AN INVESTIGATION INTO A DISTRIBUTED VIRTUAL REALITY ENVIRONMENT FOR REAL-TIME COLLABORATIVE 4D CONSTRUCTION PLANNING AND SIMULATION

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Abstract

The use and application of 4 Dimensional Computer Aided Design (4D CAD) is growing within the construction industry. 4D approaches have been the focus of many research efforts within the last decade and several commercial tools now exist for the creation of construction simulations using 4D approaches. However, there are several key limitations to the current approaches. For example, 4D models are normally developed after the initial planning of a project has taken place using more traditional techniques such as Critical Path Method (CPM). Furthermore, mainstream methodologies for planning are based on individual facets of the construction process developed by discrete contractors or sub-contractors. Any 4D models generated from these data are often used to verify work flows and identify problems that may arise, either in terms of work methods or sequencing issues. Subsequently, it is perceived that current 4D CAD approaches provide a planning review mechanism rather than a platform for a novel integrated approach to construction planning.

The work undertaken in this study seeks to address these issues through the application of a distributed virtual reality (VR) environment for collaborative 4D based construction planning. The key advances lie in catering for geographically dispersed planning by discrete construction teams. By leveraging networked 4D-VR based technologies, multidisciplinary planners, in different places, can be connected to collaboratively perform planning and create an integrated and robust construction schedule leading to a complete 4D CAD simulation. Establishing such a complex environment faces both technological and social challenges. Technological challenges arise from the integration of traditional and recent 4D approaches for construction

planning with an ad hoc application platform of VR linked through networked computing. Social challenges arise from social dynamics and human behaviours when utilizing VR-based applications for collaborative work. An appropriate 4D-based planning method in a networked VR based environment is the key to gaining a technical advancement and this approach to distributed collaborative planning tends to promote computer-supported collaborative work (CSCW). Subsequently, probing suitable CSCW design and user interface/interaction (UI) design are imperative for solutions to achieve successful applicability.

Based on the foregoing, this study developed a novel robust 4D planning approach for networked construction planning. The new method of interactive definition was devised through theoretical analysis of human-computer interaction (HCI) studies, a comparison of existing 4D CAD creation, and 3D model based construction planning. It was created to support not only individual planners' work but multidisciplinary planners' collaboration, and lead to interactive and dynamic development of a 4D simulation. From a social perspective, the method clarified and highlighted relevant CSCW design to enhance collaboration. Applying this rationale, the study specified and implemented a distributed groupware solution for collaborative 4D construction planning. Based on a developed system architecture, application mode and dataflow, as well as a real-time data exchange protocol, a prototype system entitled '4DX' was implemented which provides a platform for distributed multidisciplinary planners to perform real-time collaborative 4D construction planning. The implemented toolkit targeted a semi-immersive VR platform for enhanced usability with compatibility of desktop VR. For the purpose of obtaining optimal UI design of this kind of VR solution, the research implemented a new user-centred design (UCD) framework of

Taguchi-Compliant User-Centred Design (TC-UCD) by adapting and adopting the Taguchi philosophy and current UCD framework. As a result, a series of UIs of the VR-based solution for multifactor usability evaluation and optimization were developed leading to a VR-based solution with optimal UIs. The final distributed VR solution was validated in a truly geographically dispersed condition. Findings from the verification testing, the validation, and the feedback from construction professionals proved positive in addition to providing constructive suggestions to further reinforce the applicability of the approach in the future.

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List of Abbreviations

3D	3 (three) Dimension
4D CAD	4 (four) Dimensional Computer Aided Design
ADT	Autodesk Architectural Desktop
AEC	Architecture Engineering Construction
AI	Artificial Intelligence
BCI	Brain-Computer Interface
BIM	Building Information Modelling
CAVE	Cave Automatic Virtual Environment
CPM	Critical Path Method
CMM	Construction Method Modeller
CMMT	Construction Method Modeller Template
CSA	Critical Space Analysis
CSCW	Computer Supported Collaborative Work
DOF	Degree-Of-Freedom
DSS	Design Support System
DVE	Distributed Virtual Engineering
KB	Knowledge Based
HMD	Head Mounted Display
HCI	Human Computer Interaction
IAI	International Alliance for Interoperability
ICT	Information Communication Technology
ICL	Interactive Collaboration Laboratory
IEL	Immersive Environment Laboratory
IFC	Industry Foundation Class
IM	Instant Messaging
LOB	Line-Of-Balance
PBS	Product Breakdown Structure
RDBMS	Relational Database Management System
TC-UCD	Taguchi Compliant User Centred Design
UCD	User Centred Design
UI	User Interface/Interaction
UML	Unified Modelling Language
Uniclass	Unified Classification
VBA	Visual Basic Application
VCE	Virtual Construction Environment
VCL	Virtual Construction Laboratory
VE	Virtual Environment
VR	Virtual Reality
WBS	Work Breakdown Structure
WISIWYS	What-I-See-Is-What-You-See
WTK	WorldToolKit
XML	eXtensible Markup Language

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Chapter 1 Introduction

1.1 Background

Construction planning plays a fundamental role in the process of construction management. A good construction plan is the basis for developing the budget and the schedule for work. Depending on this function, it can further help form correct strategies for guiding construction activities, and coordinating different construction sessions. In view of its complex nature, developing a construction plan, especially a robust plan, is a critical task in construction management.

Construction planning can follow two directions (Hendrickson, 1998): one is cost-oriented for leading to direct and indirect cost control; another is schedule-oriented for controlling time and resource consumption (Figure 1-1). Construction scheduling is included in construction planning as it deals with more specific factors such as maintenance of task precedence (resulting in *critical path scheduling* procedures), or efficient use of resources over time (resulting in *job shop scheduling* procedures). In most complex projects, both cost-oriented and schedule-oriented planning is considered. On the basis of these approaches, it is possible for subcontractors to achieve effective coordination and comprehensive project management.

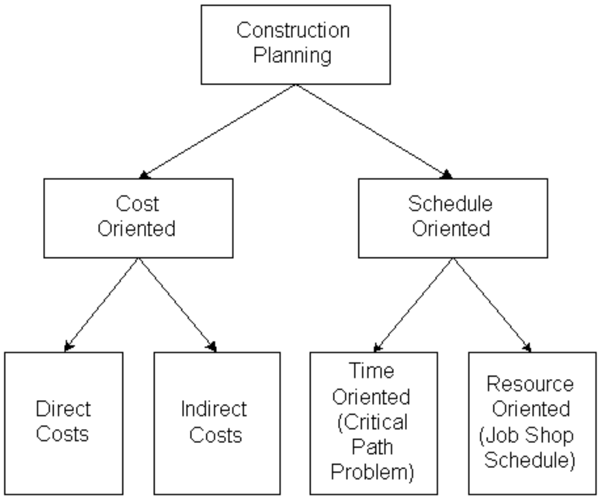

Figure 1-1 Alternative emphases in construction planning (Hendrickson 1998)

Besides project control, the utilisation of the construction plan may extend to site management and risk detection. Because the different subcontractors' activities presented in the plan enable their correlations to be shown, not only can their relevant project consumption in time, resources, and cost be estimated, but dynamic construction situations can be conceived.

It is important to form a robust plan to serve management purposes because of the multidisciplinary nature of construction. North and Winch (2002) stated that 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. However, the planner's ability to imagine a construction plan is variant depending on his or her experiences and knowledge, whilst computer based simulation is more feasible to seek a dependable solution for construction planning.

Applying information communication technology (ICT) in construction becomes popular. It has been over a decade since the 4D (3D plus time) technology in construction was applied (Collier and Fischer, 1996) in the Centre of Integrated Facility Engineering (CIFE) at Stanford University. By linking a construction schedule with its 3D models, 4D simulation can generate a dynamic construction sequence so that potential conflicts in the schedule can be disclosed before the project delivery. Some studies (Liston, 2001; Dawood, 2002; Clayton, 2002; Chau, 2003; Sriprasert, 2003; et al.) have demonstrated solutions adopting this notion. The research interests of this technology have been becoming increasingly active due to its great potentials to analyse multifactor relationship among the logical, temporal, spatial, and other dimensional information in construction.

1.2 Current state of research and practice

This research concentrates on collaborative 4D construction planning in a distributed VR environment. As an interdisciplinary study, it involves both technical and social-behavioural concerns. In the technical aspect, related considerations are associated with construction planning, 4D modelling, network computing, and VR platform utilisation. They are technological foundations to explore related functionalities for creating a collaborative 4D system. In the social-behavioural aspects, collaboration and usability is decisive for a planning team's organisation and team members' performance when they utilise the system. In the construction field, main efforts hitherto focus more on the technical respect about functions' creation for stand-alone systems. Few of them pay attention to social-behavioural issues from end users, which are regarding human-computer interaction (HCI) and influential on collaboration and the system's usability in a networked environment.

In the technical aspect, the critical path method (CPM) is currently the mainstream method for construction planning (Jongeling, 2006). Based on plans and construction strategies, planners apply this method to define related construction tasks, and generate a construction plan with a hierarchal structure and bar chart. Some software tools like Microsoft Project, Primavera Project Planner (P3), etc. are prevalent applications for planning work. Because of their static nature, CPM-based project planning tools are incapable to unveil potential conflicts in a created plan. To compensate this weakness, 4D CAD links a created plan with a 3D model so that to generate a visualised dynamic 3D construction sequence. In such a way, potential conflicts in the plan can be identified. A feasibility study of 4D CAD (Koo and Fischer, 2000) demonstrated potential of this technology beyond merely visual presentation (Smith, 2001).

Since its initiation, the 4D CAD technology has been discussed extensively in the construction field. From product modelling for visualisation to process modelling for analysis (Heesom and Mahdjoubi, 2004), substantial research efforts have been invested into different facets of Architecture/Engineering/Construction (AEC) industry in order to explore more benefits from 4D CAD. This concept is also being further advanced with initiatives such as the nD modelling project conducted by the University of Salford in the United Kingdom (University of Salford, 2005). One of focuses in the nD modelling is the use of Building Information Model (BIM) (Olofsson et al, 2008), which takes the advantage of object-oriented technology to describe discreet graphical information such as windows, doors, walls, etc., as well as non-graphical information about logical structure. It enables true “what-if” analysis and helps improve decision making process and construction performance.

Nevertheless, these efforts have not yet led to an answer for collaborative 4D planning.

Construction planning is also a multidisciplinary practice when geographically dispersed planners perform their independent planning work in different places. It is inevitable to causes conflicts when their plans are integrated eventually. For solving this problem, 4D technology is highlighted for collaborative construction planning (Heesom and Mahdjoubi, 2004). Collaborative 4D construction planning, on the one hand, is about networked 4D simulation and 3D planning. On the other hand, it is also a kind of computer-supported collaborative work (CSCW). The former asks for planning work and simulation to be conducted in a networked 3D space whilst the later is related to effectively designing and organising multiple planners' social activities and behaviours. Indicated by this point, collaborative 4D construction planning involves social-behavioural issues, which are not specifically addressed by reported 4D studies.

Considering 3D-based planning and 4D modelling, some studies (Frohlich, 1998; Waly, 2003; de Vries, 2007; et al.) report certain methods in order to effectively, efficiently, and intelligently generate a construction plan from an inputted 3D model. Nevertheless, these studies like almost all 4D CAD investigations aim at an independent system instead of the network condition. Exceptionally, an empirical study about web-based 4D CAD (Kang, et al., 2007) shows that 4D simulation across the Internet can help detect more conflicts by geographically dispersed planners. As far as CSCW is concerned, it has not been adopted into construction industry to turn information-rich multidisciplinary work into interdisciplinary collaboration (Garner, 2004). These untouched fields formulate essential research initiatives in this study.

As another research focus, the utilisation of real-time VR platform is emerging in the construction industry. VR applications in the AEC fields are mainly available for urban planning and architectural visualisation. 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. Currently, these kind of networked VR systems are mainly dedicated to creating a tele-collaborative educational environment in the AEC sectors for general design study purposes. The use of VR in construction in general is still limited. An application example in the construction sector is the Building Management Simulation Centre (BMSC) (de Vries, 2004), which is dedicated to construction on-site training in a VR environment. Some workshops (Dawood, 2006) are held in order to facilitate VR technologies' wide adoption in construction field. Some stand-alone 4D-VR applications (Kim, 2001) indicate that utilising suitable VR technologies will achieve applicability for 4D-VR based planning. The application of networked VR platform for tele-collaboration is still underdeveloped in the construction field.

Compared with related technologies in 4D CAD, usability engineering in the HCI aspect is still in its infancy in the construction ICT field in general, and 4D CAD in particular. An early statistic shows that the investment on user interface/interaction (UI) design has been dramatically increased in the ICT industry (Nielsen, 1993) in order to maximize users' benefits and minimize software providers' investment. This tendency is increasingly emphasised as Graphical Use Interfaces (GUIs) have become popular and turn technically complex information systems to be user-friendly. Because of lagging behind ICT advancement in other fields, usability engineering is short of thorough considerations in mainstream ICT-based 4D-planning studies, which are almost functional oriented rather than user centred. Although some research, e.g. Kim, et al. (2003), has been aware of 4D CAD's handicaps in this aspect, and some studies have performed related usability evaluation, e.g. Dawood et al (2005), they did not follow a user-centred approach to effective usability at large. Moreover, current user-centred design (UCD) framework also possesses pitfalls such as cost-benefits, tedious design-evolution lifecycle, etc.. Enhancing current UCD framework and applying it for the usability augmentation of the new 4D-VR solution is undoubtedly valuable to enrich usability engineering theory, and facilitate the adoption of 4D CAD in the AEC industry.

1.3 Research justification

Exposed problems of the state-of-the-art of 4D CAD studies imply that current 4D construction planning approaches can not support distributed collaborative planning, and available planning toolkits are inapplicable for network application. Furthermore, user-friendly VR-based 4D planning systems are still less emphasised by the majority of 4D investigations. Targeting these three pitfalls, this research delivered the solutions of the method for collaborative 4D planning, the system of distributed 4D-VR groupware for application, and the practice guidance to robust usability engineering. Their importance lies in that a novel 4D planning method is valuable for distributed multidisciplinary team planners to achieve collaborative 4D planning. In terms of system development, a number of mechanisms and functionalities contributing to applicable features for distributed collaborative 4D planning were implemented. The process is also useful for exploring right strategies for similar system development. In terms of robust usability engineering guidance, the research also resulted in an enhanced UCD approach, which directly served the UI design for the 4D-VR groupware, and provided guidance to robust usability engineering in the construction ICT field.

1.4 Aims and objectives

The aim of this research is to explore a distributed VR-based solution for collaborative 4D construction planning, and to investigate its related usability. The research objectives are specified as follows:

- To analyse construction planning strategies and 4D CAD development methodologies applied in the research domain and industry.
- To investigate technologies and theories of VR based collaborative work for the CSCW design of collaborative 4D construction planning.
- To design a feasible method for collaborative 4D-based planning in the distributed network condition.
- To establish a novel UCD framework for robust usability engineering applying a total quality management technique, the Taguchi Method.
- To formulate a solution of distributed groupware for collaborative 4D construction planning, and verify its applicability.

- To design UI for the VR-enabled 4D groupware following the established user-centred approach.
- To validate the developed system in a truly geographical distributed collaborative condition.

1.5 Outline methodology

In order to achieve the research goals, substantial methodologies were applied in both functional and non-functional aspects for this investigation. These methodologies include literature review, case study, theoretical analysis, prototyping, verification testing, questionnaire survey, usability testing and optimization, as well as deployment to construction professionals.

In order to gain a distributed 4D groupware solution in the functional aspect, a literature review was conducted at the beginning to understand both academic and industrial contributions in 4D CAD and construction planning domains. Related case studies helped to highlight and demonstrate typical issues appeared in 4D-VR collaborative planning. Theoretical analysis assisted to clarify essences in the CSCW design. Combining these, the method of interactive definition was formulated to support distributed collaborative 4D planning. This new 4D method laid a foundation to identify related functionalities via functional requirement analysis. System development was subsequently conducted to realising these functionalities. A verification testing was followed to verify the feasibility of the proposed 4D method.

For the purpose of delivering a VR-based 4D groupware solution, work was carried out in non-functional aspects about UI design/usability engineering. Research methods were used to address related non-functional issues. Theoretical analysis was applied for enhancing current UCD framework by adopting the Taguchi Method, which resulted in the TC-UCD framework. According to this robust UCD guidance, non-functional requirement analysis was achieved through VR platform analysis and the questionnaire survey about end users' profile. Subsequently, collaborative task analysis led to UI designs, which were prototyped on the basis of implemented 4D groupware functionalities. Their evaluation and optimization were conducted through a series of usability testing. The final 4D-VR groupware system was validated in a truly geographically distributed condition, and deployed to construction professionals to gain some feedback for future enhancement.

1.6 Contribution to knowledge and practice

The work has currently led to the publication of a reviewed journal paper and several conference papers (Appendix 10). It contributes several aspects to knowledge and practices in academia and the construction industry as follows.

- ❖ It established a feasible 4D construction planning method of the interactive definition for distributed collaboration in the network condition. Its essences include 3D model based open-ended shared planning context, social interaction, user-system interaction, simulation item definition, and CSCW design;

- It clarified CSCW design being involved in distributed collaborative 4D construction planning. This clarification highlighted critical issues for distributed collaboration theoretically, and can be a baseline to explore related collaborative applications.
- It proposed an applicable distributed 4D groupware framework suitable for the non-BIM condition with extensibility for BIM;
- It formulated an innovative TC-UCD framework for robust usability engineering, which is applied for usability engineering of the VR-enabled 4D groupware solution in the construction ICT field;

1.7 Guide to thesis

Chapter 2 presents a review of the state-of-the-art of construction planning. It summarises current planning approaches, popular planning methods, ICT-based planning, 4D CAD creation methods and technologies, database application in multi-constraint planning, as well as emerging technology of BIM and its related research of nD modelling. Industrial implementation demonstrates the projects of VIRCON for process modelling and PM4D for BIM application. The CIFE iRoom as a case study is also included in this chapter to show heuristic considerations.

Chapter 3 analyses VR technologies including hardware and software configurations, platforms, and construction solutions. Subsequently, it scrutinises CSCW design theories for 4D planning application in a semi-immersive VR environment. It clarifies related CSCW issues in 4D-VR based collaborative construction planning.

Chapter 4 specifies a research roadmap with methodologies applied in this investigation. These methodologies are used for solving both functional and non-functional problems. Particularly, two approaches are introduced respectively in this chapter for these two aspects. One is the method specification of the interactive definition for collaborative 4D construction planning. Another is the TC-UCD framework for robust usability engineering by adapting and adopting current UCD framework and the Taguchi Method.

Chapter 5 is the requirement analysis surrounding functional and non-functional aspects applied to the proposed interactive definition method. The functional requirement analysis utilises the use case diagram of unified modelling language (UML) to illustrate offline and online applications. With respect to the non-functional analysis, this chapter summarises the end users' profile based on a questionnaire survey. Besides the user profile, relevant issues in terms of platform capability and constraints are also differentiated.

Chapter 6 presents the system development of a distributed groupware solution named '4DX' for collaborative 4D construction planning. It combines the devised interactive definition method to realise related functionalities. The solution is depicted from system architecture, application mode and dataflow, as well as real-time data exchange protocol. It also discusses implemented functions, functional verification testing, and related findings.

Chapter 7 is about non-functional studies of usability engineering for the proposed solution based on a semi-immersive VR platform. It includes UI designs and their usability evaluations applying the TC-UCD framework. Backbones of its utilisation involve system design, parameter design, design of testing, prototyping, data analysis, and UI optimisation.

Chapter 8 presents the final system validation in a truly geographical dispersed condition and deployment feedback from construction professionals. It discusses relevant findings in the system validation and deployment for further system improvement.

Chapter 9 summarises this PhD research work with highlighted knowledge contributions, industry practice guidance, future research directions and system enhancement.

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Chapter 2 Current Construction Planning

2.1 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'.

In order to create a construction project plan, there are currently several approaches applied and investigated in academic and industrial fields. Typical techniques like CPM and line-of-balance (LOB) are widely applied in construction and other manufacturing fields. These types of techniques focus on temporal information for task time control, and thus request planners' domain knowledge for plan tasks specification. For the purpose of compensating this limitation, knowledge based (KB) expert system and artificial intelligence (AI) is recommended to assist planners' decision making and reasoning in planning. In addition to this effort, ICT-based approaches of 4D CAD and computer simulation add a spatial dimension on the basis of temporal schedules for dynamic visualisation. These methods, though beneficial to formulate a relevant robust plan to some extents, are still short of sufficient support for multidisciplinary planners' collaboration. Effective means are expected to be not only helpful for temporal, spatial, and logical information formulation, but also positive for stimulating planning team members' individual and social creativity.

In order to seek proper approaches for collaborative construction planning, this chapter provides a thorough analysis and discussion regarding planning approaches. It first identifies and compares current planning approaches to show their advantages and limitations. ICT based planning approaches are subsequently highlighted. As a major content of the chapter, 4D CAD is extensively discussed to gain insights about its applications, methodology, technology, industry implementation, and case study. These analytical points lay a foundation to further discuss feasible collaborative planning approaches in later chapters.

2.2 Current planning approaches

Sriprasert (2003) classified available techniques in construction planning into seven major groups: CPM, LOB, KB-AI, 4D CAD method, computer simulation method, critical chain scheduling, and last planner method.

For historical and conventional reasons, the most popular method in the construction field is the activity-based CPM. Construction planners decompose a project into activities that they associate with one or more building components (e.g. installing of handrail staircase 3) that make up the project. In accordance with project management theory (Duncan, 1996), such a CPM-based construction plan is concerned with Work Breakdown Structure (WBS) to create Product Breakdown Structure (PBS). PBS is associated with different parts of a product whilst WBS is regarding work activities for creating a product. Following this concept, CPM application in construction planning is about organising WBS items effectively to create PBS elements to be a complete building. The representation of WBS items' relationships applies Bar chart or Gantt chart, which defines and illustrates every WBS item's name (task name), time (start, end and duration), and logical relationships (predecessors) among each other. As WBS items can contain multilevel subitems with possible different predecessors, it thus can build complex hierarchical WBS network in a construction plan. Nevertheless, PBS as a spatial configuration result of WBS is not represented by the Gantt chart.

LOB is also named location-based scheduling method. It can break down the project in physical sections, or locations. As it specifically differentiates project sections, it is thus convenient to identify flow of resources through different locations, termed work-flow. It is therefore considered a promising alternative to CPM technique for planning work-flow (Jongeling, 2006). Similar to the CPM representation, LOB can be visualised using line diagrams, which are location related and represent different types of work performed by various construction crews that work on specific locations in a project. This uniqueness features LOB planning with detailed and quantified task descriptions, crew size, cost estimates, etc., in a project. A planning specification is hence directly made for the amount of work per location in a project for a construction crew. A similar result can be achieved using the CPM technique but with very detailed and unmanageable schedules (Kenley, 2004; Huber and Reiser, 2003). Using the LOB technique is able to gain a concise and compact project plan compared with that of CPM. However, spatial information using LOB is still out of reach like CPM.

KB and AI techniques strive to adopt planning knowledge into the planning process. Because traditional planning techniques like CPM and LOB are able to manipulate only the data generated by the planning process, not the knowledge used in generating the project plan (Levit, 1988), KB and AI claim ability and benefits to automate the generation of CPM schedule from the product model/drawings (Sriprasert, 2003). Underpinned by computer technologies, these techniques rely on created knowledge bases (Zozaya-Gorostiza, 1989) to make plan decisions. Particularly, the utilisation of AI theory in construction planning emphasise machine reasoning. It requests certain knowledge acquisition and sophisticated algorithms' supports (Benjaorana, 2006) when applied for planning work. In general, these types of techniques can relieve certain planning burdens but still are confined by software itself. They can not fully replace human’s creativities.

4D CAD approaches can visualise a construction sequence. In view of lacking spatial information in LOB and CPM based schedules, applying 4D CAD can visualise and examine a created construction plan. Through linking created plan tasks (the WBS) with 3D building model components (the PBS), 4D CAD is able to generate a dynamic construction sequence. Planners thus have the chance to visually detect potential conflicts hidden in their created plans. These technologies are initiated from the 1990s, and increasingly receive attention in the construction industry. Current 4D applications mainly focus on communicative and explanative purposes for product modelling. Stakeholders of a construction project, e.g. San Mateo Health Centre (USA) project (Collier and Fischer, 1996), can gain intuitive information from product modelling, and thus understand what they care about in the project. However, more advanced process modelling is still paucity for construction professionals to obtain analytical information. Related practices are reported in several projects, e.g. the project of the Virtual ConstructionSite – VIRCON, which has investigated the development of Critical Space Analysis (CSA) tools to enable a space-based analysis of construction operations (North and Winch, 2002).

Computer simulation is a comprehensive approach that is well suited to the study of resource-driven processes. As one of its simulation results, a construction plan can be generated from it. Being different from other planning techniques, this kind of planning takes place at the operation level (Halpin and Riggs, 1992) instead of targeting a project level like CPM and LOB. It gives the analyst an insight into resource interaction and assists in identifying which factors in a problem domain are important. It allows the modeller to experiment with and evaluate different scenarios. Traditionally, detailed construction resources and methods are not considered at the preliminary planning stage at a project level, but are left to contractors to decide at the construction stage. Such a planning approach has caused many problems in the industry. For instance, the original plans may be too expensive, unrealistic, or even not constructable. Detailed construction issues must be integrated into the early design stage to avoid these problems like duration and cost overruns in the industry. Since the development of CYCLONE by Halpin (1977), construction process simulation has been proven to be an effective tool for planning and improving the performance of construction processes. However, such an experimentation and study would be too costly to be carried out in the real world.

These five types of planning techniques are influential approaches to construction planning. Combining the point of view from Sriprasert (2003), advantages and limitations of these planning techniques' are listed in Table 2-1. Other enumerated techniques like critical chain scheduling, last planner method, as well as generalised network, cascade chart, time-chainage chart, TAPAS, etc., are neglected in this part in view of these currently being less popular in construction planning.

Technique	**Advantage**	**Limitation**
CPM	helpful in preparing project proposals, managing personnel and resources, tracking delays and change orders, instituting as a basis for progress payments, and co-	inability to cope with non-precedence constraints, difficulty to evaluate and communicate interdependencies, and inadequacy for work-face production

	ordinating with subcontractors	
LOB	powerful for scheduling and controlling a construction project that involves repetitive sequences of activities such as high rise buildings, tunnels, etc.	hard to show all information on one chart in large and complex projects, especially when monitoring progress.
KB and AI	capable and beneficial to automate the generation of CPM schedule from the product model/drawings	coded knowledge usually is incapable to cover uncertainties during the construction stage
4D CAD	enhanced capability of communication and evaluation of construction plans	less used for detecting information and resource constraints
Computer simulation	suitable for modelling resources, dynamic operational process, random factors, and hence generates a reliable plan	costly and indirect

Table 2-1 Techniques of construction planning

2.3 ICT approaches to construction planning

Given the identified planning techniques, some computerised toolkits are created for their application. For instance, Microsoft Project, PowerProject, and P3 are popular CPM based tools whilst DYNAProject is dedicated to LOB. Nevertheless, KB and AI based computer toolkits are discussed more within academic fields. Their commercially available software is not yet widely accessible like CPM and LOB. As important ICT approaches to construction planning, 4D CAD and computer simulation are increasingly emphasised in the construction industry. Particularly, CPM-based 4D CAD has been discussed extensively in the academic field. Commercially available tools like CommonPoint 4D (CP4D), Autodesk Navisworks, Bentley ProjectWise Schedule Simulation, etc., are also utilised in construction projects. This section focuses on ICT approaches to analyse related features for planning. In the meantime, CPM-based 4D CAD are highlighted from the perspectives of methodology, technology, industrial implementation and case study.

2.3.1 ICT for CPM approaches

Both 4D CAD and computer simulation are applicable ICT approaches to obtaining a construction plan in a virtual 3D space. Despite this similarity, there are significant differences between 4D CAD and computer simulation. According to the level of detail in the project control, 4D CAD is initiated at the project level for product modelling whilst computer simulation focuses at an operational level for operation modelling (Kamat, 2003). From a macro perspective, the product modelling, which can be further developed into process modelling, follows the top-down approach to gain a plan. From a micro perspective, operation modelling can result in a project plan following the bottom-up approach. The relationship among these computer modelling issues can be illustrated in Figure 2-1.

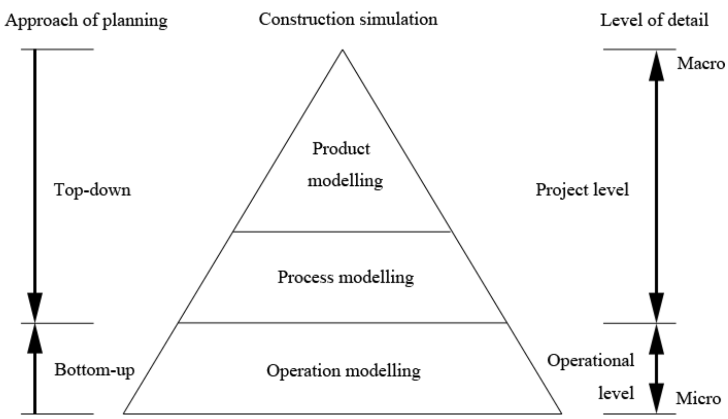

Figure 2-1 Computer modelling for construction planning

• **Top-down approach**

The top-down approach is applied in product and process modelling. Its basic rationale is to decompose a 3D model - the PBS and link its elements with specific schedule activities - the WBS to be a visualised 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 products to disclose potential logical, spatial and temporal problems in the schedule can result in a relevantly robust construction plan.

CPM-based 4D CAD is a typical top-down product modelling technique. In its creation, the project schedule needs to be generated using the bar chart first. Afterwards, it can be visually checked and enhanced by linking the 3D elements (Collier and Fischer, 1996). Normally, the linking → checking → updating procedures need 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 attempts are demonstrated for seeking more reliable plans in these areas, e.g. multi-constraint planning (Sriperate and Dawood, 2003), CSA (Dawood, 2004).

LOB or location based 4D simulation is another top-down product modelling approach. Because it can show the information of work-flow in different construction locations, it is more suitable to present the process of constructing. Jongbeling (2006) stated that the activity-based CPM 4D simulation was incapable to convey process information together as it made plan work more complex, and hard to update. Being a visual scheduling approach, LOB is able to combine product and process information in the 4D simulation. In the case study of the Luleå cultural centre in Sweden (Jongbeling, 2006), a 3D model was prepared with the definition of locations. The location quantity data from the 3D model were subsequently imported into DYNAproject for LOB scheduling. Its associated activities and other schedule information were exported to MS Excel for generating a CPM schedule, which was imported into and linked with CP4D to produce the simulation. It is noted that this LOB-related 4D simulation still needs a conversion to be a CPM schedule for linking 4D software. Commercially available tools of this kind, such as Vico Software 5D Presenter, etc., are now available on the market.

• **Bottom-up approach**

The bottom-up approach exists in operational modelling to generate a construction plan. In contrast to product and process modelling, operational modelling is regarding 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, operational 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.

From a micro perspective, the bottom-up approach can generate a construction plan by recording construction activities occurred during an operation process. 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 a construction schedule according to the planner's activities.

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

2.3.2 4D simulation

Construction planning is increasingly being supported through the application of 4D CAD and 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 been growing 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), 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 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 suggested 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 is 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 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, CSCW, and networked computing. Particularly, a suitable 4D creation method fundamentally affects the other two aspects to achieve collaborative 4D construction planning.

2.3.3 4D methodology

CPM-based construction planning can be regarded as WBS creation based on PBS. Popular project planning tools like MS Project, P3, etc., can help planners to specify every WBS item. However, PBS is dependant on planners' unreliable imaginations according to design illustrations such as blueprints. Some studies target PBS to generate WBS so that planners can use a visualised 3D building model to perform planning work. In these cases, PBS is the only input whilst WBS is the output. Comparably, 4D CAD is about PBS plus WBS to generate a dynamic construction sequence in order to detect potential conflicts in the plan. Different 4D CAD creation methods are invented to achieve this aim. In terms of PBS and WBS relationship, this section provides a blended methodology analysis about 3D-based planning and 4D modelling creation. It is constructive to find a suitable approach for the collaborative 4D planning creation.

- **Full automation**

In order to fully generate the project schedule automatically, de Vries, et al. (2007) attempted an 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 automation process, the inputted PBS was detected in an AutoCAD based prototype and by applying Visual Basic Application (VBA) code, the WBS was derived from the PBS. A log file was used to record the relationship of PBS and WBS during the analysing process. Afterwards, this log file was exported into MS Project to create a schedule of activities. However, it is concluded in the study that a completely automated schedule might be infeasible for the real project as this approach removes control of the planning process from the construction planning team. Using construction knowledge and the eXtensible Markup Language (XML) to carry necessary information will enable to generate more practical project schedules. The use of Industry Foundation Classes (IFC) based interoperability could further enhance the above approaches. The IFC provides the possibility of full automation to generate a construction plan and store this information within objects. However, the implementation of IFC's within industry practice is still limited (Froese, 2003)

- **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 included as integral 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 (Figure 2-2). 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 also keeps consistency 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).

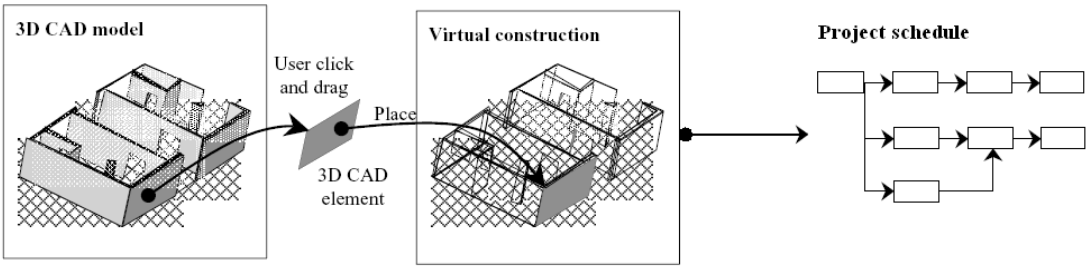

Figure 2-2 VCE Model (Adapted from Thabet, et al., 1999)

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.

- **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 Bentley ProjectWise Schedule Simulation, Autodesk Navisworks Simulate and CP4D. 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.

- **Semi-automation**

Automating PBS and WBS connection is efficient to link separate 3D model and project schedule for 4D simulation generation. Dawood, et al. (2002) applied a Unified Classification (Uniclass) database to semi-automate them in 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 the 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. Accordingly, the planner may lose flexibly to control the simulation in the linking phase.

- **AI modelling**

Aalami, et al. (1998) applied Artificial intelligence (AI) theory in the 4D construction simulation. In the investigation, the Construction Method Modeller (CMM) was developed by applying a set of semantic descriptions to connect components <C>, actions <A>, resources <R>, and sequencing constraints <S> with activities. Because the components <C> can have a 3D graphical representation, CMM thus builds a relationship of 3D components with their corresponding activities. As the construction knowledge can be stored in the CMM template (CMMT), a planner is able to select appropriate construction methods for the given project. Accordingly, the CMM can automatically generate the required adjustments to the design-centric product model.

This semantic, computer-interpretable 4D product model answers an essential question in construction: who is doing what and where. Particularly, it provides constructors with the ability to rapidly generate various production models based on design or construction method alternatives. The result can be viewed as a 4D visualisation, CPM diagram, or resource histogram. To summarise these methods, Table 2-3 lists each method according to their suitability.

Method	AI modelling	
	Manual Linking Semi-Automation	Full Automation Manual Assembly
Suitability	4D CAD	3D planning

Table 2-2 Method for 4D CAD and 3D planning creation

2.3.4 4D technology

Various technologies are applied for 4D modelling and planning, such as CAD, database, network communication, wireless transmission, multiple platforms of web, VR, mobile, etc., as well as object-oriented technology like BIM. Normally, certain development strategies for planning and/or 4D modelling decide utilisation of corresponding technologies. This section provides a comprehensive discussion of 4D creation scheme. It reviews reported technologies in planning and 4D modelling. Among diverse technologies adopted in planning and 4D modelling developments, applying a database is one of the positive approaches to centralising different information for integrated planning and 4D modelling. The multi-constraint planning is highlighted for the application of database. Being an advanced extension, BIM technology combines merits of both database and object-oriented technology together. Its investigations and applications can be represented by the nD modelling using IFC. This section also delineates their rationale and utilisations.

2.3.4.1 4D creation scheme

Heesom and Mahdjoubi (2004) specified fundamental attributes of three types 4D CAD application: product modelling and visualisation, process modelling and analysis, collaboration and communication (Table 2-3). It provides a guidance of 4D CAD creation for specific application. Focusing on reported 4D studies, four 4D modelling schemes (Zhou, et al., 2006) were identified to be independent simulating, integrated modelling, integrated scheduling, and communicated simulating. Each scheme's features, applied technologies, advantages and disadvantages are compared and discussed as follows.

Application	**Attributes**			
	Level of interactivity with 4D simulation	Level of graphical representation	Level of detail of construction schedule	Level of dynamic capability of simulation
Product modelling and visualization	Low	High	Low	Low
Process modelling and analysis	High	Low	High	High
Collaboration and communication	High	Low	High	High/Low

Table 2-3 Fundamental requirements for 4D simulation applications (Heesom and Mahdjoubi, 2004)

- **Independent Simulating** (3D||4D||Schedule)

Typically, a 4D simulation is created by independent software to generate project schedules, 3D models, and 4D visualisations respectively. This approach can be symbolized as 3D||4D||Schedule. When applying this approach, off-the-shelf tools like AutoCAD or MicroStation are used by 3D experts for 3D modelling whilst tools such as MS Project or P3 are used by schedulers for scheduling. The simulation is made by third parties' 4D software, such as CP4D, Visual STEP, Bentley Simulation Schedule, etc., which can connect schedules with 3D models, and present a dynamic 4D construction process. Because less analytical information is available in the simulation, these sorts of 4D solutions are suitable for product modelling. The merit of this approach is that the involved tools in the 4D creation are independent toolkits, hence the level of interactivity, graphical representation, and dynamic capability of simulation are only depending on 4D tool's development. However, as the schedule is closely related to the simulation but isolated from simulation environment, it is crucial to find a proper way for the seamless interoperability between them.

Many studies adopted this combination, and applied it in real projects, such as the San Mateo Health Centre (USA) (Collier, 1996) and Walt Disney Concert Hall (Haymaker, 2001). In Pusan Neospot project of Korea (Kim, et al., 2001), the simulation software WorldToolKit (WTK) was applied for the 4D simulation. Other tools like AutoCAD were used for 3D modelling, while P3 was applied for scheduling (Figure 2-3). Like other product modelling simulation, this 4D solution was used for the communicative purpose among the stakeholders.

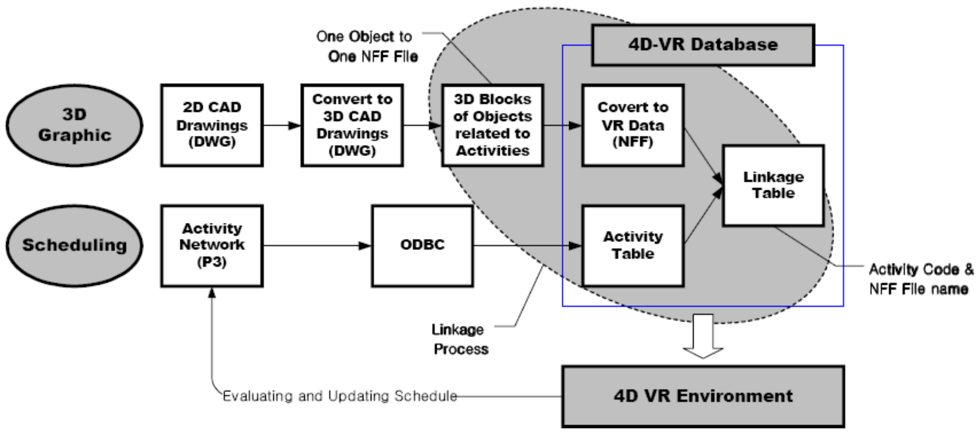

Figure 2-3 Concept of VR-4D System (Kim, et al., 2001)

- **Integrated Modelling** (3D&&4D||Schedule)

Some 4D simulations are integrated into modelling environment directly, where 3D models are controlled by plug-in applications to show dynamic construction process. Schedules, on the other hand, are created by independent commercial tools, and outputted to a database so that they can be called by modelling tools to control 3D models. This simulation can be described as 3D&&4D||Schedule. A popular approach is to make use of AutoCAD to create 3D models, and take advantage of its ObjectARX or VBA technology to develop plug-in 4D applications. Because of modelling tools' constraints in graphics processing, this simulation's dynamic capability is low but graphical representation and interactivity capability is high. The benefit of this approach is that the 4D environment is the same modelling context. Therefore it is convenient to leverage existing functions and features for process modelling. Negatively, it also can be confined by the tools themselves.

In the VIRCON project, Dawood, et al., (2002) created a 4D simulation within the modelling tool of Autodesk Architectural Desktop (ADT). A Unified Classification

(Uniclass) database was built to semi-automate the linking of PBS with WBS. VBA code was implemented in every ADT layer to extract 3D components, and populate them into the database. Additionally, another VBA code was used to transfer the MS Project schedule data to the database. The 4D simulation could be displayed in the ADT environment through retrieving data from the database to control the 3D models. Some commercial tools have integrated 4D functions in their packages, such as Graphisoft ArchiCAD, Autodesk Revit, Tekla, HVAC 4D, etc..

- **Integrated Scheduling** (3D||4D&&Schedule)

Another 4D simulation type integrates the schedules into the simulation environment. 3D models are prepared separately and imported into the environment while schedules can be made directly within the environment. This method can be tagged as 3D||4D&&Schedule. In such a condition, only modelling tools are needed to create 3D models but no independent schedule tools are involved (Heesom 2004, 2006). In view of a single project database shared by both simulation and schedule, it is positive for the simulation to obtain information for process modelling. The advantage of this approach lies in the intimate relationship between the schedule and the 4D context. Thus, it can guarantee to reach the same high level in schedule detail and dynamic simulation capability. Because the 4D environment is independent from the 3D modelling context, it has a chance to satisfy needs from 4D CAD by proper system design. Its disadvantage lies in extra workload in scheduling functions' development. Tanyer, et al. (2005) implemented such a 4D modelling tool combining cost estimation. In this integrated environment, simulating, scheduling and costing could be displayed and checked based on a single project database. 3D model objects were prepared so as to be imported into the system. The solution was a web-based application developed using the Java 3D API, which adopted IFC in the development. Therefore, the planning and costing information could be derived directly from a unique IFC file, which provides the single database of the project.

- **Communicated simulating** (3D||4D∞Schedule)

The CIFE iRoom (Fischer, 2002) demonstrates a synchronous communicated simulating scheme (3D||4D∞Schedule) using server-client mechanism on a local area network (LAN). Its components consist of a 4D simulation system (CP4D), a schedule tool (MS Project), and a cost statistical utility (MS Excel). They are augmented with network functions for achieving communication. This scheme has the same features with the independent modelling scheme. The difference is that during the simulation process, the 4D application can communicate with other networked applications, such as MS Project or MS Excel. The value of this scheme is more process information available by exchanging information during the collaborative session. Although this scheme is a LAN-based application with network features, its redundant system architecture is cumbersome for distributed application across the Internet. Combining the foregoing analysis, all the discussed 4D development schemes are listed in Table 2-4 with corresponding features, advantages and disadvantages.

Scheme	Alias	Feature	Main advantage	Main disadvantage
Independent simulating	3D‖4D‖Schedule	3D, 4D, schedule are independent	Flexible to control simulation levels; positive for product modelling	Interoperability is needed between schedule and simulation
Integrated modelling	3D&&4D‖Schedule	4D is integrated in a CAD system; schedule utility is independent	Convenient to leverage CAD functions; positive for process modelling	Confined by the CAD environment to control simulation levels
Integrated scheduling	3D‖4D&&Schedule	3D environment is independent; schedule utility is integrated in 4D	Flexible to control simulation levels; positive for process modelling to obtain plan information	Extra workload is need to create schedule functions
Communicated simulating	3D‖4D∞Schedule	3D, 4D, schedule are independent; 4D and schedule can communicate with each other	Flexible to control simulation levels; positive for both product and process modelling	Need network infrastructures for communication support

Table 2-4 4D modelling scheme

2.3.4.2 Multi-constraint planning

Multi-constraint planning seeks a universal system that remedies a typical problem of separation of execution from planning (Sriperate and Dawood, 2003). Considering the fragmented reality in different construction planning techniques, it builds an integrated information system to streamline the planning process. A design support system (DSS) is the kernel part in the integration. Its architecture core is a MS SQL Sever based central relational database management system (RDBMS), which integrates five components like product model (CAD), process model (schedule), upstream information (i.e. drawings, specifications, method statements, resources information, etc.) and downstream information (i.e. weekly work plan and feedback).

Three enablers are implemented in the development: Web-based, mobile information management system, and 4D visualisation system. The 4D visualisation system is dedicated to multi-constraint visualization of physical constraints like product clashes, illegal relationships, space congestion, enabler constraints (contract, resource, information readiness) and project status. A PDA-based 4D presentation is also developed with wireless communication capability. This research highlights a critical technical concern about integrating related information to make planning decisions. On the basis of a unique database, construction planning and 4D modelling can be supported and conducted in multiple platforms.

2.3.4.3 nD modelling and IFC

Being an extension of 4D modelling, the University of Salford initiated the nD modelling project. Underpinned by BIM technology, it further integrates an nth member of design dimensions into a holistic model. Such an information repository is bound with building objects, from which different views of the information can be generated automatically. It thus helps improve the decision making process and construction performance, and enable true “what-if” analysis to achieve the following aims: 1) predict and plan the construction process; 2) determine cost options; 3) maximise sustainability; 4) investigate energy requirements; 5) examine people’s accessibility; 6) determine maintenance needs; 7) incorporate crime deterrent features; 8) examine the building’s acoustics (Lee, 2005).

The nD modelling concept applies IFCs for creating an information repository. As BIM can greatly improve effectiveness and efficiency for the AEC industry, different companies provide their own BIM products like Autodesk Revit, Graphisoft ArchiCAD, and Bentley MicroStation. Nevertheless, these diverse BIM products lack standard specifications, and thus affect data exchange among them. For the purpose of better interoperability, IFC is advocated by the International Alliance for Interoperability (IAI). Applying a set of protocols and rules, it aims to standardize the BIM technology by providing an integrated standard model. Adopting the IFC into construction planning, multidisciplinary planners can share a unified engineering database for collaboration.

Creating an nD modelling tool is essential for any IFC-compliant applications including construction planning. The objective of the nD modelling tool is to enable an informed design decision based on a variety of design perspectives. Figure 2-4 illustrates the architecture of nD modelling tool. Indicating from the illustration, there are two approaches to access the IFC building model: model server operation and direct read IFC file. The model server approach is convenient for collaboration among multiple design work because different specialities can focus on their own aspects. An IFC-compliant planning tool is compatible with this nD modelling approach. Tanyer et al. (2005) demonstrate this rationale for 5D (4D plus cost) construction planning using a single engineering database based on the internet. Although this research targets the internet, its focus is placed on the use of IFC rather than the emphasis of collaborative planning.

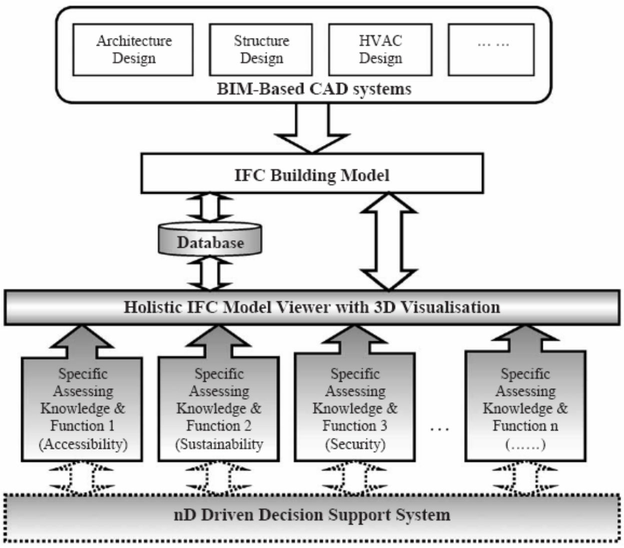

Figure 2-4 Architecture of nD modelling tool (Fu, et al., 2004)

However, the BIM adoption still faces immense barriers from both social and technical aspects in the construction industry. Some barriers were reflected in a regional survey (Tse et al, 2005) conducted in Hong Kong. They are enumerated as the spilt between architecture design and drafting, a complicated and time-consuming modelling process, inadequate objects, object customisation capability, etc.. Strategically, Autodesk (Bernstein, 2004) summarises three interrelated barriers in transactional business process models, computable digital design data, and exchange of meaningful information among applied tools. These obstacles imply that the use of BIM for collaborative 4D planning is still short of realistic support technically and socially, and therefore out of the consideration in this research.

2.3.5 Industry implementation and case study

It is still unpopular to apply analytical 4D modelling, BIM, and collaborative 4D planning in the construction field because of some technical and social barriers. A few pioneer projects attempted explorations in these aspects for both industrial applications and academic studies. This section selects two industrial projects of VIRCON and PM4D to demonstrate process modelling and BIM application. Their critical concerns are beneficial to elicit more constructive solutions for construction industry. Targeting the innovative example of the CIFE iRoom, a case study also provides comprehensive analyses and discussions about its functions, architecture, advantages and limitations at a system level.

2.3.5.1 VIRCON and PM4D projects

Critical space analysis (CSA) for construction planning is developed in the VIRCON project (Dawood et al, 2005). As CPM-based planning can not present spatial information, space resource on construction site is able to disclose potential occupation by overlapped construction activities. The VIRCON system defines several tools to assist the occupation analysis. Its central component is a database for restoring, exchanging, and retrieving information among other components. SpaceMan is one of the tools in the VIRCON system. It can detect spatial overload problems and optimize critical space and time. Its mechanism is based on the concept that overlapped tasks in one location can cause spatial overloaded. Following the time span, it can check if a site location can be overload or not by various tasks at the same time. Once there are overloaded problems, it allows the user to manually adjust corresponding task start and end time. An algorithm can also automatically adjust task start time for loading in the problem area. Its extensive usability study is executed for checking the system usefulness and user's satisfaction.

An extensive construction pilot research about IFC application is performed by the CIFE, Stanford University. The research, named Product Model and 4 Dimension (PM4D) (Kam, 2003), was carried out based on the Auditorium Hall 600 project at the Helsinki University of Technology in Finland. By leveraging commercially available state-of-the-art analytical and visualization tools, the research tests the IFC interoperability standards from the design and construction. In its construction planning study, the IFC-based interoperability can synthesise a readily available bill of materials from the mechanical consultants and the 3D geometry from the architects. It hence can accelerate cost estimates of detailed breakdown of component. This effective approach permits construction managers to generate schedules and budgets more quickly and accurately than traditional way. It suggests building owners, end-users, and project team to take the advantage of this PM4D approach for the optimization of the design, construction, and a proposed facility operation during early project phases.

2.3.5.2 CIFE iRoom

The CIFE iRoom is an integrated collaboration system developed by Centre of Integrated Facility Engineering (CIFE), Stanford University. Its objectives are "to define and evaluate new ways for project teams to interact with and visualise project information to facilitate fast and effective decision-making" (Fischer 2002). The system consists of a series of software and hardware infrastructures, and augmented existing applications. Its integration enables stakeholders to interact with and consider concurrent information from different sources in a group setting. Compared with previous 4D tools' features, the iRoom resembles the characteristics of that of independent simulating. The difference lies in its communication between 4D environment with other modules using client-server mechanism. This case review focuses on its architectural and functional analysis in order to show its added values for assisting collaboration. Its advantages and limitations are also discussed.

- **Architecture and Configuration**

The system is physically composed of a server machine and three desktop PCs with corresponded projectors and SMART boards in each of them. The software collection includes high level applications and low level infrastructures. All the necessities are listed in Table 2-5. Its configurations and installations are illustrated in Figure 2-5.

CIFE Applications, Viewers, Controllers 4D Modeler, Data Viewers, MS Project Listener, TimeController
CIFE Database and Services XML schema on eXcelon server, Import-Export Utility, Room Controller
iRoom Software Infrastructure (from iWork group in Computer Science) EventHeap, Multibrowsing, PointRight
Special iRoom Hardware SMART boards, touch panels, wireless mouse and keyboard
iRoom Computing Infrastructure Desktop PCs, Windows 2000, Java, Network support

Table 2-5 Components in the CIFE iRoom layers (Fischer, 2002)

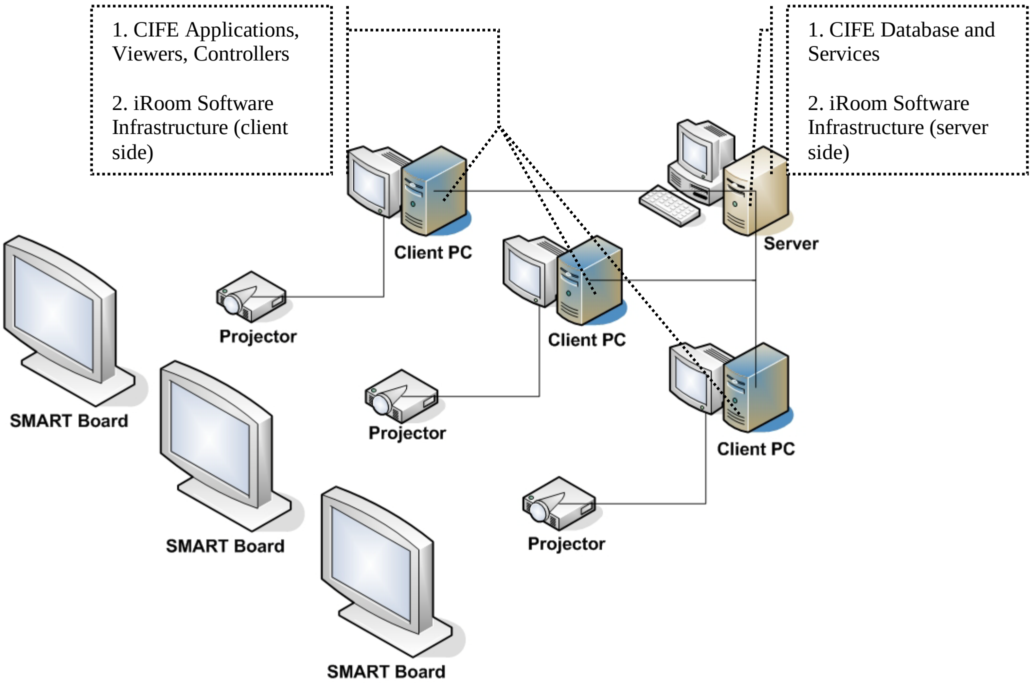

Figure 2-5 CIFE iRoom Configurations and Installations

- **Functional analysis**

The CIFE iRoom's utilisation, communication, and coordination of each application module and subsystem are differentiated as follows:

❖ The user can direct applications to the different SMART boards in one room, and also manage machines to select content for displaying.

❖ The user can simultaneously visualise a 4D scenario, multiple viewers and applications being launched and displayed on the SMART boards.

❖ An event processing utility is created as a sever-client application. The server side applications are installed in the server machine; the client applications are installed in three client PCs respectively. Every event that occurs in one of clients can be transferred to the others via the server.

- ❖ Existing stand-alone applications are all augmented to respond to coming events, and can also send events to their local client applications. These take charge of transferring the events to the server, and thus communicate with other client applications.
- ❖ The input devices, such as mouse and keyboard, are also configured with a set of server-client applications for each machine. All the machines therefore can be controlled by unique input device.

- **Advantages and limitations**

The CIFE iRoom provides stakeholders with an integrated environment to discuss solutions, form strategies, and make decisions. Its advantages lie in the following aspects.

- ❖ Its collaboration circumstance accommodates stakeholders with a suitable condition to exchange information. Its multi-display and multi-view enable users to bring forth instant opinions to the group members.
- ❖ The system makes use of existing stand-alone applications to integrate an enhanced but still familiar context. The group members can be the same experienced users who access these applications. It also demonstrates an economic way to take the advantage of legacy without heavy investment for applications' augmentation.
- ❖ Its open structure allows incorporating more stand-alone applications into a group setting. Fischer (2002) highlights that three SMART boards are not sufficient to present related information for real project utilization. Its further expanding is feasible following the same linking approach.

- ❖ The research aims a high level application incorporation rather than commonly low level data interoperability in construction IT. It triggers some new research points in groupware development, and collaboration design.

Its limitations can be addressed as follows.

- ❖ The system can not support distributed collaboration. Due to its collocated nature, it is only suitable for a group of people who are located in the same place to access the information, but not for the people in different geographical places. It would be valuable to build a networked collaborative system, which highlights the motivation of this PhD research.
- ❖ The system is not groupware though it is created for a group setting. As construction needs multidisciplinary cooperation, it is crucial for groupware to support multi-user's interactions with the system. So far the iRoom can only support singular operation at one time.
- ❖ Confined by the off-the-shelf product, the system's 4D simulation application-4D Modeller is basically a product modelling system. To be a process modelling system, its 4D application need to be improved by seeking other approaches.
- ❖ The system is incapable to convey and utilise more advanced information and techniques. Because the iRoom itself is basically a desktop system, it lacks a sophisticated mechanism to bring more added values, such as improved HCI, immersive effects, etc., which can be available by using VR technology.

2.4 Limitations in current construction planning

Based on the foregoing discussion, it can be seen that current 4D planning techniques 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 to identify workplace but is lacking in the other two aspects. Subsequently, these limitations confine their user-system interaction to creatively solve planning problems. Because of the close-ended nature of these stand-alone planning approaches, the planners' creativity and knowledge is 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. In view of stand-alone nature of current 4D CAD and planning systems, correspondingly, their associated technologies can not fully applied for the distributed collaborative 4D-VR planning.

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 also can 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 assist in formalising the link made between PBS and WBS however, and can 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. Adopting this new 4D planning method, its supportive technologies can be further identified so that to meet the demands of developing distributed 4D groupware for collaborative 4D construction planning.

2.5 Summary

This chapter presents the state-of-the-art of ICT-based construction planning and 4D simulation. It discusses related planning principles, methods, technologies, as well as industrial implementations. In the discussed planning principles, CPM is widely applied in the construction field while CPM-based 4D simulation is most accessible. Thus, the focus of this chapter is placed on CPM to clarify related methods and technologies. According to the PBS-WBS relationship in 3D-based planning and 4D simulation, a blended analysis classifies reported planning and 4D modelling methods as manual linking, manual assembly, full automation, semi-automation, and AI modelling. Furthermore, applied and emerged technologies in 4D and planning are identified. Through discussing four 4D modelling schemes, it discloses involved technologies and approaches in 4D simulation creation. Meanwhile, the use of databases as one of the key technologies is highlighted in the multi-constraint planning to demonstrate a streamlined planning consideration. Being emerging technologies, BIM and IFC are discussed to show essential rationales and key points for planning utilisation. There are two examples of VIRCON and PM4D projects illustrated as industrial implementation. VIRCON project demonstrates process modelling in 4D simulation whilst PM4D project demonstrates BIM technology influences in a construction project. Moreover, CIFE iRoom is focused to gain an insight about collaborative 4D planning at a system level. These analyses and discussions highlight current planning methods' limitations and possible solutions for distributed collaborative 4D planning.

This chapter also shows that seeking a suitable approach is imperative for creating related functionalities to support collaborative 4D construction planning. The state-of-the-art of current planning provides critical considerations of this approach. The main concern is that collaborative 4D planning is a mixed social-technical activity. Compared with most of current 4D-planning approaches, this social-technical activity involves multiple planners' work supported by the networked infrastructure. Therefore, clarifying its relevant CSCW will assist to formulate a principle of distributed collaborative 4D planning. On the basis of the formulated principle, the definition of a suitable 4D planning method will aim at the combination of current methods' merits and the invention of overcoming their demerits. In conjunction with both principle and method concerns, a complete solution will further consider proper technologies to support related implementation. In accordance with this rationale, the following chapters will respectively clarify CSCW principles, suitable method definition, and solutions with underpinned technologies.

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Chapter 3 VR-based Distributed 4D Collaboration

3.1 Introduction

VR technology can bring added values for computer applications such as improved HCI, better information visualization, sense of 'presence', improved simulation, cooperative working et al (AIG, 1994). Combining these excellent features, a VR-based 4D CAD solution may deliver a cutting-edge application for the construction industry. For a group of geographically dispersed planners, a distributed 4D-VR environment will empower their collaborative planning work to create a robust construction plan through improved HCI. In order to gain this benefit, it is in need of the support by a networked 4D-VR groupware system. This groupware is expected to cater for real team planning situations and overcome the pitfalls of current construction planning.

In the industry, the present CPM-based construction scheduling approach is mainly determinant on experienced engineers' imagination in accordance with blueprints (Chau, 2005). Moreover, subcontractors in a project specialise in their own fields, and concentrate on their own planning work in different locations. It is apparent that their static, abstract, and isolated schedules are incapable to deal with dynamic on-site situations (Heesom, 2004). Although 4D technology equips planners with advanced techniques to detect potential conflicts in a schedule, commercially available 4D tools are stand-alone solutions, which provide inadequate support for distributed collaboration. In order to solve this problem, a distributed networked virtual environment is envisaged as a viable approach to connecting geographically dispersed multidisciplinary planners for collaborative 4D construction planning (Zhou, 2006). The creation of such groupware is related to both technical and social concerns including VR technologies, CSCW, as well as networked 4D planning.

Suitable CSCW design can positively promote information exchange and communication for creative problem solving. It can therefore be employed to satisfy the needs of a collaborative VR environment. Given a VR-based distributed CSCW environment, namely a groupware system with a unique shared VR context, coordination among subcontractors will be feasible for robust construction planning. Taking advantage of such a VR-based groupware system, subcontractors, though in different locations, can conveniently discuss their strategies, exchange information, coordinate their activities, and repetitively rehearse possible planning solutions. Thus, conflicts and inconsistencies can be discerned and eliminated beforehand.

In order to probe a new 4D solution with enhanced communication and collaboration features, this chapter discusses VR technologies and CSCW design for 4D-VR based planning. The former is a pure technical topic whilst the later is a social-technical mixture. Revealed from many expensive failures of developing software for CSCW, successful groupware development primarily relies on its social aspects more than its technical aspects (da Silva, 2000). Accordingly, the contents of this chapter address following points: firstly, from the technical perspective, it summarises VR technologies and applications for construction; from the social-behavioural perspective, secondly, it discusses CSCW design for construction planning in the VR environment; thirdly, it examines applicable collaborative technologies for 4D planning; lastly, it analyses an example of distributed mechanical CAD system named CyberCAD with its highlighted CSCW features. On the basis of above discussions and analyses, a groupware framework is specified from functional and constructional perspectives.

3.2 VR-based 4D planning

VR is a promising technology that wins wide acclamations in the AEC industry (Dawood, et al., 2006; Woodard, et al., 2009). However, its applications hitherto are mainly available in architecture design and urban planning, which take the advantages of realistic immersion in visualisation and simulation. In the construction domain, contributions from VR technologies are limited contrasting to what have been achieved in other AEC fields. However, in the 4D simulation sector, VR has potentials to facilitate collaboration and process modelling. This section, adopting some findings from the report by Woksepp and Tullberg (2002), highlights applicable VR features, and requirements for distributed collaborative 4D construction simulation development.

3.2.1 VR platforms and emerging technologies

VR types can be classified into different categories. In accordance with the distinction of interface mode with user, Isdale (1998) identified VR systems into Window on World Systems (WoW), Video Mapping, Immersive Systems, Telepresence, and Mixed Reality. In terms of immersive effect, VR platforms are generally classified into three types: non-immersive VR (desktop VR), immersive VR, and semi-immersive VR (Woksepp and Tullberg, 2002). Accordingly, their equipments are desktop PC, head mounted display (HMD) or cave automatic virtual environment (CAVE), and projector-based virtual environment (VE). Desktop VR is available in the desktop PC which is popular and accessible by anyone. A number of 4D studies are based on the desktop, and can be considered desktop VR solutions. It is also reported that the value of a CAVE in 4D construction planning lies in it being ‘a tool to foster collaborative planning with improved communication among the various project planners’ (Yerrapathruni, 2003). On the other hand, projector-based VEs are the prevailing configurations in many VR labs in Europe. In a projector-based VE, several projectors can project images onto a displaying wall controlled by several computers from the front or rear side. It has a capacity to enable a group audience working collaboratively. The VR classification and its corresponding users are listed in Table 3-1.

Type	Non-immersive VR	Immersive VR		Semi-immersive VR
System	Desktop PC	HMD	CAVE	Projector-based VE
User	Individual	Individual	Individual/Group	Group

Table 3-1 VR system classification

Multimode input is widely adopted in VR technologies. Besides the keyboard and mouse, which are standard Desktop VR input devices, other available devices are applied and attempted in immersive and semi-immersive VR systems. These include 6 Degree-of-Freedom (DOF) devices such as SpaceBall or SpaceMouse, position tracker such as motion parallax, interior tracker like IS-600. Among tracking devices, eye tracking systems provide applications with knowledge of the user's gaze direction, whilst bend-sensing gloves and pinch gloves enables the users to interact with VR systems using their hand gestures (Bowman, 2004). One of feasible interactive approaches to (semi-)immersive VR is the use of the PDA (Watsen, 1999). It offers the users input and output, as well as mobility and wireless communication. Considering distributed collaborative work in a projection based virtual environment, Goebbels (2001) proposed a framework for design and evaluation based on task analysis. It describes a gesture interpretation mechanism to support the users for awareness-action in the condition of audio/video supported face-to-face communication. Additionally, speech input and physiological sensing devices, e.g. brain-computer interface (BCI) (Guger, et al., 2007), also become increasingly active in other application and research fields.

In the academic fields of North America, (semi-)immersive VR systems are used for constructing collocated interactive workspaces, such as CIFE iRoom of Stanford University, Interactive Collaboration Laboratory (ICL) at the University of New Brunswick in Canada, the Immersive Environment Laboratory (IEL) at Pennsylvania State University. 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 equipment includes interactive tabletop display, audio/video conferencing systems, and interactive board with touch-screen capability, special digital pen and eraser et al. The 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 study purposes. Their relevant investigations regarding specific project are in their agendas.

With respect to software, modelling software such as AutoCAD, 3D Studio MAX, etc., and real-time simulation software such as Multigen Creator, VEGA, VIZARD, EON, etc., is widely applied in those VR labs. Similar to modelling software, real-time simulation software has a complete environment for 3D modelling and its own toolkits for the third parties' VR development. Furthermore, it has high quality real-time performance powered by OpenGL or Direct3D technology. Besides a PC platform, some of these simulation tools can run in multiple platforms, such as Multigen Creator is applicable for both MS Windows and Silicon Graphics IRIX.

3.2.2 Feature of VR solutions for construction

An 'Ideal' VR solution for an integrated construction system should have four features, which can be summarised as **P**revision, **I**nspection, **C**ommunication, and **C**omparison according to the propositions from Issa (1999).

- ***Prevision*** - Enable designers, developers, and contractors to use the VR system and virtually test a proposed project before construction actually begins.
- ***Inspection*** - Offer a "walk through" view of the project so that problems can be found and design improvements can be made earlier.

- ***Communication*** - Provide free flow of information between CAD systems and other applications works packages by professionals in industry and minimise misunderstandings between participants in the project, especially between designers and clients.
- ***Comparison*** - Facilitate the selection of alternative designs by allowing different plans to be tested in the same virtual world.

In addition to these features, **C**ollaboration is critical for subcontractors to coordinate their construction sessions because of multidisciplinary characteristics in construction. Therefore, another feature can be added as:

- ***Collaboration*** - Support subcontractors to coordinate their construction activities by multiple users' access.

These **PIC^{3}** features can be the fundamental features when designing VR-based construction applications. Considering specific 4D planning application, functions need to be concretized to fit particular requirements.

3.2.3 4D-VR planning solutions

Given the general VR functional requirements, distributed collaborative 4D-VR solutions should also satisfy the fundamental requirements of 4D applications (Table 2-3) in Chapter 2. Heesom and Mahdjoubi (2004) summarised the requirements to develop three kinds of 4D applications: product modelling and visualisation, process modelling and analysis, collaboration and communication. For a collaborative VR environment assisting planning, it targets process modelling and analysis as well as collaboration and communication. Therefore, its requirements can merge those of two elements into one (Table 3-2).

Application	**Attributes**			
	Level of interactivity with 4D simulation	Level of graphical representation	Level of detail of construction schedule	Level of dynamic capability of simulation
Collaborative VR Environment	High	Low	High	High

Table 3-2 Fundamental requirements for collaborative 4D-VR simulation applications (adapted from Heesom and Mahdjoubi, 2004)

Indicated in Table 3-2, the prevision requirement of collaborative VR is closely related to low level graphical representation and high level dynamic capability. Normally, simulation software can provide better performance in dynamic graphics processing than modelling software, which is capable for detailed graphics representation. The inspection requirement is associated with high level interactivity in a 4D simulation, and high level detail of construction schedule. A usable 3D interactive design is the key to meet the need of interactivity. Proper communication such as synchronous and asynchronous approaches will have a significant influence on facilitating distributed collaboration. The comparison requirement also depends on the system design to display multiple simulation scenarios.

Murray, et al. (2003) implemented a stand-alone VR-based 4D system. Excepting collaboration, the system satisfied the major fundamental features of PIC[3]. Within the developed VE, the user was able to create the building design from a set of prefabricated components using Space Mouse. It also can examine the project schedule within MS Project, allow it to be manipulated with changes being fed back to the VE, and view the construction simulation in real-time in its 3D environment. It was stated that the novel aspect of the system lies in providing a single 3D environment where the user can construct their design with minimal user interaction through automatic constraint recognition that eases the task of aligning components within the 3D environment, and views the real-time simulation of the construction within the environment. In terms of collaboration and communication, related issues were irrelevant to its research and need to be further identified and clarified.

3.3 Collaboration in 4D-VR planning

VR-based collaborative construction planning is complex contrast to non-collaborative planning. Its complexity lies not in the technology aspects of networked 4D and VR technology, but lies in its social and behavioural aspects. Considering social dynamics, Grudin (1994) summarised eight challenges for groupware developers. These challenges imply that groupware development requests a clear perception on its related social issues. A proper CSCW design can help clarify these social issues in the definition of groupware functions. Greenberg (1991) stated that "CSCW is the specific discipline that motivates and validates groupware design. It is the study and theory of how people work together, and how the computer and related technologies affect group behaviour." For specifying a groupware framework, this section adopts the findings from Mills (2003) to discuss imperative points in CSCW design for VR-based 4D collaborative construction planning.

3.3.1 Design dimension

Mills (2003) distinguished ten key dimensions (Table 3-3) inherent in CSCW. These dimensions encompass Time, Space, Group size, Interaction style, Context, Infrastructure, Collaborator mobility, Privacy, Participant selection, and Extensibility. Their corresponding extreme design points are also listed in the table. Understanding these dimensions can help identify the design space of collaboration, which is a baseline for further design consideration.

Dimension	Extreme design points	***Planning***
Time	Fully simultaneous vs. fully disjoint	*Synchronous*
Space	All collocated vs. fully distributed participants	*Distributed*
Group size	Small team vs. mass audience	*Small team*
Interaction style	Assigned workflow vs. ad hoc	*Impromptu*
Context	Single vs. unlimited collaborations per participant	*Single*
Infrastructure	Fully homogeneous vs. fully heterogeneous	*Homogeneous*
Collaborator mobility	All in fixed locations vs. all mobile	*Fixed*
Privacy	Assigned by authority vs. controlled by participant	*Controlled*
Participant selection	Assigned by authority vs. free for all	*Free*
Extensibility	None vs. all functionality defined by participants	*None*

Table 3-3 Ten key dimensions in the CSCW design space for collaborative 4D-VR planning (Adapted from Mills, 2003)

The specific design options for collaborative 4D construction planning is appended in the planning column of the table. Taking a distributed real-time VR environment into account, collaborative construction planning is conducted in a concurrent and synchronous way. Normally, a planning team consists of several geographically dispersed planners, who specialise in different fields such as construction, HVAC, electricity, etc.. The interaction style in their collaboration is impromptu as there is no fixed procedure for them to follow. With regard to the collaboration context, the VR environment is the only focus for generating a robust construction schedule. The semi-immersive VR environment is considered the only collaboration infrastructure as it is the most popular VR platform in the AEC industry (Woksepp and Tullberg, 2002). Nevertheless, it is noted that mobile devices possess the advantage of having flexibility and convenience (Sriprasert and Dawood, 2003). These values are worth exploration for collaborative planning in the future. For simplifying the prototype creation, planners can fully control their own information without authority confinement, whilst other planners' information can be read only. Likewise, participants in the collaboration are all related planners without authority for the participation. Furthermore, collaboration functionalities are fixed by the CSCW system without extensibility or self-definition.

3.3.2 Essential features

One of focuses of CSCW design is to support articulation work: establishing and evolving organizational structure, plans and schedules, standard operating procedures, and conceptual schemes for classifying and indexing information objects (Schmidt and Bannon, 1992). CSCW design for 4D construction planning is typical articulation work to support constructing and managing a common, shared space, the 4D planning environment. Mills (2003) enumerated key features from six main areas for supporting articulation work. These six aspects are communication, configuration, coordination, information access, interaction, and usability. Every aspect has serial features for design considerations (Table 3-4). The associated features in VR-based collaborative construction planning are highlighted using the italic font in Table 3-4.

Design area	Features
Communication	Asynchronous, *audio*, data, private, shared, structured, *synchronous*, text, unstructured, *video*
Configuration	*Adaptation*, composition, evolution, extension
Coordination	*Access control*, *concurrency*, *consistency*, delegation, scheduling, versioning
Information access	*Distribution*, *filtering*, *retrieval*, *structure*
Interaction	*Attention management*, *awareness*, context management, relationship establishment and maintenance
Usability	Boundary crossing (cyberspace, physical space, logical space), cross-device interaction, cross-mode interaction, *metaphor*

Table 3-4 CSCW design areas and their key design features (Adapted from Mills, 2003)

- **Communication**

Human-to-human communication is one of the key features for CSCW. In concurrent collaboration, synchronous communication is one of the approaches to link individuals. Audio, video and multimedia-based videoconferencing is applicable for supporting synchronous communication. For aiding distributed collaborative planning, multiparty communication can be achieved by either ISDN or most ubiquitous Internet. Text-based chatting is another feasible way for instant communication. Though convenient in document, data, and image distribution, it is not wholly applicable for a real-time VR environment because of the confinement of the platform.

- **Configuration**

The adaptability of the collaborative 4D CAD planning system for desktop VR and semi-immersive VR platforms is within the consideration of configuration for the CSCW design. As more affordable (semi-) immersive VR systems are underpinned by desktop platforms (Belleman, et al., 2001), the adaptation feature of configuration can enable planners to perform collaborative planning and simulation on the basis of economic and standard PC infrastructures, while being enhanced by improved human-computer interaction, presence and multiple input devices.

- **Coordination**

Collaborative construction planning aims at construction processes, and its group coordination concentrates on a robust plan generation. As each planner excels at his or her own specialised domain, but is strongly dependant on cooperation from others, it is a critical concern to achieve consistent progress in a planner’s activities and control in information sharing. Therefore, it is necessary to stipulate the policy of information access-control for coordinating planners’ activities. The policy can be stated thus each planner can do any operations in his or her domain; each planner can only propose operations for other planners.

Coordination can also positively facilitate collaborative planning progress. Considering different planners’ planning progresses, their collaboration can be available at two levels. One is at a data level such that overhead planning data can be transferred to every collaborator in real time. Planners thus can make use of this data for independent and free planning. Their working progress is controlled by themselves at this level. Another level is an operational level that their planning progresses are controlled, and collaboration is still available at the data level. The advantage of operational level lies in that controlled planning progress can maintain unique focus and promote effectiveness in real time among collaborators. In order to achieve this progress control, suitable cooperation mechanisms will undoubtedly benefit real-time collaboration.

- **Information access**

Information in collaboration is classified to be subject-matter information and collaboration-support information. The former is related to the subject being discussed in a collaborative session, the later is overhead data from the collaborative session. In collaborative 4D construction planning, subject-matter information includes 3D models and PBS; schedule related information, such as task predecessors, successors, and its time information like start, end, whilst duration is collaboration-support information. WBS can be considered either subject-matter information or collaboration-support information depending on real problem context. An important ability for a collaboration system needs to structure, retrieve, distribute, filter, and index both types of information, whereas semi-structured message, for example XML, can be highly useful for the information access. Because both computer and people can make use of the same messages, XML is a practical choice to handle the information of PBS and WBS.

- **Interaction**

There are two concerns surrounding interaction: maintaining awareness of the states and activities for all collaborators, and managing attention and context when a collaborator joins a live collaboration session. A suitable awareness design may keep distributed planners informed mutually as if planners are collocated face to face. A straightforward awareness design is to set up a video camera for each party so that every body can see each other. Nevertheless, this approach is unnecessary in all conditions. Setting a user's states is an economic choice to address this issue. For a collaboration session, a planner's basic states can be three types: available, occupied, and unavailable. All operations in the collaboration sessions ought to be transparent and visible for every planner. Likewise, new collaborators' states need to be perceived by other collaborators when they join in a live planning session. All on-going planning states can be available after joining in the session. This kind of awareness design has been proven and successfully applied in many instant messaging (IM) systems such as Microsoft Windows Live Messenger and Skype.

An appropriate metaphor can facilitate interaction. Usually, metaphor design leverages users' experiences and mastered knowledge so that they can easily handle interaction tasks. In construction planning, bar chart and 3D architectural models are explicit daily experience and knowledge for planners. Seeking a proper user interface design, the metaphor combining bar charts with 3D models, can promote interaction in collaboration sessions.

- **Usability**

Besides general usability issues about effectiveness, efficiency and satisfaction in user task performances (ISO9241-11), CSCW design emphasises on sharing viewpoints among distributed collaborators. The feature of “What-I-See-Is-What-You-See” (WISIWYS) is important in collaboration planning. Moreover, multidevice and multimodal technologies may enable the achievement of more usable CSCW design for construction planning. As an extension for the future, multidevice and multimodal can be new topics in the collaborative planning.

3.3.3 Collaborative technology

There are four group processes identified in collaboration: communication, coordination, cooperation, and information sharing (Stein, 1997). Their related technologies are listed in Table 3-5. In view of the impromptu nature of interaction style, no applicable technology for coordination process is considered in planning. Therefore, supportive processes for collaborative planning are mainly relevant to communication, cooperation, and information sharing. The applicable technologies for the collaborative 4D planning are listed using the italic font in the table.

Communication	**Coordination**	**Cooperation**	**Information**
• E-mail • *Audio-, videoconferencing* • Telephone • Instant messaging	• Workflow management • Calendar and scheduling	• Electronic meeting systems • *Group authoring*	• Whiteboards • *Application sharing* • Knowledge

• *Chat* • Fax • *Screen sharing systems*	• Project management	*software*	management • Threaded discussions

Table 3-5 Collaborative technologies differentiated by the collaboration processes (Stein, 1997)

On the basis of the previous discussion of CSCW design dimensions and features, applicable technologies for the VR-based groupware can be audio-, videoconferencing, chatting, group authoring, screen sharing, and application sharing. Audio-, videoconferencing and screen sharing systems are able to support the communication process; group authoring software is the core part of the groupware to underpin the cooperation process in the planning. As collaborative planning (group planning) seeks to generate a robust plan, it is quite similar to co-author a paper in terms of concurrency and consistency. The differences lie in that the planner needs to consider time and logical issues in planning whilst the writers focus more on sentence creation and text editing. Application sharing is able to assist the information sharing process. Being different from a screen sharing system, which provides the user with visualization features in collaboration, application sharing can result in more efficient and effective collaboration when incorporating necessary information from other collaborators.

Collaborative technologies can also be sorted according to the time-place paradigm which consists of same time, different time, same place, and different place. The distributed real-time VR system belongs to a combination of same time and different place. Its corresponding technologies for collaborative construction planning are listed in Table 3-6 using the italic font.

	Same Time **"synchronous"**	**Different Time** **"asynchronous"**
Same Place **"collocated"**	• Presentation support	• Shared computers • E-mail • Shared files • Electronic bulletin boards • Workflow systems • Group calendaring
Different Place **"remote"**	• *Text chat* • *Shared applications* • *Shared screening* • *Group planning* • *Videoconferencing*	• *E-mail* • Shared files • Electronic bulletin boards • Workflow systems • Group calendaring

Table 3-6 Collaborative planning technologies in time-place paradigm (Adapted from Hall, 1999)

3.4 Case study of CyberCAD

The discussion of CSCW design dimensions, features, and collaborative technologies depict a portrait of distributed collaborative planning. It is important to integrate design considerations with those supporting technologies. This section analyses a desktop-based VR groupware system, CyberCAD (Tay and Roy, 2003) with its highlighted CSCW design. It provides insights for the integration of social issues in CSCW design and underlying technologies in groupware development. CyberCAD is a collaborative CAD system for mechanical design and assembly. It allows geographically dispersed users to co-edit 3D geometries and perform other related operations together. This collaborative groupware built some CSCW features consistent with some key points discussed in the previous sections. Although these features were not mentioned explicitly in the paper, they still can be traced back by analysing its groupware functions.

3.4.1 Three design relationships

CyberCAD created three design relationships in its collaborative functionality: designers' relationship, designer-object relationship, and objects' relationship (Figure 3-1). The designers' relationship was maintained by an internet-based videoconferencing module in the system. It allowed designers to communicate with each other in real-time irrespective of their location. In its designer-object relationship, designers could fully manipulate their 3D objects in their local computers. Simultaneously, the objects could be shared among designers via the internet. These functions demonstrated the coordination features of concurrent design performed in different locations, and consistent design perceivable by other partners at the same time. The objects' relationship was actually driven by the designer-object relationship. As all the objects were visible by designers, the matches among objects for assembling could be conducted. This relationship indicated the distributed features in information access. On the one hand, 3D objects were structured by designers in their local computers. On the other hand, they were shared and distributed seamlessly on the internet. This feature ensured that designers could drag the online 3D objects from the Internet to their local CAD environment for assembling, which was supported by application sharing technology.

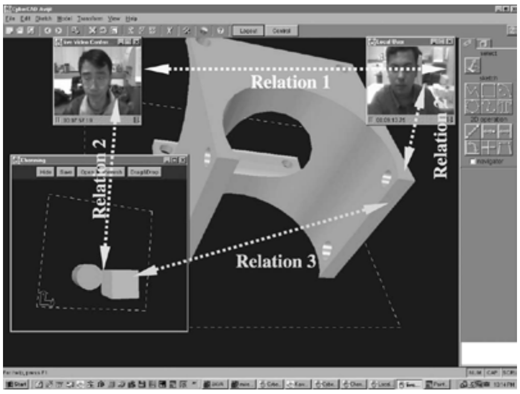

Figure 3-1 Three-design relationship in CyberCAD (Tay and Roy, 2003)

3.4.2 Communication protocol

The underlying mechanism for communication is a so-called controller/viewer protocol in the CyberCAD. The protocol regulated that every designer was both controller of his master window and viewer of his partner's window. Figure 3-2 illustrates that every designer has a master design window for his design operations. Through another window, the partner's mapping window within the master window, the designer can see his partner's design process. This screen sharing collaborative technology enables the design team to work in a parallel and collaborative way. Its implementation adopted Java technologies to underpin the functions in network, communication, and 3D graphics.

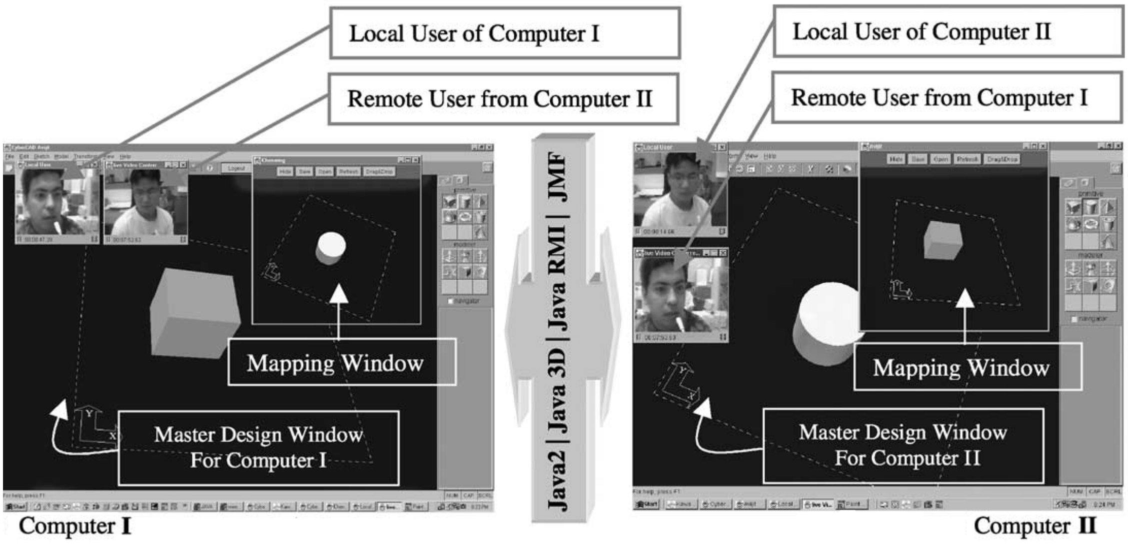

Figure 3-2 Controller/viewer protocol in CyberCAD (Adapted from Tay and Roy, 2003)

3.4.3 Interaction and usability

The controller/viewer protocol also built WISIWYS feature with the usability. It kept design transparent, and hence improved the user's effectiveness and efficiency in the design process. Nevertheless, it seems the CyberCAD system applied videoconferencing to achieve the awareness feature throughout the whole interaction sessions. There is no relevant function associated with designers' states, and no metaphor applied in the user interface design. Its 3D design environment combined with 2D graphical user interface is a popular scheme in most desktop CAD systems.

3.5 Proposed CSCW design for 4D-VR planning

In the light of above CSCW discussions and analyses, the CSCW design for 3D model based collaborative 4D construction planning can be conceptually proposed as co-navigate, co-sort, co-plan, co-simulate, and co-talk. Applying related collaborative technologies, these collaborative activities with designed CSCW features are expected to support geographically dispersed planners to achieve real-time collaborative planning.

- **Co-navigate**

Screen sharing technologies will support the co-navigate activity. The CyberCAD applied controller/viewer protocol to create master and mapping windows in the desktop environment. Nevertheless, this master/mapping window scheme is inapplicable in the immersive VR environment. In fact, 4D simulation environment needs planners to be constantly inspected and walked through. The switch between controller's and viewer's viewports is a pertinent functional requirement. Therefore, planners are expected to apply other planners' viewports to be their own local viewports, and navigate with other collaborators together. Every planner ought to have this possibility to apply another planner's viewport, and share his local viewport with others. This WISIWYS usability feature enables all planners to walk through, inspect, and maintain the same focus on sceneries in their local VR environments.

- **Co-sort**

Co-sort is necessary for multidisciplinary planners to express their planning interests and specialities for an inputted 3D building model. As construction planners focus on different aspects in a project for planning, it is above all crucial for them to obtain their own building information so that to initiate their planning work. In a networked 3D VE, a real-time tele-cooperation is a straightforward way for the co-sort activity. Via this approach, geographically dispersed planners can pick out and collect their own 3D elements from a central building model and perform their planning work locally. Such a mechanism was described as user's perspective in the research of distributed virtual engineering (DVE) (Maxfield, 1998). It applied an information mask, namely filter, to get meaningful information for different clients. The similar concept can be applicable for geographically dispersed multidisciplinary planners to identify their own information.

- **Co-plan**

Co-plan will play a dominant role in the group planning. One of the focuses of this collaboration is to support location different planners to access the subject-matter information of PBS, and other related 3D model information. Another focus of it will help organise and distribute local planners' schedule information, as well as receive other schedule information from remote planners. These operations possess the feature of information assess in the CSCW design. The ultimate goals of this activity are to synthesise and validate all schedule information for a final robust plan generation. For achieving this aim, the collaboration-support schedule information like WBS and schedule information from each planner need to be pre-processed through group processes of information sharing, communication, and coordination. These will be dealt with in the other collaboration of co-simulate, co-talk, and co-navigate.

This design will also make use of application sharing technology to accelerate planning process. Its related function is similar to the objects relationship built in CyberCAD. In view of logical and temporal constraints from each plan, other discipline's schedule information needs to support local planners' decisions. Applying application sharing, local planners can directly obtain other plan information, and adopt it into their own schedules. Such a mechanism will allow distributed planners to work concurrently and efficiently.

- **Co-simulate**

Simulation across the network will be positive for multiple planners to co-discover potential conflicts from a co-created plan. This advantage has been verified by an empirical testing using a web-based 4D simulation system (Kang, et al. 2007). Similarly, this kind of co-simulate collaboration can be applicable for a VR-based 4D environment, in which multidisciplinary planners focus on not only their own plans' but also integrated whole plan's simulation. Based on this interrelated 4D planning presentation, planners can double check their plans in terms of logical, temporal, and spatial correctness. Taking the advantage of real-time co-navigate features, collaborators are able to synchronously observe, visually identify, and/or detect hidden conflicts. A robust plan can thus be guaranteed through frequent co-simulation during planning.

- **Co-talk**

Audio and videoconferencing will be a key component in the co-talk activity. It resembles the designers' relationship in the CyberCAD. In order to effectively apply different perceptual channels, the differentiation of audio and video is made in the human-to-human communication. Videoconferencing is the most popular in synchronous conversation because it can not only acquire linguistic information from audio, but also gain communicators' facial expressions from video. This dual-channel communication is able to facilitate understanding among collaborators. However, audio-conferencing is still positive for understanding planning context especially when discussing 3D models or other visualised information. Thus it is unnecessary to get a communicator's facial information in that circumstance. Proper awareness in the collaborators' interaction will be designed to show their states and requirements.

Instant message is another useful communication approach to enables distributed communication by text chatting. Its benefit lies in simpleness, ease-of-use, and low cost to be built in applications, and is thus flexible to create social interaction among multidisciplinary planners. Nevertheless, it would be confined in a task-heavy 4D planning situation that collaborators are occupied by other operations like co-navigate, co-plan, etc., and need real-time communication for information exchange. In a semi-immersive VR environment, the usefulness of text chatting as well as e-mail can still be applicable before collaborators access the system. In such a way, collaborators can coordinate their collaboration to realise system access control. The proposed CSCW design is expected to create related features in each of the discussed design areas to assist distributed collaborative 4D planning. Their relationship is listed in Table 3-7.

Design area	Co-talk	Co-sort	Co-plan	Co-simulate	Co-navigate
Communication	✓				
Configuration		✓	✓	✓	✓
Coordination		✓	✓	✓	
Information access		✓	✓	✓	
Interaction					✓
Usability					✓

Table 3-7 Relationship between proposed CSCW design and design areas

3.6 Summary

This chapter analyses VR technologies applied in the construction fields. Besides the review of VR features for construction, it also proposes the feature of collaboration because of the multidisciplinary nature of construction. These features are summarised as the PIC^3 for the consideration of creating collaborative construction VR solutions. As far as VR-based 4D planning is concerned, an adapted attribute list is created on the basis of proposed 4D application attributes. In accordance with the adapted attribute, a 4D-VR application ought to be at a high level of 4D simulation interactivity, detail of construction schedule, and dynamic capability of simulation; but at a low level of graphical representation. These features provide a clear guidance to build a solution of distributed VR environment for collaborative 4D planning.

CSCW design is also discussed in this chapter. From design dimension, essential features, popular technologies, to a case study, this chapter identifies key issues in applying CSCW theory for 4D-VR construction planning. On the basis of this theoretical analysis, a CSCW design strategy is emerged for real-time collaborative 4D planning in a distributed VR environment. Combining this with identified collaborative technologies and features of communication, coordination, information access, interaction, and usability, a 4D-based CSCW design is specified to be several synchronous co-actions including co-navigate, co-sort, co-plan, co-simulate and co-talk. Importantly, it lays a foundation to create a suitable method for VR-based collaborative 4D planning combining discussed points in Chapter 2. It thus further helps to formulate practical tactics to develop a distributed 4D-VR groupware solution for collaborative construction planning in the next step.

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Chapter 4 Methodology and Proposed Approach

4.1 Introduction

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. Particularly, when this collaborative work is performed in a VR environment, suitable user interface/interaction (UI) designs are vitally important to support individual planners' performances and team planners' activities. However, it is unclear about VR-based UI designs for a 4D solution to achieve suitable usability. Targeting these functional and non-functional problems, proper methodologies need to be clarified for solving related issues.

With respect to the functional aspect, a novel approach of interactive definition for distributed collaboration is proposed, thus allowing interactive collaboration to create the construction plan and the subsequent 4D simulation directly from the unique 3D model. Based on the review of current planning approaches in Chapter 2 as well as CSCW design concerns in Chapter 3, this chapter proposes and develops the interactive definition method. 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. It lays a methodological foundation to create a solution of 4D-based collaborative planning in a distributed VR environment.

In view of the ad hoc 4D application platform of semi-immersive VR, suitable UI design is the key for the solution to achieve usability and applicability. A UCD approach is thus considered in the non-functional aspect to reach this aim. Since the 1980s, UCD has been becoming popular in the ICT industry. It helps to seek usable designs through a set of workflows, evaluation methods, and design approaches, which construct a comprehensive UCD framework. Along with its extensive utilisations, its pitfalls are also exposed in cost-benefit, robustness, and optimization respects. However, applying the Taguchi Method can remedy these pitfalls to gain robust optimal designs. From a theoretical perspective, this chapter depicts a practical approach to UCD framework enhancement by adopting the Taguchi philosophy. Based on the analysis of the UCD framework and the Taguchi Method, it discusses relevant adaptation points for the Taguchi philosophy adoption in the UCD framework. As a result, the Taguchi-Compliant User-Centred Design (TC-UCD) framework is proposed. This new UCD framework provided guidance to robust usability engineering for the UI design of the distributed 4D-VR collaborative planning solution.

This chapter firstly specifies a general research strategy through a roadmap, which is relevant to both functional and non-functional problem solving in the research. Subsequently, it highlights critical considerations in the interactive definition method.

Its principle, key components of 3D model based planning context, simulation item definition, user-system interaction, CSCW design, and collaborative work-flow are discussed in detail. Finally, the TC-UCD framework is discussed and proposed based on the analysis as well as adaptation and adoption of the current UCD framework and Taguchi Method respectively.

4.2 Research methodology

For the purpose of realising collaborative 4D planning in a VR environment, a distributed 4D groupware solution with suitable functionality and usability needs to be created. Therefore, this investigation concentrates on both functional and non-functional aspects for the VR-enabled 4D groupware creation. Functionalities' creation is the main focus for the groupware in the functional aspect. Applied research methods for achieving related functionalities include literature review for identifying research domain problems, theoretical analysis for clarification of VR-based 4D CSCW design and proposition of collaborative 4D planning method, functional requirement analysis of the distributed 4D groupware for system development, system specification and functionalities' implementation, as well as verification testing about the method and system functionalities. In the non-functional aspect, the UI designs of the 4D-VR groupware and their evaluations are the main focus. Applied research methods encompass theoretical analysis about the robust UCD framework of TC-UCD, non-functional requirement analysis about end users and VR platform capability, collaborative task analysis, VR-based UI designs, prototyping, evaluation and optimization. These research methods are addressed in different chapters respectively. The interrelationship about them is illustrated by a research roadmap (Figure 4-1).

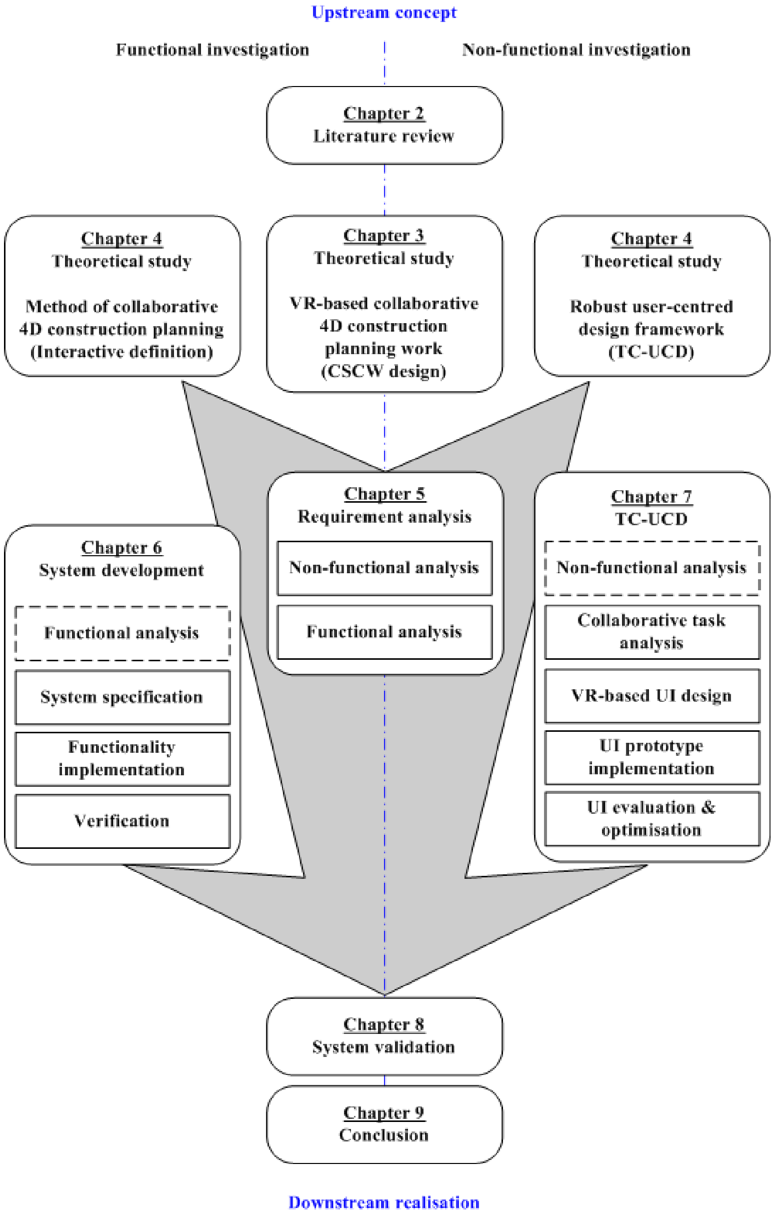

Figure 4-1 Research roadmap

As shown in the roadmap, there are several interrelated methodologies between the functional and non-functional investigations from the upstream concept to the downstream realisation. From the upstream, the research problem of distributed 4D construction planning is identified through the literature review in Chapter 2. The theoretical postulation of CSCW design for VR-enabled collaborative 4D application is highlighted in Chapter 3. Combining another two theoretical analyses of the interactive definition method and TC-UCD framework in Chapter 4, these three theory studies provide a common starting point to further discuss issues involved. They lead to the requirement analysis for both functional and non-functional aspects in Chapter 5. These requirement analyses lay the foundation for the system functional development and the interactive definition method's verification in Chapter 6. They also serve VR-based UI design and evaluation using the TC-UCD discussed in Chapter 7. Chapter 8 presents the whole VR-enabled 4D system's validation to examine its applicability. The final conclusions are discussed in Chapter 9.

The interrelated research roadmap contains two important theoretical studies about the method for collaborative 4D planning and the new framework for UCD. The former is decisive for both functional and non-functional features' realisation of the 4D groupware, whilst the later is the guidance for the groupware's UI design through a robust usability engineering approach. This chapter discusses them as the interactive definition method and the TC-UCD respectively in the following two sections.

4.3 Interactive definition method

Fischer, et al. (2005) stated 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.

Combining the collaborative essences mentioned above, the 'interactive definition' method is devised as part of this study to provide a platform for collaborative construction planning and seeks to adopt the merits of the previously discussed 4D-planning 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 is anticipated supporting distributed planners in generating a robust construction plan and simulation. The following sections specify the principle components and theories of the proposed approach.

4.3.1 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 plan 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 collaborative planning. Underpinned by a network infrastructure, planners can conduct the interactions at three levels. At a high level, social interaction is facilitated among multidisciplinary planners by human-human communication via audio-, videoconferencing. 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 another words, the planner's work is to define simulation items rather than mere 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 to examine potential problems across the network. As a by-product, the final generated 4D simulation can be used for communicative and explanative purposes. 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 method concept is illustrated in Figure 4-2.

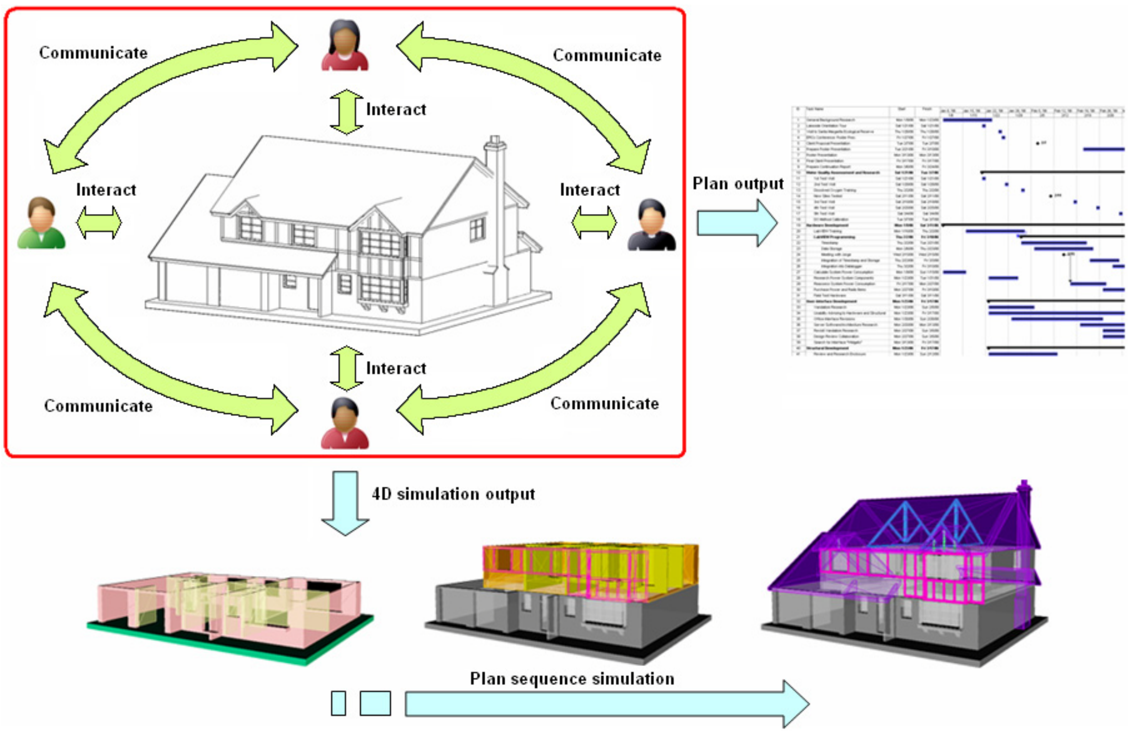

Figure 4-2 Concept of the interactive definition method (Zhou et al., 2009)

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, which is because existing WBS essentially experienced spatial information identification by planners' imagination but still needs to go back to the 3D model for connecting corresponding PBS elements. According to these comparable points, the proposed 4D planning approach is tagged as PBS-create-WBS (PBS→WBS). Synthesising the foregoing discussions in Chapter 2, all of the described methods are differentiated in Table 4-1.

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

Table 4-1 Method for 4D construction planning (Zhou et al., 2009)

4.3.2 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 input 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 formats like DWG, 3DS, DXF, etc. and latest BIM approaches including the use of IFC are applicable resources for 3D model input. Given a 3D model compatible with BIM, PBS information of a building such as door, window, beam, column, etc. can easily be generated according to its internal specification. In the case of some popular non-BIM CAD formats such as DWG, the 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 no building information is 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.

4.3.3 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 surrounds the WBS definition including individual WBS item definition, hierarchical WBS structure formulation, and the entire WBS export. Another aspect focuses on 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 a 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 logical relationships among defined WBS items such that a hierarchical and inter-related project plans 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. Given those parameters in a simulation item definition, they serve different information parts (Table 4-2). 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 to be integration, it is thus convenient for network transmission and synthesis to output the final plan and simulation.

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

Table 4-2 Task parameter for simulation item definition (Zhou et al., 2009)

4.3.4 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 via social interaction and CSCW during these tasks' performance. 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 give an impetus to 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 the 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 simulating of the build sequence throughout the whole planning process can avoid the risk to build up plan conflicts to the end. These interactive tasks can be illustrated by a task model (Figure 4-3) using ConcurTaskTrees (CTT) (Paternò, 2000), which is a popular task analysis method in the HCI domain.

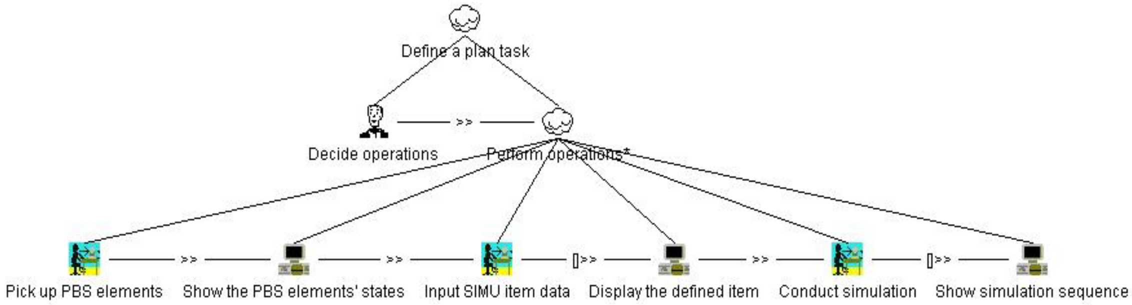

Figure 4-3 Task model of the interactive definition

Given the user tasks in the interactive definition method, they can be generalised to be a repetitive interactive task of Perform operations. When performing this user task, the planner can choose related operations according to plan tasks' availability. In case a plan task is available, the planner is able to conduct simulation and the system thus can show the simulation sequence. In case there is no defined plan task, the planner then needs to conduct definition from the beginning. A complete plan task definition includes several coherent user-system interactions. First, the planner picks up right PBS elements from the 3D model, and then the 3D model gives the feedback to show picked elements' states. Second, the planner inputs simulation items' data via artefacts like dialog box, and the system thereby displays defined plan tasks. Afterwards, the planner can decide if it is necessary to perform the instant simulation for detecting generated logical sequences. Through a series of repetitive user tasks operations of this kind, a construction plan can be created with its 4D simulation output. Collaboration can be simultaneously involved by launching additional collaborative sessions during these operations and planning workflow, which will be clarified in a later section.

4.3.5 Collaborative session

In order to effectively support distributed planning team members for collaborative 4D planning, CSCW is designed to facilitate the planners' mental process, social interaction, task performance, and make their planning processes to be open-ended, synchronous, and communicated. In the light of highlighted key features of communication, configuration, coordination, information access, interaction, and usability in CSCW design, the identified collaborative work such as co-navigate, co-sort, co-plan, co-simulate, and co-talk can be performed as a series of collaborative sessions. Among these sessions, co-navigate and co-sort are dedicated to planners' workplace identification. Planners can navigate and analyze the 3D model together via zoom, pan, rotate, and some other effective approaches to identity suitable 3D elements as workplaces for the defined tasks. In case the inputted 3D model has no building information, co-sort session enables planners to pick out related PBS items together from the 3D model. On the other hand, co-plan allows online planners to define their simulation items based on their collected 3D elements of PBS items. The defined items then are synthesized to be a complete plan. In conjunction with online planners, co-simulate can help detect potential conflicts in the generated plan across the network. Involved online planners can check potential conflicts, not only in their own plans, but also the overall plan during the co-simulate session. In order to maintain a live social interaction in planning, the co-talk session is available for this purpose. Audio-video conferencing and text chatting are also available in the session.

The collaborative sessions can be classified into two types. One is conditional session, which requires an enquiry-acceptance agreement among collaborators. Co-navigate, co-sort, and co-simulate are of this type. The conditional session has a specific lifecycle about creation, process, and termination. Its creation is dependant on a selective invitation from a session holder and acceptance from session attendees. The session holder is an online collaborator who initiates a collaborative session. Other online collaborators are potential session attendees. Once online collaborators accept an invitation from a session holder, they become the session attendees and a live conditional session is then created. During live session processes like co-navigate, co-sort or co-simulate, the involved attendees and the session holder can collaborate together for planning work. The session holder plays a dominant role in controlling the session's progress. Both the session holder and the attendees can perform related operations, which are synchronously reflected in their systems. A live session can be terminated at any time by either the session holder or the session attendees. Another session type is unconditional session that can be launched by any online collaborators in any situation. The co-talk session and the co-plan session belong to the unconditional session. The characteristic of the unconditional session is such that it can be conducted freely and randomly by online planners. There is no specific lifecycle about creation and termination in the unconditional session.

The designed collaborative activities also provide collaborators with close-ended and open-ended performance combinations for effective collaboration. Collaborations such as co-sort, co-plan, co-navigate and co-simulate are close-ended that their collaborators are only available to join in one of them at one time. It means that the same collaborators in one of these collaborations cannot attend another of them. The co-talk, on the other hand, is open-ended that online planners can perform it at any time regardless their session states. The benefit of this difference lies in that the former can help form a focus group for specific problem solving whilst the later is a bridge to allow natural and open social interaction among multiparty. Figure 4-4 illustrates two focus groups of A and B in close-ended collaborative sessions. Via the open-ended collaborative session of co-talk, however, the group members can communicate with each other not only within but also beyond a group

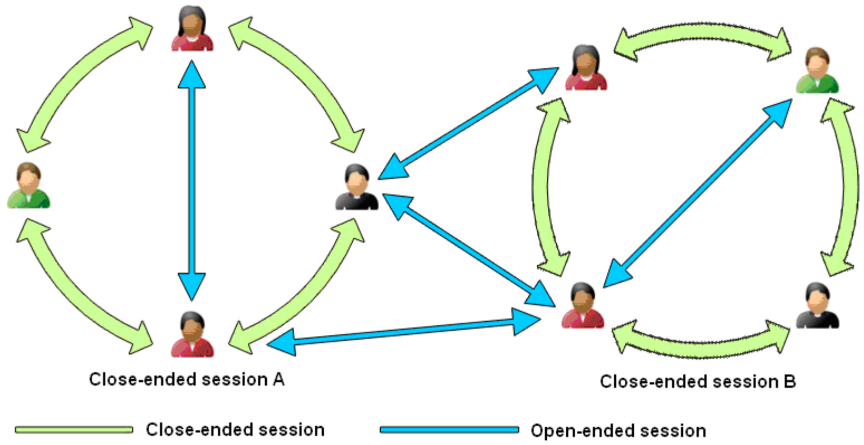

Figure 4-4 Collaborative scenario of close-ended session A and B with open-ended sessions

4.3.6 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 of feasible approaches 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 items 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 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 Figure 4-5.

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. In the 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.

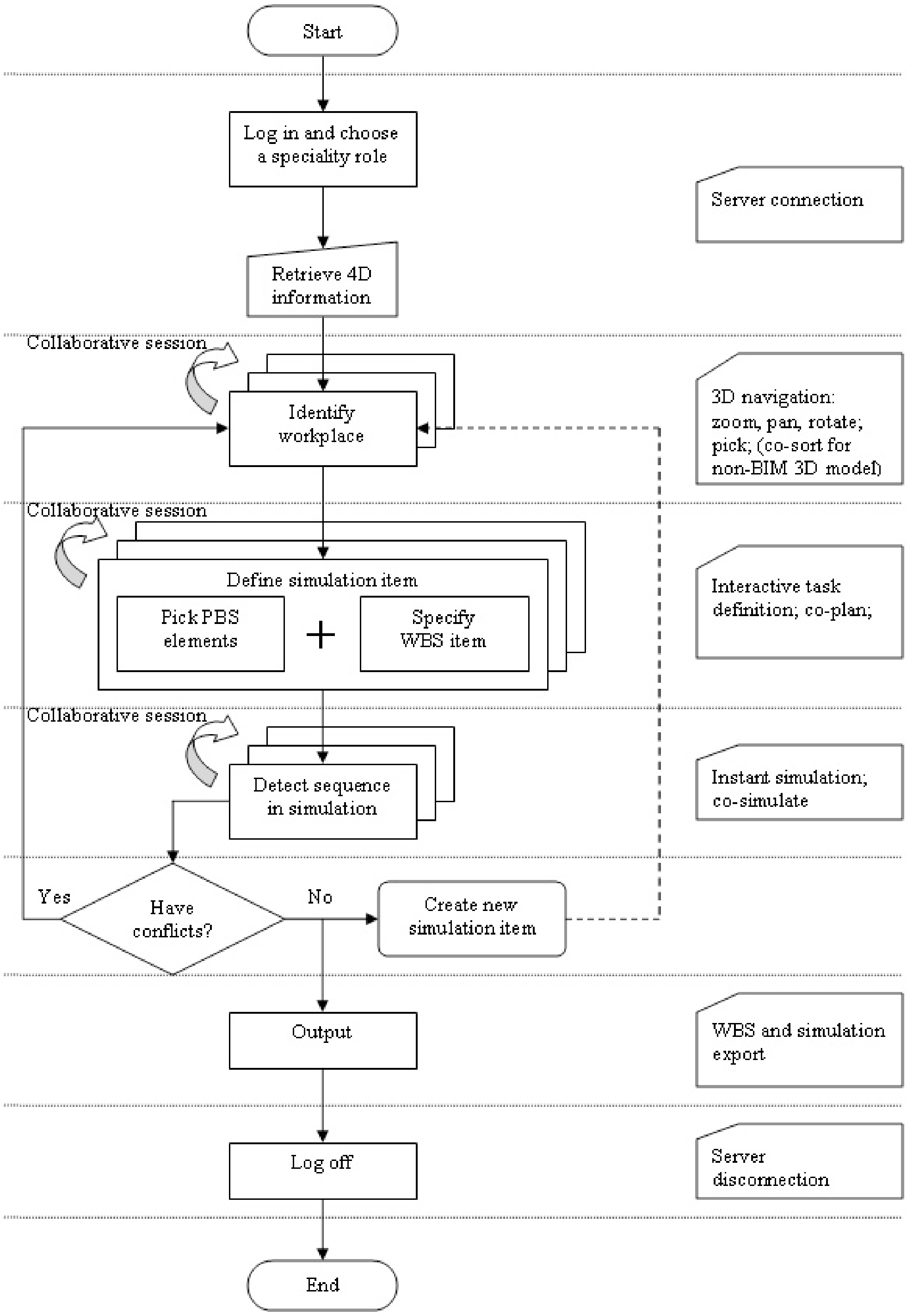

Figure 4-5 Interactive collaboration workflow (Zhou et al., 2009)

4.4 Taguchi-Compliant User-Centred Design

In order to achieve suitable UI designs for VR-based 4D groupware, UCD is considered to guide the design to solve involved non-functional problems. UCD has been recognized and applied for user interface and interaction design in Human-Computer Interaction (HCI). By involving end users throughout the whole design phases, UCD can ensure a usable design before the product delivery. In accordance with this rationale, some UCD methods are created and illustrated by HCI specialists. Many successful cases have benefited from these approaches. However, a few limitations like time-consuming design, high cost of testing, etc., are also exposed when applying them. Using UCD in the ICT industry is still confined because of cost and benefits (Weiss, 2005).

Specifically, three conspicuous pitfalls exist in current UCD need to be remedied. Firstly, the present UCD methodology is inefficient to reach a usable design. Iterative design is a prevailing approach in UCD. When applying it for design, the designer needs to design a prototype first, and then the evaluation is conducted so as to find out usability problems in the prototype. This design-testing cycle should usually be repeated several times to incrementally guarantee usability. This repetitiveness feature is a weakness of the UCD method. It costs a substantial amount of time and money to ensure usability. Secondly, current UCD is not highly effective to achieve robust usability. Design and evaluation in the UCD are two separate phases, which have no relationship or mechanism to integrate them. Nielsen (1993) pointed out it is likely in an iterative design that "additional usability problems appear in repeated tests after the most blatant problems have been corrected". This shows that the unstructured iterative design is incapable to deliver a robust design, and inevitably causes uncertainties to achieve robustness in usability. Finally, in many circumstances, a design solution might have different options in its design components. For the purpose of picking out the optimal solution, a normal approach is to make a comparison among all the design options. Nonetheless, the current parallel design approach in UCD is essentially a collection of several independent designs, which are unsystematic and short of analytical comparison among design choices. Moreover, the evaluation analysis methods, such as within-subjects, between-subjects, etc. are weak to deal with multi-variable situations, which normally have a large number of design choices for evaluating and analysing. It is formidable to undertake huge optimising work applying those evaluation methods in the UCD. In these aspects, ironically, current UCD approaches are unusable for designers to achieve robust optimal usability in designs.

In view of these drawbacks, a cost-effective approach is proposed to enhance robustness and optimization of the UCD method. Total Quality Management (TQM) theory gives us inspirations to find a practical solution to meet this goal. Its underlying philosophy of the Taguchi Method advocates designing the product quality in the design process instead of after the design. Comparably, it is possible to design usability in the user interface design process, and hence significantly shorten design-testing cycles, save cost in usability testing, and deliver optimized robust design. Its applicability in HCI was proven in the early 1990s' (Reed, 1992). Applying the Taguchi Method, Smith (1996) attempted to create another design approach Logical User Centred Interface Design (LUCID, tagged as LUCID-Smith in this report). Unfortunately, this lacks explicit specifications to adopt UCD elements whilst the UCD has been increasingly emphasized in the HCI realm. Few design practices are reported applying LUCID-Smith method. However, it has been shown that combining UCD essences with the Taguchi philosophy can overcome those weaknesses of the UCD, and achieve optimized robust usability in designs (Zhou, 2005).

4.4.1 UCD framework

UCD was advocated by Donald Norman in the 1980s (Norman, 1988). It recommends placing the user at the center of the design. Since its initiation, it has been developed into a substantial framework with various methods in requirement analysis, design, and evaluation in usability engineering. A few UCD methodologies have been invented by HCI specialists, institutions, and organizations to fit needs in the framework. This section outlines the UCD framework from UCD workflow, evaluation methods, and design approaches.

4.4.1.1 UCD workflow

Mayhew (1999) introduced a detailed roadmap of a usability engineering lifecycle. It can guide practitioners to achieve a step by step usable design. In this roadmap (Figure 4-6), a complete usability engineering lifecycle consists of requirement analysis, design/testing/development, and installation, in which a serial of specific activities needs to be carried out for gaining certain goals. The requirement analysis deals with user profile, contextual task analysis, platform capabilities and constraints, and general design principles. These analyses are helpful for determining usability goals. In the phase of design/testing/development, three level designs are differentiated: Level 1 is to eliminate major design flaws; Level 2 is to check if usability goals are met; Level 3 examines if overall goals in both functional and non-functional aspects are satisfied. This phase plays a central role in the roadmap. On the one hand, it applies design strategies, which are derived from previous phases of requirement analysis, for prototyping and development. On the other hand, it provides feedback by testing the previous phase for adjustment and improvement. The installation phase is to get deployment feedback for the further design improvement.

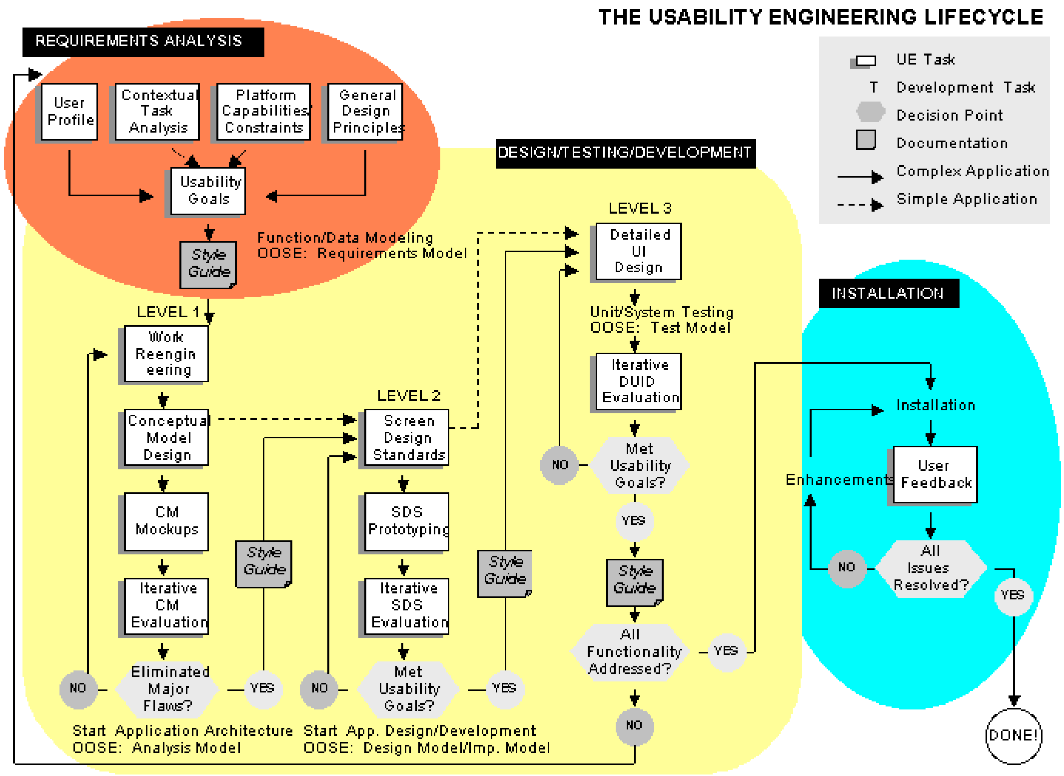

Figure 4-6 Roadmap of usability engineering lifecycle (Mayhew, 1999)

In addition to this roadmap, similar UCD models are also proposed by Nielson (1993), Hix (1999), and some commercial institutions like Cognetics Corp., which created another LUCID (Logical User Centered Interaction Design) framework. Essentially, the core concepts of these models can be generalized as several key parts: user study for requirement analysis, conceptual design/development for prototyping and implementation, usability testing for finding usability problems, and deployment for gaining design improvement points.

4.4.1.2 Evaluation method

There are three types of evaluation method for usability testing: heuristic evaluation, formative evaluation, and summative evaluation. In light of the number of needed users in usability testing, the cost of them is variant from low to high. Heuristic evaluation applies existing design guidelines or checklists without involving real users. Formative evaluation is often applied in design-testing lifecycles to identify usability problems (Figure 4-7). It can produce both qualitative (narrative) and quantitative (numeric) results. Summative evaluation is used for finalising a design in order to obtain some statistical information. Hix (1999) explained this method as "to statistically compare user performance with different interaction designs, for example, to determine which one is better, where 'better' is defined in advance."

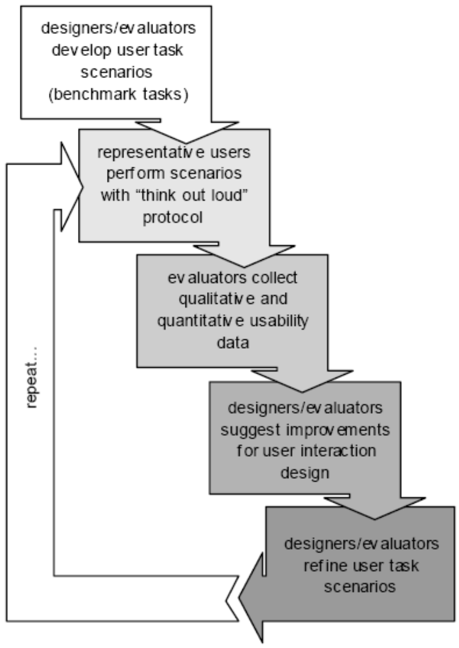

Figure 4-7 Formative evaluation (Hix, 1999)

Besides these general types of usability evaluation, Nielson (1993) summarized popular usability methods and their suitability (Table 4-3). Among these methods, thinking aloud is a typical formative evaluation, which can be further evolved to be several methods like constructive interaction (co-discovery), retrospective testing and coaching method.

Method Name	Lifecycle Stage	Users Needed	Main Advantage	Main Disadvantage
Heuristic evaluation	Early design, "inner cycle" of iterative design	None	Finds individual usability problems. Can address expert user issues	Does not involve real users, so does not find "surprises" retaining to their needs.
Performance measures	Competitive analysis, final testing	At least 10	Hard numbers. Results easy to compare	Does not find individual usability problems.
Thinking aloud	Iterative design, formative evaluation	3-5	Pinpoints user mis-conceptions. Cheap test.	Unnatural for users. Hard for expert users to verbalize.
Observation	Task analysis, follow-up studies	3 or more	Ecological validity; reveals users' real tasks. Suggests functions and features.	Appointments hard to set up. No experimenter control.
Question-naires	Task analysis, follow-up studies	At least 30	Finds subjective user preferences. Easy to repeat.	Pilot work needed (to prevent misunderstandings).
Interviews	Task analysis	5	Flexible in-depth attitude and experience probing.	Time consuming. Hard to analyze and compare.
Focus groups	Task analysis, user involvement	6-9 per group	Spontaneous reactions and group dynamics.	Hard to analyze, low validity.
Logging actual use	Final testing, follow-up studies	At least 20	Finds highly used (or unused) features. Can run continuously.	Analysis programs needed for huge mass of data. Violation of users' privacy.
User feedback	Follow-up studies	Hundreds	Tacks changes in user requirements and views.	Special organization needed to handle replies.

Table 4-3 Summary of usability methods (Nielson, 1993)

4.4.1.3 Design approach

Iterative design and parallel design are two approaches in UCD. However, the mainstream application in the HCI field is iterative design. It is realized by low-fi or hi-fi prototyping and formative usability evaluating. Usually, this design-testing cycle needs to be repeated several times to incrementally achieve a usable design. Mayhew (1999) applied this approach extensively in the roadmap (Figure 4-7). Such an iterative approach has been considered the best choice in user interface/interaction design. However, Dix (2003) specified that the iterative approach might be confined to obtain the best design due to an inappropriate start point. For overcoming this pitfall, he claimed that it is crucial to have a good initial design based on experience and judgment. Another approach is to have several initial design ideas and drop them one by one as they are developed further.

Dix's (2003) suggestion actually keeps consistency with Nielson's (1993) parallel design model (Figure 4-8), in which several independent designs can be performed simultaneously by different designers, and then merged such that their merits form further iterative design. In a case study, Nielson (1996) reported that parallel design is more expensive than iterative design because of consuming more resources. Nevertheless it can speed up time-to-market, and explore the design space in less time. It is noticed that the merged design was dependant on a senior designer's subjective judgement and individual experience. As a conclusion of the study, this method is not recommended for all projects due to its costly nature unless time-to-market is of essence.

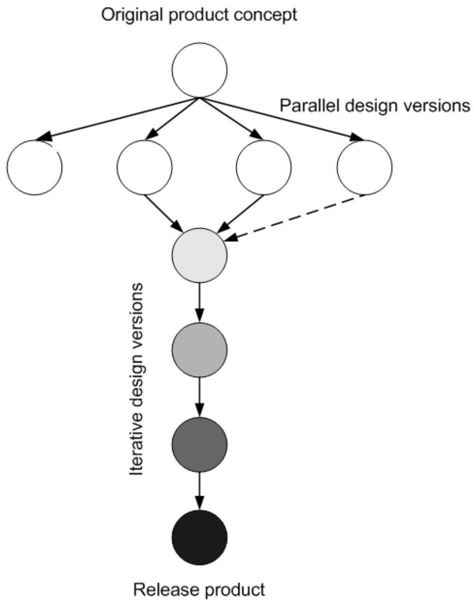

Figure 4-8 Parallel design model (adapted from Nielson, 1993)

4.4.2 Taguchi method

The Taguchi Method was devised by Dr. Genichi Taguchi in the late 1940s. It has a strong theoretical relationship with Design of Experiment (DoE), which was founded by Sir Ronald Fisher in the 1920s. Initially, the Taguchi Method was created for the purpose of quality control to deliver robust products. Nowadays, its application has been extensively used in all kinds of fields. Thousands of successful cases from diverse companies have been reported in the past 40 years (Ross 1988, Taguchi 2000).

4.4.2.1 Robust design

Taguchi establishes his philosophy about robust design, and defines robustness as: "*the state where the technology, product, or process performance is minimally sensitive to factors causing variability (either in the manufacturing or user's* *environment) and aging at the lowest unit manufacturing cost"* (Taguchi, 2000). Following this philosophy, the designer's goal should reduce output variability in the presence of noise, e.g. the product should be of such a quality that it keeps the performance consistency in the condition of various external noises.

The Taguchi philosophy breaks down conventional design approaches. Traditionally, the design approach follows this way: design → test → find problem → solve problem → test → find problem →…until the problem can be eliminated. Such a "plug-the-leak" or "whack-the-mole" design approach is obviously time-consuming and costly for improving design quality. Nevertheless, the Taguchi Method advocates designing quality into the product instead of inspecting it after its production. It treats design in an analytical way of differentiating design issues into design factors and corresponding levels. Their combinations can be examined in noise conditions in order to find most suitable design levels as final designs. For realising this aim, a three-stage design process is suggested by Taguchi in product quality control.

4.4.2.2 Three-stage design

- **Stage 1 - System Design**

The focus of the system design is to determine suitable working levels of design factors. The Taguchi Method treats design in an analytical way. It identifies design issues as design factors, design levels, and noise factors. Design factors refer to main controllable design issues for product creation. They directly influence product performance. Design levels are some options of a design factor. Noise factors are some uncontrollable external issues, which usually interfere with product performance. Essentially, noise factors come from three aspects: outer noise (environment), inner noise (product itself) and between product noise (piece-to-piece variation). The choice of design factors, levels and noise factors can be decided by the researcher's judgment based on selected materials, parts and technology.

- **Stage 2 - Parameter Design**

Parameter design aims to seek design factor levels that produce the best performance of the product/process under study. These optimal conditions are selected so that the influence of uncontrollable factors (noise factors) causes minimum variation of system performance. For searching these optimal conditions which are insensitive to the noise, a partial factorial experiment is introduced rather than a tedious full-factorial experiment. Orthogonal Array (OA) and its optimization analysis play a key role in this stage.

An OA consists of inner array and outer array. An inner array will control design factors and their levels to compose a group of parallel trials for an experiment, and achieve the purpose of partial trials to test whole design combinations. Its features of balance and orthogonality can lead to a comparable experimental result, and thus dramatically decrease the number of experiments. An outer array, likewise, can create different noise situations for testing those design combinations. Optimization analysis for experiment results is able to find the most robust design levels for creating optimized design combinations. Besides the often used ANOVA method, Taguchi (2000) suggested using Signal-to-Noise (S/N) ratio to discern right design levels which provide the best performance under study. A confirmation experiment ought to be followed up to verify the validity of the optimized designs.

- **Stage 3 - Tolerance Design**

Tolerance design is a way to refine the results of the parameter design by tightening the tolerance of factors. It is possible that design levels are improperly chosen by designers. Even after optimizing in the experiment, the optimized designs might not show desired performances in the confirmation experiment. In this situation, adjustments for design levels need to be made to initiate another design-testing cycle.

In accordance with the three-stage design as well as its OA rationale, the Taguchi Method constructs a design space or problem space by design factors and levels, in which optimal design solutions can be sought by optimization analysis. Contrasting to the "plug-the-leak" way of aimless searching, this target-oriented approach ensures a robust design, and can also be applicable for the quality control of user interface/interaction design, the usability.

4.4.3 Adoption and adaptation

The Taguchi philosophy demonstrates a structured approach to combine design with evaluation. It allows a group of correlated parallel designs to be created, evaluated, and optimised through comparison. In the UCD framework, adopting the Taguchi philosophy can compensate its weaknesses in robustness, optimization, and shorten tedious design-testing cycles to improve usability control. Some adaptations in both

UCD and the Taguchi Method are needed in order to comply with the principles of each other. In the following sections, primary adaptations in the adoption are discussed.

4.4.3.1 Taguchi design

When Taguchi design is introduced into the UCD framework, it can connect the conceptual design and the usability evaluation together to achieve robustness and optimization in application. In accordance with the Taguchi philosophy, the Taguchi design consists of system design and parameter design. Their functions are clarified below.

- **System design**

The objective of this stage is to identify main design factors and levels which are influential on usability. It has been acknowledged that task-centred process can be visionary to foster design (Davis, 2001). Therefore, task analysis is able to produce design issues, and is helpful to decide design factors and design levels. For achieving this objective, task analysis needs to be differentiated into two levels: abstract level analysis for generating design factors, and concrete level analysis for choosing specific design levels. The CTT task analysis method provides an ideal interface to meet this need in the system design. For representing user's tasks, it defines a set of task notations like abstract task , interaction task , application task  , etc., as well as task priorities to build hierarchal task relationships. As far as the system design is concerned, design factors can come from main abstract tasks in the CTT, while design levels are several specific realizations of the abstract tasks. For instance, Open a Door is an abstract level task, the design factor. It can be further interpreted as several design levels which consist of specific tasks. Figure 4-9 illustrates three design levels in the design factor of Open a Door using CTT. Besides user tasks, design elements in the user interface like layout, GUI components, etc. also could be design factors if they can cause variations in usability.

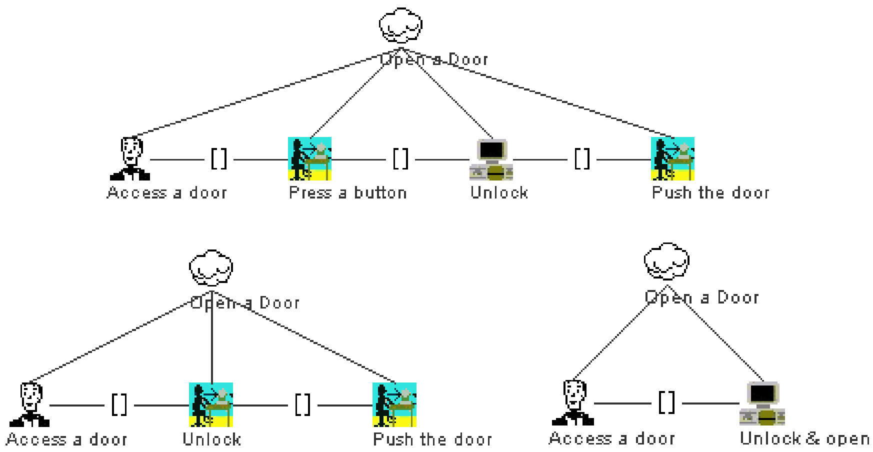

Figure 4-9 Three design levels in the design factor of Open a Door

Task analysis in the UCD framework can help to define usability goals, and thereafter to create prototypes. Similarly, it also plays the same role in the system design, but prototyping is performed in the parameter design.

- **Parameter design**

Parameter design seeks the most usable design levels through usability testing on prototypes. It needs a proper inner array to arrange identified design factors and levels which have been decided in the system design. Thereby, the inner array will construct a set of parallel combinations for prototyping. Compared with independent parallel design in the UCD framework, these parallel prototype designs are subject to the inner array, and every prototype essentially corresponds to a trial for usability testing.

The usability testing in every trial examines design factor levels in its corresponding prototype, and furthermore identifies robust design levels which are insensitive to noise factors. As these prototypes have the same design factors but with different design levels, it is hence comparable for each prototype to pick out robust design levels after the testing. Positively, the feature of balance and orthogonality of the inner array ensures a partial factorial experiment to test all the possible prototypes. It is particularly valuable for usability testing to save cost. Formative evaluation is the main approach in this evaluation. Its execution and result analysis can lead to optimized designs.

4.4.3.2 Formative evaluation and analysis

Formative evaluation is performed in the trials of the parameter design. It serves two aims of usability testing and design level optimisation. The former can check usability problems in each design level; the later is able to identify robust design levels. Among usability methods, thinking aloud and performance measure are applicable for the testing partly because both of them can be used to check usability problems in prototypes, and partly because they can all provide objective quantitative information to identify robust design levels. According to the ISO9241-11, usability is defined as effectiveness, efficiency and satisfaction. Its evaluation accordingly consists of objective evaluation for effectiveness, efficiency, and subjective evaluation for satisfaction.

In objective evaluation, effectiveness and efficiency can be associated with the index of rate of error and time cost respectively. During the test, the participant needs to perform tasks according to predefined task scenarios. Simultaneously, his or her performance results can be recorded, such as time cost and error made. These quantified test results are objective information to assess usability of design levels in terms of effectiveness and efficiency. For the purpose of identifying the most robust design levels from the test results, analysing S/N ratio can intuitively help make a judgement regarding effectiveness and efficiency. Lower-is-Better (LB) is applicable to assess both rate of error and time cost. The lower the error rate made and time cost by the participant in the test, the more robust the corresponding design levels are.

The measure of satisfaction, however, is unsuitable to apply the inner array. Because satisfaction is subjective information, it is improper to estimate participants' preference on the basis of a partial factorial experiment. Nevertheless, it is positive for the participant to pick out his or her most favourite design combinations after finishing all the trials. User's experiences in the trials will directly impact on his or her subjective preference for choosing most satisfied combinations. Based on these objective and subjective evaluations, three types of the most usable design levels can be found out in terms of effectiveness, efficiency, and satisfaction. Their levels' combinations in each type are optimal robust designs of the participant. As this analysis approach focuses on individual's behavioural information, its optimised design solutions are only applicable for the individuals. Such an analysis accordingly can be named as Within-Individual Analysis.

4.4.3.3 Human factors and outer array

Human factors are the main noises in terms of the Taguchi philosophy in the parameter design. Among three types of noise defined in the Taguchi Method, the outer noise – human factors in the social environment are influential noises in the experiment. Given a group of end users with the same educational level, similar habits and culture background, individual differences always exist, and thus generate the noises. In order to deal with the noise situation, the Taguchi Method provides the outer array to build noise conditions in experiments. Smith (1998) applied outer array to arrange objective human factors like age, gender, ethnic background, etc. On the other hand, he suggested using cognitive approaches to handle subjective human factors such as cognitive style and attitude.

However, utilising outer array to build noise conditions in usability evaluation is suspicious because human factors can not be fully controlled in the testing. It is uncertain to assert that a user's performances will be influenced by a pure human factor such as blood type, gender, or nationality, etc. Moreover, usability testing is essentially a behavioural testing, in which a participant can bring both objective factors and subjective factors in a mixed manner. In this circumstance, outer array is inapplicable to cope with human factors noise conditions. Due to these characteristics of noises, the obtained optimization results could be inconsistent among participants. The more persuasive and economic approach for dealing with these variations is to check statistical significance of obtained optimised designs. Nonparametric statistics is an applicable approach to solving this problem.

4.4.3.4 Significance analysis

Optimal robust designs can be achieved by applying the ‘Within-Individual Analysis’ in Taguchi design. These optimized designs are not the same for all people because of individuals’ difference, or interference from human factors. For a group of optimal designs generated in the evaluations, they fall into different categories of design levels’ combinations. Therefore, it triggers a question about if there are significant differences among these optimised design combinations, or if these optimised designs are drawn from expected combinations. In essence, this is a hypothesis test question of one-sample goodness-of-fit for categorical measurement. The Chi-square test (Siegel, 1988), one of the non-parametric statistical methods, can answer this question. As this test concentrates on significance analysis of optimization results from all individuals, it thus can be named as Among-Individual Analysis**.** Such an analysis is able to identify if there are the most effective, or most efficient, or most satisfactory solutions for all end users. Its results can help designers create flexible solutions according to different usability priorities among effectiveness, efficiency and satisfaction.

4.4.4 TC-UCD framework

On the basis of the foregoing discussion, an enhanced UCD framework is proposed as Taguchi-Compliant User-Centered Design (TC-UCD). The backbone of TC-UCD consists of user study, conceptual design, Taguchi design, usability evaluation, confirmation test, and deployment. TC-UCD not only keeps the UCD essences in design techniques and usability evaluations, but also has some unique features for exploring optimized robust usability in designs. Figure 4-10 illustrates the present UCD framework and the new created TC-UCD framework for comparison.

Compared with the current UCD framework, there four major characteristics of the TC-UCD. Firstly, it preserves user study as a design start point for user profile definition, functional and non-functional requirement analysis. Secondly, the Taguchi design is integrated in the UCD framework. Its system design and parameter design belong to the conceptual design and the usability evaluation respectively. The former determines design factors and levels; the later seeks robust optimal design factor levels through parallel prototyping and formative evaluation. Meanwhile, the 'Within Individual Analysis' can identify optimal design combinations whilst the 'Among Individual Analysis' can verify the significance of optimized designs. Thirdly, the confirmation test is suggested in the TC-UCD for checking the usability of optimized designs. Summative evaluation is no longer necessary in the new framework. Lastly, TC-UCD itself is compatible with iterative design. Although the emphasis of the TC-UCD is placed on the parallel design and evaluation, it is still flexible to adjust design strategies from beginning of the user study, or to tighten design levels from system design. The start point of iteration depends on real design situations.

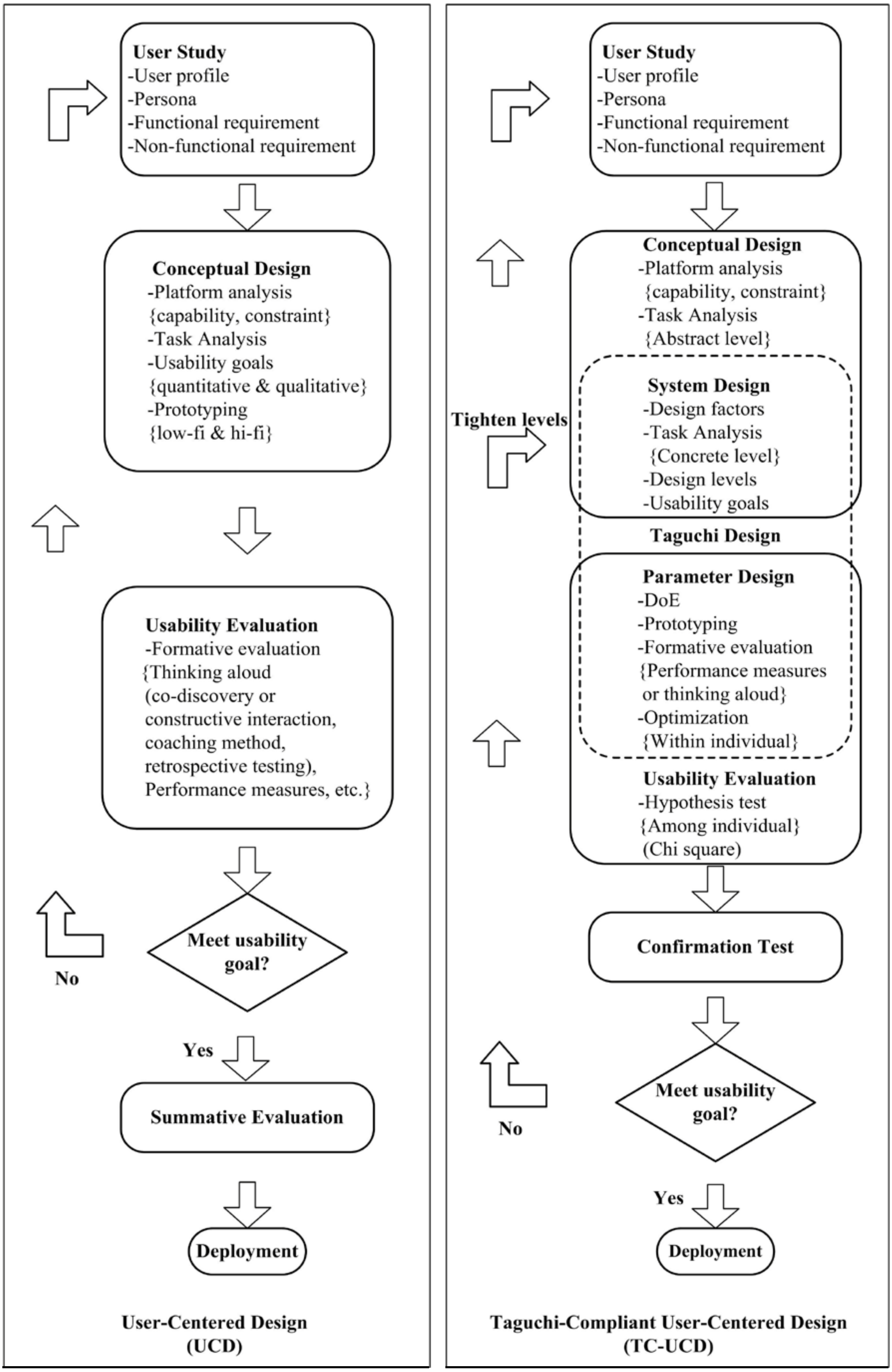

Figure 4-10 UCD and TC-UCD framework (Zhou et al., 2007)

4.5 Summary

This chapter presents a general research methodology to combine both functional and non-functional concerns, which are related to the new visions about a collaborative 4D planning method and an enhanced UCD framework. On the one hand, it depicts a novel collaborative 4D method of the interactive definition based on HCI theories' advancement. It strives to support individual planner's mental process in terms of temporal, spatial, and logical information fulfillment, as well as assist team members for social interaction in a distributed virtual environment. On the other hand, it presents the TC-UCD to overcome the current UCD framework shortcomings in robustness and optimization aspects. As a multidisciplinary field, HCI theories and methods mainly derive from behavioral sciences. Undoubtedly, it is a rewarding attempt to combine feasible engineering theories with behavioral sciences for enriching HCI framework.

The proposed interactive method possesses critical concerns to achieve distributed collaboration in 4D planning. It adopts a unique 3D model input to build a common planning context for distributed planners' planning and 4D modelling. The simulation item definition ensures both local and remote collaborators' plan information exchange and incorporation across the network. The direct manipulation in the user-system interaction provides individual planners with chances to effectively perform planning work while communicating with collaborators simultaneously. Leveraging dedicated conditional and unconditional collaborative sessions, the CSCW designs of co-navigate, co-plan, co-sort, and co-talk assist collaborators to organise flexible collaborative activities. Within such an open-ended and sufficiently complex social-technical planning context, collaborators' creativities are expected to be stimulated, and thus co-create a robust construction plan.

The formulated TC-UCD is an advanced and comprehensive design approach. It is suitable for exploring in-depth design solutions in a multi-variable situation. Particularly, the identification of design factors provides a common start point to seek appropriate design levels, and create a parallel design space. Such a design mechanism allows not only teamwork brainstorming but also independent designers' inspirations to perform a complete design. Therefore, an individual designer can undertake whole design missions only by more considerations and analyses when applying it. In fact, the Taguchi design of the TC-UCD can completely fulfil the needs of Nielson's parallel design model (Figure 4-8). Its analysis methods, theories, and comparable quantitative design approach make the model more practical and applicable without consuming extra resources. Hence the cost of this parallel design should not to be increased due to changing design mechanism.

These two kinds of methods serve the aims of creating a new collaborative 4D planning solution, and enhancing the solution's usability in a semi-immersive VR condition. Both of them are dedicated to a blended social-technical solution of VR-based collaborative 4D planning. Their difference lies in that the former adds substantial social and behavioural considerations in the traditionally technology condensed 4D CAD research domain, whilst the later embraces a typical engineering strategy with more social and behavioural sciences. In Chapter 6, the interactive definition method is implemented and validated in a prototyping. Chapter 7 fully applies the TC-UCD for the prototype's user interface and interaction design in order to verify, validate, and improve it further.

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Chapter 5 Requirement Analysis

5.1 Introduction

The proposed distributed planning system is expected to connect multiple users across the network for real-time collaborative construction planning in a VR-based 3D environment. Besides this advanced capability, its fundamental usefulness is to support individual planners for construction planning and 4D simulation creation. For the purpose of supporting these demands, the system application can be differentiated into an offline and an online application respectively. As a subset, the former can be utilised by individual planners without network support whilst the later is applicable for a group of planners underpinned by the network infrastructure. From a user's point of view, a set of use case diagrams are created in this chapter using the Unified Modelling Language (UML). They are applied for modelling related functional requirements in the offline and online applications.

Simultaneously, the system functionalities' creation is also confined by various constraints from technical and social aspects. These constraints are from non-functional requirements affecting the quality of system development outcome. Usability arises from non-functional requirements and significantly influences the system development. An early survey (Myers and Rosson, 1992) shows that software developed at that time devoted an average of 48% the code for the user interface development. It is reasonable to believe that the amount of the code invested in improving usability is dramatically increased in today's GUI era based on underlying development libraries. In the 4D CAD domain, research efforts are mainly put on functional aspects rather than non-functional issues like usability. In order to create a suitable UI design for the VR-based 4D solution, another focus of this chapter is placed on the non-functional requirements analysis about user study and semi-immersive platform capability. The user study is to gain end users' knowledge and skills, motivations and attitudes, etc. whilst the platform capability analysis is to identify strengths and constraints of semi-immersive VR. Both functional and non-functional requirement analyses provide UCD with a start point to be conducted.

5.2 Functional requirement

In accordance with the interactive definition method discussed in Chapter 4, construction planners need to conduct related operations to achieve performance goals of planning and simulation. These users' operations are associated with certain system functions. These functions can be expressed by different use cases using UML, which is a model-based software engineering approach to delineating users' requirements (Schmuller, 2004). The workflow of the interactive definition method (Figure 4-5) presented in Chapter 4 has shown desired client-side functions. Being networked software for a group of distributed planners, its utilisation can be classified into an offline and an online application. The offline application supports client-side users to perform all planning and simulation work based on their stand-alone local PCs, whilst the online application encompasses related sever-side operations, and enables its users to combine communication with data transmission for real-time collaboration. This section applies a set of use cases to illustrate user requirements of both offline and online applications.

5.2.1 Use case of offline application

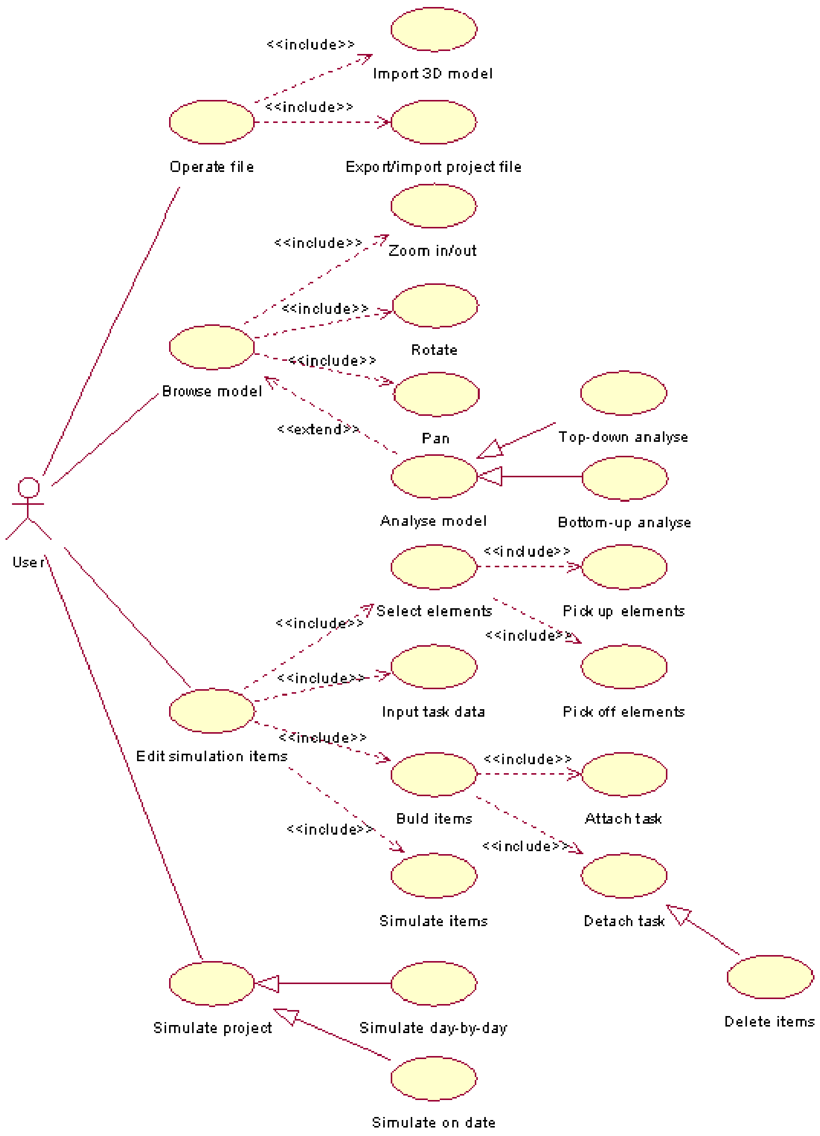

Figure 5-1 Use case diagram of offline application

In the offline application, the main use cases include operate file, browse model, edit simulation items, and simulate project (Figure 5-1). The operate file use case consists of user tasks of 3D model importing and task file exporting/importing. The user can load a 3D model, import and export task files via a file system. Subsequently, when finishing loading a 3D model into the system, the user can browse and analyse the model. These tasks are unified as the browse model use case. Specifically, it further includes use cases of zoom in/out, rotate, and pan. In addition to these use cases, another use case of analyse model is the extension of the browse model use case. The user can analyse the loaded 3D model through bottom-up or top-down decomposing operations. These analysis use cases are generalised to be the analyse model use case.

The use case of edit simulation items includes four use cases of select elements, input task data, build items, and simulate items. These use cases represent a coherent user-system interaction of simulation item definition. Firstly, the user can pick up or pick off desired PBS elements. These operations are modelled as pick up and pick off element use cases, which are included by the select elements use case. Secondly, the user can define simulation items through inputting task data. It is thus modelled as the use case of input task data. Furthermore, the user can attach defined simulation items as tasks onto selected PBS items. Conversely, the user can also detach tasks from them. These operations are illustrated as the build items use case including the attach task and the detach task use cases. Specifically, the delete task use case is considered a specialisation of the detach task use case. Lastly, the simulate project use case indicates the user's performance of project simulation. The simulation can be conducted by either continuous day-to-day simulation or random specific date simulation. These two use cases are generalised as the simulate project use cases.

5.2.2 Use case of online application

A high level use case diagram of the online application is created for representing the client-side application and the server-side application (Figure 5-2). The client-side application extends the offline application into the network environment. All use cases in the offline application like edit simulation item, browse the model, simulate the project can be supported by the server in an online condition. Simultaneously, the use cases of talk to collaborators and sort PBS items are available for planners based on the network. Both use cases of the define simulation item and the sort PBS elements in the online condition build the unconditional sessions of co-plan and co-sort. Text chatting in the co-talk also belongs to this collaborative session. Particularly, PBS items in the offline application can be regarded as a sorting result for planning. In the network condition, nevertheless, PBS items ought to be co-sorted for fulfilling different planners' specialities.

The server-side application can support the use cases of connect server and manage a session from the client side. Meanwhile, the connect server use case contains four use cases that the user can log in/off from the server, choose a role of expertise that he or she will play in the collaboration, set his or her working state during planning, and retrieve 4D planning data from the server. These use cases present the establishment of an open shared unique 4D planning context for every online planner. The use case of manage a session describes that the user as a session holder can launch and stop a collaboration session. It depicts scenarios of each conditional collaborative session's implementation of co-navigate, co-sort, co-plan, co-simulate, and co-talk. On the other hand, use cases in the server side show that the user can start or stop the server, operate a file by either loading a 4D file or saving a 4D file and add roles for planners to play or delete them.

Indicated by these use cases in the applications, the user needs to play multiple roles in collaborative planning. Planner and collaborator are two basic roles for a user. The role of planner is involved in all use cases in the client application whilst the role of collaborator is played in a collaborative session, which is launched by another planner. As a special planner and collaborator, the administrator also needs to deal with some management work in the server side before and after planning.

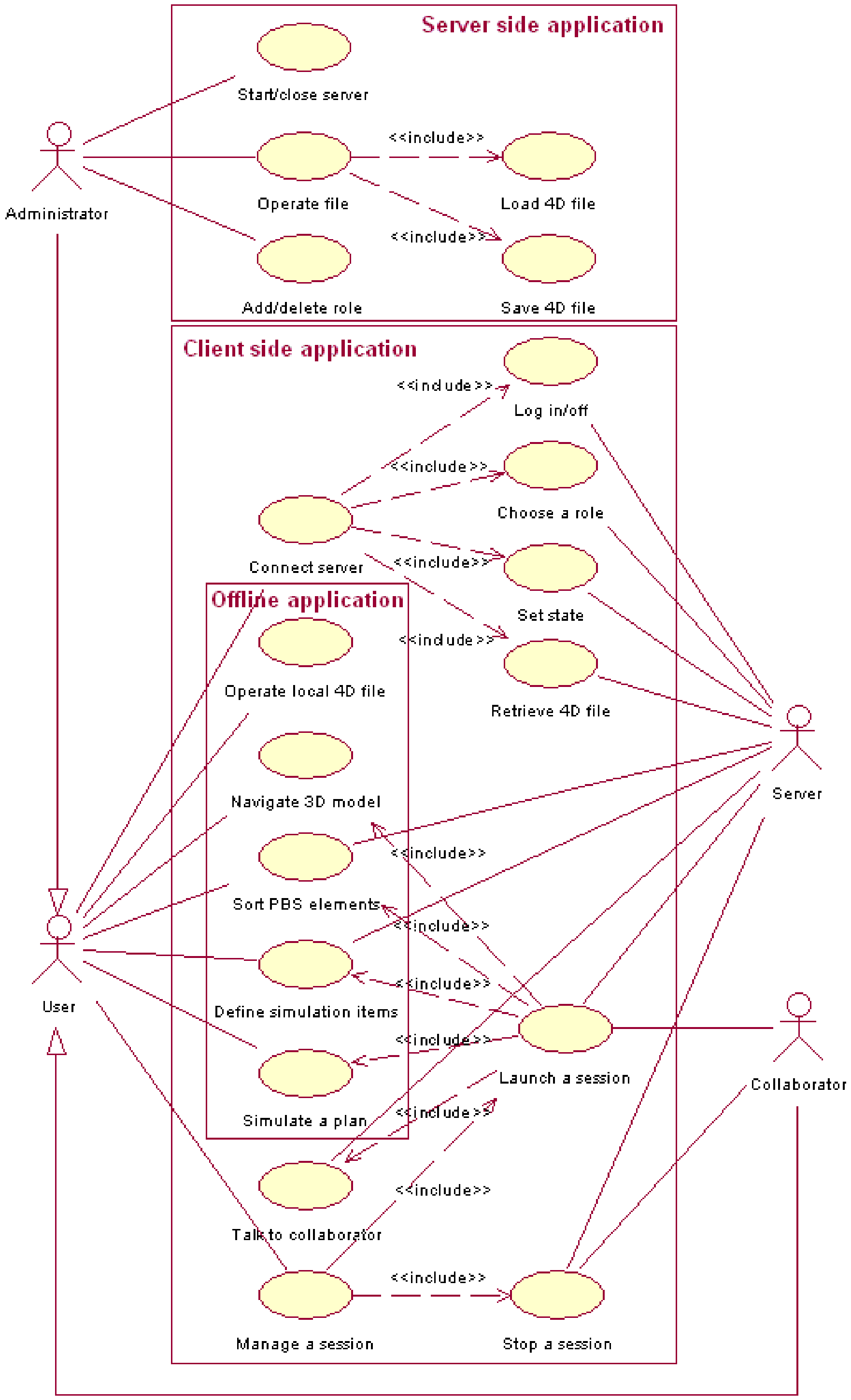

Figure 5-2 Use case diagram of online application

5.3 Non-functional requirement

Non-functional requirements can be defined (from the system point of view) as "restrictions or constraints placed on a system service" (Kotonya and Sommerville, 1998). In the creation of a VR-based 4D CAD system, the system constraints are mainly from the applied VR platform. Therefore, this section analyses a semi-immersive VR platform's capabilities and constraints. Additionally, non-functional requirements are also concerned with the qualities - the properties or characteristics of the system that its stakeholders care about and hence will affect their degree of satisfaction with the system (Bredemeyer Consulting, 2001). Usability as a major run-time quality is taken into account in this section for non-functional requirements analysis. It is also influenced by system constraints for user interface and interaction design. In order to identify critical issues in usability, it is necessary to conduct a user study about the system's end users, who are construction professionals with certain education levels and trained skills. It can build a foundation to further define usability goals as system design and development guidelines and evaluation criteria.

5.3.1 User study

In order to understand the users' requirements for the user interface and interaction design, a survey was conducted with postgraduate students studying construction management at the University of Wolverhampton. A formal questionnaire (Appendix 1) was distributed to acquire their information from four aspects: Company Situation (only for part-time student), Attitude & Motivation, Knowledge & Experience, and Physical Characteristics. The developed questionnaire was approved by the university's ethics committee. There were 23 people invited to participate in the survey with 17 valid return answers, among which part-time students who were practising in the industry accounted for 53% (in total 9 persons) whilst full-time students accounted for 47% (8 people in total). The overall respondent information is shown in Table 5-1. The full respondents' data can be found in Appendix 2.

Total respondents	17
Full-time students	8
Part-time students	9
% of respondents	74 (17/23)
Level of automation	High

Table 5-1 Overall respondent information

5.3.1.1 User profile

- **Company Situation**

There were nine part-time students from different construction companies. They all indicated in the survey that desktop based planning software like MS Project or P3 is their main approach to construction planning. It verifies that 4D CAD is still not yet fully embedded in the industry.

- **Attitude & Motivation**

All the participants in the survey expressed their interests in 3D based planning work, and enjoyment of learning new ICT functions. Many of them further explained their interests that they regard 3D approaches to be promising ways in improving productivity, better communication and understanding among stakeholders. Nevertheless, over half of participants (47% plus 6% in Figure 5-3) showed a conditional or even negative attitude towards applying ICT tools for construction planning. They stated that it depends on how easy to use ICT tools in planning work. Although 76% participants (Figure 5-4) would like to cost time to learn new ICT functions for planning work, there are still 24% participants with a conditional mind depending on if provided functions pay off. In terms of interacting with PC, a majority of people (82%) were used to keyboard, mouse, or even remote control as input devices. It is worth paying attention to the minority of people (18%) who implied no alternative for application.

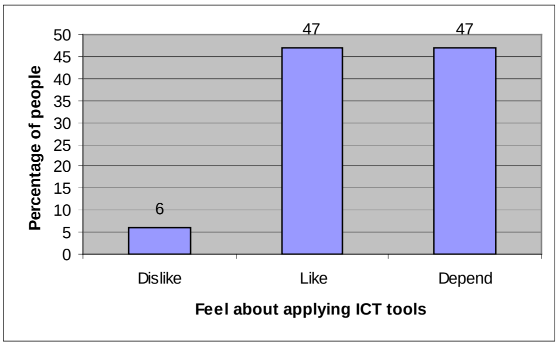

Figure 5-3 Feelings about ICT application

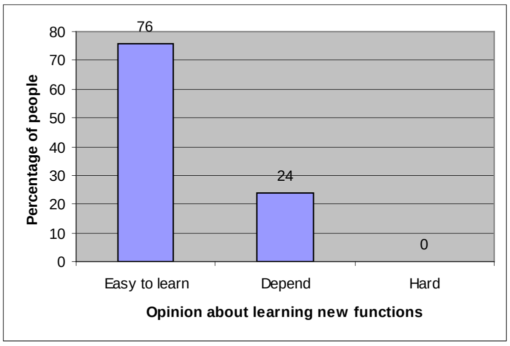

Figure 5-4 Opinions about learning new functions

- **Knowledge & Experience**

Participants in the survey are all postgraduate students with a bachelor's or equivalent degree in the construction field. They are generally computer and Internet literate (Figure 5-5, 5-6). Around 53% people have not only software application experiences but also certain programming skills. Over 90% (Figure 5-7) people have the experience of using CAD design software whilst high experience users attain to 59%. In accordance with their 3D CAD experiences, a majority of participants felt it is easy to operate 3D object applying current commercially available 3D CAD software (Figure 5-8). Fewer people (12%) showed difficulty in 3D operations. 3D gaming is also an approach to gaining 3D experience. However, the survey showed nearly one third of people have no gaming experience or even never touched it.

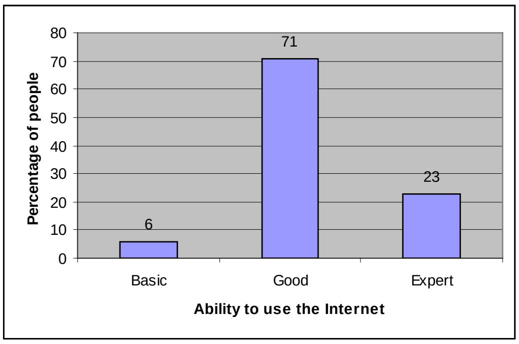

Figure 5-5 Ability to use the Internet

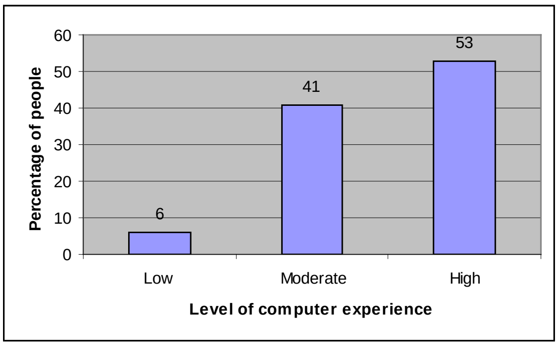

Figure 5-6 Level of computer experience

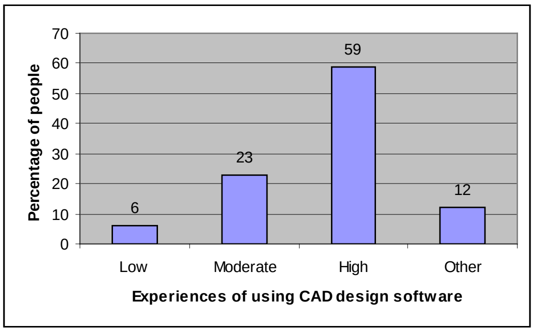

Figure 5-7 Experience of CAD software

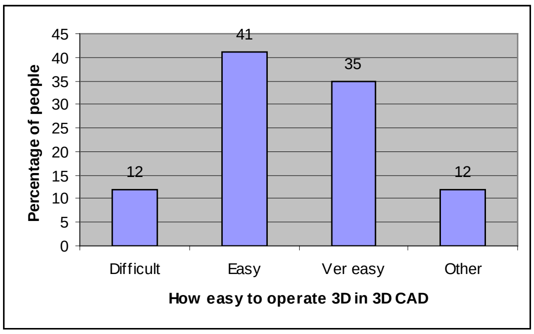

Figure 5-8 Easy level of 3D CAD operation

- **Physical characteristics**

Participants in the survey are all adults (near 80% from age 18 to 40, Figure 5-9), but there are still a proportion of senior persons (24% over 40 years old) in this field. All of them have no disability in PC utilisation, but near sighted persons account for 41% (Figure 5-10). They wore glasses or contact lens for PC operation.

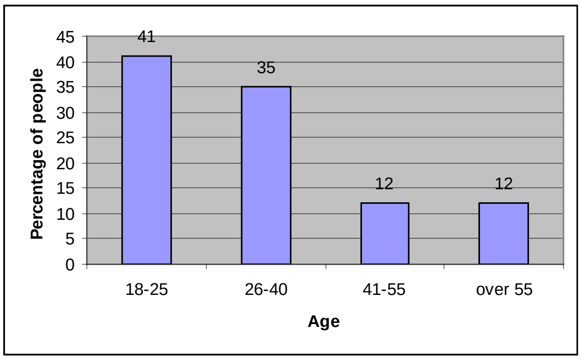

Figure 5-9 Range of ages of the participants

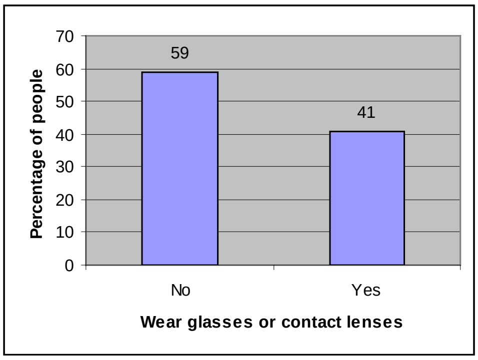

Figure 5-10 Near-sighted situation

5.3.1.2 Persona

In the light of obtained target users' profiles in the survey, a dummy figure – the persona can be conceived by centralising their significant characteristics. The benefits of persona creation lie in representing important features of diverse end users. It is thus convenient to understand and communicate users' information throughout design process (Pruitt, 2006). This persona is the targeted end user for the UCD of this study. Its description is as follows:

Joe Obama is a 38-year-old senior consultant in a construction consultancy. He obtained a Bachelor's degree in civil engineering from his university 15 years ago. His daily work is to create 3D building model by translating clients' 2D drafts for 3D visualisation. Besides this duty, he also provides services of generating detailed construction plans for his clients. 3D Studio MAX and AutoCAD are his major working tools in 3D modelling while Microsoft Project is his favourite utility to make project plans.

Because of geographically dispersed clients, he needs to contact them via the Internet. Being a good user in both 3D CAD and Internet applications, Joe is also skilful for software programming for better automating 3D modelling in his work. However, fast-paced work and life enable him to gain new application skills only from ease-of-use for software. In order to catch up with the latest ICT advancement in the construction industry, he is now a part-time student at a university for studying the master's programme of virtual construction. Although he is a health man and pays much attention to the balance of work and life, he is addicted to attractive work and ICT technologies. These do harm to his eye sight that he has to wear contact lenses for working on the PC.

5.3.2 Platform analysis

The 4D application platform in this study takes the advantage of a networked semi-immersive VR system (Figure 5-11). Its hardware components consist of a server, one or more networked client PCs, an active stereo system, shutter glasses, and input devices. The active stereo system is a projector connected with a client PC so that to project stereoscopic images onto a displaying wall from the front side. The users therefore wear the shutter glasses to gain an immersive experience, and interact with projected virtual objects using input devices. Its software component is the 4D groupware under study, which is composed with a server side application and a client side application. A normal configuration is that the server and client side applications run separately in corresponding PCs. Alternatively, both of them can run in a server PC whilst other client PCs can only run the client application. In order to gain an insight for the VR system's user interface and interaction design, its platform capabilities and constraints are analysed as follows.

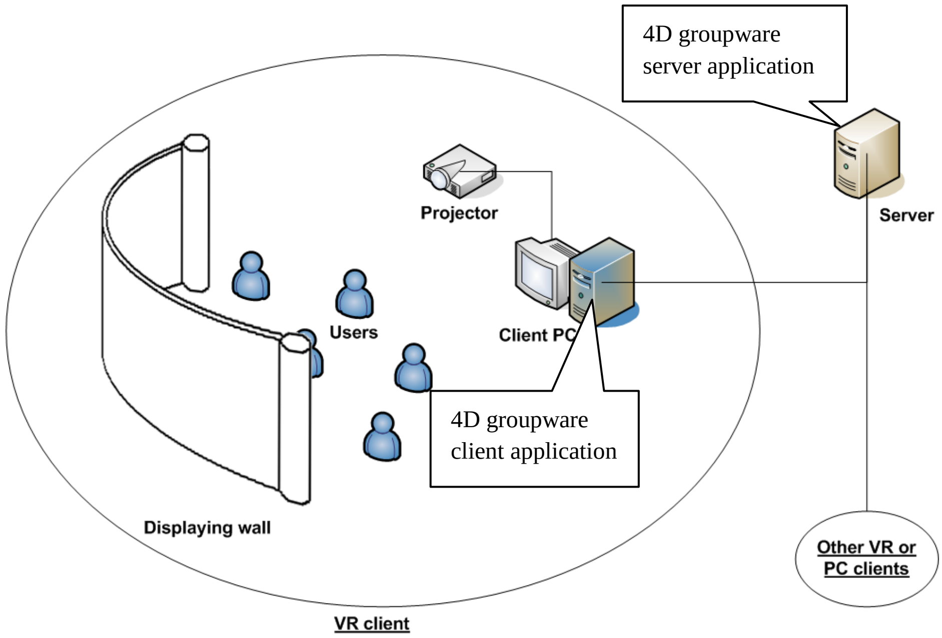

Figure 5-11 A semi-immersive VR configuration

5.3.2.1 Platform capabilities

The system intends to adopt a front-projected active stereo system as application platform. It uses a single display device (i.e. a graphics adapter and a projector) to generate stereoscopic images for the left and right eye alternately by front projection. The display of the images is synchronised with a device that ensures that the users see only the left image in the left eye and the right image in the right eye. The application, the graphics adapter's firmware and the graphics adapter's hardware must support this type of stereo through an interface that signals the end of a frame. The active stereo system of this study uses shutter glasses to direct the left and right eye images into the correct eye (Figure 5-12).

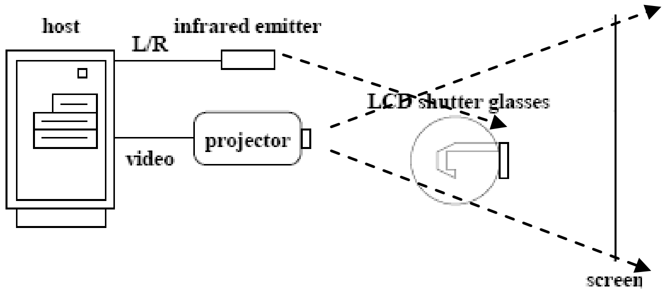

Figure 5-12 Active stereo system using shutter glasses (Adapted from Belleman, et al. 2001)

Shutter glasses use a liquid crystal material which can be turned opaque or transparent under hardware or software control. The glasses are controlled by the graphics system via wireless infra-red in synchronous with the rendered left/right images. Although this method of generating stereo images is the most commonly used, the shutter glasses can be expensive and often get uncomfortable over long periods of use.

The essential part of stereoscopic rendering is the generation of two video streams: one for the left eye and one for the right eye. The active stereo system can generate and manage stereo pair video streams. The common approach taken by most graphics adapter manufacturers is to use four frame buffers: images for the left and right eye are drawn into a "back" buffer while the user looks at the left and right images in the “front” buffer (commonly referred to as “quad buffered stereo”). Most 3D graphics adapters for OpenGL or Direct3D support quad buffered stereo in hardware, this support is available in the driver software for the MS Windows operating system.

5.3.2.2 Platform constraints

Being a front-projected active stereo system, it needs a certain space to project images onto the screen. It therefore creates a spacious place for multiple users to access the application at the same time. However, the users cannot get close to the screen because of possible occlusion (Figure 5-13). As the users can gain the sense of 3D immersion from the front screen, this kind of VR only brings the experience of semi-immersive VR. In order to avoid the side effect of occlusion, it is recommended to put the mount projector on the ceiling. Besides the standard mouse and keyboard, the spacious semi-immersive environment also allows remote control for operation. Wireless input devices with mobility are supportive for multiple users’ interactive activities.

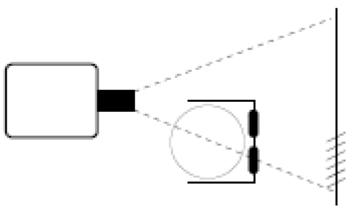

Figure 5-13 Occlusion generated by front projection (Belleman, et al. 2001)

Ray casting is one of effective interactive approaches for point devices to selecting 3D objects in the VR situation. It is considered to be adopted in the 4D groupware under study. The basic ray casting algorithm involves throwing a ray into the scene (Figure

5-14). For each pixel on the screen, a ray is cast from the eye, through that pixel, and into the image's world space. Then, every object in the scene is tested to see if the given ray intersects any of them. If there are multiple objects in a scene, it is possible that any given ray may intersect more than one object (if, for instance, one object is behind another). For each ray, the intersection that is nearest to the eye is the one that is visible to the eye (Hearn, 2003). Based on this algorithm, the user can use point devices to pick up/off desired 3D objects from the virtual environment.

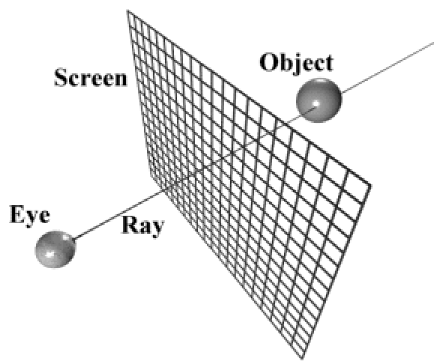

Figure 5-14 Ray casting

It is tested and verified in this research that the active stereo rendering mechanism has an effect on ray casting interaction technique. In a non-immersive VR condition, a point device can be represented by an avatar, e.g. a 2D cursor on the screen viewport. It is used for controlling a ray to intersect with 3D objects for selection operations. However, it only represents an endpoint of the ray in the immersive VR condition, in which the active stereo system can generate the 2D cursor to left and right eyes without stereoscopic depth. Because of this reason, users are prone to be misled in 3D objects' selection under the guidance of this endpoint in the 3D space. Thus a 3D ray needs to be generated to cast throughout the 3D world space for assisting 3D objects' selection for immersive VR application.

5.4 Summary

Functional and non-functional requirements are two facets for an information system development. They all contribute to product quality and success. This chapter takes both functional and non-functional requirements into consideration for a comprehensive study. In terms of functional requirement analysis, it identifies offline and online applications for use case modelling using the UML techniques. The former differentiates specific user tasks in individual planners' work whilst the later, incorporating the former, models collaborative operations from a group of users in the network condition. These user tasks' identification is based on the interactive definition method introduced in the previous chapter. In terms of non-functional requirement analysis, usability and platform constraints are particularly concentrated. It first analyses targeted construction professionals to gain their general profiles through a questionnaire survey. Four components of company situation, attitude & motivation, knowledge & experience, and physical characteristics are surveyed among the participants. As a result a persona is generated to represent these targeted populations for design communication. A semi-immersive VR platform capability is also discussed extensively. The front-projected active stereo system and ray casting interactive technique are highlighted to show their capabilities and constraints. The user study and platform analysis provide necessary guidance for 4D groupware prototyping, and its user interface/interaction design and evaluation.

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Chapter 6 System Development and Verification

6.1 Introduction

Since 4D technology initiation over a decade, almost all applications and studies are based on an independent system for individual planners. Their mainstream methods are to manually link an inputted 3D model with an existing project plan such that 3D model's elements - the PBS are connected with plan tasks –the WBS. 4D dynamic sequence simulation then can be generated using some third parties' toolkits. In this kind of 4D modelling, stand-alone tools are used for 3D modelling, scheduling, and 4D sequence generating separately. Such a fragmented working process is obviously inconvenient for networked collaboration. Targeting these problems, the interactive definition method presented in Chapter 4 delineates a viable approach to integrating these fragmented processes into a coherent, model-based simulation item definition process. Concentrating on a unique 3D model input in the method, the planners are able to conduct collaborative planning through effective social interaction and user-system interaction based on the network infrastructure. From a user's point of view, functional requirements about the utilisation of the interactive definition method are modelled in Chapter 5 applying the use case of UML techniques. This requirements' analysis specifies system functions to support users' work.

As a focus on functional aspect of this research, this chapter discusses a systematic 4D groupware solution about its functionalities. The proposition encompasses software architecture, application mode and data flow, and real-time data exchange protocol.

The software architecture ensures a server/client application model that planners can access to their local client applications to conduct real-time collaborative planning and simulation being connected by the server application. Related system modules and components in the software architecture including communication services, 4D item pool, event hub, and 4D builder. Related browsers and components are created in both server and client sides for the user's convenience in the server's management and the client's interactive operations. The specifications regarding these enablers are presented. A prototype named 4DX was implemented applying the object-oriented programming (OOP) method for the solution's realisation. The prototype is desktop-based application running in the server and client side respectively. They provide full functions specified in the use cases. In order to verify its functionalities and the feasibility of the interactive definition method, verification testing was conducted on the basis of local area network (LAN) system. This testing mimicked a real distributed collaborative planning with face-to-face communication convenience. The testing preparation, process, result and findings are discussed in this chapter.

6.2 Proposed system design

On the basis of foregoing conceptual discussion, a distributed 4D environment was developed to underpin those social-technical activities to achieve collaborative planning. It can be clarified from three aspects: system architecture, application mode, and data exchange protocol. The system architecture presents the main modules and components to support related collaborative activities. It also decides its application mode and data flow when performing collaborative work. In order to realise effective data transmission and user performance in the system, a set of data exchange protocols require stipulation. The proposed system aims at a non-BIM based 4D planning situation to discuss general collaborative conditions. The following contents specify these considerations.

6.2.1 Software architecture

The proposed system architecture consists of a client tier and a server tier (Figure 6-1). These two tiers own the modules of 4D builder and 4D item pool respectively. Both tiers also contain a module of communication services with related management components. Among these modules, the 4D builder in the client tier includes two components of 3D element container and simulation (SIMU) item container. They can provide PBS information for simulation item generation. The 4D builder also involves three components including file management, plan browser and 4D player for those containers' management and utilisation. In the server tier, the 4D item pool module owns three components of 3D element container, SIMU item synthesizer, and role-attribute reactor to provide collaborative information to the client tier. It links several components of browsers and file management. These four fundamental modules are all connected with an event hub module for data transmission between two tiers.

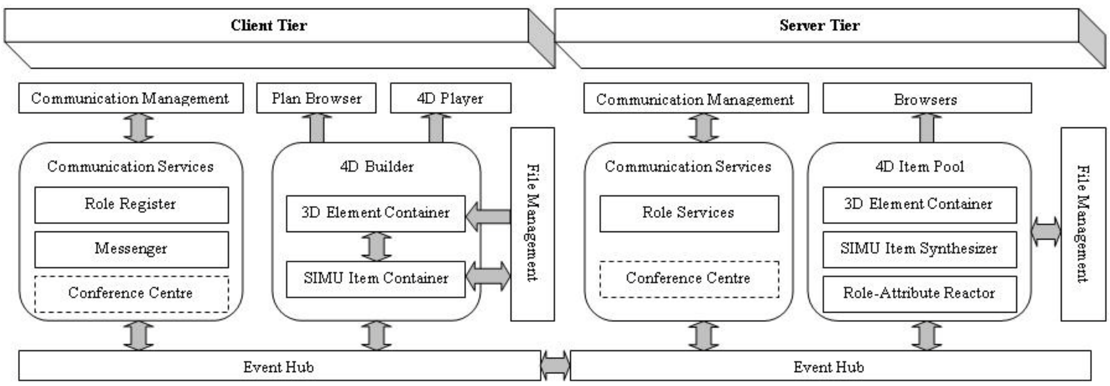


Figure 6-1 Software architecture

6.2.1.1 Event hub

The event hub is included in both the server tier and the client tier and takes responsibility for exchanging data between them. An event-based identifying, sending, and receiving mechanism is designed for the event hub to ensure effective data exchange. In order to achieve this aim, a set of components are created in the event hub including event enumerator, event identifier, data carrier, and exchange centre. The event enumerator defines a series of system events, which encompass any data operations and updates from both system and users. They help describe specific requests for data sending or receiving internally and externally, and then choose corresponding operations. The event identifier functions by getting an incoming event internally or externally, and interpreting it according to event definition by the event enumerator. As a result, the data carrier is triggered to choose a suitable data buffer for loading the coming data. This data is then passed to either the exchange centre for external transferring, or internal components directly (Figure 6-2). Both event hubs in the client tier and server tier adopt the same event-based mechanism. The only difference lies in their converse operations for data exchange, e.g. an event can result in a sending operation in the client tier whilst the same event can lead to a receiving operation in the server tier.

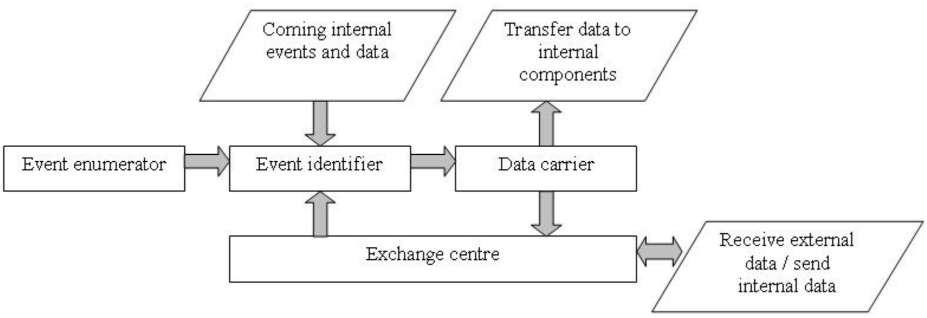


Figure 6-2 Event hub structure

6.2.1.2 Communication services

The communication services module is contained in both the client and the server tier. In the server tier, the module has the component of role services to provide speciality role definition for collaborators. In view of multidisciplinary collaboration in construction planning, collaborators need to explicitly choose their expertise in the planning process. The role services component in the server tier can record collaborators' role choices and their states in collaborative processes. The role definition is managed by the communication management component. It allows input/output or directly edit operation to manage speciality roles. Besides these role services, the communication services module is also in charge of server start or stop as well as data dispatching among collaborators. Underpinned by the event hub, the communication services module can identify incoming events' sources and destinations, and thus dispatch their carried data to right collaborators.

In the client tier, the communication services module consists of the components of the role register and the messenger. According to the user's speciality, the role register component enables collaborators to select a state and a role provided from the role services component in the server tier. It is also used for recording and displaying other collaborators' states. On the other hand, the messenger can support collaborators' communication through text chatting. By receiving data from the server tier, the messenger displays coming texts to local planners. It also ensures collaborators input text and send to targeted online planners via the server. Additionally, other advanced communication services like audio-video conferencing can be created in the conference centre component.

6.2.1.3 4D builder

The 4D builder module is located in the client tier to synthesize simulation items with 3D model elements. Its SIMU item container component contains a series of text-based task items to record defined WBS items and their associated PBS elements. Another component of the 3D element container possesses a series of 3D graphical elements to represent inputted PBS. Because a simulation item wraps PBS elements with WBS items together, the SIMU item container and the 3D element container are interrelated with each other. Every item in the SIMU item container can refer to its related 3D elements in the 3D element container, and vice versa. In the offline condition, these two containers can be managed by their file systems to input and/or output 3D model files and simulation item files respectively. In the online condition, the containers can be filled in through retrieving data from the 4D item pool in the server tier. Additionally, both of them in the client tier have a browser to view their contents. The browser of the 3D element container is also a 4D player. It can not only assist 3D model analysing and viewing, but also present a 4D simulation when defined simulation items are synthesized. The browser of the SIMU item container can help view defined simulation items and hierarchal plan structure, which is generated by a plan editor. The planner can define simulation items via this editor by inputting item parameters' values

6.2.1.4 4D item pool

The 4D item pool module is placed in the server tier with three components of 3D element container, role-attribute reactor, and SIMU item synthesizer. As a central data repository, these three components are designed to supply the client tier with unique 3D elements and their attributes, as well as synthesized simulation items. All of them provide content management through their own file systems, and each of them owns a browser for checking its content.

A simple 3D model browser can be used for checking the loaded 3D model in the 3D element container. It displays an overall 3D model profile for the administrator's management. Specific spatial information of the loaded 3D elements is unnecessary to show in the server tier. Nevertheless, their names need to be listed in the role-attribute browser to build correspondence between defined speciality roles and the 3D elements. This correspondence will help decide each 3D element's attribute for every defined role. The planners can thus perform simulation item definition according to generated 3D elements' attributes. The SIMU item synthesizer is applied for integrating defined simulation items from different planners. According to every defined item's specification and overall plan situations, the synthesizer will assign each item with a unique order to generate an integrated plan. Its browser can be applied for viewing the generated hierarchal plan.

The role-attribute reactor takes the responsibility of generating 3D elements' attributes – the PBS elements' attributes for each collaborator. As collaborators focus on their own PBS elements for task definition, the reactor can thus lead to such a result that only writable PBS elements of a collaborator can be defined with tasks. It means that collaborators ought to decide PBS elements read-write privilege beforehand so as to suit their planning specialities. In case an inputted 3D model owns building information, its PBS elements' read-write privilege for collaborators can be decided simply according to its internal differentiation. However, an inputted 3D model without building information requires a mechanism to identify PBS, and then decide its privilege for collaborators. In the proposed system, visual identification is a feasible way to realize this aim. Given a 3D model without building information, the role-attribute reactor ought to consider four possible visual identification results for attribute generation: Free (F), Readable (R), Writable (W), and Conflict (C). A specific element attribute value is dependent on all collaborators' selection results. This interrelated situation is illustrated in Table 6-1.

Situation	Collaborator A	Collaborator B	Collaborator C	Collaborator D
1	F	F	F	F
2	W	R	R	R
3	C(W)	C(W)	R	R

Table 6-1 Attribute values of a PBS element for different collaborators

Situation 1 in the table shows a PBS element initially is of free attribute for all collaborators. It can be selected by the collaborators to set the writable attribute if the element belongs to their domains. Once a PBS element – a 3D element is set with the writable attribute by only one collaborator e.g. collaborator A, then this element's attribute becomes readable for other collaborators. This condition is corresponding to the situation 2 in the table. In case a writable element is further picked out by another or more collaborators, this element then is in a conflict state. Its attribute is conflict for those co-owners but not other collaborators who do not select the element. It is still of the readable attribute for them. This condition is corresponding to the situation 3 in the table. Given an element with the conflict attribute, co-owners could give up their selections so that the element can be of either writable attribute for only one owner, or free attribute for all collaborators. This role-attribute reaction mechanism can dynamically generate a PBS element's attribute for every collaborator depending on all collaborators' selections. Its specific attribute is different from role to role. The administrator can monitor this assignment through the role-attribute browser.

6.2.2 Application mode and dataflow

The proposed distributed system architecture makes its application to be a server/client mode, in which the server owns the entire server tier whilst the client occupies the whole client tier. The server is a central data repository connecting with a series of clients (Figure 6-3). The connection between the server and the clients can be through the internet or local area network (LAN) depending on collaborative requirements. In view of adopting the file management system in the server side, one of the clients, possibly the main contractor, needs to be located in the same place with the server. Besides a planner's role in collaborative planning, the user of this client ought to play an administrator's role in maintaining the server's normal working.

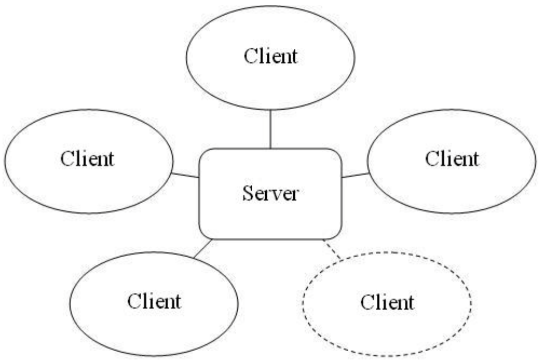


Figure 6-3 Server/client mode

The shared repository structure of the server/client mode implies that any collaborative work among clients needs the server's link. Data transmission between the server and the clients in the system follows three approaches of updated broadcast, direct transfer, and automatic retrieve. The updated broadcast and the direct transfer follow several procedures. Firstly, an operation is performed via a user interface of 4D builder or communication services in the client A. The conducted operation then carries some data from the 4D builder or communication services to the event hub. Secondly, the operation triggers its registered event to be dealt with by the event hub, and delivers the event and data via the network to the event hub of the server side. Afterwards, the server side can parse the transferred event and choose corresponding operations. These operations result in either updated broadcast or direct transfer to the client B. The former causes data updating in the 4D item pool and broadcast to all clients whilst the later causes data to be dispatched directly to target clients (Figure 6-4). Additionally, the automatic retrieve simply occurs when a client connects the server to get information from the 4D item pool. Its data flow is partly the same with that of the updated broadcast. The difference is that retrieved data are only transferred to the requested client but not to be broadcasted to other clients.

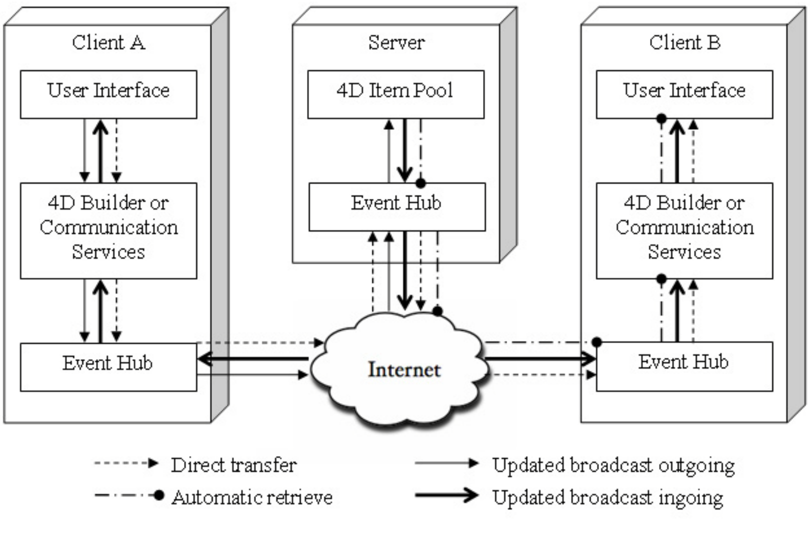


Figure 6-4 Data flow between the server and the clients

6.2.3 Real-time data exchange protocol

Given three data transfer approaches between the server and the client, a set of protocols are established to decide effective and efficient data exchange. These protocols can decide a data to be transferred following a right approach and reach its destination. These protocols include automatic data flood and controlled data transfer. The automatic data flood protocol is further differentiated into static data flood protocol and dynamic data flood protocol.

The static data flood protocol is applied to retrieve existing data directly from the 4D item pool of the server to the clients. These data, including the PBS items, their attributes, defined roles, and generated simulation items, are usually recorded and stored in the server side. When the user connects the server to log in, this data will automatically be retrieved from the server to the client. This static data transfer protocol follows the automatic retrieve approach to obtaining historical data from the server. Its transfer direction is singular from the server to a client.

The dynamic data flood protocol, on the other hand, follows the approach of the updated broadcast in order to transfer new generated information to the server for restore and synthesis, and further to broadcast to all online clients. This protocol is executed during the user's log in/off the server. When logging into the server, the user needs to input a user name, select a role and a working state. This new information will be sent to and recorded in the server, and broadcasted to other online users. Similarly, when a user leaves the server to log off, other online users will be informed instantly. During collaboration periods, moreover, newly updated PBS attributes and defined simulation items by a client also apply this protocol to broadcast them to all clients. Its transfer direction is multiple for all online clients. Both static and dynamic data transfer protocols maintain a unified real-time environment whenever collaborators join in, leave, and participate in collaborative work.

The controlled data transfer protocol works in the collaborative sessions of co-navigate, co-talk, and co-simulate. A significant feature of this protocol is that exchanged data is assistant information without the needs of restore and display in the server. The session holder can control the session's creation, termination, process, and contents whilst the session attendees are passive to receive this data. It has no influence on other online collaborators who are out of the session. Its data flow adopts the approach of direct transfer from the session holder to the session attendees. Therefore, its data transfer direction is limited within several related clients only.

Nevertheless, the controlled data transfer protocol is usually overlapped with the automatic data flood protocol in the collaborative sessions of co-sort and co-plan. In view of overhead data such as simulation items and PBS attributes generated in these sessions, the automatic data flood protocol is applied to broadcast this data to all online collaborators no matter whether they are in or out of collaborative sessions.

6.3 Implemented prototype of 4DX

In accordance with the rationale of the proposed system, a prototype named 4DX is implemented. Its development toolkits are Microsoft Visual C++ 8.0 (Visual Studio 2005), Winsock 2.0 (Microsoft, 2005), and Direct3D 9.0 (Microsoft, 2006). They are popular utilities for the Windows platform to create networked real-time 3D graphical applications, and compatible with most hardware. OOP is applied for the prototype implementation. The prototype consists of a server side application and a client side application running in the network condition. Its underlying communication is based on the TCP/IP protocol. The implementation results are presented as follows.

6.3.1 Server side application

The server side application constructs the server tier's modules of event hub, communication services, and 4D item pool. It integrates necessary collaborative planning information in the 4D item pool for retrieving and updating from client sides. This collaborative planning information includes 3D elements and their attributes, simulation items, as well as speciality roles. The management of these sorts of information is through separate file systems of the components of 3D element container, role-attribute reactor, SIMU item synthesizer, and role editor respectively. Each of these components provides a browser integrated in the user interface for content checking and managing (Figure 6-5).

A thumbnail 3D model browser is dedicated to the 3D element container. It provides a few basic 3D navigation operations such as zoom, pan, and rotate for simple browsing of a loaded 3D model. 3D elements' names are displayed in the browser of the role-attribute reactor when a 3D model is loaded in the server. The role-attribute browser can combine defined speciality roles to show the attribute of each 3D element while collaborators decide PBS elements' read-write privileges in their clients. The definition of a speciality role is through the role editor. Each defined role's state of occupied or not, its user's name and working state is displayed in the role browser. Moreover, the browser of the SIMU item synthesizer displays a synthesized result of simulation items in a text-based hierarchal structure. Additionally, the communication services component ensures the server communicate with its external clients. The administrator in the server side needs to specify an unoccupied communication port in advance for data exchange with the clients. Once the server is started, system states such as server start /stop, collaborator's log in/off, etc. are reported in an event window. Based on these transparent system states, the administrator can effectively manage the server and monitor its working conditions.

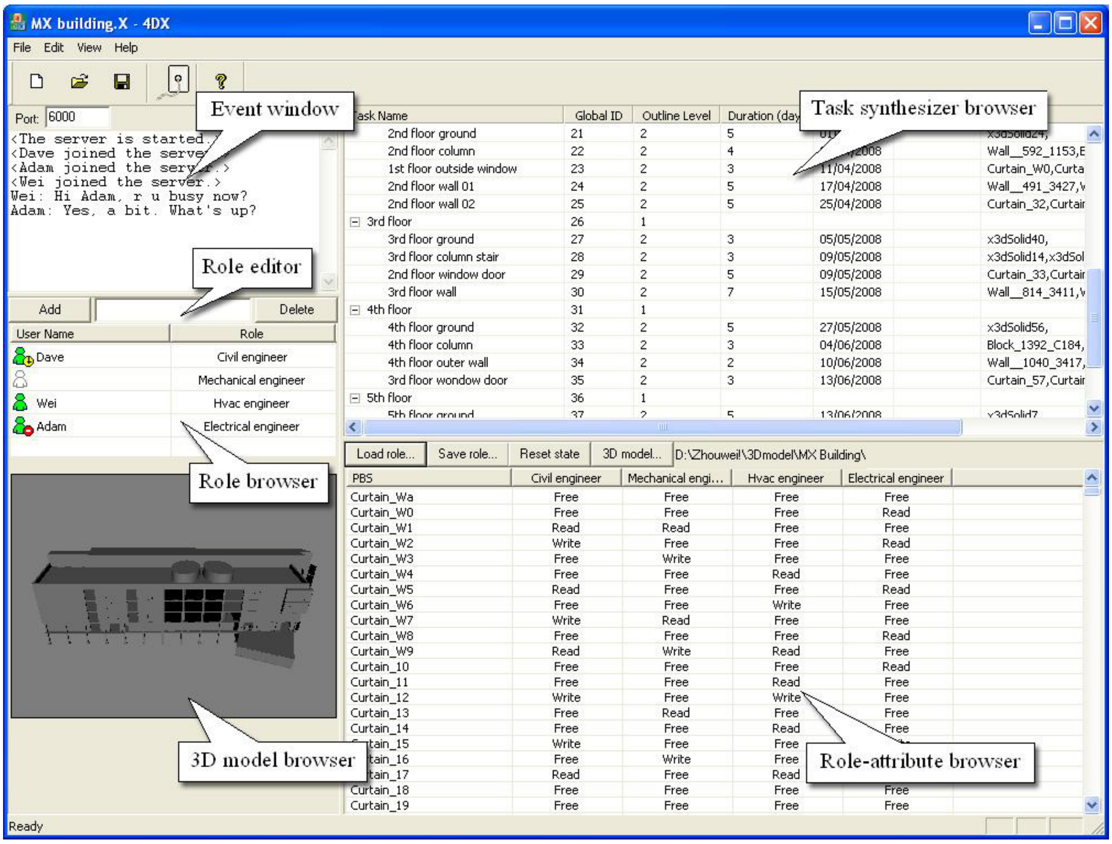


Figure 6-5 4DX server side application

6.3.2 Client side application

The client side application builds the client tier modules of 4D builder, communication services, and event hub. It enables multidisciplinary planners to conduct planning work in their local systems while communicating and collaborating with each other. Among these modules, the 4D builder supports planners' planning activities including 3D model analysis, simulation item definition, as well as 4D sequence generation. The communication services module allows planners to communicate with remote collaborators, such as server connection, role registration, text chatting, etc. The event hub module at a low level undertakes all data transmission to underpin high level operations from planners.

The client side application integrates the user interfaces of all the modules' components together (Figure 6-6). A communication panel is prepared for the user to connect the server, select a predefined speciality role, and list all online collaborators and their states. An instant messenger is also available for the planner to communicate with other online collaborators. A 3D-based planning environment is created as the 4D player for 3D model browsing and analysing, 3D elements picking, simulation item defining, and 4D simulation player. A loaded 3D model and plan from a local system can fill in the 3D element container and the SIMU item container. They are displayed in the 4D player and the plan browser respectively. The same result can be achieved by retrieving data from the 4D item pool in the server side when planners are connected with the server.

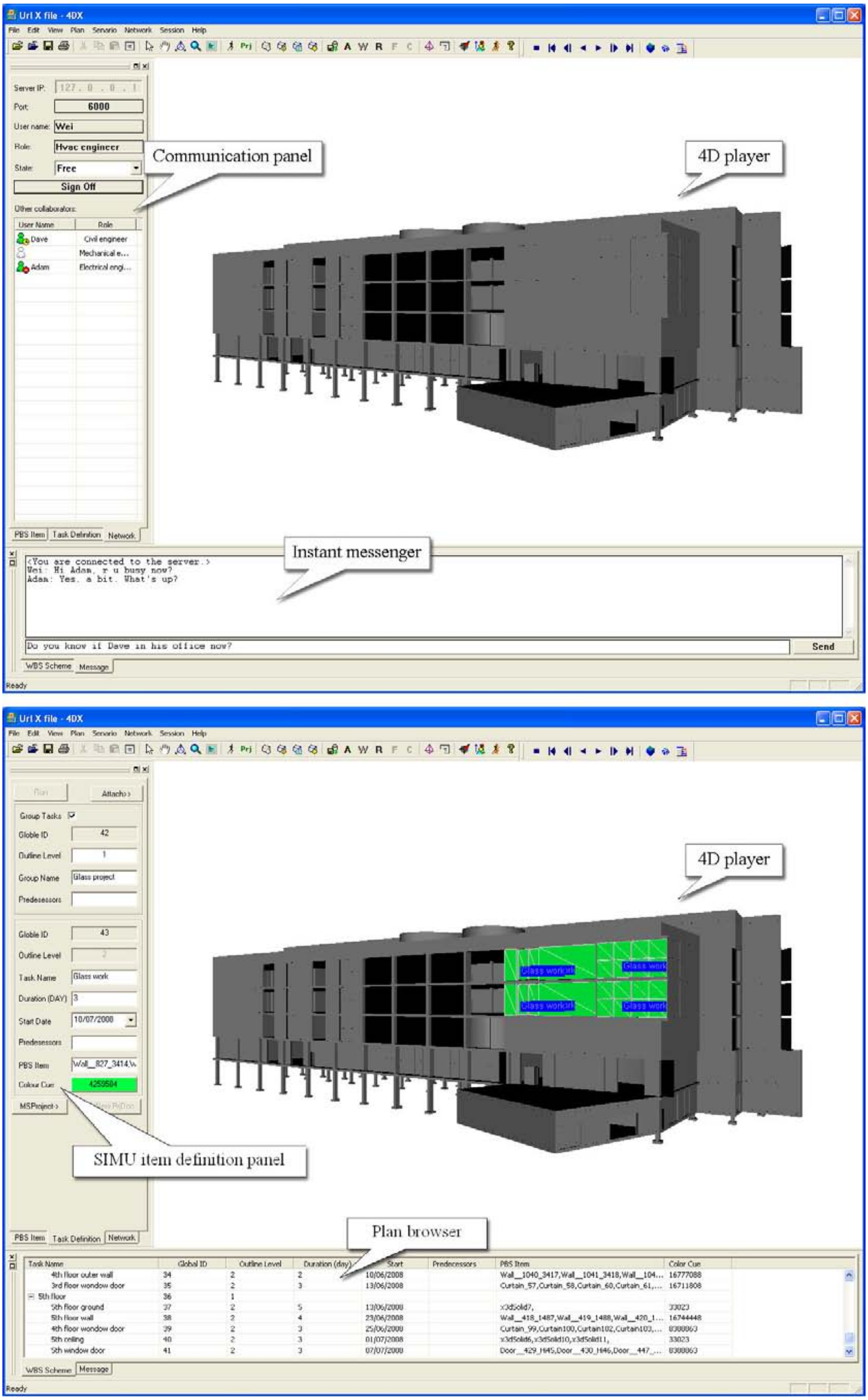


Figure 6-6 Integrated 3D-schudeling environment in 4DX client side

Applying the 4DX client application for creating a plan, planners can navigate and analyze the 3D model first in the 4D player via zoon, pan, and rotate operations. In view of the overlapped nature of 3D elements in the model, a topology displaying control is devised to help planners decompose the 3D model. It is able to control the 3D model's elements display one by one in a bottom-up or top-down order. Planners thus have chance to scrutinize every 3D element of the model for workplace identification. Once deciding a task definition, planners can pick up related 3D elements to specify the task via a definition panel. The defined task is then synthesized with picked 3D elements to be a simulation item. The newly created simulation item is automatically sent to the server for integration with other defined simulation items, and then received and recorded in the local SIMU item container. With created simulation items, the 4D player is thus available for detecting potential conflicts in the plan by its 4D simulation. Leveraging the network support, all these planning activities can be conducted across the network by collaborative sessions of co-navigate, co-sort, co-plan, co-simulate, and co-talk. Therefore, the planners' work is open-ended, communicated, and provides possibility to achieve a robust plan.

6.4 Verification test

A verification test was conducted to examine the feasibility of the interactive definition method and the created functionalities. For the convenience of the testing, a collocated 4DX system was configured to mock up a distributed planning situation, where planners focus on their own clients and collaborate with each other via the network simultaneously. The convenience of this initial approach lies in no geographical distance barrier so that collaborators can communicate face to face.

Thus, the testing can be under control and focus on critical issues of the method and software itself. The testing setup, process and result, as well as findings are discussed as follows.

6.4.1 Test setup

The testing configuration consists of two LAN-based PCs. Both of them run a 4DX client application, and one of the PC also runs a 4DX server application. A hub is used to connect both PCs in the same place so that the whole system creates a collocated collaborative environment for two planners (Figure 6-7). The testing targets a real 3D building model of the MX building, the University of Wolverhampton (Figure 6-8). The 3D model was originally created using Autodesk Architectural Desktop (ADT) without building information. It is composed of object entities but only geometry information is available. In order to be applicable for the 4DX system, the model is converted into the Microsoft .X format before the testing. Two participants join the testing as two planners. One participant acts as a structural planner to develop a plan for columns, ground and stair's construction. Another planner, concentrated on wall, window and door's construction. One of them also plays a role in administrating the server in the same PC. Therefore, two planners can collaborate with each other via the server connection. This collaborative planning requires two planners to perform their own work while considering their collaborators' spatial, temporal, and logical relationships. It is hence suitable to verify the essence of the interactive definition method.

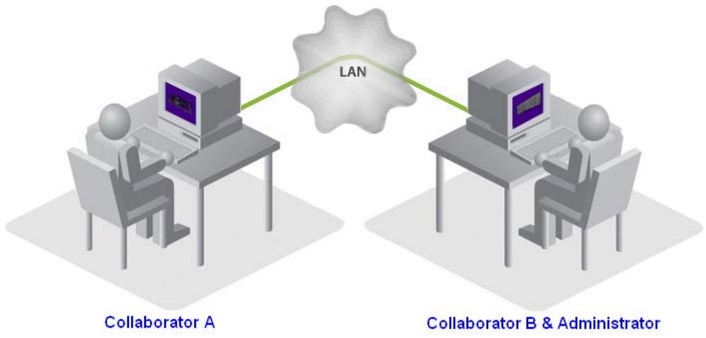


Figure 6-7 Verification test setup

Figure 6-8 3D model of MX building, the University of Wolverhampton

6.4.2 Preparation

Before the testing, preparations were conducted for speciality role definition and 3D model's building information sorting. As the planners specialize in two aspects for planning, two roles are defined as structural engineer and another team engineer in the server side. The 3D model of MX building is also loaded in the server. When the server starts, the planners then connect to the server and choose their roles respectively. Subsequently, the 3D model is automatically retrieved and displayed in their local systems supported by the static data flood protocol. Because the MX building model is of an object-rich 3D model without building information, the planners are required to classify the building information from the model to meet defined specialities' needs. The planners thus initiate the co-sort session to achieve this aim.

The co-sort session helps the planners decide their read-write privileges on related 3D elements by directly picking from their client sides. One of planners sends an invitation to another planner. The session is then created when the invitation is accepted. Leveraging the topology displaying control and co-navigation in the 4DX client, the planners can synchronously identify every 3D element and decide its read-write attribute. According to their predefined specialities, the structural engineer picks out columns, grounds and stairs while the other team engineer collects windows, doors and walls from the 3D model. Based on the dynamic data flood protocol, these client side's operation results are processed by the role-attribute reactor, and reflected in the role-attribute browser in the server side. Simultaneously, the processed results are broadcasted to the clients and shown on the 3D model. During the session, the planners discuss with each other to identify and decide related elements' attributes once conflicts emerge.

The read-write attribute of 3D elements is visualized in a different way in the server and the client. In the server side, concrete 3D elements' spatial information is omitted but their names are displayed in the role-attribute browser. Every read-write attribute of 3D elements is recorded as a text item. In the client side, the spatial information of the 3D elements' are specifically displayed. Their read-write attributes are mapped on the model using a colour code. The colour code stipulates that a writable element is displayed as grey-solid whilst a readable elements is displayed as black-mesh. Free elements have a green outline but conflict elements have a red outline (Figure 6-9). Applying this information visualization, the planners can identify, pick out, and filter out their own 3D elements for later task definition. The co-sort results from the two planners are illustrated in Figure 6-10.

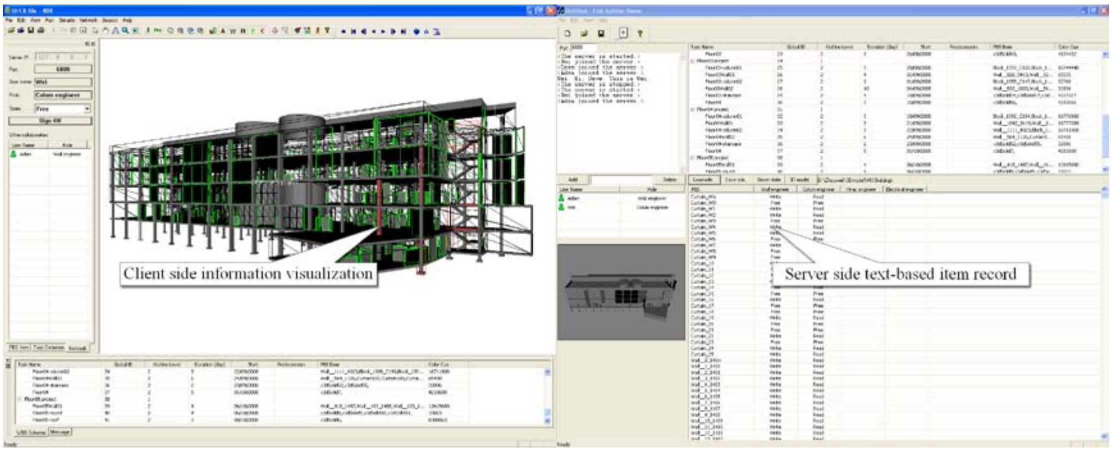


Figure 6-9 Information visualization of 3D elements' attributes in one of the clients

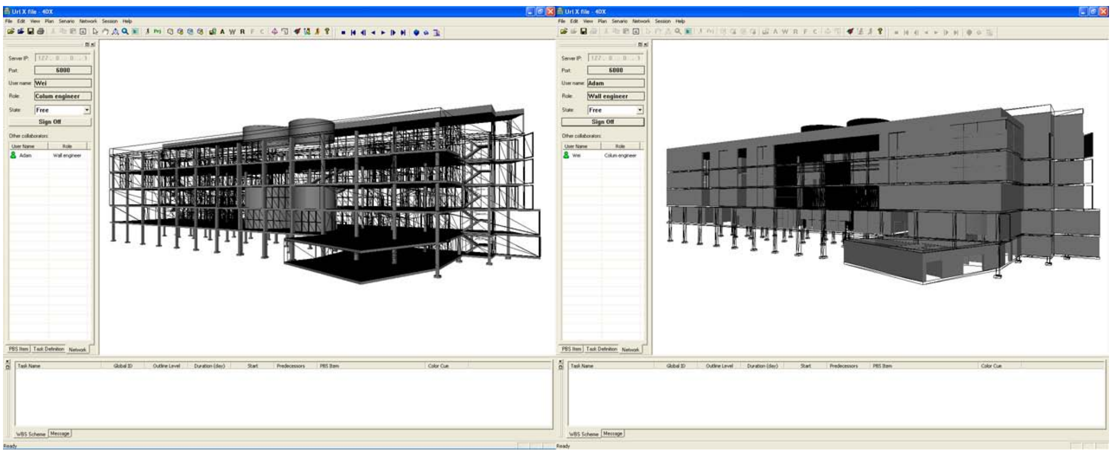


Figure 6-10 Co-sort result of the MX building displayed by two clients

6.4.3 Process and result

Given the sorted 3D model, the planners can proceed to task definition on their writable 3D elements. The definition follows the interactive approach of picking up the right PBS items from the 3D model, inputting simulation items' data via the SIMU item definition panel, and conducting instant simulation to check plan logical sequences. This definition process is based on the unconditional session of co-plan and the dynamic data flood protocol. Defined simulation items by the planners are automatically sent and synthesized in the server, and then broadcasted to other planners. These internal system operations are performed instantly so that the planners can not only get their own but other defined items from collaborators immediately. It also results in a consistent plan accessible in both clients and the server.

During the planning testing, 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 transferring lead 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 with a full simulation in the end. The generated simulation can be replayed for the project's communication and explanation (Figure 6-11). The final created plan is outputted into the MS Project, which shows a consistent hierarchical structure and a Gantt chart (Figure 6-12).

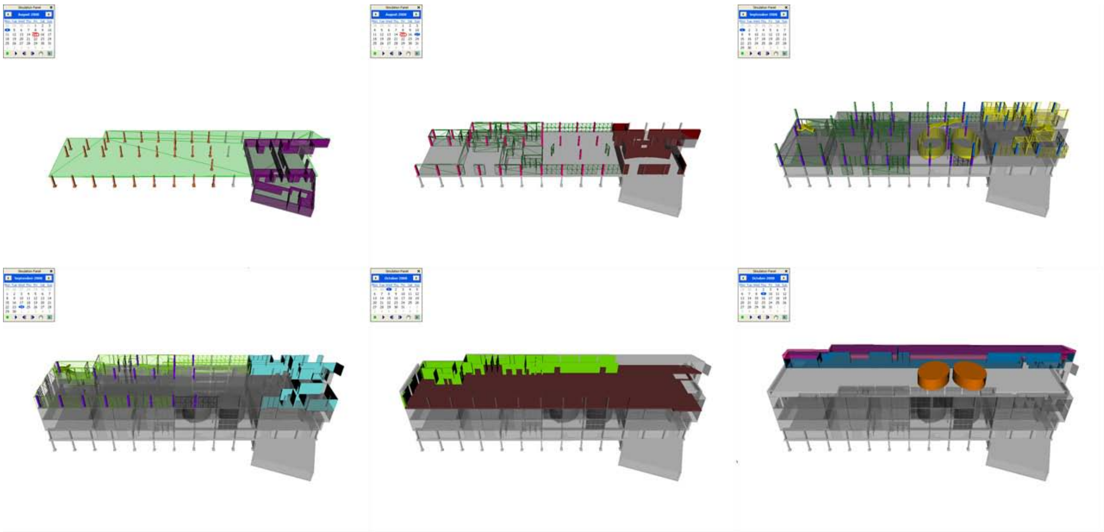


Figure 6-11 Generated 4D simulation sequence in the testing

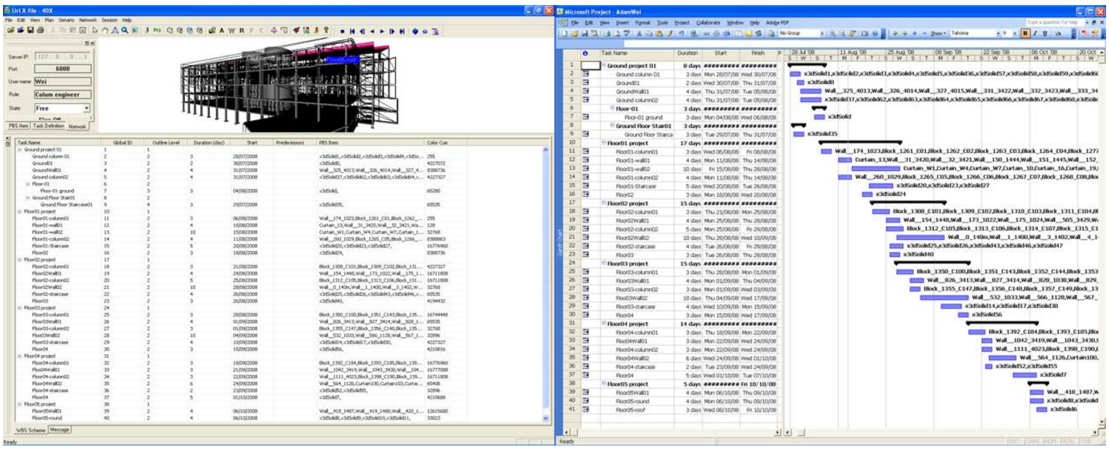


Figure 6-12 Consistent plan displayed in the 4DX and the MS Project

6.4.4 Test findings

Through the testing, some benefits are highlighted but some weaknesses are also exposed when applying the method. The testing shows that the co-sort is an applicable way to obtain PBS information from non-BIM 3D model. Nevertheless, it costs substantial time for collaborators to gain their desired building information. The MX building model has hundreds of 3D elements which are a heavy burden for manual picking. This negative issue advocates that applying BIM e.g. IFC-compliant 3D model in the method can be an effective solution to efficiently obtain PBS information. However, in view of lacking necessary technical and social supports at current time, this positive choice has to be delayed for future adoption. Because of the dominance of entity-based CAD model in the industry, the use of co-sort is still a helpful and generic way in the interactive definition method regardless the inputted 3D model has building information or not. 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 were applied throughout the whole collaboration process. It is disclosed from the testing that combining specific 4D planning methods, e.g. the interactive definition of this study, is the key to create effective CSCW for collaborative 4D planning.

The use of a unique 3D model to foster collaboration achieves a satisfactory result in the testing. Collaborators focus on the same model to conduct their own planning and consider constraints from each other. The structural planner is responsible for column, ground and stair's planning, which needs related wall plans from the other team planner, and vice versa. 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 the behaviours of the collaborators', real-time collaboration is a feasible approach to support collaborative planning. Social interaction is irreplaceable in this collaboration. In order to conveniently conduct the social interaction, the testing setup avoids the true distributed planning situation but using the collocated system to mock up. It clearly shows that the collaborators communicate with each other frequently while analysing the model and defining simulation items. The prevalent communication approach for social interaction is via verbal talking. The created co-talk of text-chatting has no chance to be used in the mock up condition. This phenomenon implies that audio, video-conferencing is a must for distributed real-time collaborative planning, especially the audio-conferencing.

The method's capability in LOD creation and management is also verified in the testing. Because the test targets collaborative planning, the plan creation was 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 at one time. 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 like AutoCAD, Microstation, etc., which demonstrate mature CAD operations in object or entity selection.

Additionally, instant simulation is effective to disclose potential conflicts in the planning process. Disclosed conflicts in the testing actually 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 reduces the conflict risk during the plan creation. Conflict detection in the 4DX prototype mainly relies on planner's subjective visual judgement. Seeking more reliable approaches, e.g. task collision detection, in the simulation is appreciated for conflicts' detection and elimination. Moreover, the creation of simulation item is verified to be a convenient way for the network transmission. The defined simulation item parameters can sufficiently support the whole plan's synthesis and the final simulation generation.

6.5 Summary

This chapter demonstrates a proposed 4D groupware solution from the perspective of system architecture design, implemented prototype, and verification test. In terms of software architecture design, the system consists of a server tier and a client tier. Both of them own an event hub for a low level's data exchange and transmission. A high level's communication service module in the server tier is designed for the server administrator to define roles in order to suit different planners' specialities in collaboration. In the client tier, this module provides the user with possibility to log in the server and thus to choose a specific role for collaboration. The software architecture also creates the key modules of 4D item pool in the server tier and 4D builder in the client tier. The 4D item pool in the server tier is used for retaining, updating, synthesizing, and broadcasting defined simulation items on each preserved PBS element. Correspondingly, the client tier allows the user to retrieve PBS elements from the 4D item pool in the server tier. The user thus can focus on the unique 3D model to perform simulation item definition supported by the 4D builder module. This kind of server/client software architecture design guarantees a distributed application model of server/client application. The server application is a central data repository connecting with a series of client applications. Planners though in different area can access to their local client applications to connect the server, which is able to transfer, update, and broadcast defined simulation items to all clients.

The real-time data exchange protocol in the software architecture defines a set of rules to control data flow between the server tier and the client tier. The protocol includes static data flood protocol, dynamic data flood protocol, and controlled data transfer protocol. The former two protocols belong to the automatic data flood protocol. The static data flood protocol is applied to retrieve existing data from the server to a specific client side, whilst dynamic data flood protocol is utilised to control new created data transmission from a client side to the server, and the server further broadcast them to other clients. The controlled data transfer protocol confines data flow within several dedicated clients only for collaboration. The transmitted data are occurred in collaborative sessions like co-navigate, co-talk, and co-simulate for an assistant purpose, and no need of being stored in the server. Usually the controlled data transfer protocol is mixed with dynamic data flood protocol in the collaborative sessions of co-sort and co-plan. As these two collaborative sessions bring both assistant data and new created data, the later type of data needs to be dealt with by the server.

The implemented prototype of 4DX adopts the OOP method to realise full functions designed in the software architecture. Through a mock up verification testing based on a LAN network, the prototype verifies the feasibility of the interactive definition method and the created functionalities. Some positive points are reflected in the testing from several aspects: applying BIM in the interactive definition method would significantly relief the burden of manually co-sorting building elements from the inputted 3D model; CSCW design is irreplaceable during the whole collaborative planning; the use of unique 3D model as only input can foster related social interaction for collaboration; The method's capability in LOD creation and management is suitable for both macro and micro planning; real-time collaborative planning in the testing demonstrates a robust approach to a conflict-free construction plan. The proposed software architecture is also verified to be applicable software design for distributed 4D CAD in real-time collaborative planning. Nevertheless, pitfalls shown in the testing also call further remedy in audio-video conferencing and flexible 3D element group creating.

Chapter 7 UI Design and Evaluation

7.1 Introduction

Being another focus on non-functional aspect of this research, the UI design of the 4D groupware system targets a semi-immersive VR environment to build a VR-enabled 4D system. The created desktop-based 4D system applies the Windows GUIs and standard point input devices like mouse to build its UIs. Nevertheless, the semi-immersive VR environment has different features and excellences such as projected display wall, capacity for mass audience, improved HCI, immersive effect, etc. which have been discussed in Chapter 5. In order to satisfy these non-functional requirements from the platform and end users, the proposed TC-UCD framework in Chapter 4 is applied for the UI design of VR-based 4D system. The design focus is placed on taking the advantage of better human computer interaction from the semi-immersive VR platform. According to the framework of the TC-UCD, key design practices consist of user study, conceptual design, Taguchi design (system design and parameter design), usability evaluation, confirmation test, and deployment. Chapter 5 have covered the non-functional requirement analysis about user study and platform capability analysis. This chapter concentrate on its rest parts for a discussion.

The Taguchi design practices discussed in this chapter is dedicated to obtaining optimal UI designs for the VR-based 4D system. In its system design, three main design factors are identified as picking method, editing approach, and navigation device. Moreover, two design levels are further clarified for each design factor based on the collaborative task analysis model for planning. Usability goals are hence specified to guide subsequent prototyping and evaluation. In its parameter design, a parallel prototyping is performed in accordance with the arrangement of orthogonal array $L_4(2^3)$. This selected orthogonal array leads to four prototypes for a partial factorial testing. The prototyping considers generic operations, collaborative and non-collaborative operations for related UI designs applying a designed scenario tasks. Followed usability tests are conducted on those parallel designed prototypes by a group of participants. Their testing data and feedback are compared and analysed using the within-individual analysis and the among-individual analysis. These analyses result in a final optimal UI design. A confirmation test is performed on the optimal UI design by reusing the scenario tasks applied in previous prototypes' tests. The result shows that the obtained optimal UI design achieved the predefined usability goals.

7.2 Taguchi design

In accordance with discussed TC-UCD framework in Chapter 4, the Taguchi design consists of system design and parameter design. The former is to identify influential design factors which have significant influences on usability. On the basis of this work, the later subsequently can proceed to prototyping and usability testing. Through data analysis of the testing result, it can lead to a final system with optimal UI designs. Both designs strive for creating a VR-based 4D planning system with optimal UI design. This section discusses critical considerations about the system design and the parameter design respectively.

7.2.1 System design

The system design in the TC-UCD framework encompasses identifying design factors, concrete task analysis, and differentiating design levels. The following contents discuss these issues in detail.

7.2.1.1 Design factors

The developed 4D groupware system in Chapter 6 demonstrates the essence and functionality of the interactive definition method. Through the verification testing, it can be discerned that the major work for planning and 4D simulation is simulation item editing during the planning process. Therefore, influential design factors for usability can be identified from related simulation item editing tasks. Following the principle of the interactive definition method as well as the model-based task analysis (Figure 4-2) in Chapter 4, an individual planner's work in the simulation item definition consists of two most often performed tasks of picking up desired 3D elements – the PBS elements and editing a simulation item such as define a new plan task, modify or delete an existing plan task, etc. Meanwhile, 3D navigation plays a key role in these operations that the planner needs to constantly manipulate the 3D model in order to build PBS element groups, identify potential workplaces for defining plan tasks, as well as edit possibly existing tasks. Given these major user operations, design factors are focused on picking method, editing approach, and 3D navigation device.

7.2.1.2 Collaborative task analysis

The task analysis model in Chapter 4 (Figure 4-2) illustrates a simulation item definition performed in an offline condition by an individual planner. Furthermore, in an online collaborative situation, the task model can be developed into a collaborative task model including both online and offline user's tasks. Collaborative tasks involve the interaction from both planners and collaborators at the same time. These online tasks are partially modelled using UML use case diagram in Chapter 5 (Figure 5-2) to explain necessary functions for the planner and the collaborator that the system needs to support. Applying the CTT method, this section further clarifies involved collaborative tasks in those use cases from a behavioural point of view. It is helpful to highlight the importance of identified design factors for the usability, and hence to obtain more specific design levels for the guidance of UI design in the next step.

- **Overview**

Collaborative task analysis consists of online planner's task analysis, online collaborator's task analysis, and their collaborative task analysis. The task model of online planner (Figure 7-1) illustrates the planner's tasks that can be conducted in the network condition. It is an extended CTT model which includes the offline planner's task analysis. The major tasks in the offline condition are navigate 3D building model, sort building information from the 3D model, edit simulation item, and simulate the construction plan. These tasks can be performed collaboratively in the online condition that the planner needs to perform the extra task of *select collaborators*, and then conduct the collaborative task of *select a cooperation*. The followed tasks then become co-navigate, co-sort, co-plan, co-simulate, etc.. Once choosing a kind of cooperation, the other tasks are the same with those of offline planning. It is worth a note that the task of navigate 3D model has a priority relationship of the concurrent with information exchange |[]| to other tasks of sort 3D model, edit simulation item, and simulate project. It means that the planner can perform navigation operations during these tasks' performance at the same time. This transparent operation also indicates that convenient 3D model navigation can significantly affects other tasks performance and system usability.

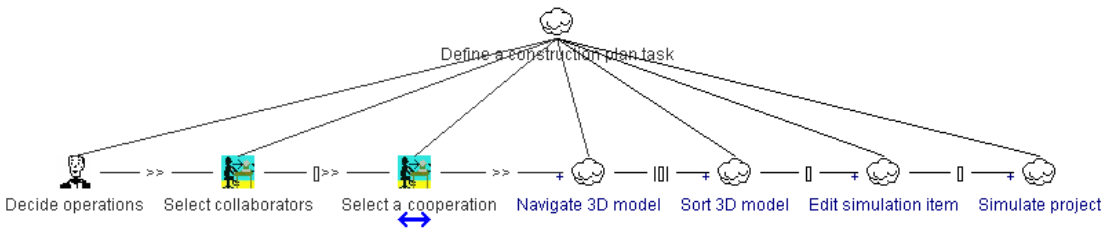


Figure 7-1 Task model of online planner

The online collaborator's task model (Figure 7-2) is almost the same with that of online planner's. The differences lie in no task of the select collaborators, and the collaborators must conduct the collaborative task of the *accept cooperation* to initiate a collaborative session of co-navigate, co-sort, co-plan, or co-simulate. During a collaborative session, collaborators are subject to the online planner in navigation and simulation progress control. However, they can still perform their own sorting, editing tasks in their local system. The importance of collaborative task between an online planner and other online collaborators is the connection of the task of *select a cooperation* with the task of *accept cooperation* from each side. This collaborative task, namely *provide collaboration* (Figure 7-3), actually builds a relationship between a collaborative session holder – the online planner and session attendees – the other collaborators. It models the conditional session creation procedure that session holder sends an invitation to intended collaborators, who then accept the invitation to start the collaborative session.

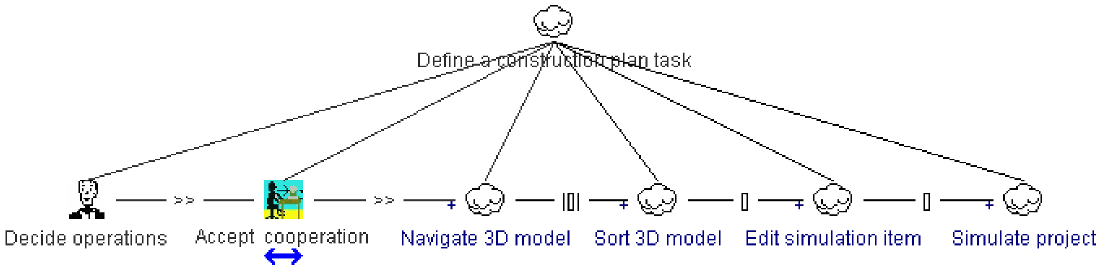


Figure 7-2 Task model of online collaborator's

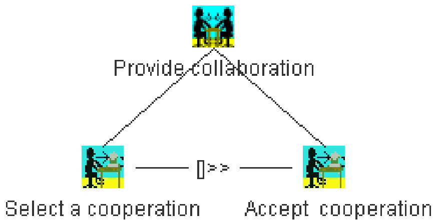


Figure 7-3 Task model of collaborative work

- **Navigate 3D model**

The task of navigate 3D model is composed of several user operations and system responses mutually (Figure 7-4). The user first can *choose a navigation command*, e.g. zoom in/off, pan, or rotate, then the system *shows an indication* such as a corresponding cursor on the screen, subsequently the user *operates the 3D model*, and synchronously the system *shows the model state* on the screen. This task sequence targets a normal mouse operation in a 3D environment. Nevertheless, applying the Logitech 3D mouse named SpaceNavigator can manipulate the 3D model directly without extra commands' supports. Therefore, the 3D navigation can be simplified to be a task sequence of *operate 3D model* and *show state*. Regarding the input device options of the standard mouse and the 3D mouse, it will be clarified further in another section.

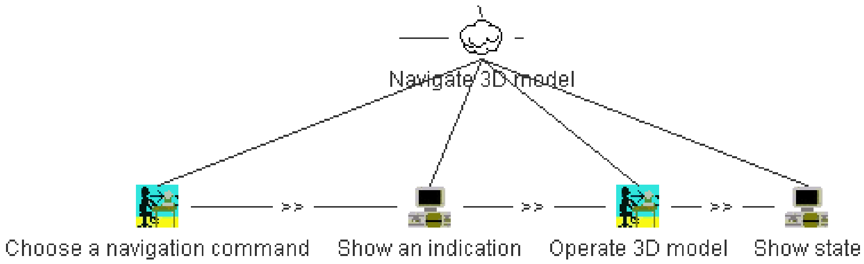


Figure 7-4 Task model of navigate 3D model

- **Sort 3D model**

In the proposed 4D solution of this study, an entity-based 3D model without building information is focused as the only input to develop a 4D-based construction plan. It needs a key procedure of visually sorting building information from the mass entities of the 3D model. The task of sort 3D model (Figure 7-5) consists of several user operations and system responses. The planner first needs to *choose a command* to trigger some visual clues on the 3D model displayed by the system. These visual clues include the outline of each entity and some filters for displaying identified entities. The system correspondingly can *show an indication* related to the user's operation on the model. On the basis of this building information visualisation, the user then can *pick up/off elements* from the model for later simulation item definition. Chosen entities in the 3D model accordingly can be shown with certain visual states so that user can perceive the chosen results. In the task of pick up/off 3D elements, the user can directly use mouse to conduct the operation. Besides this option, the implemented topological displaying for 3D model decomposing also provides the user with a choice to focus on and thus select a last displayed 3D entity during the displaying control process. This alternative of focus selection is also applicable for the editing new simulation item task that involves the 3D entities' picking operation.

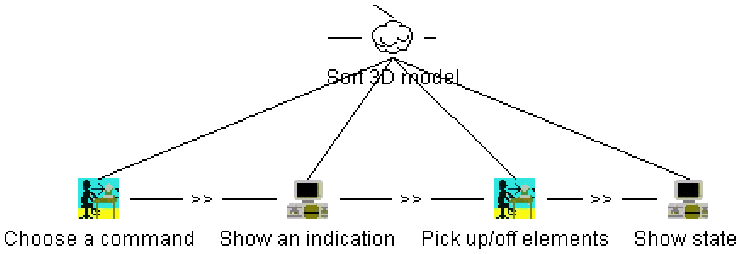


Figure 7-5 Task model of sort 3D model

- **Edit simulation item**

The task of edit simulation item (Figure 7-6) contains two meanings of modifying an existing simulation item and creating a new simulation item. As the essence of 4D CAD creation is about PBS-plus-WBS, the access to an existing item can be available from either PBS or WBS. From the entry of WBS, the user is able to browse a defined text plan and select a wanted task for modification, which is modelled as *select a task place*. This selected task then can be correspondingly mapped on the PBS - the 3D model as the workplace indicated by the task of *show the workplace*. Subsequently, the user can conduct some operations via on-screen buttons to modify a wanted simulation item as *conduct the task's operation*. The modified simulation item conversely can be updated in both WBS and PBS as *show operation result*.

From the entry of PBS, the user can gain an insight about defined WBS items on a specific PBS element. Thus the user needs to select a PBS element specifically using the standard mouse or the focus selection. Through a popup dialog box which is associated with the PBS element, the user can pick out a wanted WBS item to modify. These serial user’s tasks are modelled as *select a task place*. To be the selection result, the system can highlight this WBS item – the simulation item in both WBS and PBS as the task of *show the workplace*. The user then can continue to conduct modification operations modelled as *conduct the task’s operation*, and the final result is displayed in the updated WBS and PBS modelled as *show operation result*.

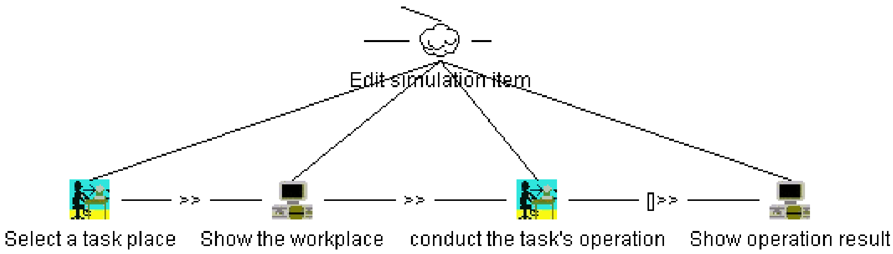


Figure 7-6 Task model of edit simulation item

The creation of a new simulation item is relevant to both PBS and WBS operations. The user ought to locate a hierarchical level in the WBS structure for the new defined item, and also select PBS elements as the task workplace. These two user tasks are modelled as *select a task place*. After the operation of *show the workplace* in the system, the user can further *conduct the task’s operation* via a popup dialog box or on-screen button for the new item’s definition. The defined item then is presented by the system operation of *show operation result*.

- **Perform 4D simulation**

The task of perform 4D simulation (Figure 7-7) illustrates the operation of simulating a created construction plan. When entering this task mode, the system ought to *show the project calendar* for the created plan. The user thus can *access the calendar* to control the simulation progress date by date. Accordingly, the system will *show the simulation states* on the screen.

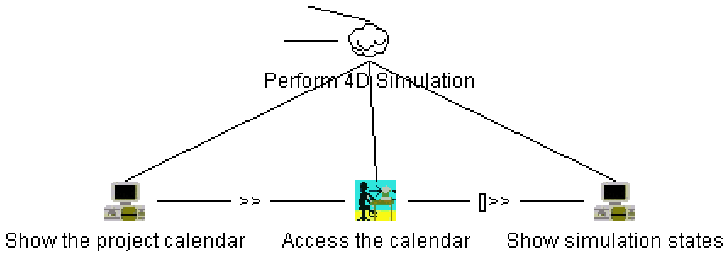


Figure 7-7 Task model of simulate project

7.2.1.3 Design levels

From the task analysis, the design factors of picking method, editing approach, and 3D navigation play a central role in the user's task performances. Picking method is applied in the tasks of sort 3D model and edit simulation item. Two applicable approaches are enumerated in these tasks as direct selection using the standard mouse and focus selection applying the topological displaying control. In terms of editing approach, two possible ways are discussed for targeting the WBS and the PBS entries respectively. One is text-based editing utilising on-screen buttons for the WBS entry. The other is graphics-based editing utilising popup dialog boxes for the PBS entry. Additionally, two feasible 3D navigation devices are identified as standard mouse and

3D mouse for 3D navigation. They are applicable throughout the whole plan definition process. These options in each design factor create specific design levels for design consideration. Each design level's features are discussed as follows.

- **Direct selection and focus selection**

The direct selection method can support the user to pick up/off wanted 3D elements from a 3D building model. A pointing input device such as standard mouse is able to help achieve this aim. In view of the spatially overlapped nature of 3D elements, normally the utilisation of this direct selection method needs assistance from 3D navigation and topological displaying control. Through these assistances, the user can perceive all the 3D elements in the model and thus has a chance to pick up wanted 3D elements. The advantages of this method are random, direct, and quick that the user can build 3D element selections for simulation item definition interactively and immediately. However, its disadvantages lie in relying heavily on the assistance from 3D navigation and topological displaying control, as well as accurately perceiving to make precise selection.

Being different from the direct selection method, the focus selection method can achieve the same aim of picking up wanted 3D elements from a 3D building model using screen button control. The user can take the advantage of the topological displaying control via on-screen buttons to control the 3D model's display. Through the control of bottom-up or top-down displaying, the system can display a higher or lower 3D element in the 3D coordinates before showing the next one. Thus the user has a chance to decide whether or not to pick up a current displayed element via pressing a button. Figure 7-8 illustrates this rationale that the tube is the currently displayed by highlighting its wire frame (a). Thus the use can select it and then continue to control the displaying to show the next one of the ball (b). If the user is interested in this geometry, the ball can be selected and then the next one of the torus (c) is proceeded to for further selection judgement.

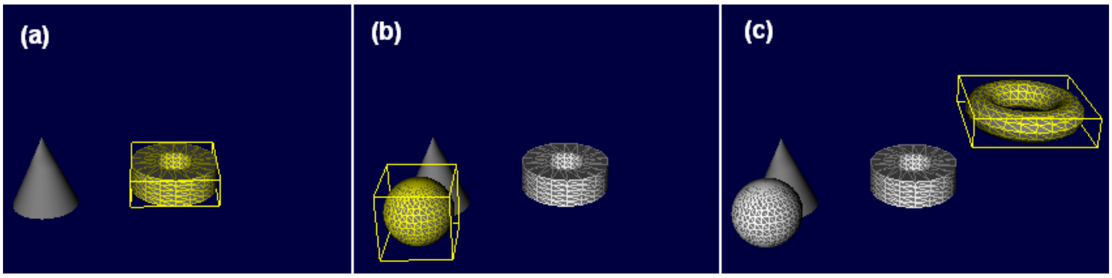


Figure 7-8 Rationale of focus selection

The advantage of this method is to make use of topological displaying to select elements when decomposing 3D model. The user can use some buttons to control the displaying progress such as go forward in single step or automatically, pause, or conversely go back in single step and automatically. Enhanced by some 3D graphical effects such as transparency, the user can always pick up wanted 3D elements even if they are hidden behind other elements. To this end, 3D navigation can be omitted when creating the 3D element selection to some extents. As the system can not neglect any 3D element's displaying, this method provides more accurate selection than the direct selection method which depends on the user's visual perception and judgement. Nevertheless, the disadvantage of this method lies in frequent displaying control and time cost.

- **Text-based editing and graphics-based editing**

The text-based editing targets the hierarchal plan structure which consists of text task items and hierarchal levels. This typical WBS structure can be edited using on-screen buttons for necessary operations including edit for a new or existing plan task, detach a task from a 3D element, delete a task from a 3D element selection, etc.. When performing related operations, the user needs to select an existing task from the WBS entry and then access on-screen functional buttons for operations. Subsequently, PBS – the 3D model is used for presenting editing results. This kind of editing approach is considered for the users who are familiar with project planning tools, such as MS Project or P3.

The graphics-based editing aims at 3D model for plan tasks' definition. In view of spatial relationship with each defined plan task, the user can access every task via a specific 3D element selection. An associated popup dialog box (Figure 7-9) can be designed to support related editing functions for defining a new task, modifying an existing one, detaching a task from an element, and deleting a task from one 3D element selection. When performing related operations, the user needs to choose a specific 3D element to be the PBS entry and then activate this popup dialog box for accessing functional buttons. The value of displaying the WBS using this method is in text presentation for the plan. As much editing work is based on 3D model operations, this graphics-based editing requires good skills in 3D navigation, and presumably more suitable for 3D designers.

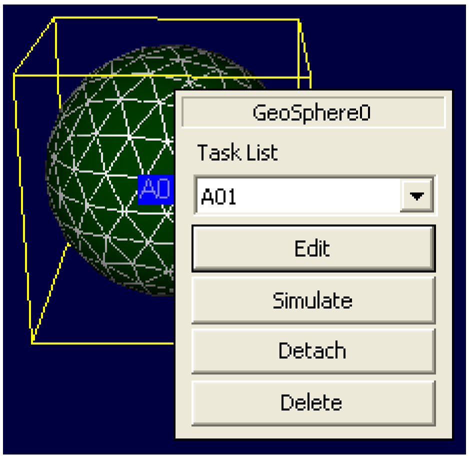


Figure 7-9 Popup dialog box associated with a selected 3D element

By creating a new plan task – the simulation item, the user needs to locate a hierarchal level for the defined task via the WBS entry. On the other hand, the user needs to activate a task definition edit box directly from an on-screen button, or from the 3D element-associated popup dialog box. The two options of both on-screen button and popup dialog box provide the same operation result of showing the definition item dialog box for the new item's creation.

- **Air mouse and 3D mouse**

Logitech Air mouse is an ideal pointing input device with mobility in the semi-immersive VR environment (Figure 7-10). As the semi-immersive VR based 4D system projects images on a display wall for a group of audiences, the use of air mouse can meet the user's need of mobility to present and explain projected contents in the front of audiences. The user can hold the mouse in the air to perform 3D navigation and simulation item definition like using standard mouse. Simultaneously, it can still be used as a normal mouse with a fixed position on the desk. Indicated in the task analysis, the use of the air mouse for 3D navigation needs a specific command for the operations of zoom in/out, pan and rotate. The user's operations for other task performances are inevitably interrupted if involving 3D navigation from the air mouse assistance.

Figure 7-10 Logitech air mouse manipulation

3D mouse is a dedicated peripheral input device for 3D navigation. It can accompany a standard mouse for 3D operations but cannot take the place of the standard mouse to perform other tasks. The selected 3D mouse is the Logitech SpaceNavigator which provides 6-freedom control in the space (Figure 7-11). The user can control these freedoms via finger movements on a controller cap. In accordance with the finger movements' analysis, the system will reflect the incremental values on the 3D model for rotation around X, Y, and Z axis, or movement in the direction of X, Y, and Z. Through this approach, the user can control 3D navigation while conducting other paralleled tasks synchronously without interruption. This 3D mouse is suitable for 3D experts with high desires for 3D performances.

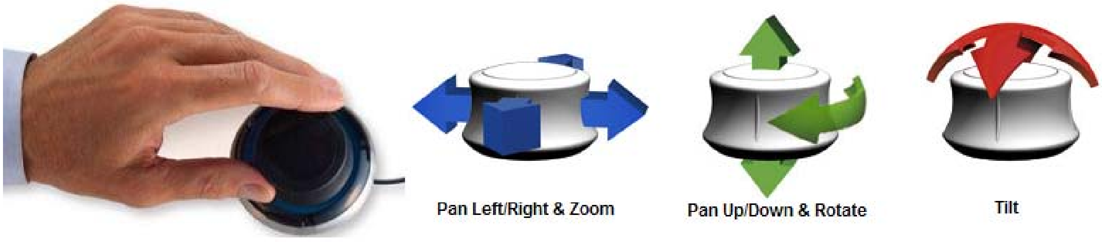


Figure 7-11 3D mouse manipulation

7.2.1.4 Usability goal

Based on the collaborative task analysis and the obtained user profile of Joe Obama in Chapter 5, the usability goals are specified in this section. In order to guide UI design and its usability testing, these goals are classified into qualitative and quantitative goals respectively. Quantitative goals are further specified to be ease-of-use in this study. These are objective and measurable for serving as acceptance criteria during usability evaluation.

In accordance with the generated persona, the targeted end users are IT literate construction professionals with busy working and living styles. Construction planning and 3D operation are their familiar working performances. The usability goal of this study thus is set to be **ease-of-use**. For the purpose of achieving this goal, the qualitative goals are listed below. In the meantime, high priority goals are marked with a tick.

- ❖ The system should integrate planners' tasks, as opposed to integrating underlying technology.

- ❖ The system should recognise planners from different disciplines involved in a construct project.
- ❖ The system should facilitate group operations.
- ❖ Using the system should require knowledge transfer from prior project planning toolkits.
- ✓ The design must support users' working in a virtual 3D environment, in which a lot of 3D building elements being displayed on screen to remind users where they are, proceed to, and focus on.
- ✓ The design must support users of a complex task. Thus, it must simplify task and be easy to deal with.
- ✓ The design must support users by visually identifying defined schedule items and progress differences when simulation is in process. Therefore, it must be self-explanatory and easy to remember and trace.
- ✓ The design ought to ensure users' 3D manipulations are precise, predictable, and self-adaptable.
- ✓ The design must allow users to be aware of performances from collaborators in the same 3D context, and keep users collaboration always in transparent states.
- ❖ The design would allow enhanced communication with remote communication supports.
- ❖ The design would keep consistency and low threshold between new 3D-based and traditional planning toolkits.
- ❖ The design would ensure smooth transfer among users' tasks with different attributes, and keep consistency in operation context.

In terms of effectiveness, efficiency and satisfaction in the usability definition, quantitative goals are concerned with satisfaction and effectiveness in the proposed system's usability considerations. In view of collaborative nature of the system, time and speed issues from the users' operations are of minor influences on its usability. Normally, collaborative work needs to cost significant time contrasting to non-collaborative work. In order to measure, evaluate and quantify satisfaction and effectiveness, a questionnaire and performance measure can be applied to gain related quantification. As satisfaction is a kind of subjective issue, it is can be measured using a questionnaire with a 5-point likert scale ranging from lowest "Not at all satisfied" to highest "Extremely satisfied." The designed questionnaire can be seen in Appendix 3. On the other hand, effectiveness is relevant to errors occurred in users' operations, thus its measure adopts task performance. These two usability goals are specified below.

- **Satisfaction**

1) Users should rate a higher scale on their navigation in term of ease-of-learning, 3D element selection in term of ease-of-use;

2) Users should rate a highest scale on plan item definition in term of ease-of-learning and higher scale in term of ease-of-use;

3) Users should rate a higher scale on plan items' visualisation and simulation in terms of ease-of-use;

4) Users should rate a higher scale on collaborators' states in terms of ease-of-use;

5) Users should rate a higher scale regarding collaborators' assistance;

6) Users should rate a higher scale regarding information visualisation in simulation;

7) Users should rate a higher scale in using input device for navigation, task item definition, and simulation checking

- **Effectiveness**

1) The user should make no error in task editing;

2) 100% users should complete tasks successfully;

7.2.2 Parameter design

From a design point of view, the identified design levels provide multiple options for the UI design decision of VR-based collaborative 4D planning system. The choice of right design levels among all the options is the matter of design trades-off that a final design decision ought to satisfy the defined usability goals. In accordance with the obtained end user profile, the identified design levels are expected to formulate acceptable designs for the target users. A convinced approach is through the usability testing to verify whether or not related design options can meet the defined usability goals. Following an orthogonal array arrangement for a parallel design testing, the parameter design in the TC-UCD framework is commitment to explore optimal design combinations for the end users.

7.2.2.1 Design of experiment

A suitable orthogonal array can arrange certain design factors and design levels to create a design space, in which optimal design combinations can be sought. The identified design factors have three items and each of them own two design levels (Table 7-1). In order to suit the need of design space creation, the orthogonal array of L_4 (2^3) (Table 7-2) is chosen to arrange these design factors and design levels. It thus can lead to four prototypes for the testing. Every prototype is composed of a group of design levels from three design factor respectively. Through this kind of partial factorial testing, optimal design combinations can be examined by these four prototypes without creating eight prototypes for a full factorial testing.

Level \ **Factor**	**Factor 1:** picking method	**Factor 2:** editing approach	**Factor 3:** 3D navigation device
1	direct selection	graphics-based	3D mouse
2	focus selection	text-based	air mouse

Table 7-1 Design factors and design levels

Test	**Factor 1**	**Factor 2**	**Factor 3**
Prototype 1	**Level 1**: direct selection	**Level 1**: graphics-based	**Level 1: 3D mouse**
Prototype 2	**Level 1**: direct selection	**Level 2**: text-based	**Level 2: air mouse**
Prototype 3	**Level 2**: focus selection	**Level 1**: graphics-based	**Level 2: air mouse**
Prototype 4	**Level 2:** focus selection	**Level 2:** text-based	**Level 1:** 3D mouse

Table 7-2 L_4 (2^3) orthogonal array

7.2.2.2 Prototype

The prototyping follows the stipulation of the orthogonal array of L_4 (2^3), which arranges related design factors' levels to formulate a set of diverse designs in the client side. Besides this design rationale, some design decisions are made in line with the platform capabilities and constraints as well as the task analysis. One of major considerations about the semi-immersive VR environment is that the projected image on the display wall declines its resolution and thus causes lower clarity than that of desktop system. Therefore, user's performance in planning ought to target a specific planning associated task at one time for better clarity rather than integrated multiple tasks like desktop-based 4D system. A group of planning associated tasks are differentiated as non-collaborative tasks and collaborative tasks depending on whether or not involving collaborators. Incorporating these concerns, a low-fi paper-based prototype was devised initially (Appendix 3). Based on this low-fi prototype, four working prototypes were implemented with related UI designs for assisting corresponded design levels' performances.

- **Generic operation**

A general consideration in the prototypes' designs is about some generic operations, which have fewer usability influences and are out of design scope to identify design factors and their levels. These sorts of operations include a unique entry to access either the remote server for networked 4D planning or the local file system for stand-alone 4D planning (Appendix 4-1). In case of selecting the networked 4D from the UI, the planner can log in the server via a dialog box (Appendix 4-2). The system can subsequently retrieve defined roles from the server, and bring a role selection dialog box to the client (Appendix 4-3). Other generic operations in the UI are the Network for assessing communication services, the Reload for retrieving 4D information from the server and refreshing the local 4D planning context, the Scenario for loading different plan schemes from the local system, the Exit for quitting the system, as well as the Performance for accessing the planning associated tasks. Defined collaborative planners are also listed as silhouettes on the right side of the screen. A colour scheme indicates their availability for collaboration in the layout illustration (Appendix 4-4).

Planning associated tasks, such as the non-collaborative tasks of Navigate, Sort, Plan, and Simulate, and collaborative tasks, such as Co-Navigate, Co-Sort, Co-Plan and Co-Simulate, are designed to be collaboration awareness to switch mutually. Once a collaborator listed in the right side is chosen by the user in the client, then the collaborative sessions are ready to launch (Appendix 4-5). Otherwise, only the non-collaborative tasks are available (Appendix 4-6). When a session holder launches a collaborative session from the UI, invited session attendees can receive an invitation presented in a dialog box (Appendix 4-7). They are able to select one of buttons in the dialog box for accepting or refusing the collaboration.

- **Navigate and Co-Navigate**

The design of Navigate and Co-Navigate involves two design levels of the air mouse and the 3D mouse in the design factor of 3D navigation device. In order to support the air mouse's operations, the specific commands of Zoom, Pan and Rotate buttons are presented on the screen for the user's choice (Appendix 4-6). Related mouse cursors are also differentiated into three types accordingly. However, 3D mouse's operations do not need users' commands. It therefore has no specific on-screen button presented (Appendix 4-7). These design decisions are applicable for the design of other planning associated tasks as they are all in need of 3D navigation operations.

- **Sort and Co-Sort**

The design of Sort and Co-Sort requests the design factor of picking method to obtain related 3D elements for later simulation item definition on them. For implementing the design level of direct selection, the design decision is about the mouse clicking left and right. The left clicking of the mouse indicates the elements' selection whilst the right clicking is confirmation choice. In order to assist the picking operation using the mouse, a group of topological displaying control buttons are presented on the screen. Their specific usages are described as the legend (Appendix 4-8).

In addition to the progress displaying controls, a group of state displaying filters are designed for filtering related 3D elements from the building model, and thus helping visual identification in the Sort and Co-Sort. Their specific usages are explained in the legend (Appendix 4-9). These progress displaying controls and state displaying filters are all adopted in the design implementation of focus selection. Comparing with the direct selection, the design of the focus selection uses the on-screen buttons of pick and accept to take the place of mouse clicking left and right respectively. A yellow outline mesh is applied to highlight and focus on a last displayed 3D element for selection decision.

- **Plan and Co-Plan**

The design factor of the editing approach is emphasised particularly in the Plan and Co-Plan designs. The WBS entry is designed as a plan task list on the screen so that the user can browse the whole text-based plan structure by clicking the up or down arrows (Appendix 4-10). The focused task's information is displayed in the task window, and its spatial information is presented on the 3D building model which provides the PBS entry for the user. In order to implement the design level of text-based plan tasks editing via the WBS entry, a set of on-screen buttons are designed as edit, detach, delete, etc. to edit the WBS items.

The design level of graphics-based plan tasks' editing is implemented via the popup dialog box in which related buttons are presented as edit, detach, delete, etc.. In view of graphics-based editing is closely related to specific PBS element's picking from the PBS entry, the popup dialog box's activation is accordingly dependant on the specific picking method levels. For the direct selection level, the user can use mouse left clicking to choose a PBS element, and right clicking to activate the dialog box. However, the use of focus selection design level is designed to left click the pick button to select a PBS element, and right click the pick button to activate the dialog box (Appendix 4-11). From the dropdown list window and the edit button in the popup dialog box, the user can either browse associated plan tasks for modification on the element or create a new task for definition.

- **Simulate and Co-Simulate**

In the Simulate and Co-Simulate designs, the involved design factors are the same with those of the Navigation and Co-Navigation. A significant design of the Simulate and Co-Simulate lies in its project calendar that the user can access the calendar to check the simulation state manually. For the convenience of simulation state checking, a set of button are presented on the screen. Their specific meanings are explained as the legend in the illustration (Appendix 4-12).

7.2.2.3 Task Scenario

For the purpose of usability testing, a task scenario is created to generate a construction plan (Figure 7-12) based on a 3D building model input. The 3D model is composed of some 3D entities like external walls, internal walls, staircase, handrail, window frames, doors, glasses etc. (Figure 7-13). By inputting the model in the four prototypes respectively, participants in the testing are requested to create the construction plan and modify them. Related plan tasks' information is listed in Table 7-3. As all design factors and their design levels are involved in planning working, the task scenario hence can be applicable for examining all possible design combinations through the parallel testing.

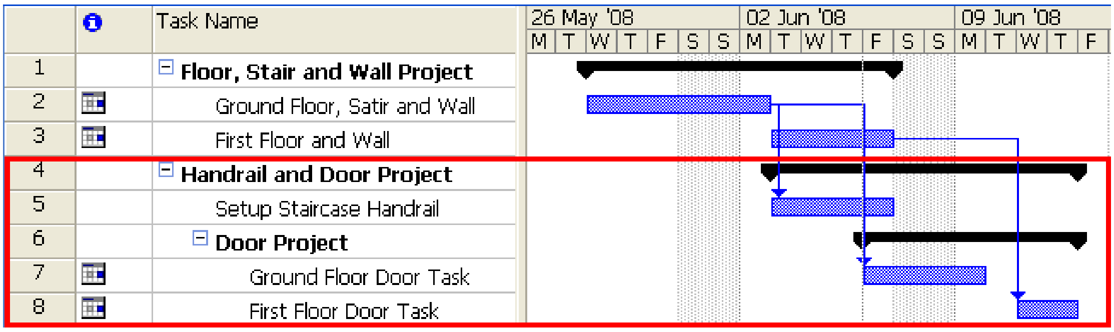


Figure 7-12 Bar chart of project plan in the task scenario

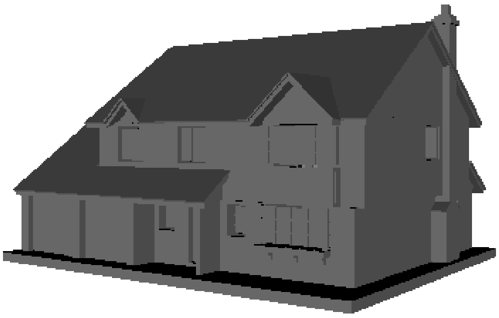


Figure 7-13 3D building model input

Task Name	Duration	Start Date	Predecessors
Handrail and Door Project			
Setup Staircase Handrail	4	03/06/08	2
Door Project			
Ground Floor Door Task	2	06/06/08	2
First Floor Door Task	2	11/06/08	3

Table 7-3 Project plan in the task scenario

The designed user tasks in the scenario consist of several editing tasks of create task, modify task and erase task. They are described as follows:

(1) Create task: you are going to define a *Handrail and Door Project* with a hierarchical structure:

- According to the desired bar chart illustration, please create the tasks on associated 3D elements and assign each task with a unique colour;

(2) Modify task: you hope to modify the defined task of *Setup Staircase Handrail*:

- Task name: *Install Handrail*;
- Colour cue: *another* one;
- Predecessors: *First Floor and Wall's ID*;

(3) Erase task: you want to eliminate the defined task from *Door Project:*

- Please *detach* the task of *Ground Floor Door Task* from any *2* door elements;
- Please *delete* the task of *First Floor Door Task*;

7.2.2.4 Testing process

The usability testing was performed on the basis of the implemented four prototypes. In accordance with the created task scenario, nine participants took part in the testing. These participants were drawn from the end users who also filled in the user profile questionnaire survey. Therefore, their knowledge and skills can meet the needs from the testing. Given the implemented four prototypes, every participant needs to perform the designed testing tasks in the prototypes one by one. In order to gain user's performance information during the testing, the tester concentrated on participants' operations to collect the testing data. After finishing all four trials in a test, the participant was asked to choose his or her most desired design level from each design factor. Some measures were taken during the testing so that to guarantee its validity. The specific testing setup and bias elimination are discussed below.

- **Testing setup**

The testing was based on a semi-immersive VR platform in the VR centre, the University of Wolverhampton. The prototypes were projected on a display wall (Figure 7-14) whilst the participant applied a wireless keyboard, an air mouse, or/and 3D mouse to interact with the system. In view of the input work requirement and the connected 3D mouse, the participant conducted testing in a fixed position in front of the display wall. The tester also sited aside to observe and direct the participant's operations. Because of the full functionality available in the implemented prototypes, the participant could actually operate the system to perform the tasks. Therefore, the evaluation method in the usability testing adopted performance measures to gain a quantitative result. Time cost and errors were chosen as indicators to measure efficiency and effectiveness about the user-system interaction. They were recorded and logged by the tester during the participant's task performances. The stop watch was used for recording time whilst errors' judgment was dependant on the tester's subjective decision. The collected testing data is used for result analysis and UI design optimization.

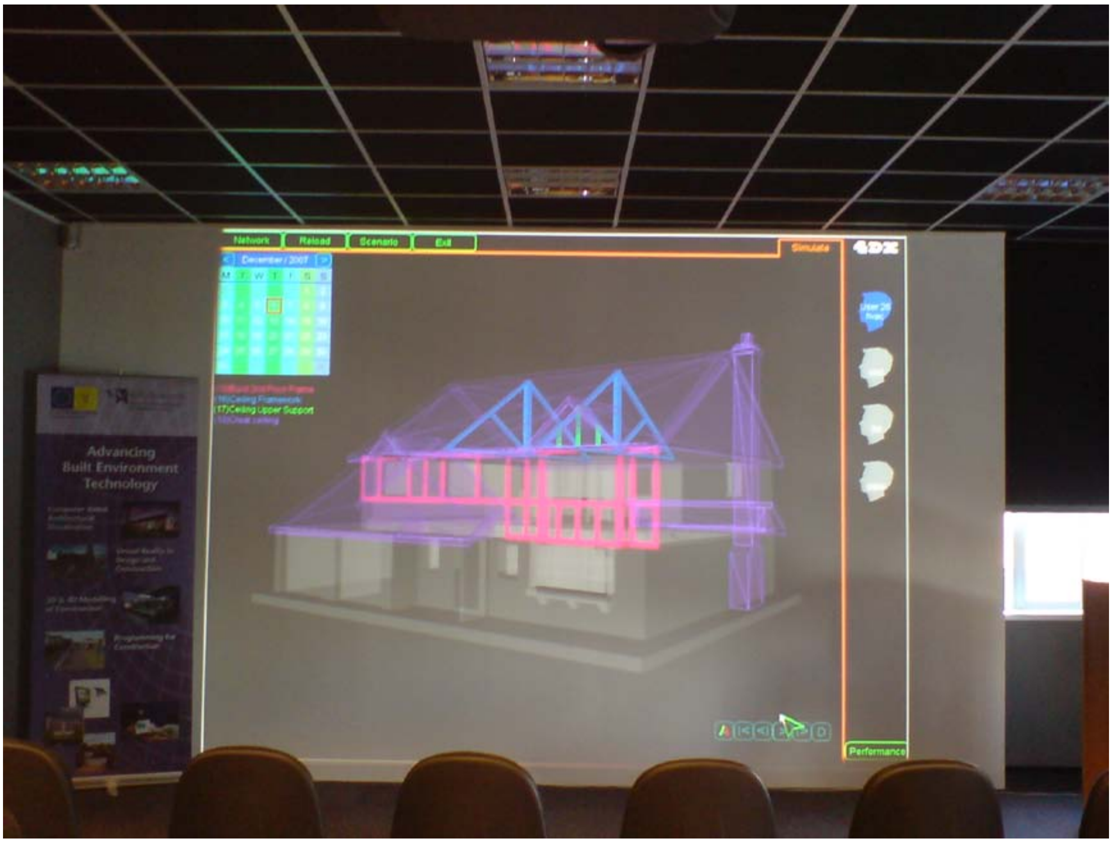


Figure 7-14 Testing setup in the semi-immersive VR environment

- **Bias elimination**

In order to gain a valid result from the usability testing and system optimisation, several controls were taken during the testing to avoid possible bias. Initially, the test intended to be conducted in the semi-immersive condition that the participants need to wear the glasses to gain immersive effects. Considering its side-effect of eye fatigue on the participants and design focus of improving interactivity, the real testing was conducted on the basis of the semi-immersive VR platform without immersive effects. The identified design factors and their design levels are objective issues that they can be under control during the testing. This feature ensured the parallel testing to be comparable and also complies with the fundamental requirements of the Taguchi Method application.

Single task scenario is another effective control to guarantee a comparable testing result. The participants performed the same tasks in each prototype during the testing. A comparison could be made among different prototypes based on the task performance. For the purpose of achieving the same familiarity in task performance, the coaching method as one of usability testing methods was applied for training the participants before the real testing took place. In accordance with the obtained user profile, the created design levels for UI designs were dedicated to expert users. In order to turn novice users of the system into expert users, the tester directed every participant to get familiar with the system before the testing was conducted in each prototype. After the participant got acquainted with a prototype, the real test then started and the participant's operations were recorded by the tester.

7.3 Testing data analysis

The analysis of test data consisted of within individual analysis and among individual analysis. For the convenience of data analysis, logging results of four trials in a testing are summarised into one table. The within-individual analysis is conducted based on the table in order to gain an optimal user interface/interaction design for a participant. Subsequently, the among-individual analysis is carried out so that to check the significance of optimal designs statistically from all the individuals' testing results.

7.3.1 Within-individual analysis

Table 7-4 is a testing result from one participant. The logging data for time cost and errors made are listed correspondingly in the efficiency and the effectiveness columns. According to the proposed S/N ratios analysis of the Taguchi Method in Chapter 4, the S/N ratios are used for measuring the effect of noise factors on performance characteristics. In this testing, the effect of the S/N ratios for efficiency and effectiveness is *the Smaller the Better*. It means that the less time cost and the fewer errors made in a trial, the better the corresponding design level is. Therefore, the data analysis can be performed by simply comparing two design levels' test results in efficiency and effectiveness respectively.

An example of the specific data analysis for a participant is as follows. To compare the direct selection and focus selection design levels in the picking method design factor, their total time cost regarding efficiency is 1064 and 1674 respectively in the test. Hence, the direct selection is better than the focus selection for this participant as it costs less time and thus more efficient in task performance. Similarly, the same design level of direct selection is also better than the focus selection in effectiveness because of fewer errors made (6 verses 13) and thus more effective. The same data analysis and interpretation are applicable for other design levels' analyses. The optimal user system design combinations for this participant therefore are A1B1C2 (Direct selection - Graphics editing - Air mouse) for efficient performance, and A1B2C2 (Direct selection - Text editing - Air mouse) for effective performance. The most satisfied design combination is chosen as A1B1C1 (Direct selection - Graphics editing – 3D mouse) by the participant in Table 7-5. The complete testing data analysis is in Appendix 5.

Trial \ Factor	Picking Method (A)		Editing Type (B)		Input Device (C)		Performance: Efficiency (second)	Performance: Effectiveness (error)
1	1) Direct selection		1) Graphics editing		1) 3D mouse		537	4
2	1) Direct selection		2) Text editing		2) Air mouse		527	2
3	2) Focus selection		1) Graphics editing		2) Air mouse		702	7
4	2) Focus selection		2) Text editing		1) 3D mouse		972	6
Y_{j1}	1064	6	1239	10	1509	10		
Y_{j2}	1674	13	1499	8	1229	9		
Optimal level	A1	A1	B1	B2	C2	C2	A1B1C2	A1B2C2
							Satisfaction	A1B1C1

Table 7-4 Testing result and within-individual analysis

(A) Picking method	(1) Direct selection ☑	(2) Focus selection □
(B) Editing type	(1) Graphics editing ☑	(2) Text editing □
(C) Input device	(1) 3D mouse ☑	(2) Air mouse □

Table 7-5 Testing result of satisfied design levels

7.3.2 Among-individual analysis

Based on the within individual analysis, all the obtained participants' optimal combinations in efficiency, effectiveness, and satisfaction fall into several categories (Table 7-6, Table 7-7, and Table 7-8). Among these optimal combinations, it needs to verify whether or not there exist optimal combinations in those usability items applicable for all the users. From the statistical point of view, the problem surrounds whether it is reasonable to believe these obtained combinations are from expected combinations. Essentially, this is one-sample goodness-of-fit test for categorical measurement. The TC-UCD method introduces the chi-square hypothesis testing to answer this question. The hypothesis testing results are also presented in the tables. These results conclude that only the design level of direct selection shows significance statistically in user's satisfaction. It thus can refuse the design level of focus selection in the picking method design factor. As for other design levels in rest design factors, it is necessary to integrate all of them as the UI design for the final optimal 4D-VR solution.

Combination	A1B1C2	A1B2C1	A2B2C2	A1B1C1	A1B2C2
Frequency	1	5	1	1	1
$(O-E)^2/E$	0.356	5.69	0.356	0.356	0.356
Sum = SUM[$(O-E)^2/E$] = 7.11; df = 5-1=4; $p<0.05$ = 9.49; E = 9/5 = 1.8; **refuse**					

Table 7-6 Chi-square hypothesis testing result for efficiency

Combination	A1B2C2	A1B2C1	A1B1C2	A2B2C2	A2B2C1
Frequency	2.5	4	1	1	0.5
$(O\text{-}E)^2/E$	0.27	2.69	0.36	0.36	0.94
Sum = SUM[$(O\text{-}E)^2/E$] = 4.62; df = 5-1=4; p<0.05 = 9.49; E = 9/5 = 1.8; **refuse**					

Table 7-7 Chi-square hypothesis testing result for effectiveness

Combination	A		B		**C**	
Level	A1	A2	B1	B2	C1	C2
Frequency	9	0	6	3	7	2
$(O\text{-}E)^2/E$	4.5	4.5	0.5	0.5	1.39	1.39
	Sum = 9; p>0.05= 3.84; **Accept**		Sum = 1.0; p<0.05= 3.84; **refuse**		Sum = 2.78; p<0.05= 3.84; **refuse**	
Sum = SUM[$(O\text{-}E)^2/E$] = 6.23; df = 2-1=1; E = 9/2 = 4.5						

Table 7-8 Chi-square hypothesis testing result for satisfaction

7.4 Optimal UI design

The hypothesis testing results provide the design decision that the final optimal UI design needs to integrate all the design levels from those design factors except the design level of focus selection. This optimal user system features the following design characteristics compared with previous prototypes.

Firstly, it provides both air mouse and 3D mouse operations for 3D navigation. It can suit 3D experts' skilful needs to use 3D mouse and also permit novice users' utilise command-based standard mouse for navigation. The UI designs about Navigation and

Co-Navigation still present on-screen buttons of zoom, pan and rotate. Secondly, it preserves the design of direct selection as the only picking method. Corresponded UI designs in Sort and Co-Sort keep the consistency with the prototypes which use the direct selection. This design decision is directly related the integration of text-based editing with graphics-based editing of the editing type design factor.

Because the text-based editing is WBS oriented whilst the graphics-based editing is PBS oriented, their integration for the user interface designs of Plan and Co-Plan follows the prototypes with on-screen buttons for the text-based editing. Simultaneously, they also support specific PBS elements' pointing by the mouse for editing from the popup dialog box. The buttons' functions on the dialog box keep the consistency with the on-screen buttons of the text-based editing. As the graphics-based editing only allows single PBS item's selection, the on-screen button of Pick in their user interfaces provides a switch function between multiple selection for new plan task's definition and single selection for specific task's editing from the PBS entry. Lastly, the Simulate and Co-Simulate UI design still cater for the air mouse operations but support the 3D mouse at the same time. The design of generic operations has no change.

7.5 Confirmation test

The confirmation test for optimal UI design was performed by inviting six participants, who took part in the previous usability testing and subsequently had knowledge of essential system operations. The participants are asked to repeat the tasks in the designed task scenarios on the optimal UI designs. In order to validate the test, the participants were still trained using the coaching method, and thus they got familiar with the optimal UI designs beforehand. During the testing, the tester recorded and logged participants' operations for post testing check. After the testing, every participant was requested to fill in a reflection questionnaire (Appendix 6) to get his or her feedback about related designs' usability.

The questionnaire was created with ten questions to measure the participants' subjective attitudes about satisfaction and effectiveness towards specific designs when they utilise the optimal UI. It requests the participants to rate a scale from the range of 1 to 5. Correspondingly, these likert scales are literally expressed as Strongly Disagree (1), Disagree (2), Neutral (3), Agree (4), and Strongly Agree (5). Indicated by the feedback (Appendix 7), the rated scales are all positive selections of either Agree or Strongly agree. Plotting these feedback selections on the questions, the produced graphics is marked with the percentage of participants who respond to each question (Figure 7-15). This empirical testing result verifies that the final optimal UI design has achieved its defined usability goals in terms of ease-of-learning and ease-of-use. The results also keep the consistency with the tester's logging results that 100% participants completed all the defined tasks in the testing.

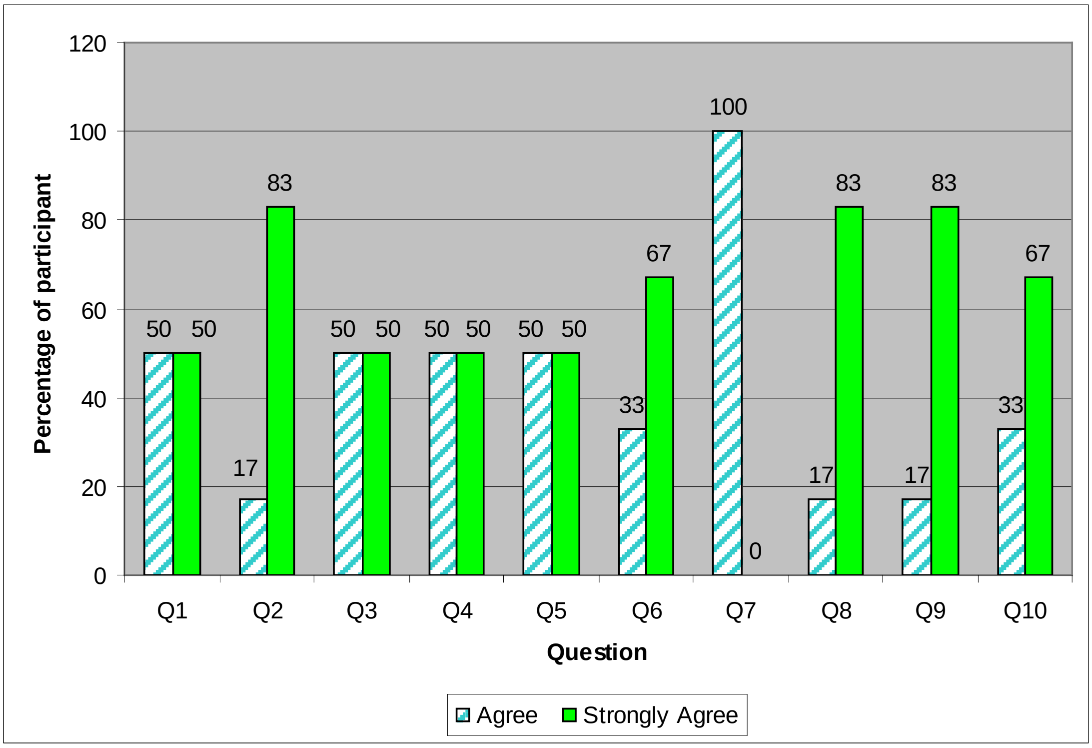


Figure 7-15 Results of confirmation test

Nevertheless, it was discovered in the testing that the forgetting rate about system operations causes an error in two participants. They overcame the error after the tester's reminding. It is believed that extensive training can improve end users familiarity with the new system, and can avoid minor errors significantly.

7.6 Summary

This chapter presents essential design activities to deliver a usable optimal UI design for the VR-based 4D planning system. The applied TC-UCD in this design practice consists of key procedures of requirement analysis, conceptual design, system design, parameter design, usability evaluation, confirmation test. In the meantime, the system design and the parameter design build the Taguchi design. Excepting the requirement analysis discussed in Chapter 5 including functional and non-functional analysis of user study and platform analysis, this chapter focuses on the rest parts for a continuous discussion.

The VR-based UI design was initiated from the system design in the Taguchi design. It identified three kinds of design factors of picking method, editing approach and navigation device. A followed design practice was task analysis. In view of targeting a collaborative planning activity, the task analysis adopted collaborative analysis to clarify related concurrent tasks from users. Correspondingly, two specific design levels of each design factor were differentiated into direct selection and focus selection for picking method, text-based editing and graphics-based editing for editing approach, air mouse and 3D mouse for navigation device. These design concerns led to the usability goals' definition consequently.

In the parameter design of the Taguchi design, the identified design factors and their levels built a design space by four structured parallel prototypes. The usability testing was conducted on those prototypes by a group of participants. An optimal design was sought through within-individual analysis, which was dedicated to optimal UI designs for individuals, and among-individual analysis, which was used for hypothesis testing to check the significance of obtained optimal designs. The final optimal UI design was the integration of all design levels excepting the focus selection. A confirmation test verified that the optimal UI design met the predefined usability goals.

Chapter 8 System validation and deployment

8.1 Introduction

The final VR-enabled 4D groupware system was validated in a truly geographically distributed condition. In this circumstance, planners focused on their own client systems to collaborate with each other across the Internet simultaneously. A multiparty video conferencing system named ooVoo was leveraged to bridge the gap among geographically distributed planners, who were not in the same place but still could communicate with each other face-to-face in real time during the planning process. In order to gain some suggestions for the system improvement, the validation also aimed to deploy the system to potential end users through their real utilisation. This section addresses the system's validation, results, deployment feedback and findings.

8.2 System configuration

In contrast to the verification test, there were a few significant differences in the system configuration for the validation test. Besides the geographically distributed condition and multiparty video conferencing system, the validation adopted the VR-enabled 4DX client with the optimal UI design based on the desktop VR platform. Although the UI design was tailored for the semi-immersive VR platform, it had compatibility and applicability for the desktop VR. For the purpose of convenient test, the client application however still targeted the PC platform. A high speed broadband network was involved to underpin network communication in the testing. Because ooVoo allows up to six people online to communicate at the same time, more collaborators thus can be engaged in the planning together. These differences require related hardware and software configurations to meet the needs of distributed collaborative 4D planning.

The standard client hardware configuration in the validation was a networked PC with dual-monitor connection (Figure 8-1). The dual-monitor setting was convenient for displaying both 4DX and ooVoo in one system. Additionally, other requirements for the PC were multimedia capability and Internet availability. Because of the requirements for video conferencing, the PC also needed to support the input/output of audio/video, therefore a webcam and a headset were configured in the PC as well. An extra monitor was used to connect the laptop for displaying the extended window from the laptop. A standard mouse and a keyboard were input devices in the system. However, the 3D mouse was excluded from the validation as it is not the standard input device and unpopular for mainstream PCs.

Based on the hardware configurations, one client PC ran both ooVoo and the 4DX client at the same time in the validation. The collaborator could operate them to deal with related tasks in the planning. The 4DX client adopted the optimal UI design in the validation. Particularly, the 4DX server ran in one of collaborators' PCs so that to provide services for all collaborators. In order to allow all collaborators to access the server, the server side PC was required to open a specific port for data transmission if there is a firewall in the PC. In most cases, anti-virus software in a PC can protect the system from external access. Hence, it is necessary to permit network traffic from the Internet during the testing.

Figure 8-1 Hardware configurations for the validation

8.3 Validation preparation

One of objectives of validation was to deploy the system to potential end users so that gain some feedback from professionals. There were five participants plus two testers taking part in the validation in three sessions. In order to gain wide reflections, new participants were recruited for the validation and evaluation. They were all part-time and full-time students majoring in construction management or architecture visualisation, but they were all novice users of the 4DX. Testers were considered experts of the system to provide novice users with certain helps if needed during the testing.

The validation test has the similarities with the verification test in 3D model preparation and role definition. The 3D building model (Figure 7-13) and task scenario (Table 7-3) used for the optimal UI design were adopted again for the validation. This 3D model is simpler than the MX building, but still provides sufficient building information of 3D elements for testing purposes. According to the number of participants for the validation as well as types of 3D element in the 3D model, related roles were defined on the server side beforehand for all participants to play. As ooVoo ensures six people to be online for real-time communication, the number of role for the validation was limited in six participants in one test session.

In order to streamline the testing process, all participants were advised to get familiar with the 4DX system in advance. During the testing process, participants were located in different buildings at the University of Wolverhampton campuses, which provide unlimited wireless Internet access for all users. One of the testers on the server side played an administration role in the server management and also a control role in the testing. A questionnaire was prepared for participants to fill in after the validation test. It was designed to gain feedback regarding the system usability in accordance with their experiences in the validation.

8.4 Validation process and result

The validation process encompassed three procedures including co-sort, co-plan, and co-simulate. Co-talk was performed using the ooVoo throughout the whole validation process. One of the validation sessions contained four people and their roles were defined as structural planner, window planner, door planner, and glass planner for these four people. Being one of the planners, the control tester initiated the co-sort first so that all collaborators can pick up their 3D elements from the 3D building model. Taking advantage of the created building information visualisation by the system as well as real-time multiparty video conferencing from ooVoo, all planners successfully picked up their own 3D elements collaboratively across the Internet. The typical result is illustrated in Figure 8-2.

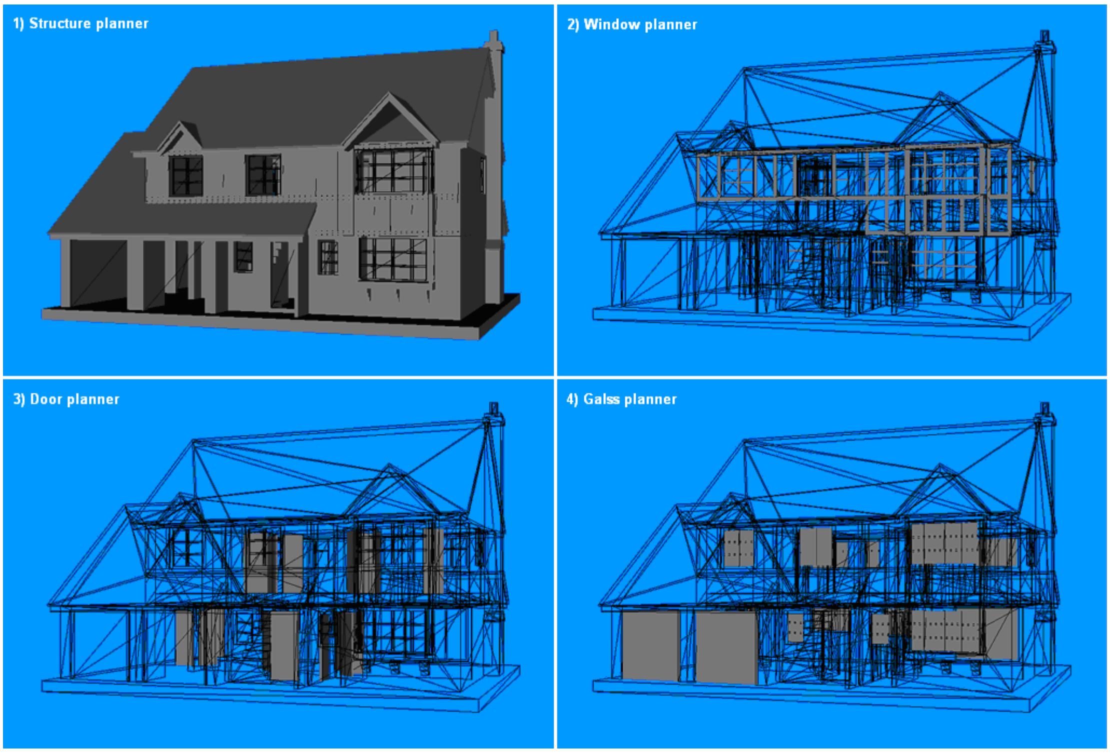


Figure 8-2 Co-sort results of four planners in the validation

After obtaining their own 3D building elements, collaborators then proceeded to co-plan to conduct collaborative planning. They focused on their own 3D elements to define simulation items. During this procedure, collaborators still maintained social interaction via the ooVoo to exchange planning strategies, adjusted their own definition, and proposed suggestions to other collaborators simultaneously. As they shared the same plan context, any update by any collaborator could be reflected on other collaborators' sides via the server transmission in real time. The screen shot of this co-plan working is illustrated in Figure 8-3. Co-simulate was also conducted in the co-plan occasionally so that to identify and eliminate potential conflicts in the co-created plan.

Figure 8-3 Dual monitors' screen shot of co-plan in one client side

The final created construction plan is of a hierarchal structure, and can be imported into the MS Project to gain the same structured plan with a static bar chart (Figure 8-4). This end keeps consistency with that of the verification test. The complete 4D simulation sequence is presented in Figure 8-5. These results indicated that the interactive method and its implemented 4D groupware achieved the desired outcome of a co-created construction plan with its 4D simulation. Combining the off-the-shelf multiparty video conferencing system of ooVoo, the proposed approach and application were proven to be applicable for geographically dispersed planners to collaboratively conduct planning and simulation across the Internet. This collaborative approach would be positive to gain a robust construction plan before the project delivery.

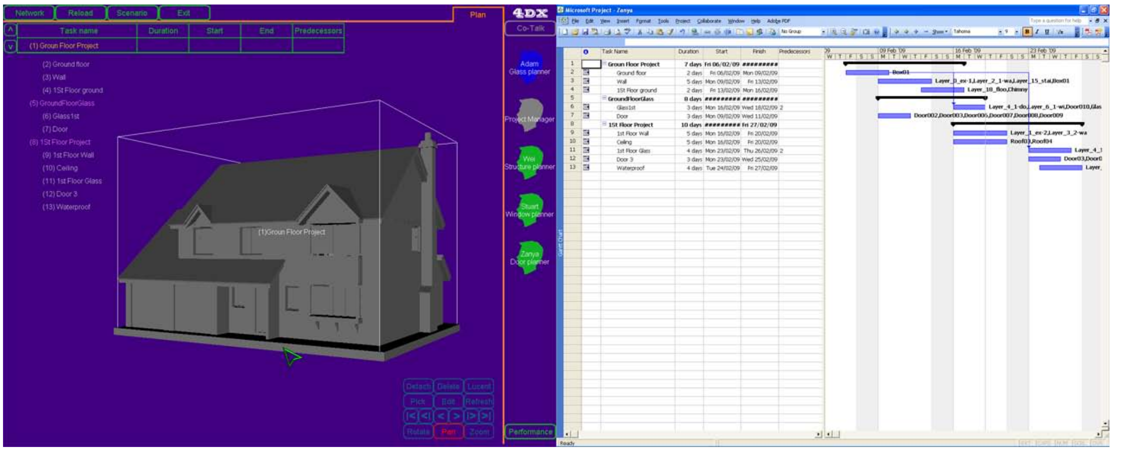


Figure 8-4 Consistent construction plan created by 4DX and outputted into MS Project

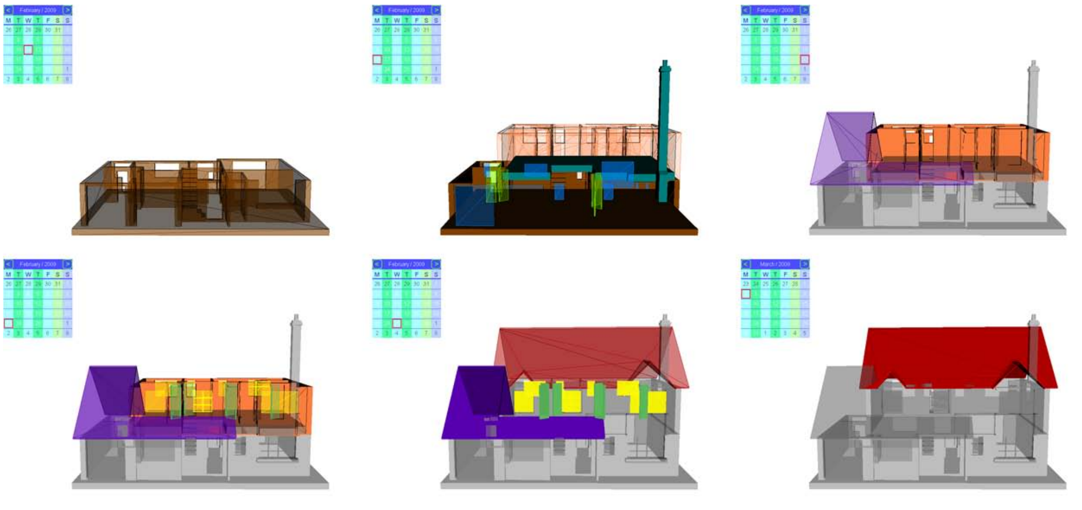


Figure 8-5 Generated 4D simulation sequence in the validation

8.5 Deployment feedback

A questionnaire was filled in by every participant after the validation test. It was designed to gain some feedback and measured their user experiences of system usability. The questionnaire (Appendix 8) consists of twenty two single selection questions, and each of them has five-point likert scales enumerated to be Strongly Disagree (1), Disagree (2), Neutral (3), Agree (4), and Strongly Agree (5). Some of them had been used in the confirmation test to measure participants' subjective attitudes in terms of satisfaction and effectiveness towards the system UI designs. Compared with the questionnaire used in the confirmation test, which targeted the offline UI designs of the system, this questionnaire considers more collaborative issues in an online state. It is helpful to further clarify successfulness of the CSCW design in the 4D system. In total, five participants completed the questionnaire summarised in Appendix 9. Their answers are presented by the histograms (Figure 8-6, Figure 8-7) to disclose the tendency of user experiences. The histograms provide a descriptive statistical analysis about user experiences in the validation. In general all participants held a positive point of view in both UI/interaction design and CSCW design of this collaborative 4D planning system.

Regarding UI/interaction design (Figure 8-6), it is noted that some participants reflected negative points in the question 2 and 14. These two questions are about interactive picking 3D elements from the 3D model for sorting and planning. However, the similar questions in the confirmation test got a converse answer. The reason for this conflict feedback is because of participant differences. The final VR-enabled 4D groupware is designed for construction planners. Some experts had demonstrated skilful operations in the confirmation test. However, novice users as the participants in the validation disclosed the training need of 3D model based planning. The same reason can explain question 10 that 20% users disagreed with the planning approach as it was inconsistent with their prior bar-chart based planning knowledge. Such conflicts approved that not all planners can reach an expert level. Even the expert users were impacted by the forgetting rate in the confirmation test. These ergonomic influences indicate there is a learning curve for novice users to master the model based 4D planning for collaboration when they access the new 4D groupware.

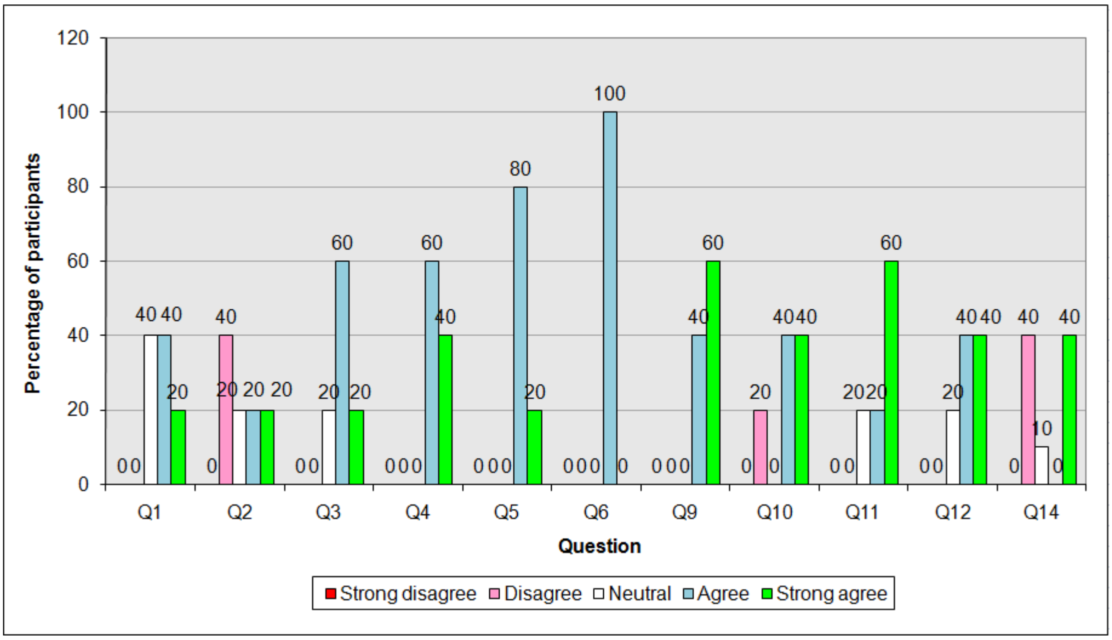


Figure 8-6 Results of validation test regarding UI/interaction design

The CSCW design in the 4D system achieved positive feedback in the deployment. Figure 8-7 implies that a majority of participants agreed that the CSCW design for the 4D system were helpful, useful and satisfactory for collaborative planning as co-navigate, co-sort, co-plan, co-simulate, and co-talk. Question 7 shows that 80% of participants agreed that the 4D system is well designed for them to know their collaborators' performances. However, there were still 20% of participants who denied this awareness design. In order to enhance WISIWYS in the CSCW design, the system can further add cursors movement from all collaborators, or take some other measures to ensure awareness for all users in collaboration. Other CSCW design issues were also disclosed in the validation from the tester's point of view. They are discussed in the next section.

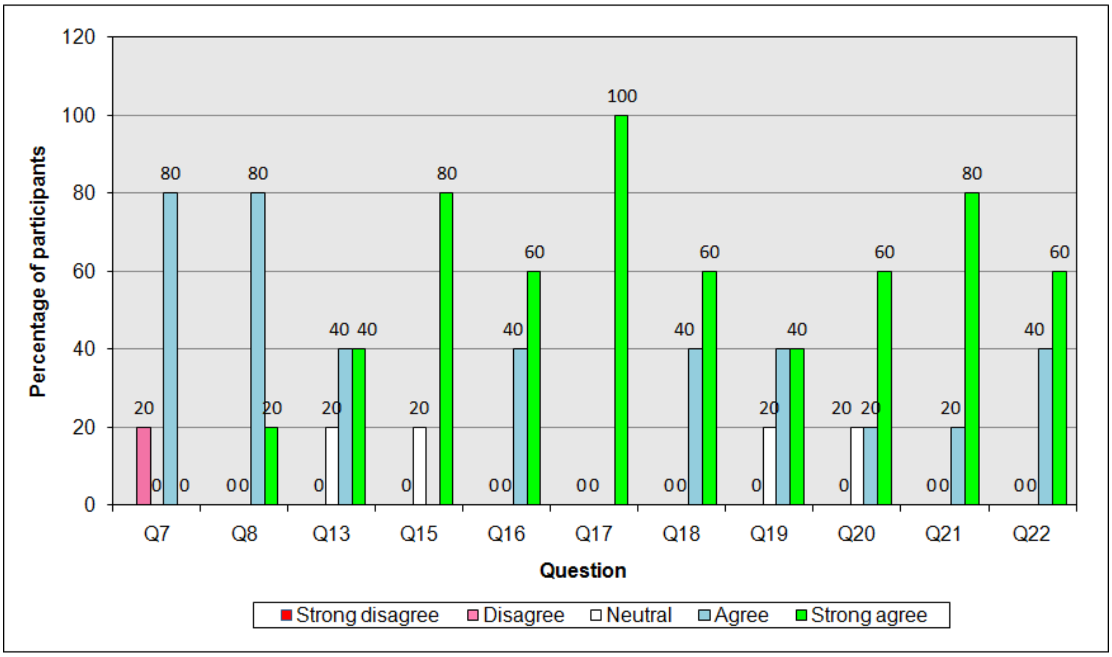


Figure 8-7 Results of validation test regarding CSCW design

8.6 Findings in validation

The use of third party software like ooVoo for co-talk in the validation was very flexible and applicable for social interaction. As this sort of independent multiparty video conferencing system is a specialised toolkit, it features reliable functionalities of real-time multiparty audio/video and text communication. These powerful features connected geographically distributed planners for maintaining social interaction. It provided desired functions to satisfy the needs in collaborative 4D planning. As ooVoo is freeware for use and download, it is unnecessary to develop a built-in multiparty conferencing system in 4D groupware. Although it allows up to six people online for communication at one time, this limitation can still meet the needs of real collaborative planning, which is often conducted by a small group of planners.

The dual monitors' configuration of the system was beneficial for users. Because of using multiple application operation of 4DX and ooVoo at the same time, a clear and ease-of-use arrangement for the system is important for good usability. Real-time collaborative 4D planning has high demands for user tasks' performance including 3D operation, interactive definition, and social interaction. These mixed complex user tasks are in need of suitable UI designs to support user's task performance. The dual monitors' configuration permits users to focus on main task operations instead of frequently switching user interfaces among different applications. It thus can be helpful to improve the usability of the whole system. This sort of multiple monitors based interaction design can be an advanced research topic to further explore human computer interaction in distributed 4D groupware application. The success of this desktop-based validation is applicable for a networked semi-immersive VR situation for tele-collaborative 4D construction planning. As applying the VR-enabled 4DX client in the validation, it can achieve the same interaction result performed in the networked semi-immersive VR environment. Nevertheless, it needs extra display wall and projector to deal with ooVoo displaying for co-talk. Such an expanded hardware configuration can be incorporated into the whole semi-immersive VR infrastructure to achieve an integrated social-technical VR environment.

Social coordination is critical for the real time collaborative 4D planning, especially for a distributed system. The validation showed the involved participants ought to be coordinated beforehand and during the planning process. To be an advanced 4D system for users, the system asks for expert users with certain knowledge, skills and familiarity with 4D CAD and project planning. Because of learning curve influences on novice users, necessary training in advance can ensure a smooth planning process. Coordination in the planning process usually requires a team leader to control different collaborative sessions, particularly for planners who are in different locations. In view of collaborative sessions designed in the operated CSCW, a team leader is important to play a leading role in initiating, controlling, and managing different collaborative sessions of co-sort, co-plan and co-simulate. The control tester in the validation acted as this figure.

The CSCW design for the 4D system showed effectiveness in the collaboration, but still can be improved for easier transition among different collaborative sessions. The CSCW performances in the 4D groupware were designed to apply unconditional and conditional sessions. The conditional sessions of co-sort, co-plan, and co-simulate currently are independent with each other. When initiating one session of them, it needs to terminate another possible live session, and then start the new one. In view of the frequent switch between co-plan and co-simulation for detecting potential conflicts during planning, it is inconvenient and tedious to repeat this operation. An improvement of this problem could be the integration of all conditional sessions into one general session. This improvement can enhance the coherence and efficiency of collaborative planning.

Co-navigate session in the CSCW design can be cancelled from the conditional sessions. In view of the fundamental nature for 3D navigation, the co-navigate operations of zoom, pan and rotate are embedded and frequently used in co-sort, co-plan and co-simulate. Therefore, an independent co-navigate session is no much of meaningfulness. Its cancellation will further simplify the UI design for the semi-immersive VR platform. Additionally, the filter control for state displaying in the co-sort session ought to be managed by the session holder. Because of strict synchronous demands in real time collaboration, the session holder's macro control of the state displaying filters on all session attendees could maintain a smoother planning process.

The enhancement of system transparency for collaborators is able to achieve by creating some new functionalities. Besides the cursor movement displaying for all collaborators, an observation function would enable every collaborator to watch other partners' operations at any time in their local clients. This function could be very useful particularly when collaborators have not received their partners' data, but wish to know partners' progresses in planning. From a technical point of view, the realisation of this observation is feasible as necessary information can be retrieved directly from the 4D item pool directly. For a real time collaborative system, the observation function can positively reinforce the feature of WISIWYS in the CSCW design.

Last but not least, the 4D simulation sequence generation in the system should be remedied. An assumption of the created 4D system is that defined plan tasks are in an ideal top-down order. It requests the planners to define their tasks one by one according to the real logical construction sequences. This assumption is helpful to expose and analyse possible problems in every single step of the collaborative planning. However, in the real distributed situation, planners may freely and concurrently define their plan tasks once obtain their own 3D elements. This freedom may cause some later defined tasks being neglected in the simulation because of its earlier start time than earlier defined tasks with later start time. In order to fit the concurrent definition, the 4D simulation ought to be time oriented rather than order oriented. The remedy of this weakness needs to consider time issues in every defined task when generate final 4D simulation sequence.

8.7 Summary

The VR-based 4D groupware with the optimal UI designs were validated in a truly distributed situation, and deployed to construction professionals. The validation took the advantage of dual monitors and wireless network communication in hardware configuration, as well as the off-the-shelf multiparty video conferencing application of ooVoo in software configuration. Underpinned by the hardware and software, the developed 4DX groupware prototype demonstrated applicable features and good usability. Further enhancement will target exposed weaknesses in the CSCW design and 4D simulation sequence generation in order to fit real industrial practices. As a research oriented development, current collaborative 4D system mainly concentrates on methodological innovation, verification, system proposition, and validation. These fundamental issues have been clarified in the research. An expectation of the created system is to remedy all disclosed pitfalls in the interactive definition method, the CSCW design, as well as relevant system functions for further improvement and wide adoption.

Chapter 9 Conclusions and Recommendations

9.1 Summary and review

This study concentrates on an interdisciplinary investigation of VR-based distributed 4D CAD for collaborative construction planning. Targeting exposed pitfalls in the state-of-the-art of 4D CAD and construction planning, the research tackled three problems including no suitable approach to distributed collaborative 4D planning, no applicable toolkit to support collaborative 4D planning, and lack of practical approach to user-friendly 4D-VR planning system. In terms of approaches to distributed collaborative 4D planning, this research created the interactive definition method to achieve collaborative 4D planning. The method clarified critical theoretical issues involved in the collaborative 4D planning, and provided a baseline to develop a distributed 4D groupware system. In terms of toolkits to support collaborative 4D construction planning, this research proposed and implemented an applicable distributed 4D groupware solution. Multidisciplinary construction planners, though they are geographically dispersed, can be connected with it to co-create a construction plan in real time across the Internet. In terms of guidance to a user-friendly 4D-VR planning system, this research established a novel UCD framework of TC-UCD, and demonstrated a robust usability engineering approach to the UI design of the 4D-VR planning system. The final distributed 4D-VR groupware system was validated in a truly geographically dispersed condition by a group planners.

Given the research aim of delivering a distributed VR-based solution with suitable usability for collaborative 4D construction planning, this research have achieved this goal completely through the realisations of identified objectives. They are summarised as follows

9.1.1 Summary of literature review

In the objective of reviewing construction planning strategies and 4D CAD development methodologies applied in the research domain and industry, a thorough literature review was conducted to examine the state-of-the-art of 4D CAD and construction planning. It was relevant to current construction planning approaches, popular planning methods, ICT-based planning, 4D CAD creation methods and technologies, database application in multi-constraint planning, as well as emerging technology of BIM-based nD modelling. Two industrial implementations were discussed as the projects of VIRCON for process modelling and PM4D for BIM application. To be a heuristic illustration, the CIFE iRoom was analysed as a case study to show both positive and negative aspects for collaborative 4D construction planning. Via this literature review, the pitfalls were highlighted as no suitable approach to collaborative 4D construction planning with applicable toolkit's support, and user-friendly 4D-VR system's delivery is in need of guidance.

9.1.2 Summary of technologies and theories

In the objective of scrutinising technologies and theories of VR based collaborative work for the CSCW design of collaborative 4D construction planning, theoretical analysis was performed to analyses VR technology application for construction and CSCW design. In the VR application analysis, it discussed hardware and software configurations, application feature, platform utilisation, and ideal VR-based 4D solution proposition. Subsequently, it scrutinised CSCW design theories for 4D planning application in a semi-immersive VR environment. It clarified 4D CSCW design from design dimension, essential feature, and collaborative technology to consider real-time collaborative 4D-VR construction planning. Relevant 4D CSCW activities were identified to be co-navigate, co-sort, co-plan, co-simulate, and co-talk. By this theoretical analysis, it differentiated fundamental and essential technical and social activities that a group of planners is going to conduct. This differentiation also laid a foundation to further consider related functional and non-functional issues involved in distributed collaborative 4D planning.

9.1.3 Summary of collaborative 4D method

For the purpose of creating a feasible method for collaborative 4D construction planning in the distributed network condition, this objective was met applying theoretical analysis about HCI, 4D CAD, and network computing. In accordance with individual creativity and social creativity relationship from human computer studies, the created new 4D planning method, named interactive definition, seeks a PBS-create-WBS approach and emphasises three kinds of interactions to achieve the distributed collaboration in 4D planning. The method requires a unique 3D building model input to create a building information base across the network and foster those three interactions. Based on this unique 3D model, user-system interaction as one of the interactions is available for online planners to directly manipulate the 3D model, and define their own plan tasks on related 3D elements. A set of simulation item parameters are used for describing plan tasks and their associated simulation information. They are created to wrap related PBS elements and WBS items into integration for convenient network transmission. Social interaction is another interaction which enables online planners to communicate with each other via the network. Hence they can exchange ideas and discuss plan strategies. The third interaction is the data incorporation that generated simulation items from different planners can be synthesised and outputted to generate a final construction plan and its 4D simulation. In the meantime, the devised collaborative sessions enable online planners to perform collaborative work. In this way, the 4D simulation can be conducted to eliminate potential conflicts in the created plans, and thus to gain a robust construction plan. This method's creation concretized essential functionalities for realising distributed collaborative 4D planning.

9.1.4 Summary of novel UCD framework

Being another objective of establishing a novel UCD framework applying the Taguchi Method, it strives for exploring a robust usability engineering approach to the optimal UI design of VR-based collaborative 4D planning system. It was achieved on the basis of theoretical analysis about adoption and adaptation between the Taguchi Method and the existing UCD framework. The new UCD framework of TC-UCD was generated to deliver a group parallel UI designs for partial factorial usability testing. One of critical design decisions in the TC-UCD is the identification of design factors and design levels which are influential on system usability. This decision can directly lead to structured comparable UI designs for prototyping and usability testing. Some formative evaluation methods in the UCD were adopted into the TC-UCD for quantitative data analysis. The created data analysis methods are the within individual analysis and among individual analysis. The former can gain optimal UI designs for individual participants whilst the later can be used for hypothesis testing to gain optimal UI designs. In view of the ad hoc VR platform of semi-immersive VR for the collaborative 4D planning application, the TC-UCD framework can be practice guidance to the realisation of non-functional development for VR-based UI designs in the 4D system.

9.1.5 Summary of distributed groupware solution

The objective of formulating a solution of distributed groupware for collaborative 4D construction planning was realised through system development. On the basis of created the interactive definition method and functional requirement analysis, the distributed 4D groupware solution was specified by software architecture, application mode and dataflow, as well as data exchange protocol. The software architecture was composed of a series of functional modules and components in a sever tier and a client tier. This kind of server/client application structure requires certain dataflow to coordinate different data's dispatching between the server and the client. Therefore, a real-time data exchange protocol was designed to control data retrieve and broadcast between the server and the client. Incorporating these design concerns, the system was implemented with full functions on the desktop platform. The implemented desktop 4D groupware system named 4DX was applied for the verification of the interactive definition method in a mimic distributed situation. Two planners were connected via a LAN to collaboratively create a construction plan face-to-face by applying 4DX. They generated a robust construction plan and 4D simulation. This result verified the feasibility of the interactive definition method and the applicability of proposed 4D groupware functionalities.

9.1.6 Summary of VR-enabled 4D groupware UI design

The objective of designing VR-enabled UI for the 4D groupware was achieved by applying TC-UCD as guidance. Based on the implemented 4D groupware solution, the semi-immersive VR platform was targeted to extend the desktop 4D groupware to be a VR-enabled solution. Through the non-functional analysis of user study and platform analysis, the Taguchi design was performed by implementing the system design and the parameter design respectively. In the system design, three influential design factors on usability were identified as picking method, editing approach, and 3D navigation device. Through a collaborative task analysis, two specific design levels were selected for each design factor. Subsequently, usability goals were specified for the VR-enabled 4D groupware system. In the parameter design, a group of parallel UI prototypes were designed, implemented and tested. The final optimal UI design was created through data analysis. A group of part-time and full-time postgraduate students took part in the usability testing of prototypes and the confirmation test of optimal UI design. The final confirmation testing verified that the optimal UI design met the defined usability goals. At the same time, it also proved that TC-UCD is applicable for robust usability engineering to solve non-functional problems.

The final VR-based 4D groupware system with the optimal UI design was validated by construction professionals and deployed to them for further feedback and improvement. The validation was conducted in a truly geographically dispersed condition. Leveraging the hardware configuration of dual monitor, wireless network communication, and off-the-shelf multiparty video conferencing system of ooVoo, the VR-enabled 4D groupware system demonstrated applicable functions and suitable usability in collaborative 4D construction planning across the Internet. The validation results kept consistent with those of verification test. Along with the system validation, its deployment gained positive feedback regarding collaborative 4D planning. To this end, this research had achieved the aim of delivering a distributed VR-based solution with suitable usability for collaborative 4D construction planning. The relevant objectives were achieved by applying a series of interrelated methods for clarifying both functional and non-functional issues.

9.2 Contribution to knowledge

A series of knowledge and practice contributions are outputted from this research as follows.

- ❖ It proposed an applicable method of the interactive definition for collaborative 4D construction planning and simulation in the distributed network condition. Its essences include a 3D-based open shared planning context, necessary social interactions with related CSCW designs, direct manipulation as a reasonable user-system interaction, and suitable simulation item definition. This method distinguishes itself by connecting multidisciplinary planner in a social-technical environment and fostering their interactive activities to co-create a construction plan;

- ❖ It clarified CSCW design being involved in distributed collaborative 4D construction planning. This clarification highlighted critical issues for distributed collaboration theoretically, and can be a baseline to explore related collaborative applications. The CSCW design in this research is created as co-navigate, co-sort, co-plan, co-simulate, and co-talk. Their applicability and usability had been validated in a truly geographically dispersed condition.
- ❖ It established an applicable distributed 4D groupware framework applicable for the non-BIM condition and extensible for the BIM condition. Its prototype named 4DX is now with full functions, and ready to be improved further as a BIM-compliant system. With this 4D groupware, geographically dispersed multidisciplinary planners can realise real-time collaborative 4D planning;
- ❖ It demonstrated robust usability engineering implementation in creating the information system of VR-based 4D planning on the basis of the innovative TC-UCD framework. Compared with existing UCD approaches, TC-UCD provides a structured parallel design approach to gain comparable and optimal designs. It is not only beneficial for this research but also applicable for other UCD related studies;

These achievements have been published in related journals and disseminated in international conferences. The specific information is listed in Appendix 10.

9.3 Impact on industry practice

The industry can gain three main benefits from this research. Firstly, construction planners can realise real collaboration in a truly geographically dispersed condition underpinned by the created 4D groupware. Although they are in different locations, construction planners are able to conduct planning work by focusing on a unique 3D model. Through effective social interaction and user system interaction in this open-ended shared 3D social-technical environment, planners' individual creativities and their social creativity are invoked in the planning work. With defined and synthesised simulation items, planners can co-create a construction plan and examine it applying synchronously generated 4D simulation across the Internet. In such a way, a robust construction plan and its complete 4D simulation can be gained.

Secondly, the research creates an applicable and extensible 4D groupware architecture for collaborative application in the construction ICT field. The proposed software architecture in this research targets a non-BIM 3D model's input and can output a robust construction plan with its 4D simulation. The same rationale is completely applicable for a BIM condition to achieve consistent results. Its flexible software architecture only needs minor modifications to deal with a BIM input. Therefore, a wholly new project planning and 4D simulation tool can be created on the AEC software market. Although there are realistic barriers of BIM application from social and technical aspects, this advanced choice has become a trend and been adopted in some commercially available toolkits such as Autodesk Revit, Vico Office Suit, Tekla structures, etc.. The proposed 4D groupware architecture caters for this trend and prepares future adoption of BIM for the industry.

Thirdly, the demonstration of VR utilisation through UCD in the research shows a practical way to solve social-behavioural issues involved in a technology application for the industry. The implementation of usability engineering in the research highlights that social-behavioural issues in ICT applications are as important as technical issues or even more critical. This point is helpful to draw attention of the industry from pure technical concerns to the broader awareness of social-behavioural influences, and positively improve the quality of ICT applications. Particularly and practically, the new UCD framework of TC-UCD provides an analytical approach to parallel UI design and evaluation for optimal UI design solutions. This positive influence benefits not only the construction ICT industry but also other ICT sectors directly.

9.4 Future work

Future work will focus on enhancement of the implemented 4D system and development in new research directions. The former will solve many of the problems that emerged in the verification testing. The later will centre around 4D CAD, especially BIM, to explore advanced ICT applications for enhancing construction activities. Particularly, it will further explore more practical solutions in the construction field to promote collaborative work on the basis of current research achievement.

9.4.1 Software enhancements

Targeting the emerged problems in the verification testing, the created distributed 4D system needs to be reinforced from the following aspects. BIM support for the system can be enhanced thought incorporation of IFC-compliant functions. With this capability, the system can read IFC formatted files to generate the 3D planning context, and write related planning information into the files. This enhancement is particularly helpful to integrate the information stored in the 4D item pool in the server side, and simplify the sorting operation to pick out related building information. The second enhancement surrounds the operation of multiple 3D elements' picking. As revealed in the verification testing, current picking operation is only available to pick a single 3D element at a time. It will be more efficient to pick multiple 3D elements at one time. Combing both single and multiple picking operations will be more flexible for the user-system interaction in the system. The third enhancement to the 4D system is to add the function of generating a bar-chart according to the simulation items' definition. Although the created 4D system builds a data interface with external planning tools e.g. MS Project for bar chart displaying, it is still useful and convenient to show a static task duration displaying. Enhancing these three aspects can deliver a wholly new distributed collaborative 4D-based planning tool to the AEC software market.

9.4.2 Future research directions

As 4D CAD and BIM are going to become fundamental approaches in the construction sector, related construction management can be conducted on the basis of

4D modelling and BIM. One of these kinds of activities is health and safety management that safety hazard identification and accident precaution can be achieved by applying 4D simulation. Related research makes use of visualisation technology such as VR to address these issues but short of considerations of changing time and space, which are related to a construction plan. Linking an dynamic 4D construction sequence with high temporal resolution and graphical visualisation, on-site conditions can be genuinely scrutinized and thus lead to the accurate identification of potential hazard and accident. Such a 4D application can thoroughly clarify involved health and safety issues, and improve the quality of construction management.

Wireless communication and mobility is also a valuable application combining 4D modelling for the construction industry. Because of dynamic nature of construction, not only the building objects like wall, window, slab, etc. but also on-site people are constantly changed. Handling both issues correctly is critical for construction management. Available devices such as mobile, PDA, Tablet PC, etc. provide applicable platforms to explore advanced 4D modelling applications for on-site engineers. With provided conveniences from this sort of applications, on-site engineers can communicate with each other in real time, instantly demonstrate and analyse their situations via the 4D model. In such a way, emerging problems in construction can be highlighted and solved in time.

Appendix 1 User profile questionnaire

Dear Sir/Madam,

*You are invited to fill in this questionnaire in order to assist in the investigation and development of a new 4D construction planning tool. All questions are **single** selection questions. It will take you **10 minutes** or so to complete the questionnaire. All responses are confidential, and will not be disclosed.*

***How to fill in**?*

*Please **double click** the dark block of your chosen question's answer, and you will see a popup dialog box. In the dialog box, you can choose one of default values as **Not checked** or **Checked**, and then press **OK** button. When you finish all questions, please **SAVE** and e-mail it to **wei.zhou@wlv.ac.uk***

Thank you for your cooperation.

Wei ZHOU, M.Sc., PDEng

The University of Wolverhampton

(Company Information)

1. Please check the **planning approach** that best describes your company's situation (for part-time student answer only)

☐ Using **desktop based planning software** e.g. Microsoft Project or Primavera Project Planner

☐ Using **desktop based simulation tools** for planning (e.g. 4D CAD)

☐ Using **Virtual Reality (VR) based tools** for planning

☐ Using others (If so, please specify: ______________________.)

(Attitude & Motivation)

2. In general, how do you feel about **applying ICT tools** for construction planning?

☐ I **don't** like applying ICT tools.

☐ It **depends** on how easy to use them, no obvious bias.

☐ I **like** applying ICT tools.

☐ **Other** (please explain: ______________________________________

____)

3. Would you take the time to **learn new** functions on ICT planning tools?

☐ **Yes**, it pays off because ICT tools benefit my work.

☐ **Depends,** if they pay off, otherwise not.

☐ **No**, it is **difficult** for me to handle new ICT tools' functions, and not useful enough to justify the learning time

☐ **Other** (please explain: ____

____)

4. Do you **enjoy** learning how to use new ICT planning tools?

☐ **Yes**, it is usually interesting and rewarding.

☐ **No**, it is difficult to learn in most cases.

☐ **Other** (please explain: ____

____)

5. Do you like interacting with a computer using **keyboard**, **mouse** or **remote control**?

☐ **Yes**, because: ____

____

.

☐ **No**, because: ____

____

.

☐ **Other** (please explain: _____________________________________

____)

6. Are you **interested** in **3D CAD applications** for planning your work?

☐ I am **not** interested in 3D application because: __________________

____

.

☐ **Yes**, I am interested in 3D application because: ______________

____

.

☐ **Other** (please explain: _____________________________________

____)

(Knowledge & Experience)

7. What is your **highest qualification**?

☐ **No** formal qualification

☐ **HND/HNC**

☐ **Undergraduate**

☐ **Postgraduate**

☐ **Other** (please specify: _________________________________.)

8. How would you rate your ability to use the Internet?

☐ I am an **expert**.

☐ I am a **good** user.

☐ I am a **basic** user.

☐ I am a **new** user.

9. How would you describe your general **level of computer experience**?

☐ **None** (I have never used any software applications)

☐ **Low** (I have only used one or two software applications)

☐ **Moderate** (I have learned and used many software applications but have no programming skills)

☐ **High** (I have used many software applications and have some programming skills)

☐ **Other** (please describe: ___________________________________.)

10. Do you have any experiences of using **CAD design software** (e.g. AutoCAD, 3D Studio MAX, ArchiCAD etc.)

☐ **None** (I have never used any design software)

☐ **Low** (I am able to perform basic functions)

☐ **Moderate** (I am proficient at using them for 2D drafting)

☐ **High** (I consider myself an expert user)

☐ Other (please describe: ___________________________________.)

11. If you use 3D CAD, **how easy** do you find it to manipulate 3D object and navigate 3D space?

☐ **Very easy**

☐ **Easy**

☐ **Difficult**

☐ **Very hard**

☐ **Other** (please describe: ________________________________.)

12. Do you have any experiences of **computer gaming**?

☐ **None** (I have never played computer games)

☐ **Low** (I have played some **stand-alone 2D games**)

☐ **Moderate** (I have played **stand-alone 3D games**)

☐ **High** (I have played **online 3D games**)

☐ **Other** (please describe___________________)

13. If you play **3D game**, how easy do you find it to manipulate 3D object and navigate 3D space?

☐ **Very easy**

☐ **Easy**

☐ **Difficult**

☐ **Very hard**

☐ **Other** (please describe: ___________________________________.)

(Physical Characteristics)

14. Are you:

☐ **Male**

☐ **Female**

15. Do you suffer from any **colour blindness** that impacts your use of computer applications?

☐ **No**

☐ **Yes**

16. How old are you?

☐ **18 - 25**

☐ **26 - 40**

☐ **41 - 55**

☐ **Over 55**

17. Do you wear **glasses** or **contact lenses**?

☐ **No**

☐ **Yes**

-This is the end of the questionnaire-

*Please **SAVE** it, and e-mail it to **wei.zhou@wlv.ac.uk***

Thank you for your cooperation.

Appendix 2 Summary of user profile survey

Company Information

Question	**Answer**	**Sum**	**%**
Q1: planning approach	Desktop based planning software	9	100
	Desktop based simulation tools		
	Virtual Reality (VR) based tools		
	Others		
Remark	This question is applicable only for full time students		

Attitude & Motivation

Question	**Answer**	**Sum**	**%**
Q2: feel about applying ICT tools	Don't like	1	6
	Depends	8	47
	Like	8	47
	Other		
Q3: opinion about learning new	Easy to learn	13	76

functions			
	Depends	4	24
	Difficult		
	Other		
Q4: enjoy learning new functions	Yes	17	100
	No		
	Others		
Q5: like interacting with PC input devices	Yes 1) it's fun 2) I get adequate interaction which satisfies my work 3) it is easier and quicker to use 4) I need less time to finish my projects or plans using this technology 5) it's ease-of-use and familiarity, although other methods can be better 6) I am used to using the keyboard and mouse, they	14	82

	are second nature and therefore I am very comfortable with their use 7) I'm used to it now, possible through VR 8) I enjoy the hands on apparatus 9) designing and creating visualisation is self awarding 10) it improves skill levels 11) I like using the keyboard for interacting as I believe there is more control functions available for modifying object and moving around 12) both tools are easy to use, remote control needs some practice, not sure about it		
	No 1) sometimes a mouse can be awkward to use, especially for 3D	2	12

	modelling 2) very restrictive. Personally I'm from a VR background. So other tools could be used		
	Others 1) interaction with the mouse and key board allows for controlled movement, however these tools are readily available and there is no other alternative means presently available	1	6
Q6: interested in 3D planning work	No		
	Yes 1) it's easier to market my designs with it 2) its visualised interface and improved communication 3) in my present employment I do not need to use 3D applications. I	17	100

	am still interested in using 3D applications for future work 4) I am working more efficiently 5) my clients require it 6) my work involves 3D modelling and therefore any application which relates to my field of work is advantageous 7) I enjoy learning new programmes such as Revit or ADT 8) it gives a clear visualisation of the proposed building 9) this can enhance my work with clients 10) collaboration of data is improved 10) 3d renders are amazing and it helps share ideas with one another 11) it provides greater		

	flexibility for extracting data 12) I'm interested in 3D Cad because I find it a lot quicker for modelling than conventional software 13) it is the future of designing buildings and structures		
	Other		

Knowledge & Experience

Question	Answer	Sum	%
Q7: highest qualification	No formal qualification		
	HND/HNC		
	Undergraduate	16	94
	Postgraduate		
	Other: MRICS, MSST	1	6
Q8: ability to use the Internet	Expert	4	23
	Good	12	71
	Basic	1	6

	New		
Q9: general level of computer experience	None		
	Low	1	6
	Moderate	7	41
	High	9	53
	Other		
Q10: experiences of using CAD design software	None		
	Low	1	6
	Moderate	4	23
	High	10	59
	Other: 1) I have used ADT/3DS Max for 3D applications but do not consider myself an expert 2) I would not say I'm a professional but I can do what I want to achieve	2	12
Q11: how easy to operate 3D in 3D	Very easy	6	35

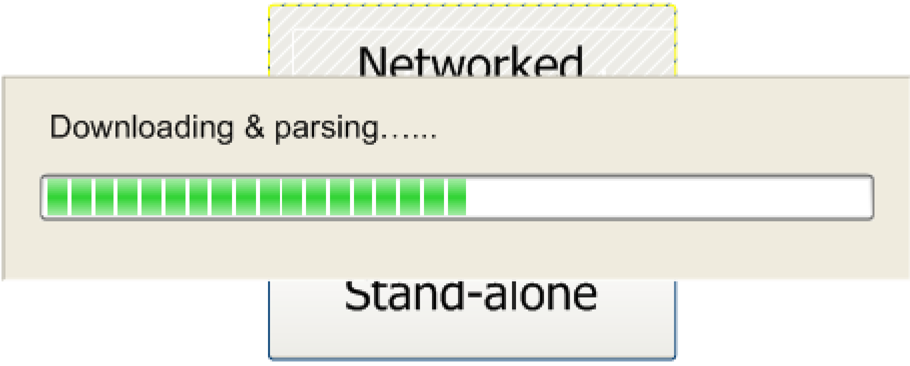
CAD			
	Easy	7	41
	Difficult	2	12
	Very hard		
	Other: 1) dependant on software being used 2) I find it very easy but I use 3D Studio Max more than AutoCAD	2	12
Q12: experiences of computer gaming	None	5	29
	Low	1	6
	Moderate	7	41
	High	3	18
	Other 1) sorry, I'm not interested at all in gaming	1	6
Q13: how easy to operate 3D in 3D game	Very easy	4	33
	Easy	6	50
	Difficult	2	17

	Very hard		
	Other		
Remark	5 person has no 3D game experience		

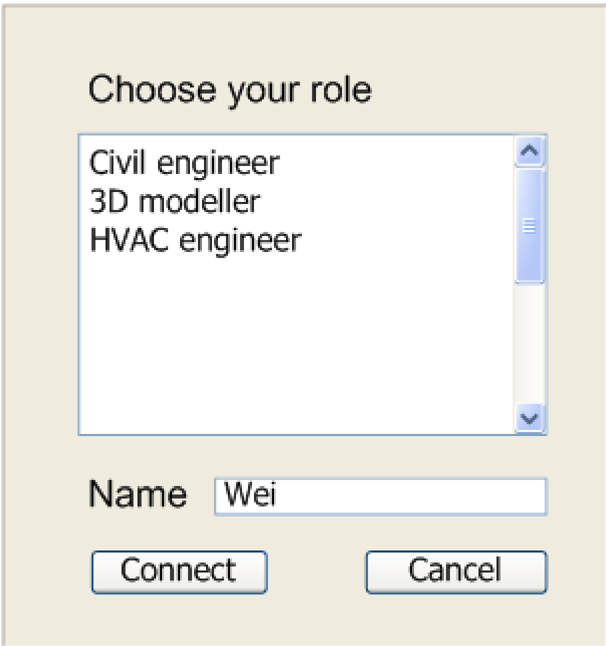
Physical Characteristics

Question	**Answer**	**Sum**	**%**
Q14: gender	Male	14	82
	Female	3	18
Q15: disability of PC utilisation	No	17	100
	Yes		
Q16: age	18-25	7	41
	26-40	6	35
	41-55	2	12
	Over 55	2	12
Q17: wear glasses or contact lenses	No	10	59
	Yes	7	41

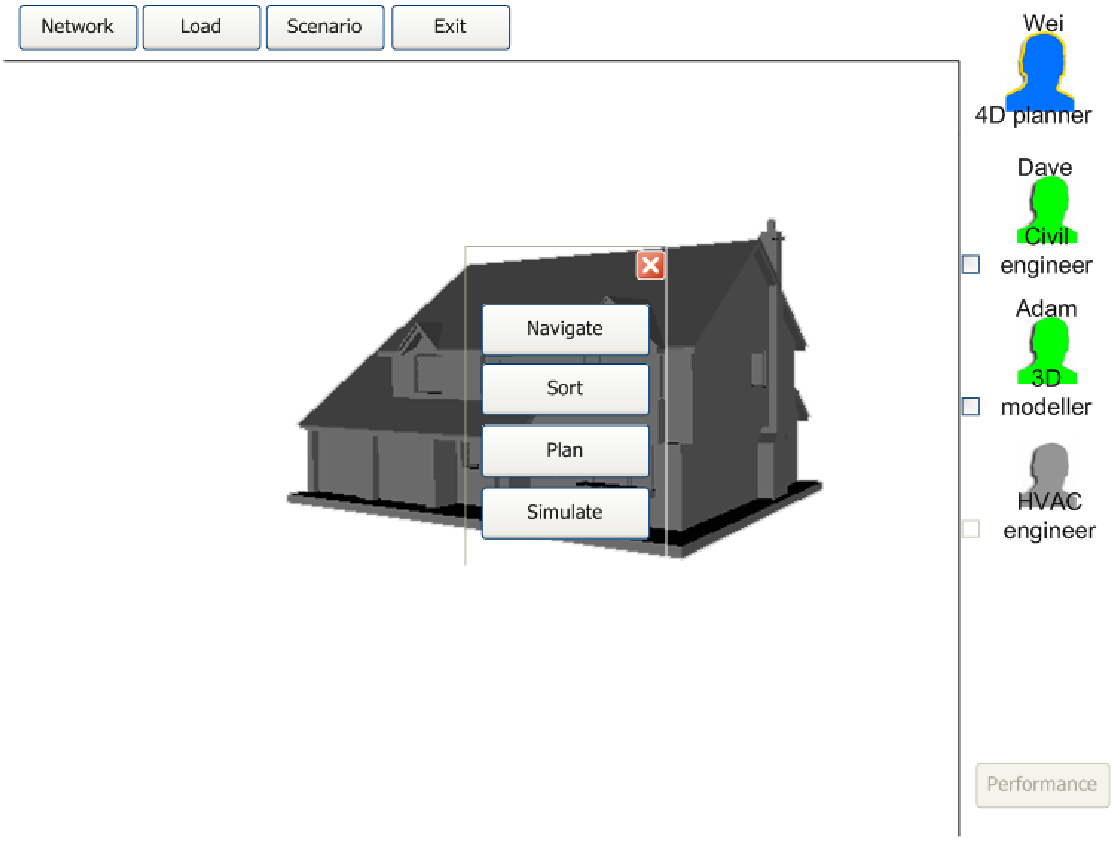
Appendix 3 Low-fi prototype



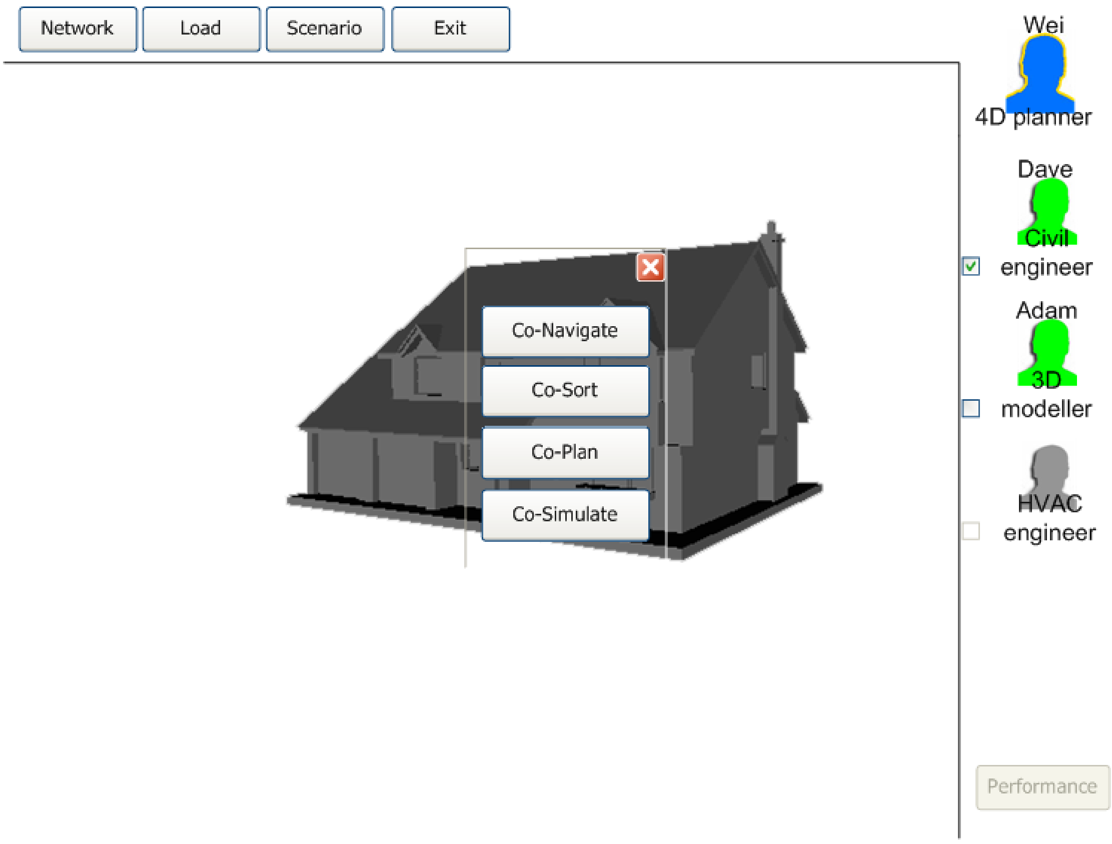
Appendix 3-1 Downloading



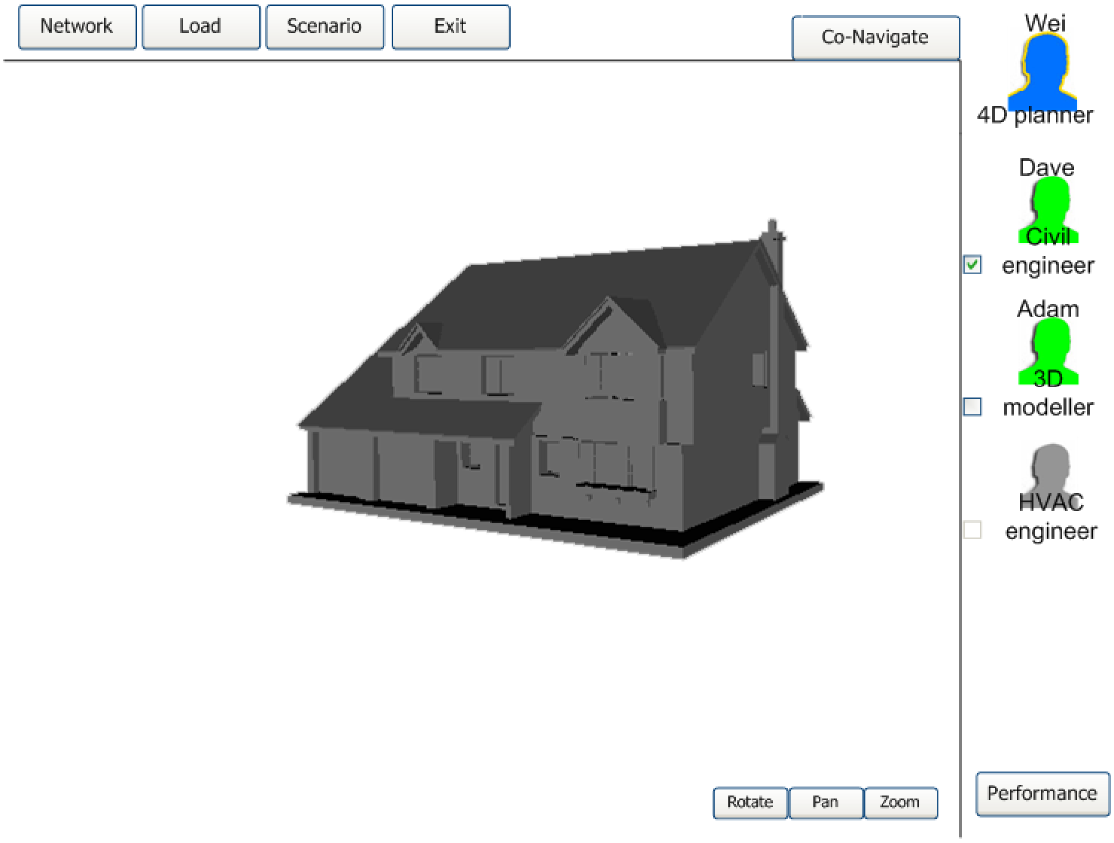
Appendix 3-2 Log in dialog box



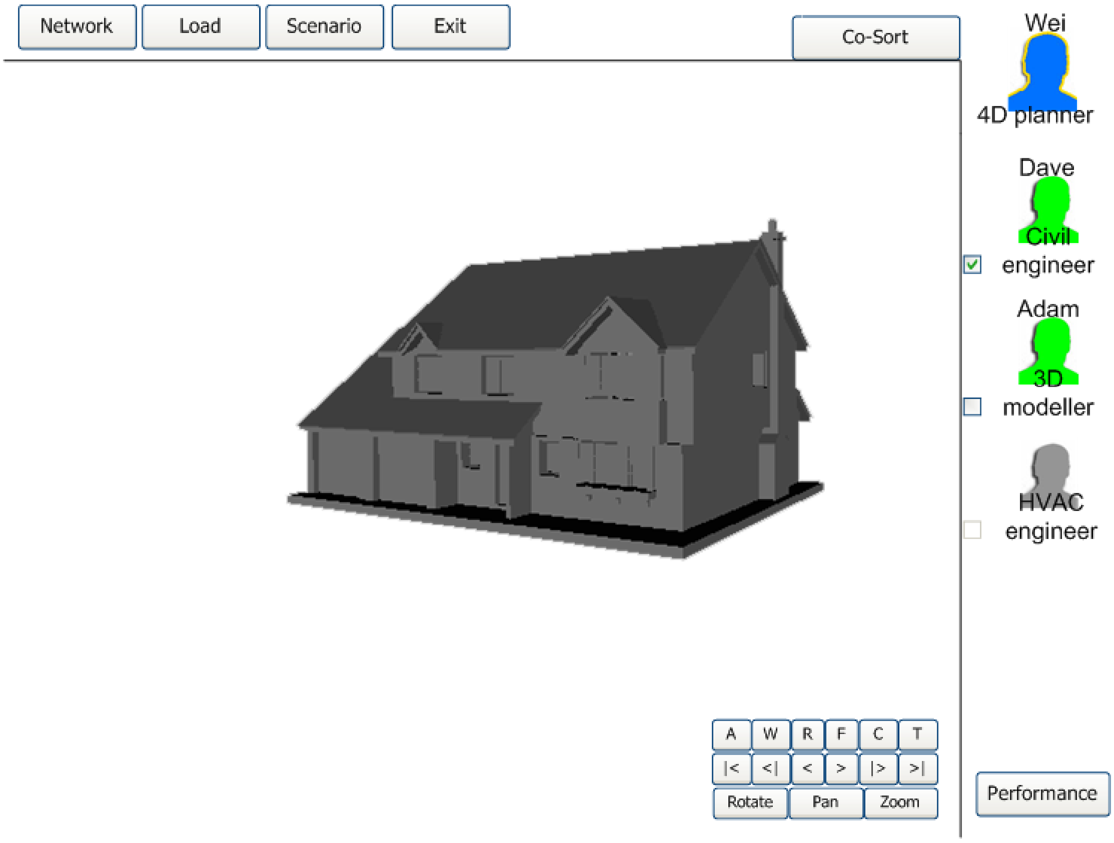
Appendix 3-3 Stand alone application



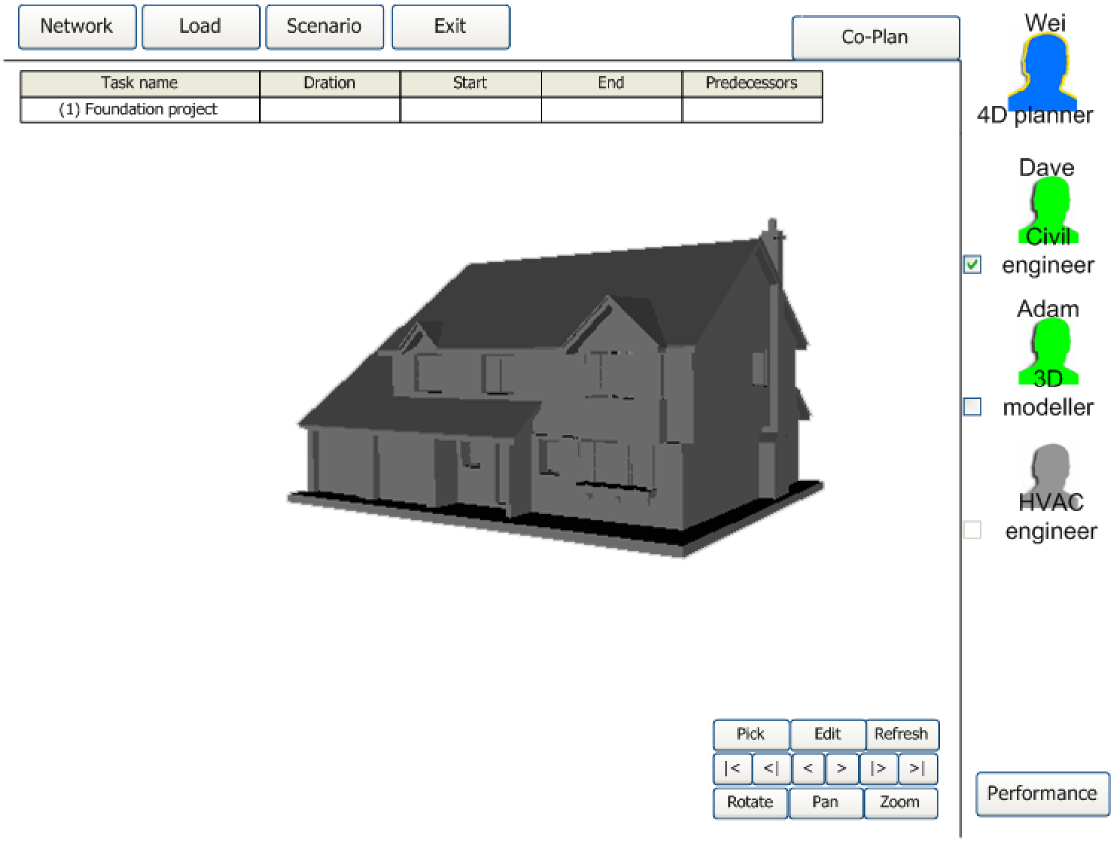
Appendix 3-4 Networked application



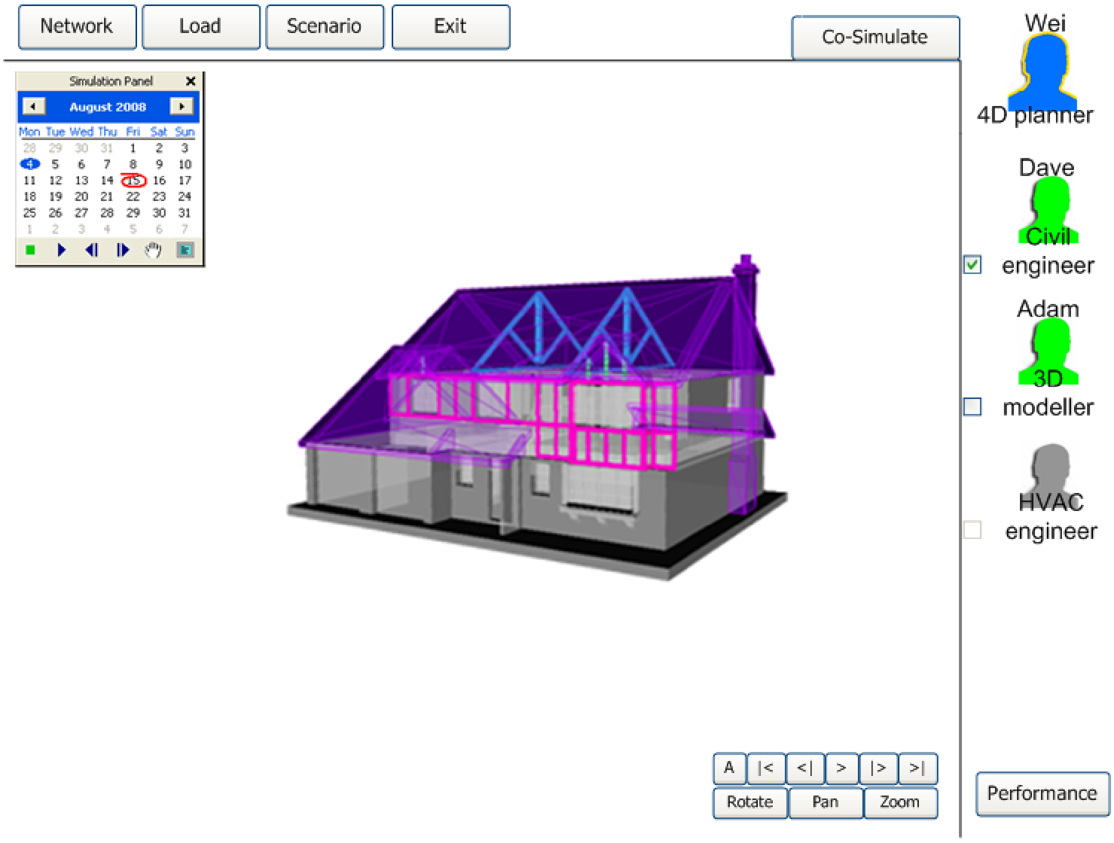
Appendix 3-5 Co-navigate



Appendix 3-6 Co-sort

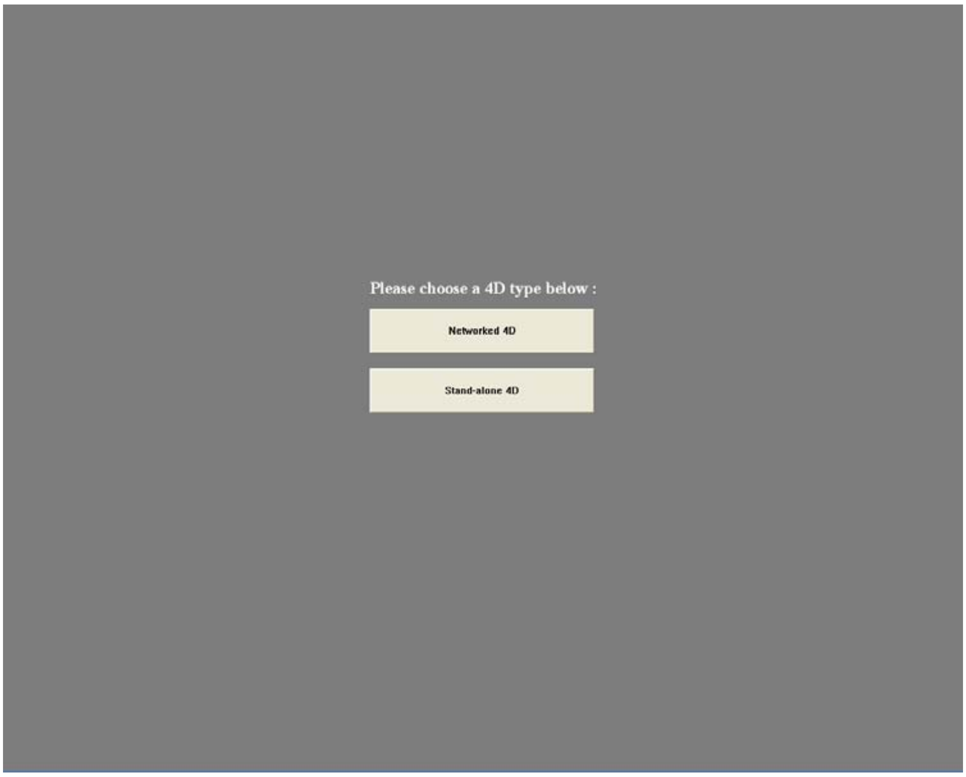


Appendix 3-7 Co-plan

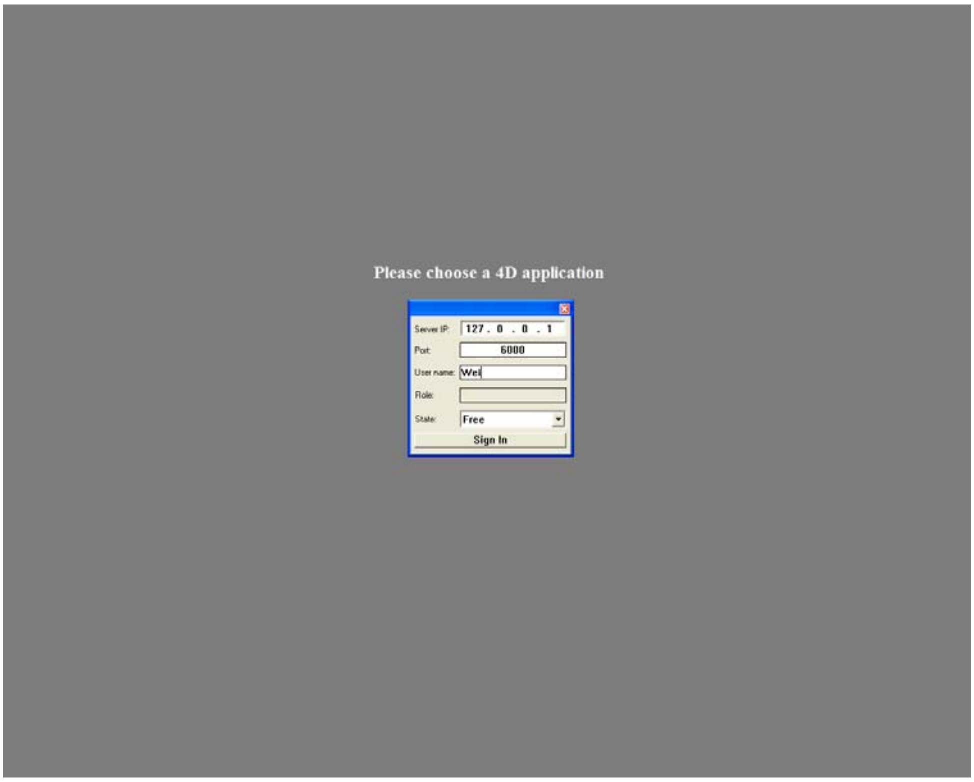


Appendix 3-8 Co-simulate

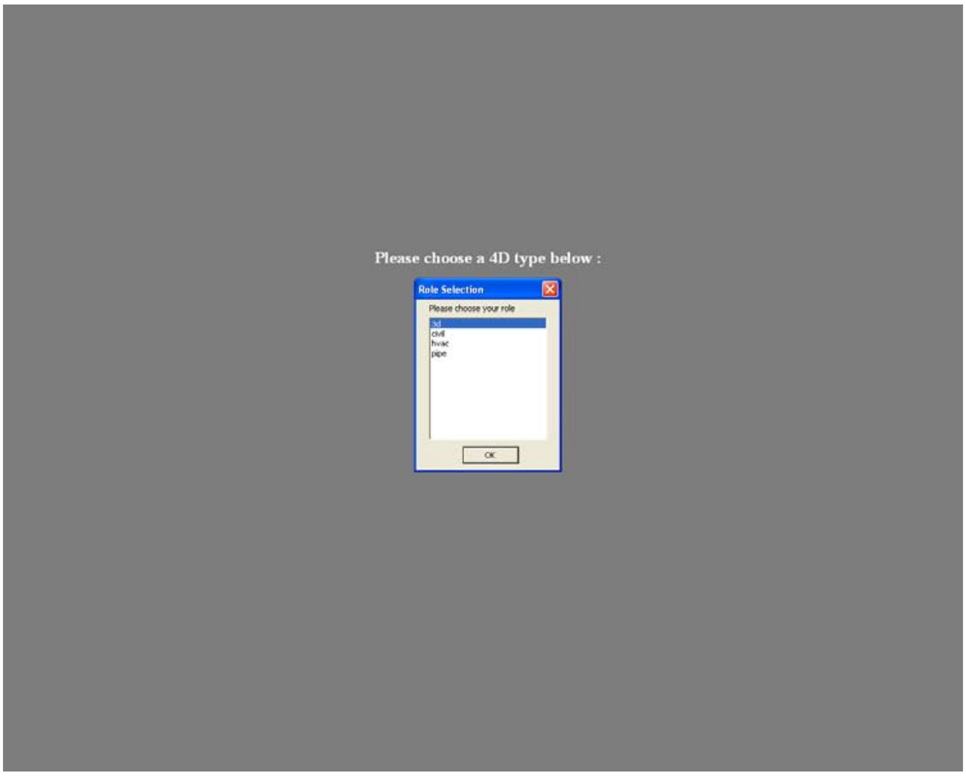
Appendix 4 UI design of VR-based 4DX client



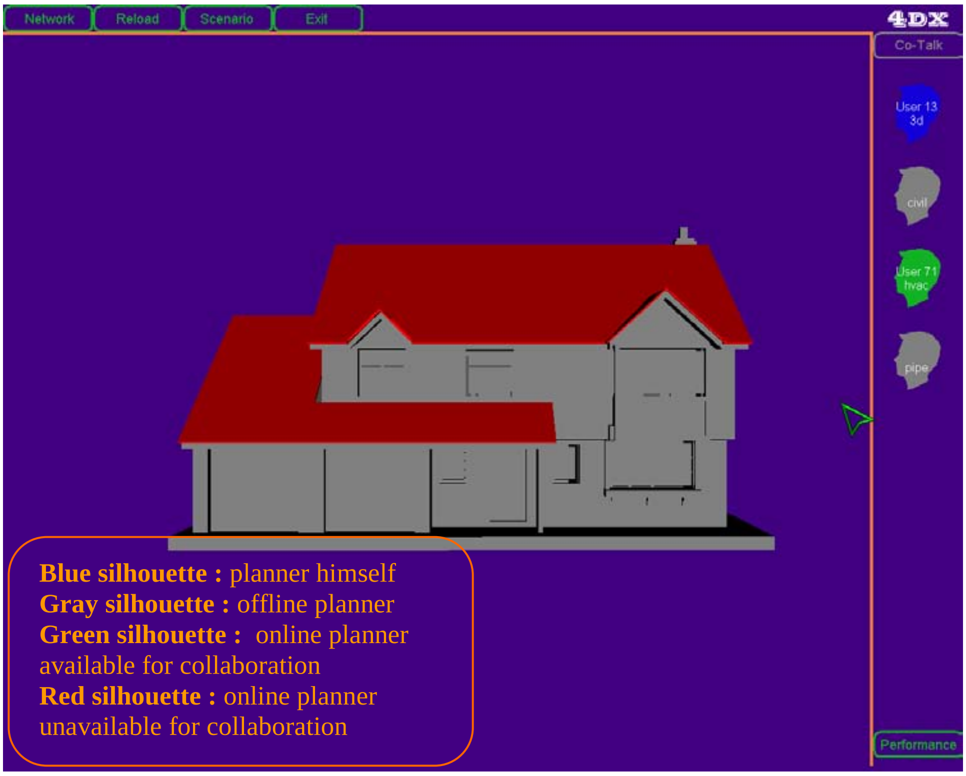
Appendix 4-1 UI of system entry



Appendix 4-2 UI for sign in

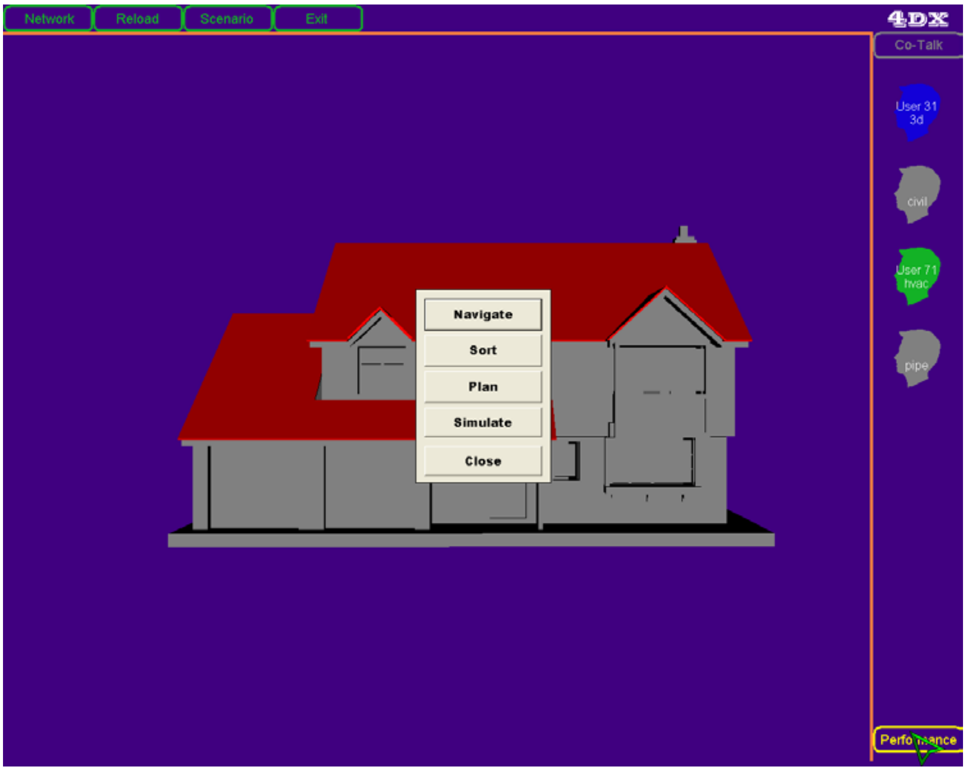


Appendix 4-3 UI for role selection

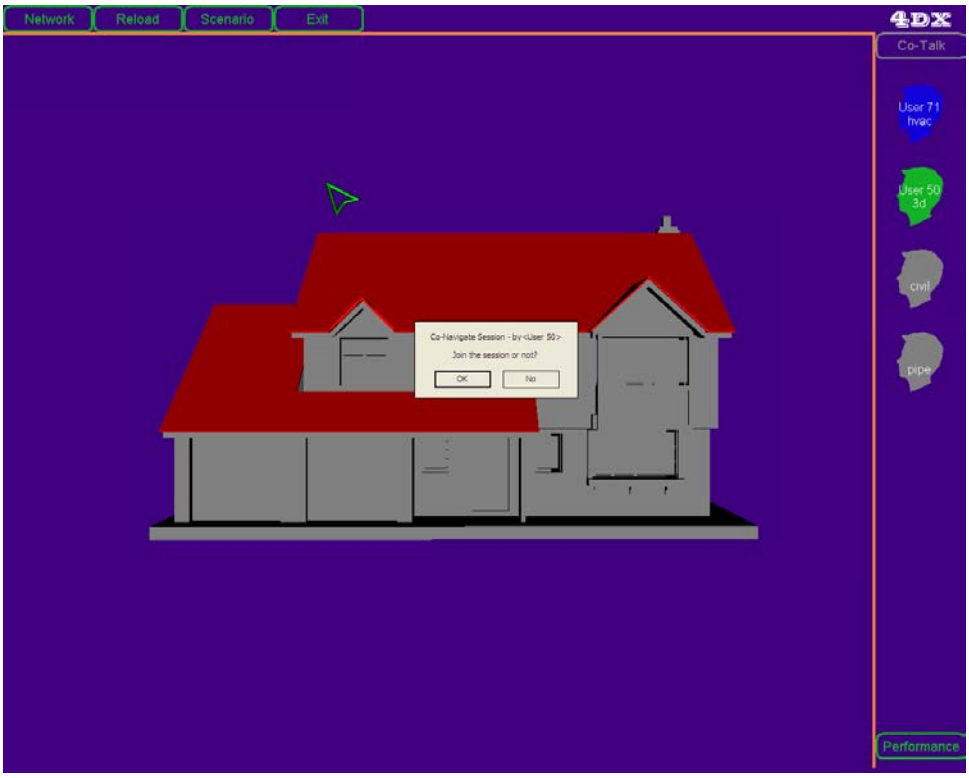


Appendix 4-4 System UI layout

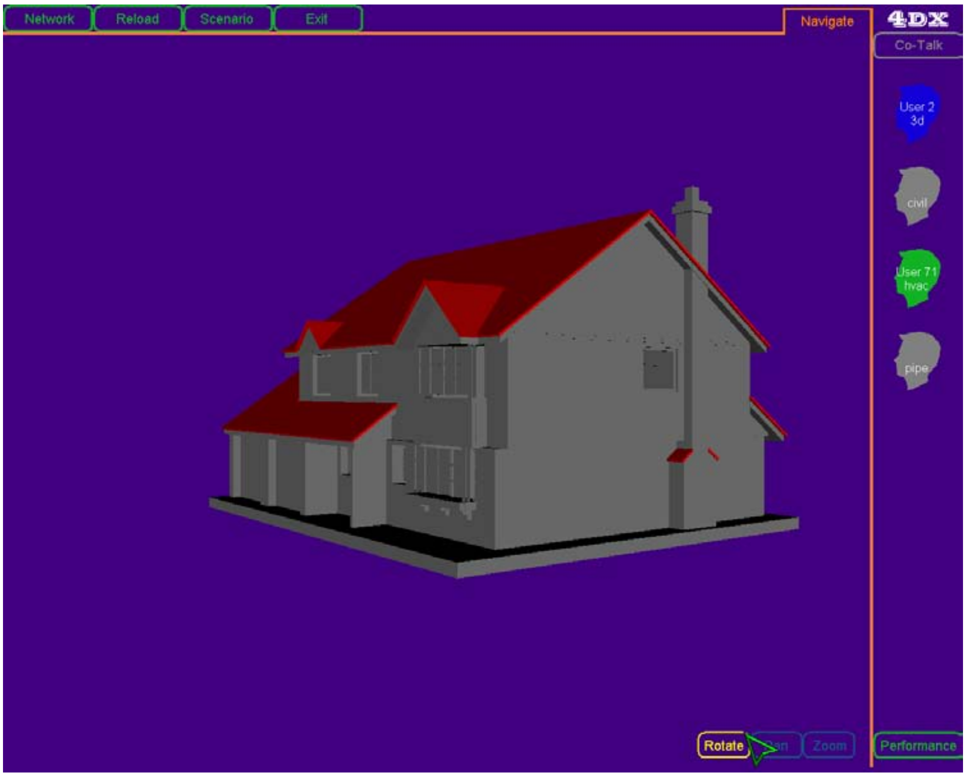
Appendix 4-5 Collaborative tasks



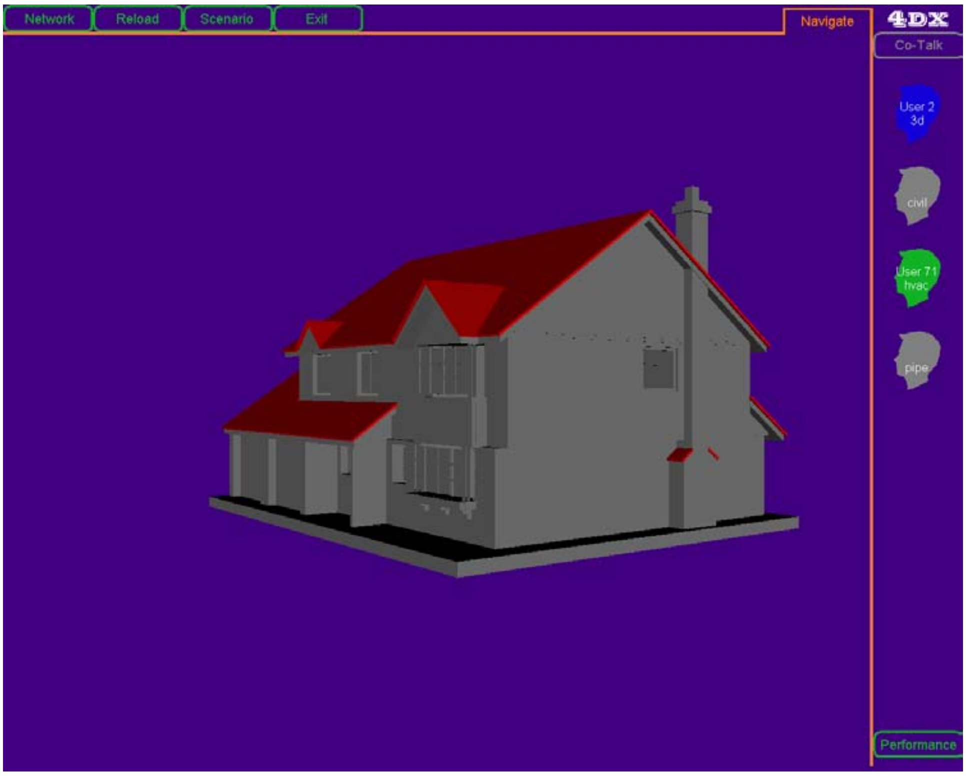
Appendix 4-6 Non-collaborative tasks



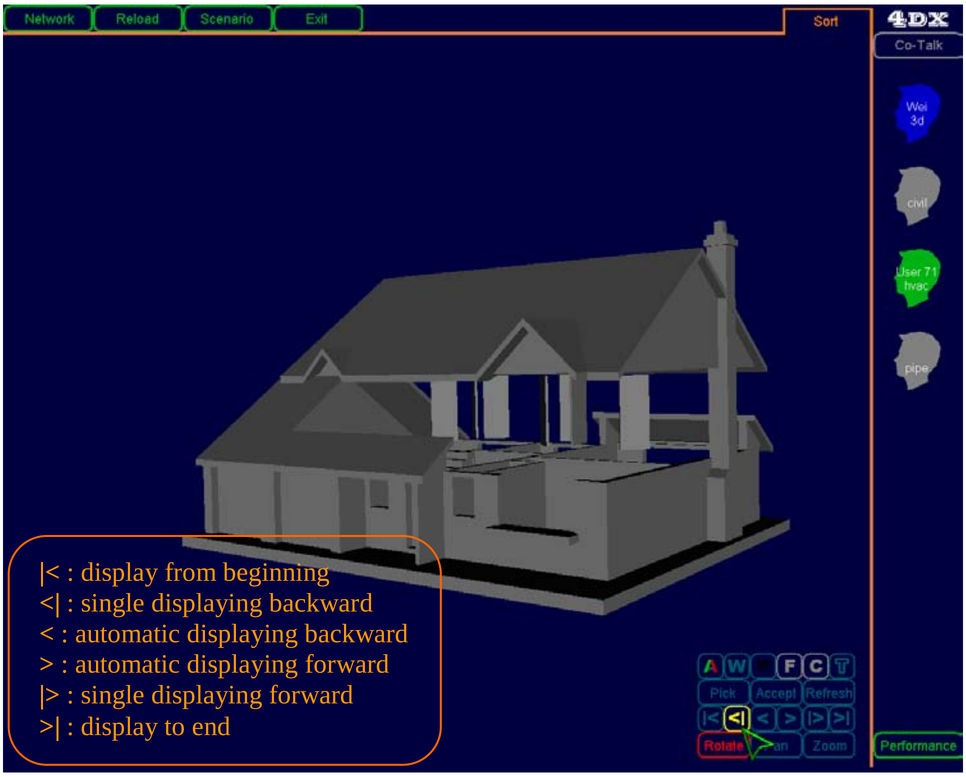
Appendix 4-7 UI for collaboration invitation



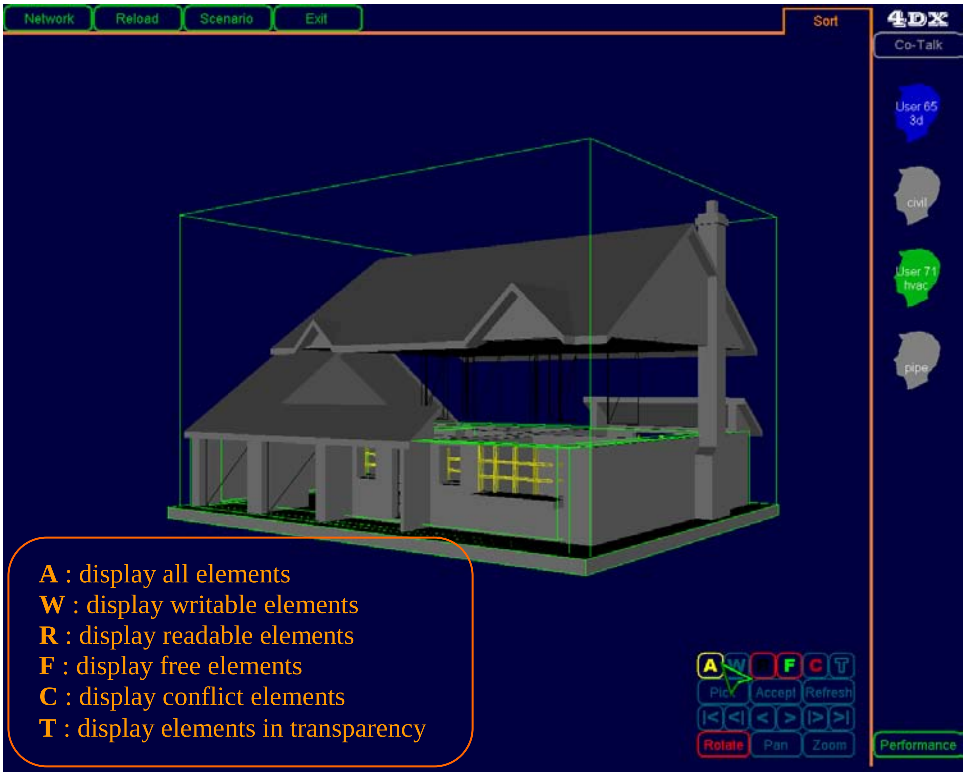
Appendix 4-8 Navigation UI for standard mouse



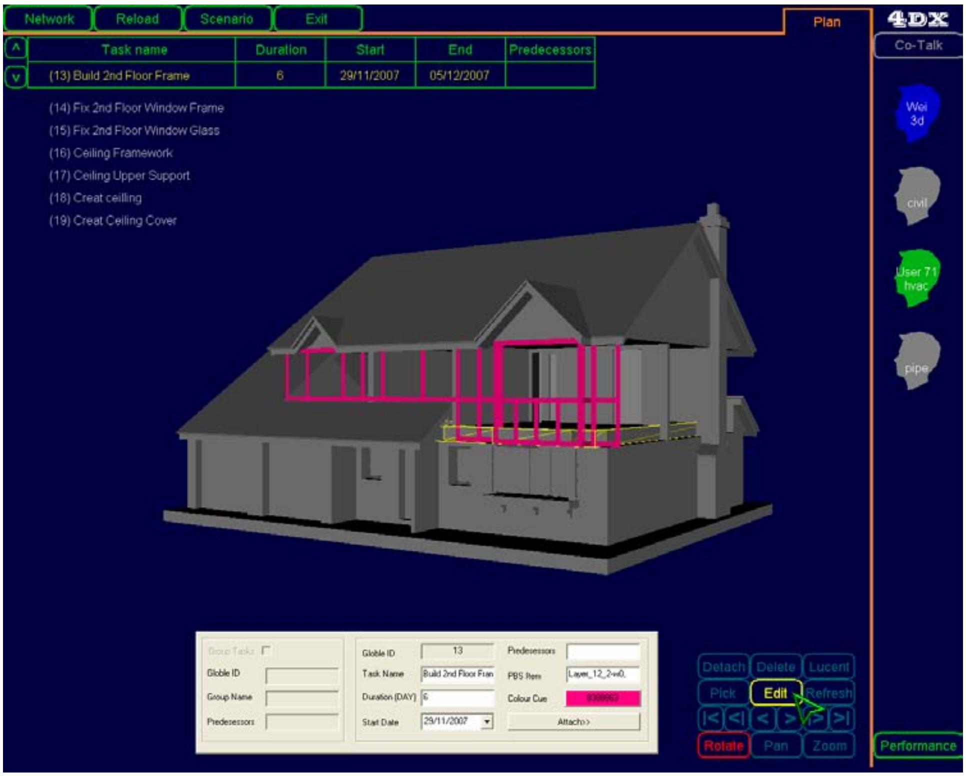
Appendix 4-9 Navigation UI for 3D mouse



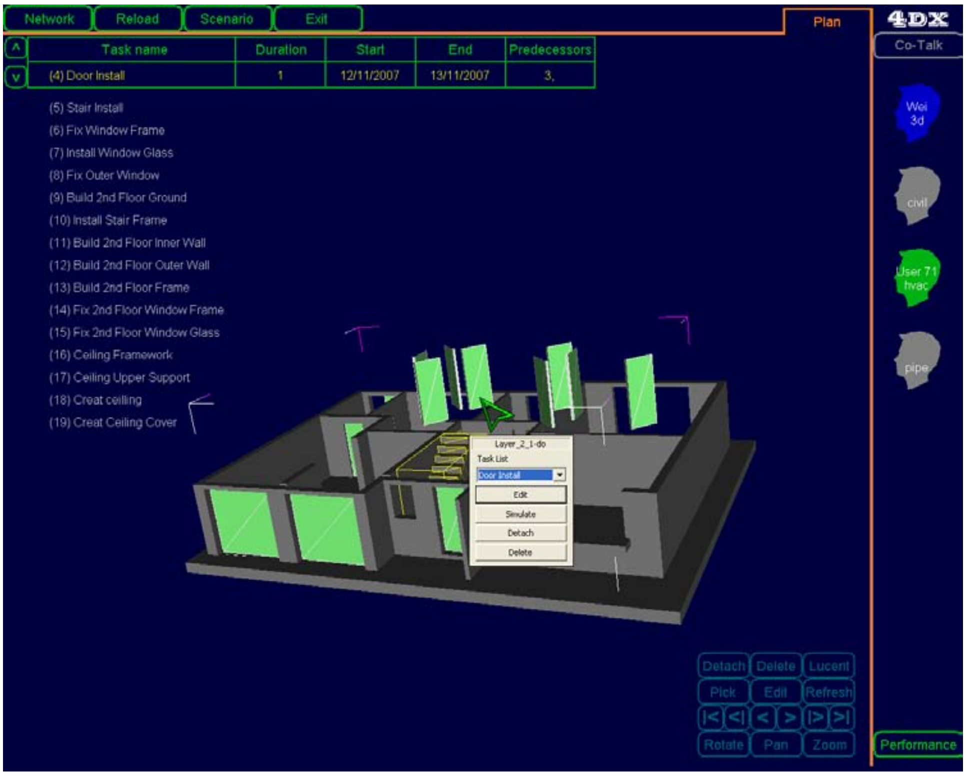
Appendix 4-10 Progress displaying controls in Sort UI



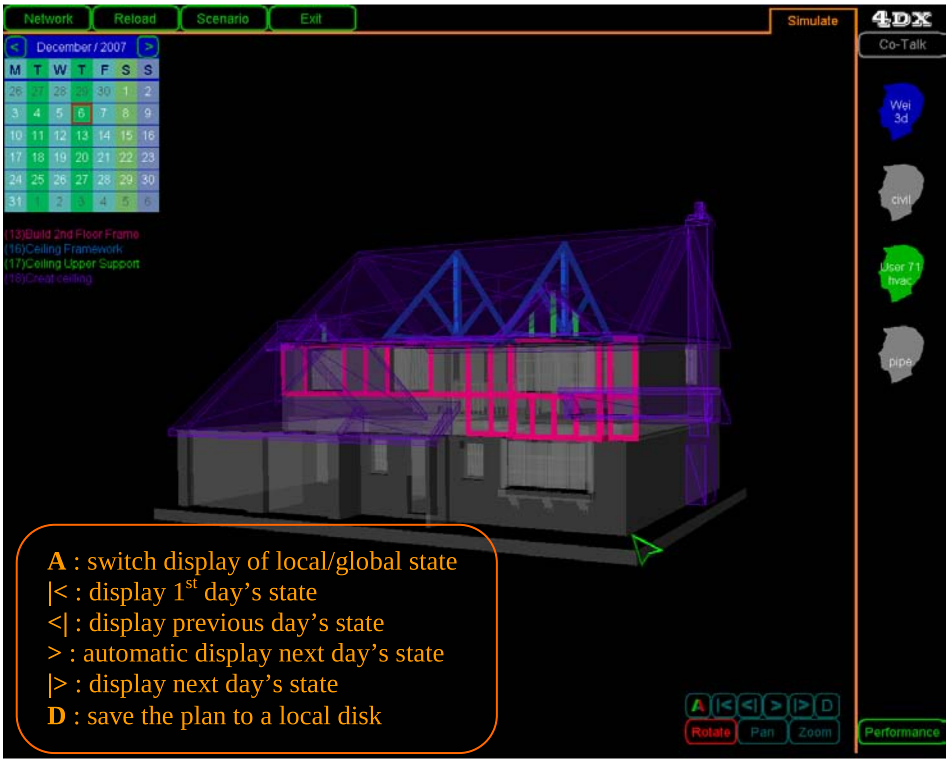
Appendix 4-11 State displaying filters in Sort UI



Appendix 4-12 Editing a task in Plan UI



Appendix 4-13 Plan UI of graphics-based editing



Appendix 4-14 Simulation UI

Appendix 5 Evaluation of 4D-VR UI Design

No. 01 **Date:** 17 Nov 2008

Trial \ Factor	Selection Type (A)		Editing Type (B)		Input Device (C)		Performance	
							Efficiency (second)	Effectiveness (error)
1	1) Direct selection		1) Graphics editing		1) 3D mouse		537	4
2	1) Direct selection		2) Text editing		2) Air mouse		527	2
3	2) Focus selection		1) Graphics editing		2) Air mouse		702	7
4	2) Focus selection		2) Text editing		1) 3D mouse		972	6
Y_{j1}	1064	6	1239	10	1509	10		
Y_{j2}	1674	13	1499	8	1229	9		
Optimal level	A1	A1	B1	B2	C2	C2	A1B1C2	A1B2C2
							Satisfaction	A1B1C1

Please pick out your most desired design combination below according to your experience.

(A) Picking method	(1) Direct selection ☑	(2) Focus selection □
(B) Editing type	(1) Graphics editing ☑	(2) Text editing □
(C) Input device	(1) 3D mouse ☑	(2) Air mouse □

No. 02 **Date:** 18 Nov 2008

Trial \ Factor	Selection Type (A)		Editing Type (B)		Input Device (C)		Performance: Efficiency (second)	Performance: Effectiveness (error)
1	1) Direct selection		1) Graphics editing		1) 3D mouse		477	3
2	1) Direct selection		2) Text editing		2) Air mouse		460	3
3	2) Focus selection		1) Graphics editing		2) Air mouse		681	6
4	2) Focus selection		2) Text editing		1) 3D mouse		503	4
Y_{j1}	937	6	1158	9	980	7		
Y_{j2}	1184	10	1141	7	1141	9		
Optimal level	A1	A1	B2	B2	C1	C1	A1B2C1	A1B2C1
							Satisfaction	A1B2C2

Please pick out your most desired design combination below according to your experience.

(A) Picking method	(1) Direct selection ☑	(2) Focus selection □
(B) Editing type	(1) Graphics editing □	(2) Text editing ☑
(C) Input device	(1) 3D mouse □	(2) Air mouse ☑

No. 03 **Date:** 19 Nov 2008

Trial \ Factor	Selection Type (A)		Editing Type (B)		Input Device (C)		Performance	
							Efficiency (second)	**Effectiveness (error)**
1	1) Direct selection		1) Graphics editing		1) 3D mouse		470	4
2	1) Direct selection		2) Text editing		2) Air mouse		345	3
3	2) Focus selection		1) Graphics editing		2) Air mouse		436	7
4	2) Focus selection		2) Text editing		1) 3D mouse		315	2
Y_{j1}	815	7	906	11	785	6		
Y_{j2}	751	9	660	5	781	10		
Optimal level	A2	A1	B2	B2	C2	C1	A2B2C2	A1B2C1
							Satisfaction	A1B1C2

Please pick out your most desired design combination below according to your experience.

(A) Picking method	(1) Direct selection ☑	(2) Focus selection □
(B) Editing type	(1) Graphics editing ☑	(2) Text editing □
(C) Input device	(1) 3D mouse □	(2) Air mouse ☑

No. 04 **Date:** 19 Nov 2008

Trial \ Factor	Selection Type (A)		Editing Type (B)		Input Device (C)		Performance	
							Efficiency (second)	**Effectiveness (error)**
1	1) Direct selection		1) Graphics editing		1) 3D mouse		452	4
2	1) Direct selection		2) Text editing		2) Air mouse		252	0
3	2) Focus selection		1) Graphics editing		2) Air mouse		843	9
4	2) Focus selection		2) Text editing		1) 3D mouse		420	2
Y_{j1}	704	4	1295	13	872	6		
Y_{j2}	1263	11	672	2	1095	9		
Optimal level	A1	A1	B2	B2	C1	C1	A1B2C1	A1B2C1
							Satisfaction	A1B1C1

Please pick out your most desired design combination below according to your experience.

(A) Picking method	(1) Direct selection ☑	(2) Focus selection □
(B) Editing type	(1) Graphics editing ☑	(2) Text editing □
(C) Input device	(1) 3D mouse ☑	(2) Air mouse □

No. 05 **Date:** 23 Jul 2008

Trial \ Factor	Selection Type (A)		Editing Type (B)		Input Device (C)		Performance	
							Efficiency (second)	**Effectiveness (error)**
1	1) Direct selection		1) Graphics editing		1) 3D mouse		292	3
2	1) Direct selection		2) Text editing		2) Air mouse		262	1
3	2) Focus selection		1) Graphics editing		2) Air mouse		416	3
4	2) Focus selection		2) Text editing		1) 3D mouse		326	2
Y_{j1}	554	4	708	6	618	5		
Y_{j2}	742	5	588	3	678	4		
Optimal level	A1	A1	B2	B2	C1	C2	A1B2C1	A1B2C2
							Satisfaction	A1B1C1

Please pick out your most desired design combination below according to your experience.

(A) Picking method	(1) Direct selection ☑	(2) Focus selection □
(B) Editing type	(1) Graphics editing ☑	(2) Text editing □
(C) Input device	(1) 3D mouse ☑	(2) Air mouse □

No. 06 **Date:** 24 Jul 2008

Trial \ Factor	Selection Type (A)		Editing Type (B)		Input Device (C)		Performance	
							Efficiency (second)	**Effectiveness (error)**
1	1) Direct selection		1) Graphics editing		1) 3D mouse		376	4
2	1) Direct selection		2) Text editing		2) Air mouse		580	5
3	2) Focus selection		1) Graphics editing		2) Air mouse		753	5
4	2) Focus selection		2) Text editing		1) 3D mouse		886	7
Y_{j1}	956	9	1129	9	1262	12		
Y_{j2}	1639	12	1466	12	1333	10		
Optimal level	A1	A1	B1	B1	C1	C2	A1B1C1	A1B1C2
							Satisfaction	A1B1C1

Please pick out your most desired design combination below according to your experience.

(A) Picking method	(1) Direct selection ☑	(2) Focus selection □
(B) Editing type	(1) Graphics editing ☑	(2) Text editing □
(C) Input device	(1) 3D mouse ☑	(2) Air mouse □

No. 07 **Date:** 21 Nov 2008

Trial \ Factor	Selection Type (A)		Editing Type (B)		Input Device (C)		Performance	
							Efficiency (second)	**Effectiveness (error)**
1	1) Direct selection		1) Graphics editing		1) 3D mouse		323	5
2	1) Direct selection		2) Text editing		2) Air mouse		273	2
3	2) Focus selection		1) Graphics editing		2) Air mouse		841	3
4	2) Focus selection		2) Text editing		1) 3D mouse		362	4
Y_{j1}	596	7	1164	8	685	9		
Y_{j2}	1203	7	635	6	1114	5		
Optimal level	A1	A1/A2	B2	B2	C1	C2	A1B2C1	*A1B2C2*
							Satisfaction	A1B1C1

Please pick out your most desired design combination below according to your experience.

(A) Picking method	(1) Direct selection ☑	(2) Focus selection □
(B) Editing type	(1) Graphics editing ☑	(2) Text editing □
(C) Input device	(1) 3D mouse ☑	(2) Air mouse □

No. 08 **Date:** 24 Nov 2008

Trial \ Factor	Selection Type (A)		Editing Type (B)		Input Device (C)		Performance	
							Efficiency (second)	**Effectiveness (error)**
1	1) Direct selection		1) Graphics editing		1) 3D mouse		412	5
2	1) Direct selection		2) Text editing		2) Air mouse		213	1
3	2) Focus selection		1) Graphics editing		2) Air mouse		385	4
4	2) Focus selection		2) Text editing		1) 3D mouse		339	0
Y_{j1}	625	6	797	9	751	5		
Y_{j2}	724	4	552	1	598	5		
Optimal level	A1	A2	B2	B2	C2	C1/ C2	A1B2C2	*A2B2C1*
							Satisfaction	A1B2C1

Please pick out your most desired design combination below according to your experience.

(A) Picking method	(1) Direct selection ☑	(2) Focus selection □
(B) Editing type	(1) Graphics editing □	(2) Text editing ☑
(C) Input device	(1) 3D mouse ☑	(2) Air mouse □

No. 09 **Date:** 26 Nov 2008

Trial \ Factor	Selection Type (A)		Editing Type (B)		Input Device (C)		Performance	
							Efficiency (second)	**Effectiveness (error)**
1	1) Direct selection		1) Graphics editing		1) 3D mouse		401	3
2	1) Direct selection		2) Text editing		2) Air mouse		253	0
3	2) Focus selection		1) Graphics editing		2) Air mouse		540	5
4	2) Focus selection		2) Text editing		1) 3D mouse		322	2
Y_{j1}	654	3	941	8	723	5		
Y_{j2}	862	7	575	2	793	5		
Optimal level	A1	A1	B2	B2	C1	C1/ C2	A1B2C1	A1B2C1
							Satisfaction	A1B2C1

Please pick out your most desired design combination below according to your experience.

(A) Picking method	(1) Direct selection ☑	(2) Focus selection □
(B) Editing type	(1) Graphics editing □	(2) Text editing ☑
(C) Input device	(1) 3D mouse ☑	(2) Air mouse □

Appendix 6 Confirmation test questionnaire

Dear Sir/Madam,

*You are invited to fill in this questionnaire in order to assist in the investigation and development of a new 4D construction planning tool. All questions are **single** selection questions. It will take you **5 minutes** or so to complete the questionnaire. All responses are confidential, and will not be disclosed.*

***How to fill in**?*

*Please **double click** the dark block of your chosen question's answer, and you will see a popup dialog box. In the dialog box, you can choose one of default values as **Not checked** or **Checked**, and then press **OK** button. When you finish all questions, please **SAVE** and e-mail it to **wei.zhou@wlv.ac.uk***

Thank you for your cooperation.

Wei ZHOU, M.Sc., PDEng

The University of Wolverhampton

01) I quickly got familiar with navigation in the 3D environment using the input device.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

02) The process of defining plan tasks was easy and the visualisation ensured assisted me in checking defined project tasks.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

03) It was quite easy for me to pick desired 3D elements for plan task definition.

☐ Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree

04) I was quite familiar with the plan item definition which keeps consistency with my acquired knowledge on project planning.

☐ Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree

05) The defined hierarchal task items kept consistent with what I expected to see.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

06) I was clear on how to control my navigation in terms of the 3D model's zoom, pan and rotate.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

07) I was satisfied with the approach of plan item definition as it is almost the same with my prior knowledge of project planning.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

08) The visualisation and simulation provided me with sufficient indications to identify the defined project tasks.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

09) The plan task's definition realises what I expected to see in planning work.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

10) I could conveniently choose my desired 3D elements in planning.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

-This is the end of the questionnaire-

*Please **SAVE** it, and e-mail it to **wei.zhou@wlv.ac.uk***

Thank you for your cooperation.

Appendix 7 Summary of confirmation test questionnaire

Question 1	Answer	Sum	%
I quickly got familiar with navigation in the 3D environment using the input device.	Strongly Disagree		
	Disagree		
	Neutral		
	Agree	3	50
	Strongly Agree	3	50
Question 2			
The process of defining plan tasks was easy and the visualisation ensured assisted me in checking defined project tasks.	Strongly Disagree		
	Disagree		
	Neutral		
	Agree	1	17
	Strongly Agree	5	83
Question 3			
It was quite easy for me to pick desired 3D	Strongly Agree	3	50
	Agree	3	50
	Neutral		

elements for plan task definition.	Disagree		
	Strongly Disagree		
Question 4			
I was quite familiar with the plan item definition which keeps consistency with my acquired knowledge on project planning.	Strongly Agree	3	50
	Agree	3	50
	Neutral		
	Disagree		
	Strongly Disagree		
Question 5			
The defined hierarchal task items kept consistent with what I expected to see.	Strongly Disagree		
	Disagree		
	Neutral		
	Agree	3	50
	Strongly Agree	3	50
Question 6			
I was clear on how to control my navigation in terms of the 3D model's zoom, pan	Strongly Disagree		
	Disagree		
	Neutral		
	Agree	2	33
	Strongly Agree	4	67

and rotate.			
Question 7			
I was satisfied with the approach of plan item definition as it is almost the same with my prior knowledge of project planning.	Strongly Disagree		
	Disagree		
	Neutral		
	Agree	6	100
	Strongly Agree		
Question 8			
The visualisation and simulation provided me with sufficient indications to identify the defined project tasks.	Strongly Disagree		
	Disagree		
	Neutral		
	Agree	1	17
	Strongly Agree	5	83
Question 9			
The plan task's definition realises what I expected to see in planning work.	Strongly Disagree		
	Disagree		
	Neutral		
	Agree	1	17
	Strongly Agree	5	83

Question 10			
I could conveniently choose my desired 3D elements in planning.	Strongly Disagree		
	Disagree		
	Neutral		
	Agree	2	33
	Strongly Agree	4	67

Appendix 8 Validation test questionnaire

Dear Sir/Madam,

*You are invited to fill in this questionnaire in order to assist in the investigation and development of a new 4D construction planning tool. All questions are **single** selection questions. It will take you **8 minutes** or so to complete the questionnaire. All responses are confidential, and will not be disclosed.*

***How to fill in**?*

*Please **double click** the dark block of your chosen question's answer, and you will see a popup dialog box. In the dialog box, you can choose one of default values as **Not checked** or **Checked**, and then press **OK** button. When you finish all questions, please **SAVE** and e-mail it to **wei.zhou@wlv.ac.uk***

Thank you for your cooperation.

Wei ZHOU, M.Sc., PDEng

The University of Wolverhampton

01) I quickly got familiar with navigation in the 3D environment using the input device.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

02) It was quite easy for me to pick desired 3D elements for sorting and planning.

☐ Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree

03) I could easily adapt my manipulation in 3D navigation using the input device.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

04) The process of defining project tasks was easy and the visualisation ensured assisted me in checking defined project tasks.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

05) I was quite familiar with the plan item definition which keeps consistency with my acquired knowledge on project planning

☐ Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree

06) The defined hierarchal task items kept consistent with what I expected to see.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

07) It was convenient for me to review my collaborator's state during collaborative planning sessions.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

08) The collaborative sessions provided assistance during my planning operations.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

09) I was clear on how to control my navigation in terms of the 3D model's zoom, pan and rotate.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

10) I was satisfied with the approach of plan item definition as it is almost the same with my prior knowledge of project planning.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

11) The visualisation and simulation provided me with sufficient indications to identify the defined project tasks.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

12) The plan item definition realises what I expected to see in planning work.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

13) I was aware of my collaborator's planning progress in the planning session.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

14) I could conveniently choose my desired 3D elements in sorting and planning.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

15) In general, I was satisfied with this collaborative approach to my planning work.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

16) I was satisfactory to exam the 3D building model and its components in the co-navigate session.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

17) I could get assistance from other collaborators in the co-navigate session for co-sorting and co-planning.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

18) I was satisfied with co-sort collaboration as it provided a clear collaborative context to identify 3D elements for planning.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

19) I was aware of my collaborators' 3D elements and hence sorted my own 3D elements correctly in the co-sort session.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

20) The co-plan session enabled me to define my own schedule while to consider other collaborators' planning work in integration.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

21) I was satisfied with the co-simulate across the network since it enabled me to check my own schedule as well as other collaborators' planning work simultaneously.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

22) The co-talk in the planning provided me chances to coordinate planning process and consider appropriate strategies with other collaborators together.

☐ Strongly Disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly Agree

-This is the end of the questionnaire-

*Please **SAVE** it, and e-mail it to **wei.zhou@wlv.ac.uk***

Thank you for your cooperation.

Appendix 9 Summary of validation test questionnaire

Question 1	**Answer**	**Sum**	**%**
I quickly got familiar with navigation in the 3D environment using the input device.	Strongly Disagree		
	Disagree		
	Neutral	2	40
	Agree	2	40
	Strongly Agree	1	20
Question 2			
It was quite easy for me to pick desired 3D elements for sorting and planning.	Strongly Agree	1	20
	Agree	1	20
	Neutral	1	20
	Disagree	2	40
	Strongly Disagree		
Question 3			
I could easily adapt my manipulation in 3D navigation using the input device.	Strongly Disagree		
	Disagree		
	Neutral	1	20
	Agree	3	60
	Strongly Agree	1	20
Question 4			

The process of defining project tasks was easy and the visualisation ensured assisted me in checking defined project tasks.	Strongly Disagree		
	Disagree		
	Neutral		
	Agree	3	60
	Strongly Agree	2	40
Question 5			
I was quite familiar with the plan item definition which keeps consistency with my acquired knowledge on project planning.	Strongly Agree	1	20
	Agree	4	80
	Neutral		
	Disagree		
	Strongly Disagree		
Question 6			
The defined hierarchal task items kept consistent with what I expected to see.	Strongly Disagree		
	Disagree		
	Neutral		
	Agree	5	100
	Strongly Agree		
Question 7			

It was convenient for me to review my collaborator's state during collaborative planning sessions.	Strongly Disagree		
	Disagree	1	20
	Neutral		
	Agree	4	80
	Strongly Agree		
Question 8			
The collaborative sessions provided assistance during my planning operations.	Strongly Disagree		
	Disagree		
	Neutral		
	Agree	4	80
	Strongly Agree	1	20
Question 9			
I was clear on how to control my navigation in terms of the 3D model's zoom, pan and rotate.	Strongly Disagree		
	Disagree		
	Neutral		
	Agree	2	40
	Strongly Agree	3	60
Question 10			
I was satisfied with the approach of plan item definition as it is	Strongly Disagree		
	Disagree	1	20
	Neutral		
	Agree	2	40

almost the same with my prior knowledge of project planning.	Strongly Agree	2	40
Question 11			
The visualisation and simulation provided me with sufficient indications to identify the defined project tasks.	Strongly Disagree		
	Disagree		
	Neutral	1	20
	Agree	1	20
	Strongly Agree	3	60
Question 12			
The plan item definition realises what I expected to see in planning work.	Strongly Disagree		
	Disagree		
	Neutral	1	20
	Agree	2	40
	Strongly Agree	2	40
Question 13			
I was aware of my collaborator's planning progress in the planning	Strongly Disagree		
	Disagree		
	Neutral	1	20
	Agree	2	40

session.	Strongly Agree	2	40
Question 14			
I could conveniently choose my desired 3D elements in sorting and planning.	Strongly Disagree		
	Disagree	2	40
	Neutral	1	10
	Agree		
	Strongly Agree	2	40
Question 15			
In general, I was satisfied with this collaborative approach to my planning work.	Strongly Disagree		
	Disagree		
	Neutral	1	20
	Agree		
	Strongly Agree	4	80
Question 16			
I was satisfactory to the co-navigate session to exam the 3D building model and its components	Strongly Disagree		
	Disagree		
	Neutral		
	Agree	2	40
	Strongly Agree	3	60
Question 17			
I could get assistance from	Strongly Disagree		
	Disagree		

collaborators in the co-navigate session for co-sorting and co-planning.	Neutral		
	Agree		
	Strongly Agree	5	100
Question 18			
I was satisfied with co-sort collaboration as it provided a clear collaborative context to identify 3D elements for planning.	Strongly Disagree		
	Disagree		
	Neutral		
	Agree	2	40
	Strongly Agree	3	60
Question 19			
I was aware of my collaborators' 3D elements and hence sorted my own 3D elements correctly in the co-sort session.	Strongly Disagree		
	Disagree		
	Neutral	1	20
	Agree	2	40
	Strongly Agree	2	40
Question 20			
The co-plan	Strongly Disagree		

session enabled me to define my own schedule while to consider other collaborators' planning work in integration.	Disagree		
	Neutral	1	20
	Agree	1	20
	Strongly Agree	3	60
Question 21			
I was satisfied with the co-simulate across the network since it enabled me to check my own schedule as well as other collaborators' planning work simultaneously.	Strongly Disagree		
	Disagree		
	Neutral		
	Agree	1	20
	Strongly Agree	4	80
Question 22			
The co-talk in the planning provided me chances to	Strongly Disagree		
	Disagree		
	Neutral		

coordinate planning process and consider appropriate strategies with other collaborators together.	Agree	2	40
	Strongly Agree	3	60

Appendix 10 Publications of this research

1. Zhou, W., Heesom, D., Georgakis, P., Nwagboso, C., Feng, A. (2009) **An interactive approach to collaborative 4D construction planning**, ITcon Vol. 14, Special Issue Technology Strategies for Collaborative Working , pg. 30-47, http://www.itcon.org/cgi-bin/works/Show?2009_05

2. Zhou, W., Heesom, D., Georgakis, P. (2007). **Enhancing User-Centred Design by Adopting the Taguchi Philosophy**. Proceedings of 12th International Conference on Human Computer Interaction (HCI International 2007), Beijing, China, 2007. Human-Computer Interaction, Part I, HCII 2007, LNCS 4550, pp. 350–359, 2007. Springer-Verlag Berlin Heidelberg 2007. (With presentation).

3. Zhou, W., Heesom, D., Georgakis, P. (2007). **CSCW Design for 4D Construction Planning in a Distributed Real-Time VR Environment**. Proceedings of 7th International Postgraduate Research Conference in the Built and Human Environment. ISBN 978-1-905732-22-7. pp.202-211. University of Salford, United Kingdom, 2007. (With presentation).

4. Zhou, W., Heesom, D., Georgakis, P. (2006). **Designing a Distributed VR Environment for Collaborative Construction Planning**. Proceedings of

World Conference of Accelerating Excellence in the Built Environment (WCAEBE 06’). Birmingham, United Kingdom. (With presentation).