasises interaction in a networked environment, where a shared 3D model is accessible for all online planners to foster a collaborative planning session. Through multilevel interaction, it enables distributed multidisciplinary planners to perform their planning work. Using a 3D model as a common start point plays a role in connecting distributed planners. Although multidisciplinary planners focus on different planning aspects, all their considerations originate from a unique design illustration. Concentrating on this common design illustration, represented by the 3D model, planners are able to analyse the design, discuss planning strategies with each other, and examine possible solutions. In order to maintain an open planning context, interactions among planners, between planner and system, as well as plan data incorporation are essential in the collaborative planning process.

Underpinned by the network infrastructure, planners can conduct the interactions at three levels. At a high level, social interaction is facilitated among multidisciplinary planners by communication. At a middle level, user-system interaction allows planners to interact with the 3D model for PBS analysis and interact with individual elements within the software tool such as 3D geometric elements, dialog boxes, menus, or buttons to facilitate WBS definition. The defined WBS items wrap PBS elements together to be integrated simulation items. In other words, the planner's work is to define simulation items rather than only the WBS itself. At a low level, the system can broadcast generated or updated simulation items in real time to every collaborator. Formulated plan tasks are exchanged and synthesised together. The 4D simulation, developed through this process, acts as a conflict eliminator for examining potential problems across the network. As a by-product, the final generated 4D simulation can be used for a communicative and explanative purpose afterwards. In such an open and shared social-technical setting, individual and social creativities are motivated by the interactions. Collaborative planning in this context is liable to achieve a more robust plan than those generated in isolation by individual planners working on discrete work packages. This concept is illustrated in Fig.2.

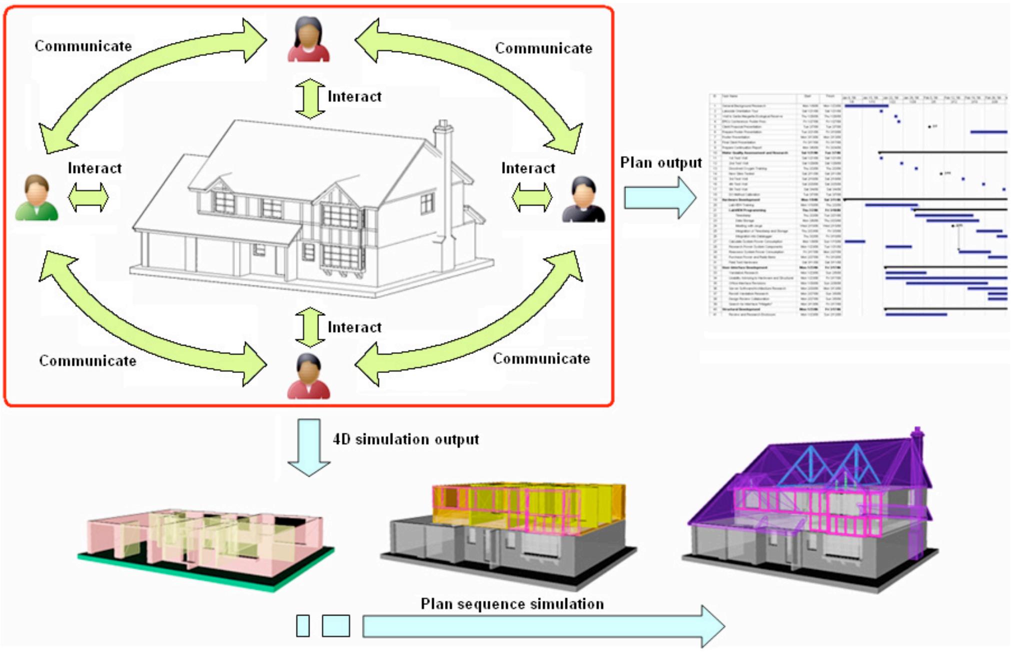

FIG 2: Concept of the Interactive Definition Method

The proposed interactive collaboration approach combines some characteristics of the reported 4D creation methods but is unique at the same time. Similar to the full automation and manual assembly methods, the interactive definition method targets an existing 3D model - the PBS to generate WBS. But the former applies some automated reasoning mechanisms to realise it. They can be named as PBS-deduce-WBS (PBS=>WBS). However, the generation of WBS in the interactive definition method is through open-ended interactions rather than close-ended machine reasoning. Emphasising interaction in the proposed method is not contradictory with any effective automation for planning. However, they are expected to promote creative problem solving instead of attempting to replace the planner's creativity. In another respect, the interactive approach adopts the manual linking for PBS-WBS connection, which is noted as PBS-plus-WBS (PBS+WBS). Nevertheless, this linking is a natural operation following the coherent mental process when applying the interactive definition method. It is unlike the manual linking method that PBS+WBS is of redundant task-workplace recognition. According to these comparable points, the proposed 4D planning approach is tagged as PBS-create-WBS (PBS→WBS). Synthesising the foregoing discussions, all of the methods described are differentiated in Table 1.

TABLE 1: Method for 4D Construction Planning

Method	Manual Linking Semi-Automation	Full Automation Manual Assembly	Interactive Definition
Approach	PBS-plus-WBS	PBS-deduce-WBS	PBS-create-WBS
Alias	PBS+WBS	PBS=>WBS	PBS→WBS
Suitability	4D CAD	3D planning	4D planning

3.2 3D Model Input

A 3D model is the only data input required in the interactive definition method. It is used to create an open and shared planning context to foster collaboration. Planners can focus on this unique design illustration for planning strategy analysis, and interactively perform planning work. In view of the diversity of strategies in construction planning, the inputted 3D model should be flexible enough in its level of detail (LOD) in order to suit different detail level in WBS. LOD matching is a matter of trade-off between PBS and WBS as it will decide both modelling workload and schedule definition. If a 3D graphical model has a low LOD, some tasks may be ignored in the simulation. On the contrary, a 3D model with an unnecessary high graphical LOD could be no interest for the planner (Tanyer and Aouad 2005). It would increase extra modelling burden, and decrease the system performance. In the manual linking method, the 3D model LOD is tailored for the existing WBS because it has been created in advance. However, considering no WBS is created beforehand when using the interactive definition method, the LOD of the inputted 3D model is dependent on real requirements from constructors.

The inputted 3D model file format significantly influences PBS generation using the interactive definition method. Prevailing CAD files like DWG, 3DS, DXF etc. and latest Building Information Model (BIM) approaches including the use of Industry Foundation Classes (IFC) are applicable resources for 3D model input. Given a 3D model compatible with BIM, PBS information of a building like door, window, beam, column etc. can be easily generated according to its internal specification. In case of some popular non-BIM CAD formats such as DWG, PBS information can be obtained according to defined regulations, e.g. to retrieve certain entities from a specific layer (Dawood, 2002). Under these kinds of conditions, the use of the interactive definition method has no barrier for collaboration. Multidisciplinary planners can obtain their PBS elements directly from the inputted 3D models. However, if there is no building information available in an inputted 3D model, PBS information only relies on visual identification when the 3D model is displayed in a 3D space. It thus needs a 'sorting' procedure to pick out related 3D elements for corresponding planners.

3.3 Simulation Item Definition

A simulation item describes the planner's consideration while defining a plan task. This takes into account where (workplace, the PBS), what (task, the WBS), when (time), and how (logic) a task is going to be conducted. A simulation item definition consists of two aspects. One aspect is about the WBS definition including individual WBS item definition, hierarchical WBS structure formulation, and the entire WBS export. Another aspect is about the connected PBS items description in each WBS item. Therefore, a simulation item contains four parts of information. The first part is related to a WBS item. The planner needs to provide information about defined task item's name and time. The second part is relevant to one or more PBS items being linked with the defined WBS item. The third part associates to logical relationship among defined WBS items such that a hierarchical and inter-related project plan can be formulated. The planner needs to identify predecessors of the defined WBS item depending on his or her domain knowledge about construction procedures and sequences. The fourth part involves a suitable data interface with external toolkits for data export. Reasonably, a generated plan is expected to export into commercially available project planning tools for some possible refinement.

In order to express simulation item information, a set of parameters are defined referring to off-the-shelf project planning toolkits e.g. MS Project, which provide necessary information for the parameters' definition. The parameters consist of single task parameters and group task parameters. The differentiation of single and group task parameters is because single tasks are usually wrapped into various groups. The single task parameters can control single WBS item definition. They are composed of Task ID, Task Level, Task Name, Duration, Start Time, Task Predecessors, PBS Item, and Task Colour Cue. On the other hand, the group task parameters are used for group task definition. They are composed of Group ID, Group Level, Group Name, and Group Predecessors. Those parameters in a simulation item definition serve different information parts (Table 2). All of the parameters create a suitable data interface to export a generated plan. As a simulation item wraps the information of both WBS and PBS, it is convenient for network transmission and synthesis to output the final plan and simulation.

TABLE 2: Task parameter for simulation item definition

Function	Parameter
Define a WBS item	Task ID, Task Name, Duration, Start Time Group ID, Group Name
Define a PBS item	PBS Item, Task Colour Cue
Build WBS logical relationship	Task Level, Task Predecessors, Group Level, Group Predecessors

3.4 User-system Interaction

In the interactive definition method, user-system interaction is designed to assist the planner's full mental process for planning work. Corresponding to the traditional process, the planner's tasks in planning consist of picking the right PBS elements from the 3D model, inputting simulation items' data via the selected artefacts, and conducting instant simulation to check generated logical sequences. Collaboration is involved during the performance of these tasks. In order to support these interactive activities, direct manipulation is adopted in the distributed workplace for analysing and geometric element picking in a 3D space. It is highlighted that applying the direct manipulation can promote user's task performance and social interaction for problem solving (Bottino, 1998). The utilisation of the direct manipulation enables the planner to analyse the 3D model by zoom, pan, rotate, pick etc. These meaningful manipulations motivate the planners to ponder planning strategies, exchange ideas with other collaborators, and thus create right planning solutions (Songer et al., 2001). Thereafter, the simulation item specification is performed via a 2D graphical user interface (GUI) so that planners can input data to define a simulation item. A 4D based simulation is conducted instantly once finishing the definition. It is unnecessary to perform the simulation after every item definition, but frequent simulation of the building sequence throughout the whole planning process can avoid the risk to build up plan conflicts to the end.

3.5 Collaborative Planning Workflow

Applying the interactive definition method in a network condition follows a collaborative workflow to realise collaborative 4D planning. A server-client application is one feasible approach to support this collaborative 4D planning approach. The server side application provides planners with a shared 3D model, and the client side application enables planning activities to be undertaken at a local level. Given this networked situation, the planner first connects to the server to choose a speciality role, which is defined in the server in advance. Subsequently, 4D information including the 3D model and possible existing plan data can be retrieved from the server to the client. Focusing on this shared 3D model, the online planners can perform planning in a collaborative real time environment to identify workplace, create simulation item by picking up proper 3D elements and specifying tasks, and conduct simulations. Task sequence simulation is performed after the simulation item definition. It is used for detecting temporal, spatial and logical conflicts in the created plan. In case of conflicts detected, the related planners need to reconsider the item definition from the beginning of the workplace identification. A new simulation item definition can be followed if no conflict is detected in the defined items. Finally, the completed project plan can be exported into a third party toolkit for further refinement. After finishing all planning work, the planner(s) can log off from the server. The planning workflow with desired functions is illustrated in Fig.3.

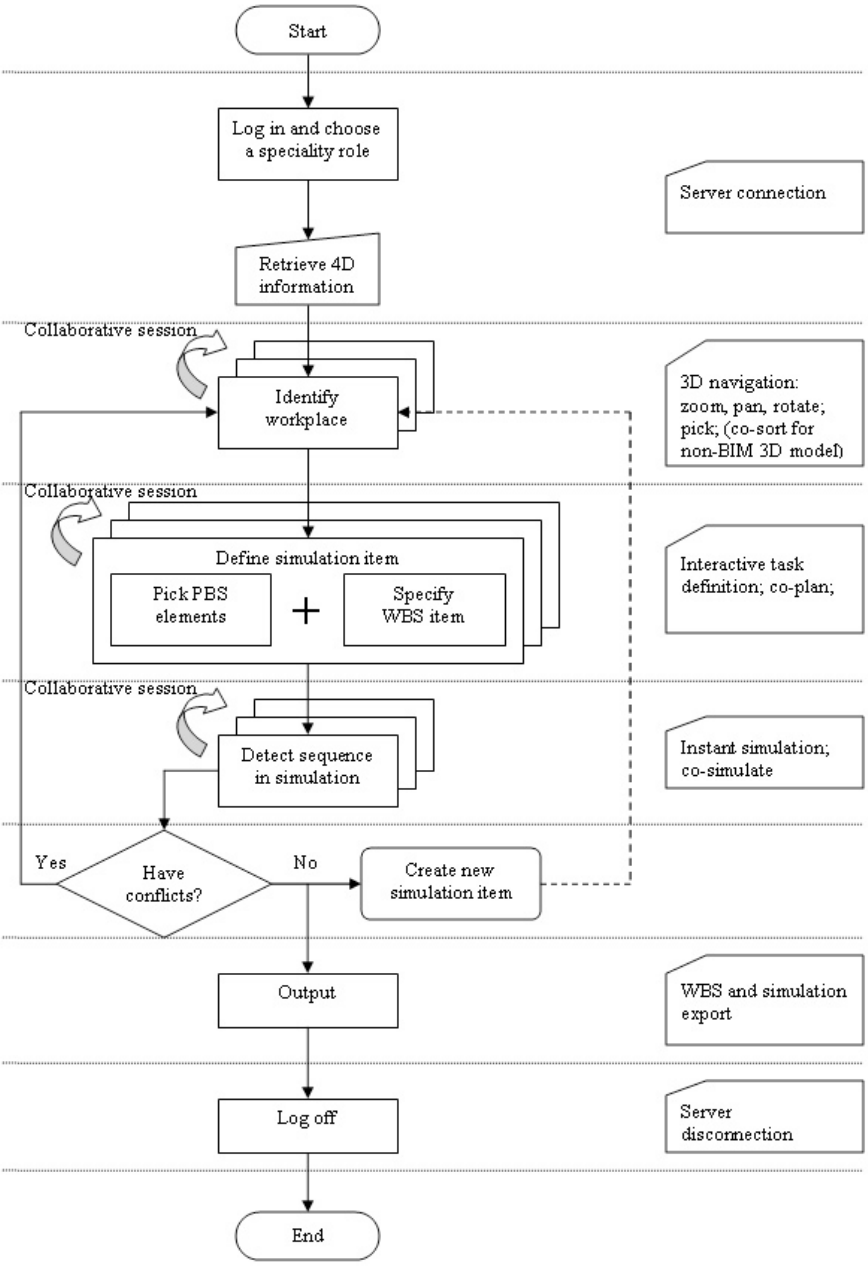

FIG 3: Interactive Collaboration Workflow with Proposed Functional Features

CSCW is created as a series of collaborative sessions to assist online planners' mental processes in the workflow. These processes are open-ended by incorporating the sessions. Combining the interactive definition method, the CSCW is designed to be co-navigate, co-plan, co-simulate, co-sort, and co-talk. In the meantime, co-talk as instant communication among collaborators maintains a live social interaction. This element is undertaken through use of proprietary meeting tools, such as audio and video conferencing and instant messaging. In the workplace identification procedure, co-navigate can be conducted by collaborators for analysing 3D model via zoom, pan, and rotate. If the loaded 3D model in the server is a BIM model, planners can directly obtain corresponding building information. In case of inputting a 3D model without building information, planners need to co-sort the 3D elements to suit their specialities before task definition. In the simulation item definition procedure, the planner can pick up desired PBS items from the 3D model, and then specify an associated task - the WBS item to create a simulation item. Taking advantage of a network transmission, the defined or updated simulation items are sent and synthesised in the server and broadcasted to all online planners in real time. This co-plan collaboration ensures planners exchange and incorporate plan data to be an integrated plan. In the simulation procedure, the co-simulate session enables task sequence simulation across the network. It allows online planners to examine not only their own but also the overall plan sequence.

4. PROTOTYPE IMPLEMENTAION

In accordance with the principle of the interactive definition method, a prototype system named 4DX has been implemented. It consists of a server side and a client side application. This server/client mode enables distributed planners to perform real-time collaborative planning across the network. Its implementation applies Microsoft Visual C++ 8.0 (Visual Studio 2005), DirectX 9.0, and Winsock 2.0. These are all popular utilities for the Windows platform for the development of networked 3D graphical applications, and well supported by most hardware. The underlying network communications are based on the internet TCP/IP protocol. Object-oriented (OO) programming was adopted for the entire system development.

4.1 Client Side Application

The 4DX client application builds a series of functional features to assist the planner's mental process in planning. For a full planning process, functional features are created as direct graphical manipulation in a 3D environment, topology displaying, interactive task definition, instant simulation, and seamless data export. The 3D graphical environment displays a 3D model of the building / facility when the planner loads it from the local system or retrieves it from the server. A set of basic 3D navigation functions like pan, zoom, and rotate are provided for conveniently browsing the 3D model. Meanwhile, topology displaying ensures planners analyse the 3D model and scrutinise every 3D element in a bottom-up or top-down order. This analysis applies the rationale of the full automation method to control the display of 3D elements' but not to create a plan automatically. It provides planners with an effective and efficient means to simplify 3D elements' spatial displaying. Planners hence have chances to interact with and analyse the 3D model for workplace identification, and pondering planning strategies.

In order to enable social interaction and collaboration during planning, the client planners can select one of the defined roles while connecting to the server. After the role registration, independent planners become collaborators being connected with other online planners within the project team. An instant messenger and video conferencing are available in the client for planners' to co-talk throughout the session. Additionally, collaborative sessions including co-navigate, co-sort, co-plan, and co-simulate are created for collaborators' utilisation. Being assisted by these CSCW design principles, the planners can manipulate the same 3D model while thinking about suitable planning strategies, discussing solutions with online collaborators, identifying workplaces for a considered plan task, and thus formulating a correct plan task definition. Once a task definition is decided, the planner can pick up related 3D elements using input devices, and specify a simulation item from a definition dialog bar (Fig.4). After finishing this simulation item definition, the planner can perform instant simulation in the local system or across the network if needed. In such an open shared social-technical environment, the planners' full mental processes are supported, and enhanced by the designed CSCW for collaboration. Therefore, it is possible to achieve a robust collaborative 4D planning.

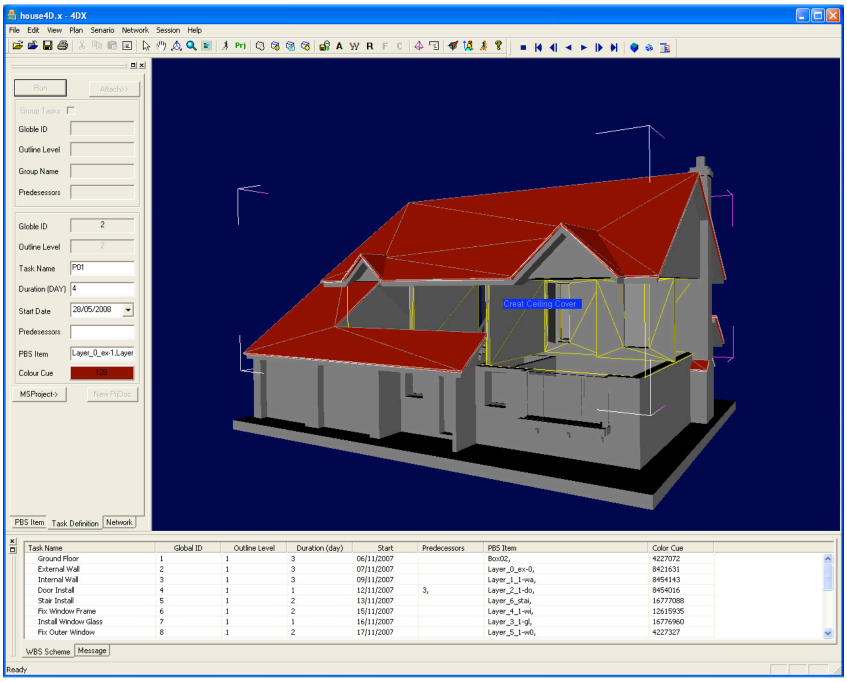

FIG 4: Simulation Item Definition in the 4DX Client Application

4.2 Server Side Application

The server side application encompasses the necessary collaborative information into a 4D item pool for the client side retrieving and operating when planners log in the server. The information includes planner's role of speciality, PBS information, synthesised simulation items, and role-attribute data. A set of functional modules are provided to conveniently manage the 4D item pool. These include; 3D model browser, simulation item synthesiser, role editor, and role-attribute browser. The role editor is created to edit (and add or delete) a role according to the collaborators' specialities in planning, and the 3D model browser is embedded in the server side in order to help check loaded 3D models. The 4DX system adopts a non-building information model approach using the Microsoft .X format so that more collaborative issues can be clarified in the investigation. Except the specific name of each element in the 3D model, their detailed spatial information is neglected in the server side. The name of each 3D element is displayed by the role-attribute browser, which records a read-write correspondence between collaborators and 3D elements for plan task definition. The simulation item synthesiser functions by integrating defined plan tasks and the simulation items from different planners to be a complete hierarchical structure.

The server side application is designed as a central data repository connecting with client applications. The connection between the server and the clients is through the internet or local area network (LAN) depending on collaborative requirements. After logging into the server, online planners can retrieve their own PBS information through utilising the co-sort functions within the client application. For a .X formatted 3D model without building information, planners in their clients need to visually sort related PBS information as writable elements beforehand so that they can be applied for later plan task definition. Based on a real time multicast transmission mechanism, the server can receive and then broadcast sorted PBS information, synthesised plan information, as well as other collaborative information to every online client.

5. VERIFICATION TESTING

Preliminary verification testing has been conducted to examine the applicability of the interactive definition approach to collaborative 4D planning. For the convenience of preliminary testing, a 4DX system was configured to mock up a distributed planning situation, where planners focus on their own clients and collaborate with each other via a LAN. For the purpose of the testing, the collaborators were located in the same room. Without geographical distance barrier, the collaborators can communicate face to face. Thus, the testing can be under control and focus on critical issues of the methodology itself. The testing setup, process and result, as well as findings are discussed as follows.

5.1 Testing Setup

The testing system consists of LAN-based PCs. Each of the PC's run a 4DX client application, and one of the PC's also runs a 4DX server application. A hub is used to connect the PCs so that the whole system creates a collocated collaborative environment for the planners (Fig.5). The testing targets a real 3D building model recently constructed at the University of Wolverhampton (Fig.6). The 3D model was originally created by the Architect using Autodesk Architectural Desktop (ADT) without building information. It is composed of parametric object entities, however only geometry information is available and organised by layers within the CAD model format. The model was converted into .X format by proprietary tools in order to be applicable for the 4DX system. Planners then took part in a collaborative planning session, with each taking on specialist roles, for example structural contractor, services contractor and main contractor. One of the planners also holds the role of administrating the server in the same PC. This collaborative planning requires the planners to perform their own work while considering their collaborators' spatial, temporal, and logical relationships. It is hence suitable to verify the collaboration principles using the interactive definition method.

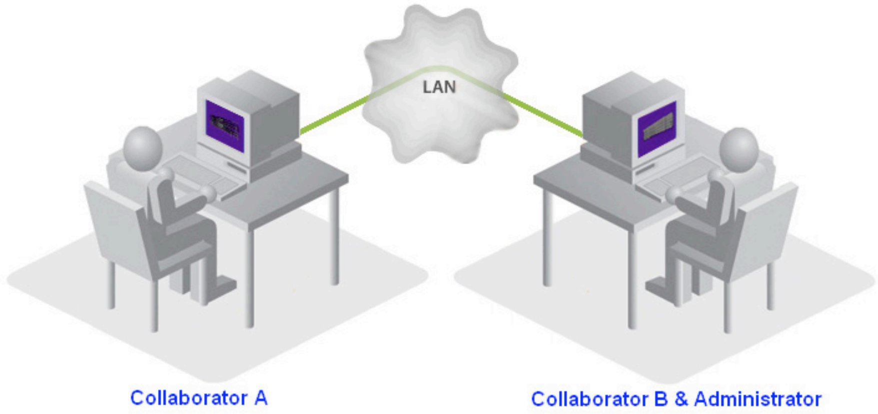

FIG 5: Verification Testing Setup

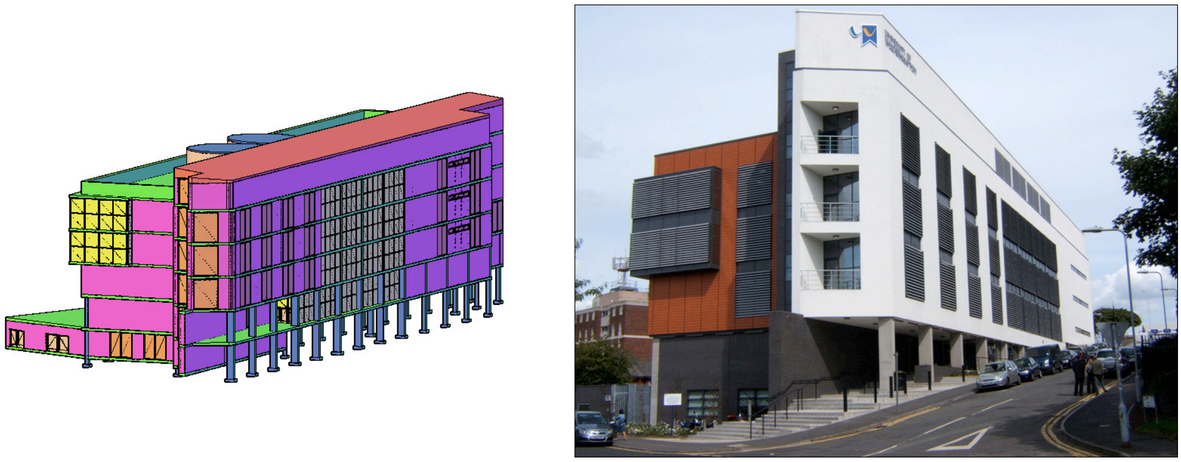

FIG 6: 3D Model of MX building, the University of Wolverhampton

5.2 Process and Result

The planning test complies with the method workflow. Before the real test, preparation work is conducted to meet collaborative planning needs. The roles of the collaborators are defined in the server side and a 3D model of the facility is also loaded on the server. The names of 3D elements are then displayed in the role-attribute browser, which builds a correspondence between the roles and the elements. Subsequently, the collaborators log into the server from their clients respectively. The 3D model's elements are retrieved from the server to the clients automatically. In view of no building information available in the 3D model, a co-sort collaborative session is performed so that the collaborators can pick out the 3D elements that relate to their particular work packages for later task definition. This co-sort session results in a classified 3D model for the collaborators. Selected elements by a person are writable whilst other elements selected by another collaborator are readable for this person, and vice versa. Only writable elements can be defined with plan tasks and readable elements can not. This correspondence is transferred to the server in real-time during the session for recording and displaying in the role-attribute browser. In the clients, the 3D models are displayed in grey-solid and black-mesh states to differentiate writable-readable elements (Fig.7).

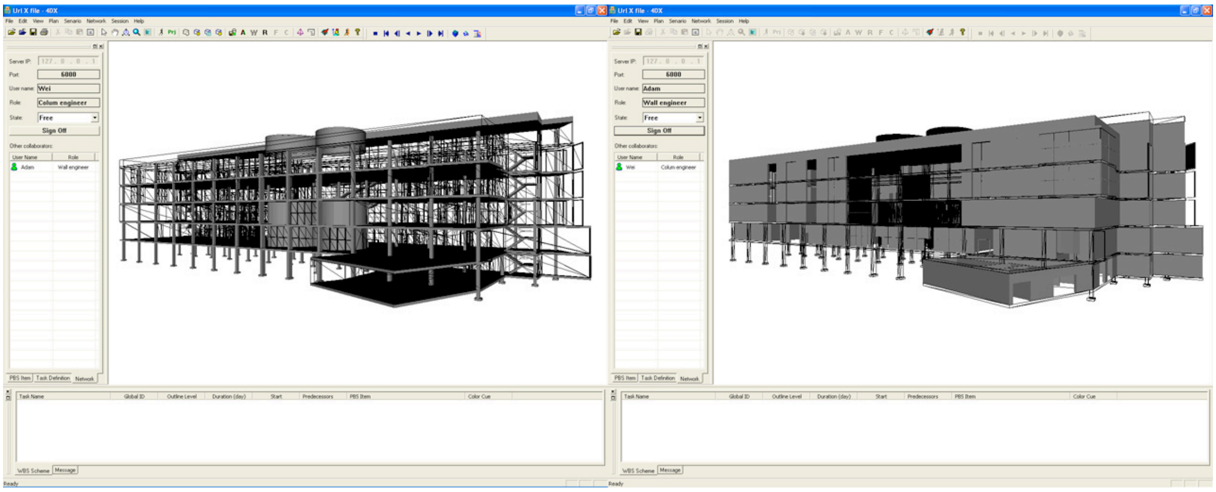

FIG 7: Co-sorting Result of Writable-Readable Elements Displayed by Two Clients

During the testing, the collaborators focus on the sorted 3D models in their own clients while discussing planning strategies mutually. Taking the advantages of direct manipulation, collaborators navigate and analyse the 3D model for workplace identification. Once deciding their plan tasks, collaborators then pick up identified 3D elements and specify tasks according to the simulation item parameters via the definition dialog bar. This dialog bar builds the picked 3D elements and a specified task to be a simulation item. Defined simulation items in each client are simultaneously sent to the server for synthesising according to their tasks' specifications. The synthesised simulation items are then broadcasted to all the collaborators immediately. This real-time collaboration and data transfer leads to a common plan accessible in both the clients and the server. In order to check possible conflicts, instant simulation is conducted throughout the collaboration for visual detection. Through a series of simulation items' definition, the participants collaboratively create a complete construction plan leading to a full 4D simulation of the construction process. The generated simulation can be replayed for the project's communication and explanation (Fig.8). The final created plan is outputted into the MS Project, which shows a consistent hierarchical structure and a Gantt chart (Fig.9).

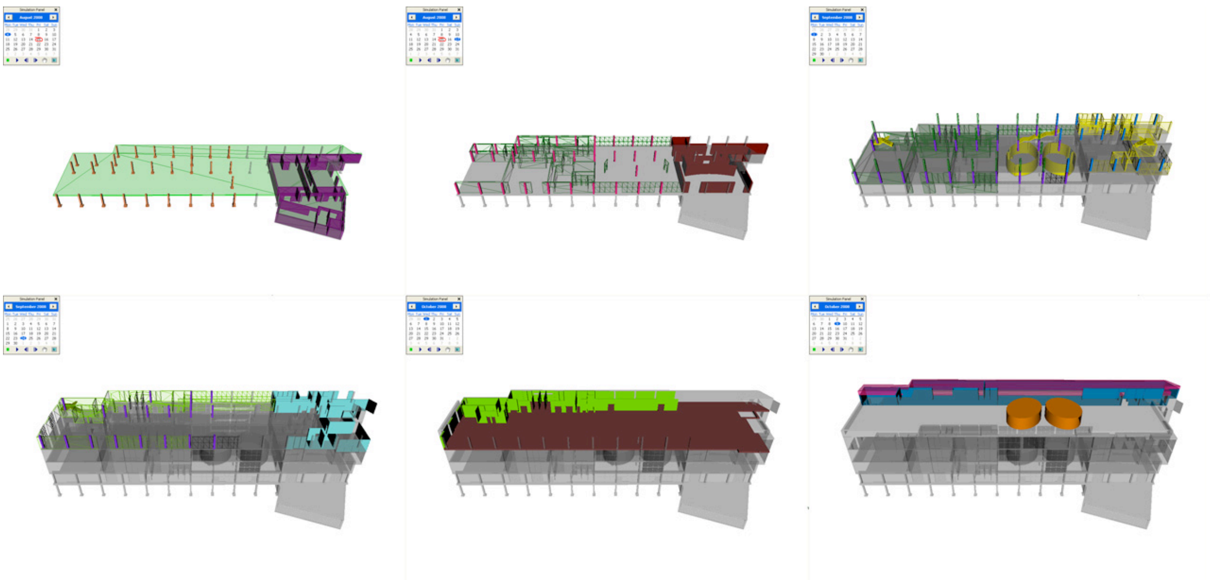

FIG 8: Generated 4D Simulation Sequence in the Testing

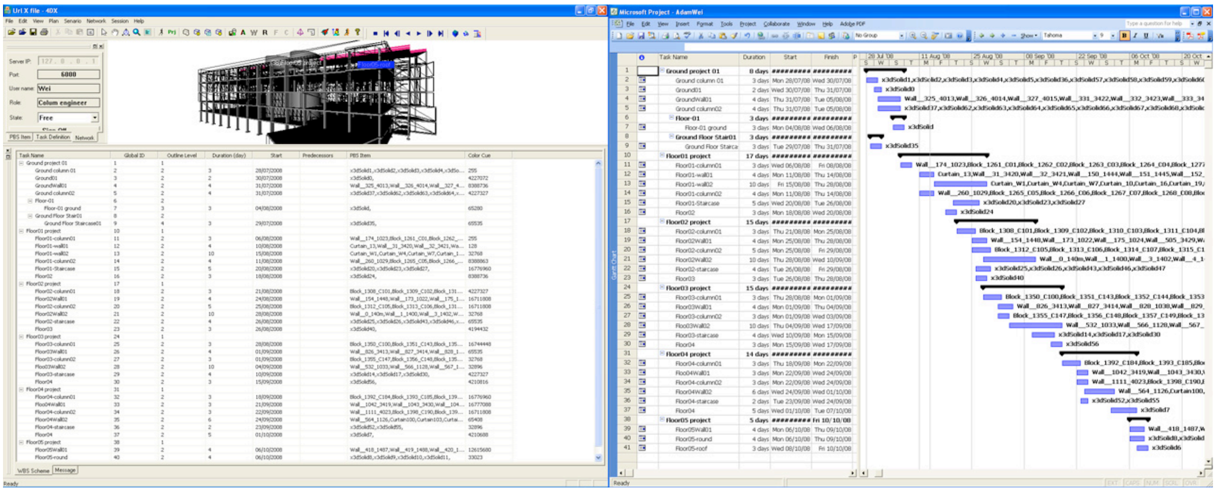

FIG 9: Consistent Plan Displayed in the 4DX and the MS Project

5.3 Test Findings

Through the preliminary testing, some benefits of the proposed approach have been highlighted and some areas for future development have been identified. The testing shows that the co-sort is an applicable way to obtain PBS information from non-BIM 3D model and allow collaborators to identify elements of the building that are to be constructed as part of their work packages. Nevertheless, it takes substantial time for collaborators to gain their desired building information. The model used during the initial testing has hundreds of 3D elements which are a heavy burden for manual picking. This complication advocates that applying BIM e.g. IFC-compliant 3D model or utilising the Uniclass structured approach in the method can be an effective solution to efficiently obtain PBS information. Because of the dominance of entity-based CAD models in the industry, the use of co-sort is still a helpful way in the interactive definition method when the inputted 3D model has no building information. The testing also shows that CSCW is crucial for collaborative planning. The devised collaborative sessions like co-sort, co-navigate, co-plan and co-simulate are applied throughout the whole collaboration process. The discussion about CSCW design and testing for 4D CAD are out of the scope of this paper (further discussion can be found in Zhou et al., 2007). It is concluded from the testing undertaken that combining specific 4D planning methods, e.g. the interactive definition approach, is the key to create effective CSCW for collaborative 4D planning.

The use of a unique 3D model to foster collaboration achieved a satisfactory result during the testing. The planning collaborators focused on the same model to conduct their own planning and consider the constraints from each other. This approach, on the one hand, caters for the planners' mental processes for their own planning. On the other hand, it triggers their common concerns in interrelated tasks' definition for social interaction. Corresponding to these behaviours, real-time collaboration is a feasible approach to support collaborative planning. Social interaction is irreplaceable in this collaboration. In order to conduct the social interaction, the testing clearly shows that the collaborators communicate with each other frequently while analysing the model and defining simulation items. The prevalent communication approach in the social interaction is via verbal talking. This phenomenon implies that audio, video-conferencing is a must for distributed 4D collaborative planning.

The method's capability in LOD creation and management is also verified in the testing. Because the test targets collaborative planning, the plan creation is requested to be a relevantly macro planning. According to this requirement, the collaborators interactively pick up related 3D elements for simulation item definition. Some detailed 3D elements like window frames, handrails et al. are included in the window or stair project, but not further used for more detailed subtasks. In case a more detailed plan is needed, planning can go deeper to build associations with these detailed 3D elements' collections for subtasks' definition. An inconvenience in the tasks' definition is that the 4DX prototype provides planners with single object selection such that collaborators have to pick up multiple elements one by one to build a task PBS collection. Although single element picking is accurate to collect 3D elements, it is inefficient to collect multiple elements with ease. Creating more efficient PBS collection approaches can remove the burden of repetitive picking when using direct manipulation in the method. Solutions for this problem can refer to commercially available CAD tools such as Autodesk AutoCAD and Microstation, which demonstrate more mature CAD operations in object or entity selection.

Instant simulation is effective to disclose potential conflicts in the planning process. Disclosed conflicts in the testing are some inadvertent inputs rather than real problems caused by spatial, temporal and logical aspects. It indicates that applying the interactive definition method can avoid major planning conflicts through collaboration. Particularly, the co-simulate session permits a created plan to be checked across the network by multiple planners at the same time. It hence reduced the time-space conflict risk during the plan creation. The conflict detection in the 4DX prototype mainly relies on planner's subjectively visual judgement. Seeking more reliable approaches (e.g. task collision detection) in the simulation is future development for conflict detection and elimination. Moreover, the creation of a simulation item is verified to be convenient for network transmission. The defined simulation item parameters can sufficiently support the whole plan's synthesis and the final simulation generation.

5.4 Method Validation

As discussed above, verification testing has examined the applicability of the interactive definition approach to collaborative 4D planning. To further validate this approach, initial tests have been performed in a real distributed setting. A multiparty video conferencing system (Muchmore, 2008) has been leveraged to bridge the gap among geographically distributed planners, who are not in the same place but still can communicate with each other face-to-face and in real time during the planning process. The conferencing system has been implemented and operates in conjunction with the 4DX prototype to maintain face to face and virtual collaboration. This process is ongoing with industry practitioners; however initial results show that the geographically dispersed validation test achieves results that are consistent with those of the verification test. The complete validation of the system and approach includes several variables including social coordination and familiarity with the operation of the software tool, and the full results of the validation will be reported in a future paper.

6. CONCLUSION AND FUTURE WORK

The interactive definition method is a feasible approach to collaborative 4D construction planning. It caters for the planner's mental process to create a construction plan, and suitable for both stand-alone application and networked collaboration. The essence of the method developed and implemented in this paper lie in several aspects: the unique 3D model input to foster collaboration and social interaction, direct manipulation for user-system interaction, proper CSCW design to support collaborative planning workflow, and simulation item creation for real-time network transmission and plan synthesis. The findings from the methodology developed propose further enhancement in the approach including BIM adoption for conveniently obtaining PBS information, more efficient PBS collection using direct manipulation, and more reliable mechanisms for conflict detection and elimination in the simulation. Reinforcing these aspects will enhance the method to achieve a robust plan in distributed 4D collaborative construction planning. Further industry testing is planned to take place in the future to further examine these proposed improvements to the developed system.

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