MULTI-CONSTRAINT INFORMATION MANAGEMENT AND VISUALISATION FOR COLLABORATIVE PLANNING AND CONTROL IN CONSTRUCTION

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SUMMARY: In complex and concurrent construction projects, reliable planning becomes a centre for effective collaboration across upstream supply chains and downstream operations at the work face. Thousands of literatures in construction planning have been published over the past 50 years; introducing, testing, and implementing mountain of techniques and tools. However, they are very fragmented and have not yet provided a universal system that remedies a typical problem of separation of execution from planning. To solve this puzzle, this paper introduced a new methodology called 'multi-constraint planning', which possesses five superior characteristics including (1) collaborative and multi-level planning; (2) multi-constraint consideration; (3) effective uncertainty handling; (4) appropriate visual representation; and (5) practicable optimisation. An integrated decision support system that incorporates web-based and mobile information management system, 4D-visualisation system, and evolutionary optimisation system is successfully developed as an enabler for implementation of the proposed methodology. The two modules of information management and visualisation are detailed and demonstrated in the paper. It is envisaged that successful implementation of this system will enable generation of reliable plans and constraint-free execution assignments, in turn, reduce production risks and improve on-site productivity.

KEYWORDS: 4D visualisation, lean construction, multiple constraints, planning and control, web-based information system

1. INTRODUCTION

Planning in complex and concurrent construction projects is very complicated due to tremendous pressure to complete projects under conditions of uncertainty in less time and without sacrifice to cost and quality. Without reliable planning, there is a strong tendency for weak collaboration across upstream supply chains and downstream operations at the work face. In a case study of a £120 million Private-Finance-Initiative (PFI) project in UK, it was found that tasks were frequently executed even if not all the pre-requisite works were completed and required resources and information were available (Sriprasert and Dawood, 2002a). This tendency known as *separation of execution from planning* (Koskela and Howell, 2001) inevitably resulted in variability of tasks' duration and, frequently, obsoleteness of the plans in many construction projects.

Substantial amount of literature in construction planning has been published over the past 50 years. However, those proposed techniques and tools are very fragmented and partly address the problem either from strategy-pull or technology-push perspective. Many of them are initiated from other industries or are mere applications of computer science- and operation research-based techniques. It is apparent that no universal planning system that can remedy the typical problem of separation of execution from planning has currently existed in the construction industry.

Therefore, it is the objective of this paper to synchronise the two paradigms of strategy-pull and technology-push research and strive for a universal planning methodology and supported tools that will be able to remedy the critical problem of separation of execution from planning in construction. In doing so, the paper firstly presents a

puzzle of construction planning systems in a form of matrix between existing techniques and a common set of system characteristics (section 2, 3, and 4). The paper then proposes a solution by identifying major requirements for the next generation of planning system and arriving at a primary design of an innovative technique called *Multi-constraint planning system* (section 5). To enable effective implementation of the proposed technique, an integrated decision support system that incorporates web-based and mobile information management system, 4D-visualisation system, and evolutionary optimisation system is successfully developed and tested with real case study data. Section 6 presents the overall system architecture. Section 7 and 8 demonstrate the two modules of information management and visualisation respectively. The evolutionary optimisation module has, however, been detailed in Sriprasert and Dawood (2003). Finally, opinions of senior planners on the system prototype and suggestions for future research are elaborated in section 9. It is envisaged that the integration of strategy-pull and technology-push research paradigms presented in this paper will enable planners to generate more reliable plans and constraint-free execution assignments, in turn, reduce production risks and improve on-site productivity.

2. CLASSIFICATION OF PLANNING TECHNIQUES IN CONSTRUCTION

Seven major groups of techniques have been classified through reviewing and analysing numerous literatures in construction planning. These groups of techniques are:

2.1 Critical path method

Critical Path Method (CPM) has been invented by the aerospace industry and adopted in the construction industry since late 1950s. The CPM applications have well served project managers in preparing project proposals, managing personnel and resources, tracking delays and change orders, instituting as a basis for progress payments, and co-ordinating with subcontractors (Jaafari, 1984). However, the CPM has been widely criticised in terms of inability to cope with non-precedence constraints, difficulty to evaluate and communicate interdependencies, and inadequacy for work-face production (Pultar, 1990; Jaafari, 1996; Choo et al, 1999).

2.2 Line-of-balance method

The line-of-balance method (LOB) is a powerful tool for scheduling and controlling a construction project that involves repetitive sequences of activities such as high rise buildings, tunnels, roadways, and pipeline construction. The basis of the method is to find the required resources for each stage of construction so that the following stages are not interfered with and the target output is achieved (Harris and McCaffer, 1989). However, in large and complex projects, there is a problem to show all information on one chart especially when monitoring progress. A recent computerised development for this method can be referred to Arditi et al (2002).

2.3 Simulation method

Since 1960s, construction simulation has been developed as a definitive tool for resource optimisation and productivity improvement. Examples of popular tools are CYCLONE (Halpin and Riggs, 1992) and STROBOSCOPE (Martinez, 1996). However, the types of operations that can be simulated need to be cyclical or repetitive in nature and the construction industry has also been reluctant to adopt this method in their planning (Halpin and Martinez, 1999).

2.4 Knowledge-based expert system and artificial intelligent method (KBES and AI)

The research in this area has become popular since 1980s. The method claims ability and benefits to automate the generation of CPM schedule from the product model/drawings. Examples of these works can be referred to SIPE-2 (Kartam et al, 1991), BUILDER (Cherneff et al, 1991), and OARPLAN (Winstanley et al, 1993). However, a major drawback of this method involves around the flexibility of coded knowledge which doesn't usually cover uncertainties during the construction stage.

2.5 Visualisation method

Started in mid 1990s, construction research has employed the advancement of visualisation technologies to enhance capability of communication and evaluation of the construction plans. Two major approaches including 4D CAD (3D+time) and Virtual Reality (VR) have been successfully applied to aid evaluation of physical constraints i.e. technological dependency (McKinney and Fischer, 1998, Koo and Fischer, 2000, Kähkönen and

Leinonen, 2001), space (Akinci et al, 2002, Dawood et al, 2002a), and safety (Hadikusumo and Rowlinson, 2002). However, the method has not been used to detect information and resource constraints.

2.6 Critical chain scheduling

Critical chain is an application of theory of constraints (TOC) to project management (Goldratt, 1997). A breakthrough of the critical chain is an incorporation of behavioural sciences into project time management. Two assumptions regarding human behaviour are: (1) Murphy's Law - people do make considerable provision for contingencies when estimating activity duration; and (2) Parkinson's Law - people normally expand their works to fill the time available by improving the quality of the works even well beyond the requirement (Steyn, 2000). To address these behaviours, the critical chain method encourages reduction of contingencies through optimistic estimation of task duration and insertion of aggregated buffers. Furthermore, the method attempts to avoid the inefficiency of *multi-tasking* by taking into account the limitations of resources when developing the project schedules (Herroelen and Leus, 2001).

2.7 Last planner method

Based on the lean construction concept, the last planner method focuses on short-term planning at crew level (Ballard, 2000). The method seeks improvement of plan reliability through shielding task execution from potential constraints and generation of workable backlog (what *can* be done). At the beginning of each week, the crew performs commitment planning by selecting tasks from the workable backlog (what *will* be done). At the end of the week, percent plan completion and reasons for variance are monitored (what *was* done). Implementation of this method significantly resulted in waste reduction and productivity improvement in several case studies (Ballard et al, 1996, Horman et al, 1997, Junior et al, 1998).

It should be noted that there is still a diversity of techniques that cannot be classified into the seven groups identified above. However, it is beyond the scope of this paper to discuss all those techniques as they are less popular and has less influence in the construction industry. Examples of these miscellaneous methods are: Generalised network, Cascade chart, Time-chainage chart (Mawdesley et al, 1997) and TAPAS (Jaafari, 1996).

3. CHARACTERISTICS OF PLANNING TECHNIQUES IN CONSTRUCTION

To systematically differentiate and characterise all the planning techniques identified above, this section classifies characteristics of planning techniques into six major groups as follows:

3.1 Underlying concepts

Underlying concepts significantly influence the characteristics and aims of planning techniques. Four major concepts can be listed as follows:

1. Project management body of knowledge (PMBOK) – is a classical bible for planning and control in construction. The principle is to breakdown the project into small elements and manage them (Duncan, 1996);

2. Theory of constraints (TOC) – is a management philosophy that supports a continuous improvement scheme. TOC uses global safety time to schedule the project and focuses on the constraints that block the achievement of goal of the project (Goldratt, 1990);

3. Lean construction (LC) – is a concept derived from Toyota lean production system. LC highlights pitfalls of PMBOK and focuses on management of flow and value in addition to conversion process. The primary goal of LC is to understand the physics of production at the task level, and then design support systems to minimise the combined effects of dependence and variation between activities (Howell, 1999); and

4. Concurrent engineering (CE) – is "parallel execution of different development tasks in multidisciplinary teams with the aim of obtaining an optimal product in minimum time and with minimum costs respect to functionality, quality and producibility" (Rolstadås, 1995).

3.2 Levels of planning

Three levels of planning can be generally listed as follows:

1. Project or product level – represents breakdown of project into different product components such as foundations, superstructure, M/E services. Examples of planning at this level are planning at tendering stage and master planning at early construction stage;

2. Process or operation level – represents further breakdown of product into processes or operations required to build that product i.e., excavation, steel fabrication and erection, and concrete pouring. Examples of planning at this level are baseline planning and look-ahead planning; and

3. Assignment level – represents further breakdown of process into locations and work quantities that are manageable at crew level i.e., erection of column in gridline A/1-B/5. Examples of planning at this level are commitment planning at weekly and daily intervals.

3.3 Concerned constraints

In this paper, a construction constraint is defined as "one that restricts, limits, or regulates commencement or progress of work-face operations from achieving construction products within agreed time, cost, and quality." Four major groups of construction constraints can be classified as (Sriprasert and Dawood, 2002b):

1. Physical constraints – include technological dependency, space, safety, and environment;

2. Contract constraints – include time, cost, quality, and special agreement;

3. Resource constraints – include availability, continuity, capacity, and perfection; and

4. Information constraints – include availability and perfection (e.g. accuracy, clarity, and relevancy).

3.4 Uncertainty handling approaches

Uncertainty is a risk element in construction projects. Many uncertainties such as uncertainty of activity duration, physical conditions, scope of work, resource requirement, and delivery of information are generally found. Three main uncertainty handling approaches existed to date are:

1. Probabilistic analysis – normally deals with uncertainty of activity duration and resource requirement. Well known techniques are Program Evaluation and Review Technique (PERT), Monte Carlo simulation, and process simulation (Mawdesley et al, 1997);

2. Buffer management – considers a wide range of uncertainty. The principle of this technique is to pre-identify possible uncertainties and insert appropriate size of buffers to absorb any effects that may interrupt critical paths or critical chains. (Goldratt, 1997, Ballard and Howell, 1998); and

3. Shielding production and look-ahead analysis –was designed based on Lean construction concept. The principle of this technique is to detect and satisfy all potential constraints prior to releasing operation assignments to the work face (Ballard and Howell, 1998).

3.5 Visual representations

Visual representations are important for effective evaluation and communication of construction plans. Seven visual representations can be listed below:

1. Worksheet – is easy to prepare and generally used for work-face instruction or method statement;

2. Bar chart or Gantt chart – is used at crew level planning or as a representation of CPM network;

3. Line-of-balance – is a particular representation for Line-of-balance scheduling technique;

4. 2D drawings – is normally used for site layout and space planning;

5. 3D CAD – is generally used for product clash detection or clarification of detailed connections;

6. 4D CAD (3D + time) – presents temporal and spatial aspects of construction plan thus becomes useful for plan evaluation and communication;

7. Virtual Reality (VR) – allows users to navigate, manipulate and interact with virtual objects in 3D space and, therefore, has huge potential to be applied in construction planning.

3.6 Optimisation techniques

Construction planning requires a trade-off analysis between different objectives dependent on parameters such as time, cost, resource, space, safety, and pollution. The followings are four available optimisation techniques:

1. Mathematical models – attempts to model the optimisation problem using quantitative operation research methods such as linear programming and integer programming. This approach seems to be infeasible to solve the problem of real world construction projects since the nature of problem is large and complicated.

2. Heuristic approaches – are very popular and have been implemented in most project management software for solving the resource-constrained project scheduling problem (RCPSP). Few examples of well-known heuristic rules are earliest start prioritisation (EST), latest start prioritisation (LST), minimum job slack (MINSLK) and greatest resource utilisation (GRU). Several studies confirm that the heuristic approaches can provide 'good' solution within a short processing time (Shi and Deng, 2000, Abeyasinghe et al, 2001). However, the heuristic approaches can perform with varied degree of success on different problems.

3. Evolutionary algorithms such as Genetic Algorithms (GA) – employs a probabilistic yet directed search inspired by the process of natural evolution and the principles of *survival of the fittest* for locating the globally optimal solution (Goldberg, 1989). Several studies have successfully applied GA for time-cost trade-off problem and resource allocation and levelling problem in construction scheduling (Li et al, 1999, Leu and Yang 1999). These studies prove that GA is able to provide near optimum or optimum solution in large combinatorial problems without a necessity to search for all solution spaces. Moreover, the processing time only increased as the square of the project size and not exponentially.

4. Hybrid approaches – combines simplicity of heuristic approaches with efficiency of GA. The approach is very useful as it facilitates implementation of GA in project management software. An example of the utilisation of this hybrid approach can be found in Hegazy (1999) where GA was employed to search for an optimum set of tasks' priorities, thereby, improved resource allocation and resource levelling heuristics in MS Project.

It is worth mentioning that the characteristics of construction planning techniques identified above do not cover all possible factors. The factors like types, complexity, size, and organisation (single or multiple) of project are still remained. It is assumed that the planning techniques discussed in this paper are based on large and complex building construction in the single project organisation.

4. PUZZLE OF CONSTRUCTION PLANNING TECHNIQUES

Based on the classification of available planning techniques in section 2 and the identification of their characteristics in section 3, a puzzle of construction planning techniques can be drawn in Table 1.

From Table 1, it is apparent that major research efforts have significantly improved traditional construction planning techniques such as CPM in various aspects. For instance, the last planner method highlights the importance of short-term planning at crew level and consideration of multiple constraints prior to releasing quality assignments to the work face. The 4D/VR visualisation technology provides better mediums for evaluation and communication of the construction plans. The critical chain and the last planner offer more effective ways to handle uncertainty through buffer management and shielding production. Furthermore, efficient optimisation techniques such as Genetic Algorithms and hybrid approaches allow planners to generate better plans that meet time, cost, and resource requirements. However, none of the available techniques provides a universal framework for collaborative planning at all levels (project, process and assignment levels) and has yet to offer all advancements in uncertainty handling, visualisation and optimisation. Therefore, it is impetus of this research to solve the puzzle by synchronising the available techniques and crafting an innovative approach that possesses all the advancements.

TABLE 1: Puzzle of construction planning techniques.

Technique	Concept	Level	Constraint*				Uncertainty Handling Approach	Visual Representation	Optimisation
			Physical	Contract	Resource	Information			
CPM	PMBOK	Project, Process	Dependency	Time, Cost	Availability, Continuity, Capacity	NA	PERT, Monte Carlo simulation	Bar chart, Gantt chart	Math, Heuristic, Evolutionary, Hybrid
LOB	PMBOK	Project, Process	Dependency	Time, Cost	Availability, Continuity, Capacity	NA	NA	Line-of-balance	NA
KBES & AI	PMBOK	Project, Process	Dependency	Time, Cost	Availability, Continuity, Capacity	NA	NA	Bar chart, Gantt chart	Math, Heuristic, Evolutionary
Simulation	PMBOK, LC	Process	Dependency	Time, Cost	Availability, Continuity, Capacity	NA	Probabilistic	2D, 3D, Animation	Math, Heuristic, Evolutionary
4D/VR Visualisation	PMBOK	Project, Process (to some extent)	Dependency, Space, Safety, Environment	Time, Cost	NA	NA	NA	4D, VR	NA
Critical Chain	TOC	Project, Process	Dependency	Time, Cost	Availability, Continuity, Capacity	NA	Buffer management	Bar chart, Gantt chart	NA
Last Planner	LC	Assignment	Dependency, Space, Safety, Environment	Time, Cost, Quality, Special agreements	Availability, Continuity, Capacity, Perfection	Availability, Perfection	Shielding production, Buffer management	Worksheet, Bar chart	NA
Multi-constraint (proposed in this paper)	TOC, LC, CE	Project, Process, Assignment	Dependency, Space, Safety, Environment	Time, Cost, Quality, Special agreements	Availability, Continuity, Capacity, Perfection	Availability, Perfection	Shielding production, Buffer management	4D, VR, Bar chart, Worksheet	Hybrid

* Constraints that are explicitly concerned in each planning technique.

5. MULTI-CONSTRAINT PLANNING TECHNIQUE

According to the discussion in section 4, requirements for an innovative planning approach can be identified as follows:

1. Collaborative and multi-level planning – planning must be carried out by collaborative efforts from upstream supportive participants to central project planners to downstream operators at the work face throughout the construction phase;

2. Multi-constraint consideration – the approach must effectively evaluate and communicate all potential construction constraints regarding physical, contract, resource and information constraints prior to releasing assignments to the work face;

3. Effective handling of uncertainty – the approach must proactively identify all uncertainties and absorb them by inserting appropriate buffers into project schedule. Various types of buffer are (a) project buffer; (b) feeding buffer; and (c) resource buffer (Herroelen and Leus, 2001). Furthermore, the approach must reduce inflow variability by shielding tasks from any potential constraints and generating workable backlog;

4. Appropriate visual representation – planning output must be carefully evaluated and informed project participants using advanced visualisation technologies. However, simple worksheet and bar chart should be used for instruction and planning at crew level; and

5. Practicable optimisation – hybrid optimisation technique that combines simplicity of the heuristic approaches and evolutionary search power of the Genetic Algorithms should be implemented in current project management software (Sriprasert and Dawood, 2003).

Taking these requirements into account, an innovative planning technique called *multi-constraint planning* has been designed. Fig. 1 illustrates an overall process for the multi-constraint planning technique.
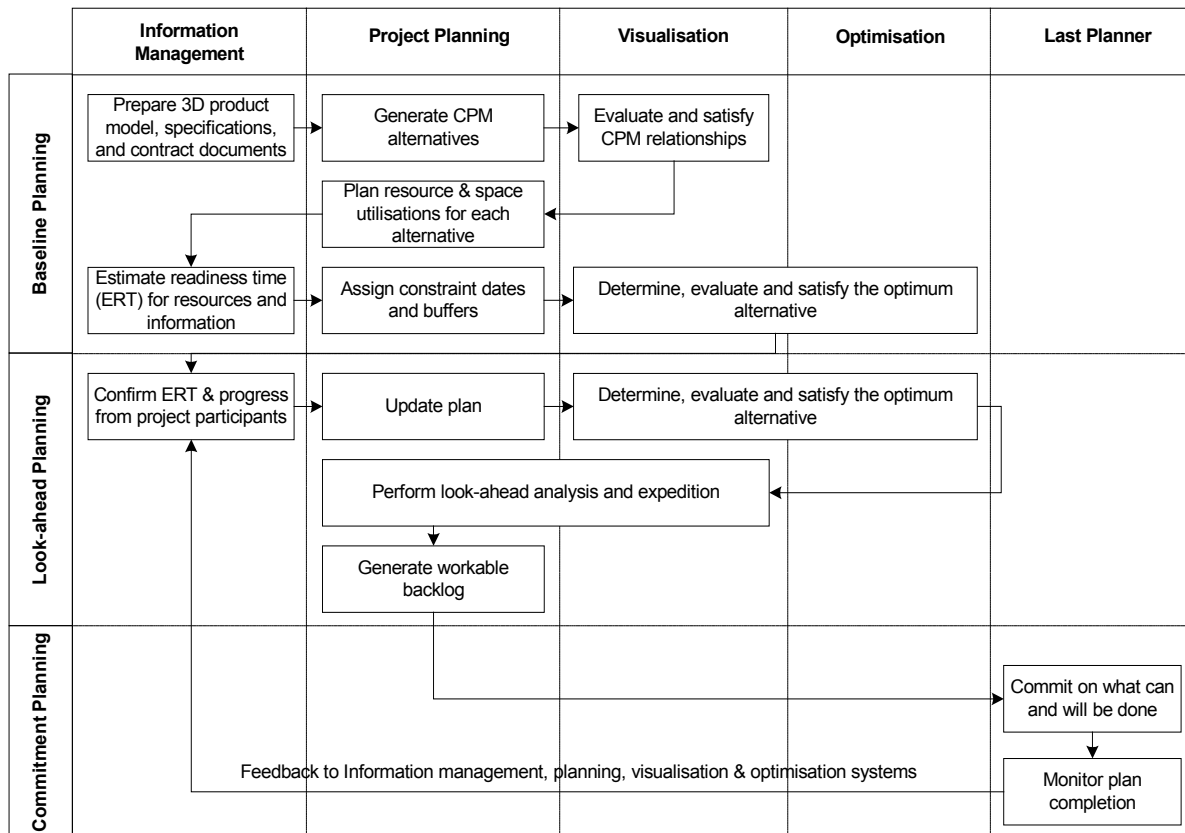

FIG. 1: Overall process for multi-constraint planning technique.

6. DECISION SUPPORT SYSTEM FOR MULTI-CONSTRAINT PLANNING

According to Finlay (1989), a Decision Support System (DSS) encompasses both information management and intelligent computer-based systems and is used to assist in a concurrent decision-making process. To enable the multi-constraint planning process described in section 5, a DSS that integrates both horizontal and vertical lines of subsystems is required. In this research, the design of DSS is based on a compound applications concept in which data extensibility and making use of the existing capabilities in off-the-shelf application packages can be beneficial (Heindel and Kasten, 1997). The core of the architecture is a central relational database management system (RDBMS) where 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) are integrated. The database system is named *as Lean Enterprise Web-based Information System (LEWIS)*. Microsoft SQL Server 2000 is chosen for the database implementation because of its wide availability, scalability, and multi-users supportability.

However, it is important to note that the design of our DSS is neither meant to be a fully integrated system nor to replace enterprise resource planning systems and proprietary applications. Instead, it is designed as a system that gather processed information from upstream supportive organisations for the benefits of planning and work-face instruction. Fig. 2 presents an overall DSS architecture for multi-constraint planning. The architecture is organised into three main layers and each of them is described as follows.
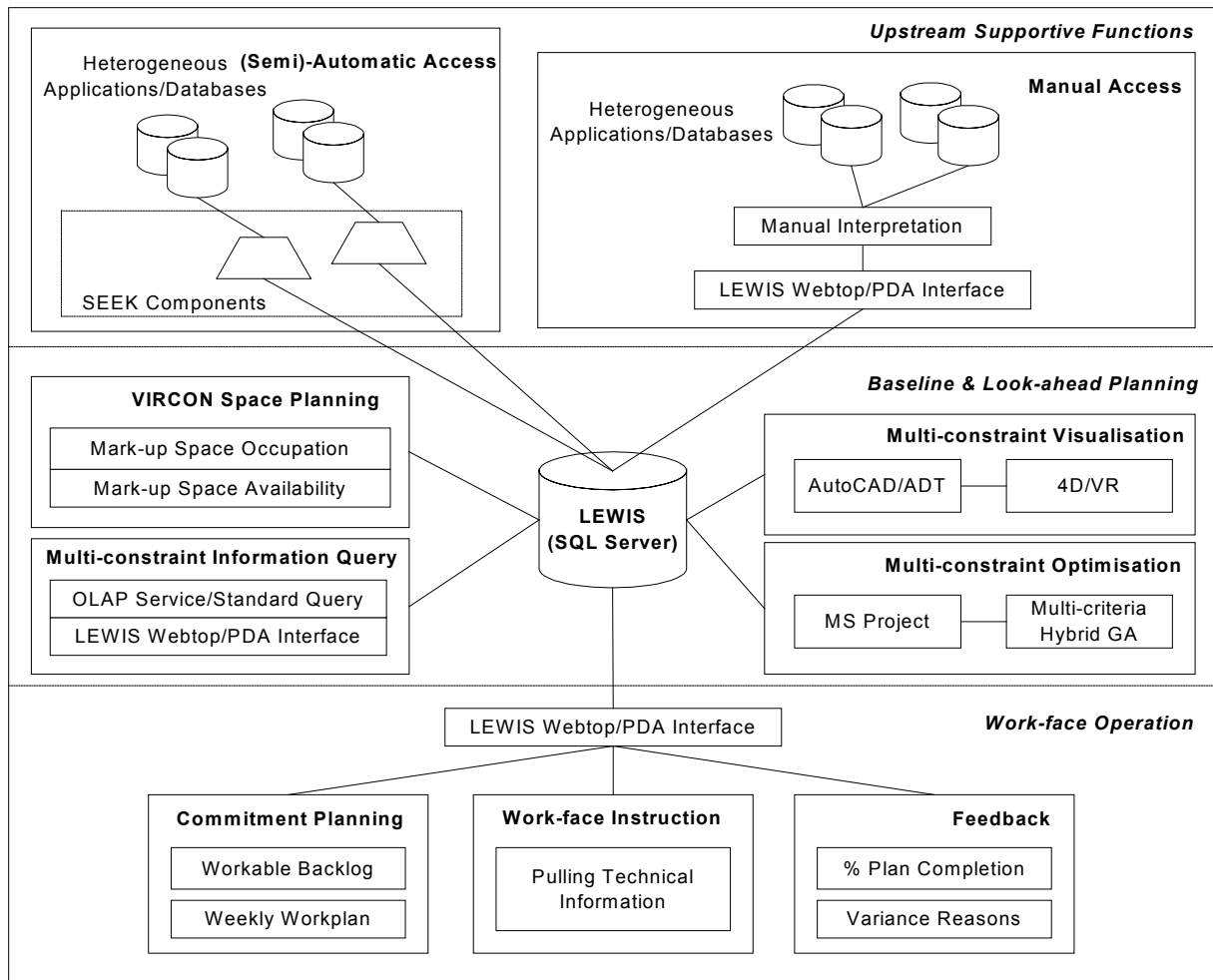

FIG. 2: Overall DSS architecture for multi-constraint planning.

6.1 Upstream supportive functions layer

Upstream supportive functions may include design, engineering, contract management, accounting and cost control, procurement, inventory control, quality assurance, safety and risk management, and so on. These

functions are usually performed by multiple organisations (i.e. designer, consultant, contractor, suppliers and subcontractors), from multiple locations both off-site and on-site and during multiple periods throughout the construction stage using heterogeneous applications and databases.

As seen in Fig. 2, there are two possible ways to access the LEWIS database:

1. Semi-automatic access – an utilisation of the Scalable Extraction of Enterprise Knowledge (SEEK) components (O'Brien et al, 2002) as a translator between heterogeneous applications/databases and the LEWIS is seen to be appropriate. As far as data standardisation and system interoperability are concerned, our assumption is similar to those of (O'Brien et al, 2002, Amor and Faraj, 2001, Turk, 2001, Zamanian and Pittman, 1999) in that hundreds or thousands of firms composing a project will not subscribe to a common data standard for process related data. It seems more likely that firms will maintain the use of legacy applications/databases for process data, selectively transitioning to new applications (O'Brien and Hammer, 2002). Furthermore, the work on IAI/IFC has focussed on product models while limited process extensions have been developed (Froese et al, 1999). It is perceptible that the recent version of IFC2x2 is still inadequate for the implementation of the DSS in this research. A proposal to integrate the LEWIS with SEEK has been initiated and funded. The result of this integration will be reported in the future; and

2. Manual access – upstream supportive participants can currently access the LEWIS via webtop interface (ordinary PC and web browser) and wireless PDA interface (Pocket PC). Nevertheless, the users have to manually interpret the data from their legacy systems and re-input in the LEWIS. Examples of data input are estimated readiness time and delivery details of resources and information.

6.2 Baseline and look-ahead planning layer

Given contract finished date and allowable budget, an optimum baseline plan that has been accounted for unforeseen circumstances is generally prepared at the very beginning of construction stage. Once the construction progresses and deliveries of resources and information are confirmed, look-ahead planning should be performed so that constraints that are associated with scheduled activities can be proactively satisfied (Ballard, 1997). The main contractor's planning department with collaborative supports from upstream and downstream personnel are normally in charge of these two functions. To facilitate this collaborative process, four major components were developed and are described briefly as follows:

1. VIRCON space planning – is an integrated set of tools developed within the Virtual Construction Site project (VIRCON), funded by the UK government (Dawood et al, 2003a). In this research, the VIRCON tools, in particular, PlantMan (Heesom and Mahdjoubi, 2001) and AreaMan (North and Winch, 2002) are utilised as tools for marking up space occupation and space availability in construction site respectively;

2. Multi-constraint information query – utilises the On-Line Analysis Processing (OLAP) service to create interactive browser-based queries for multi-constraint information. This technology provides a powerful tool helping project planners in understanding problems more clearly and making decisions more effectively (Chau et al, 2002). Furthermore, the system provides users with the ability to generate on-demand queries using standard search forms. More details of this feature are available in section 7;

3. Multi-constraint visualisation – extends the capability of 4D (3D+time) and Virtual Reality (VR) visualisation technologies to evaluate not only physical constraints but also contract, resource, and information constraints. The 4D prototype has been developed using Visual Basic for Application (VBA) embedded in the Autodesk Architectural Desktop 3.3 (IFC 1.5.1 supported) environment. Section 8 demonstrates this feature using real case studies; and

4. Multi-constraint optimisation – employs hybrid optimisation approach to re-schedule project plan. Given multiple constraints such as activity dependency, limited working area, and resource and information readiness, the algorithm alters tasks' priorities and construction methods so as to arrive at optimum or near optimum set of project duration, cost, and smooth resources profiles. This feature has been practically developed as an embedded macro in standard project management software such as MS Project. Formulation of the optimisation problem and experimental results can be found in Sriprasert and Dawood (2003).

6.3 Work-face operation layer

Information systems at the work face can be classified into three main areas including commitment planning, work-face instruction and feedback. Each of which is explained as follows:

1. Commitment planning – importance of the work in this area has not been raised until the introduction of lean construction concept and development of WorkPlan tool (Choo et al, 1999). Unlike the WorkPlan tool that was developed as a standalone application in MS Access, this research employs a system architecture that enables an integration of commitment planning with upstream management systems and higher level planning;

2. Work-face instruction – an extensive literature review in the area of IT applications in construction reveals that research and development of systems that can provide technical information and instruction to the work-face personnel during construction stage has been largely ignored (Sriprasert and Dawood, 2001). A few prototype systems for delivering information to operators during facility management stage (Pakanen et al, 2001, Song et al, 2002) may be adaptable; and

3. Feedback – this area involves the process of monitoring project progress and providing feedback to planning department and upstream supply chain. The focus of the development in this research is to gather feedback about weekly percent plan completion and reasons why the committed tasks were not completed as planned. Many other studies focus on automatic labour monitoring (Sacks et al, 2003) and equipment and materials tracking (Bernold, 1990) using GPS and Bar Code technologies.

More discussion and demonstration of the systems in this layer can be found in section 7.

7. MULTI-CONSTRAINT INFORMATION MANAGEMENT SYSTEM

An emergence of the Internet has offered a new standard and cost effective way for communication in construction project management. Since the mid 1990s, both academic researchers (i.e., Rojas and Songer, 1999, Deng et al, 2001, Lam and Chang, 2002) and leading software vendors (i.e., Primavera® and Microsoft®) have developed or commercialised many web-based applications for project management information systems. These systems were benchmarked (Jaafari and Manivong, 1998) and users' perceptions towards the implementations of these systems were investigated (Mohamed and Stewart, 2003). There is no question about the increasing popularity and realised benefits of the web-based systems in managing construction projects.

To enhance the vision for applications of the web-based systems, this research has extended the basic capability of existing systems from being documentation management and communication tools to become a DSS for the multi-constraint planning as described in section 5 and 6. An implementation of the proposed vision has resulted in a prototype called "LEWIS – Lean Enterprise Web-based Information System for Construction". The system is proposed as a tool for endorsing production-oriented culture and bridging the gap of management, planning, and execution in the construction enterprises. It is designed as a web-based information repository that allows users to analyse multiple construction constraints imposed by upstream supportive organisations, planners, and work-face personnel. In this case, the supportive organisations can be informed of the recent updated project status and requirements at the work face. Planners can be informed of ability of the supportive teams to supply required information and resources in the Just-In-Time manner and, in turn, can realistically updated execution plan and assure quality assignments and instructions to the work face. Finally, work-face personnel can retrieve information and send request or discuss problems to the responsible teams promptly. More details regarding the LEWIS data model, input interfaces, information analysis, and work-face information are discussed below.

7.1 LEWIS data model

An abstract LEWIS data model (EXPRESS-G) is presented in Fig. 3. The data model illustrates how product, information, resource, space, process, and work-face information are interrelated and integrated. In this case, Uniclass, the unified classification for the construction industry, that complies with the international work set out by ISO technical report 14177 (Crawford et al, 1997) is utilised for data structuring in the LEWIS. The Uniclass provides a standard for structuring building information as well as a systematic way of classifying and integrating Product Breakdown Structure (PBS) with Work Breakdown Structure (WBS). In turn, it allows a product model-based information system and a meaningful 4D model to be generated (Dawood et al, 2002b). Fig. 4 presents an example of translating the abstract data model into a physical database diagram.
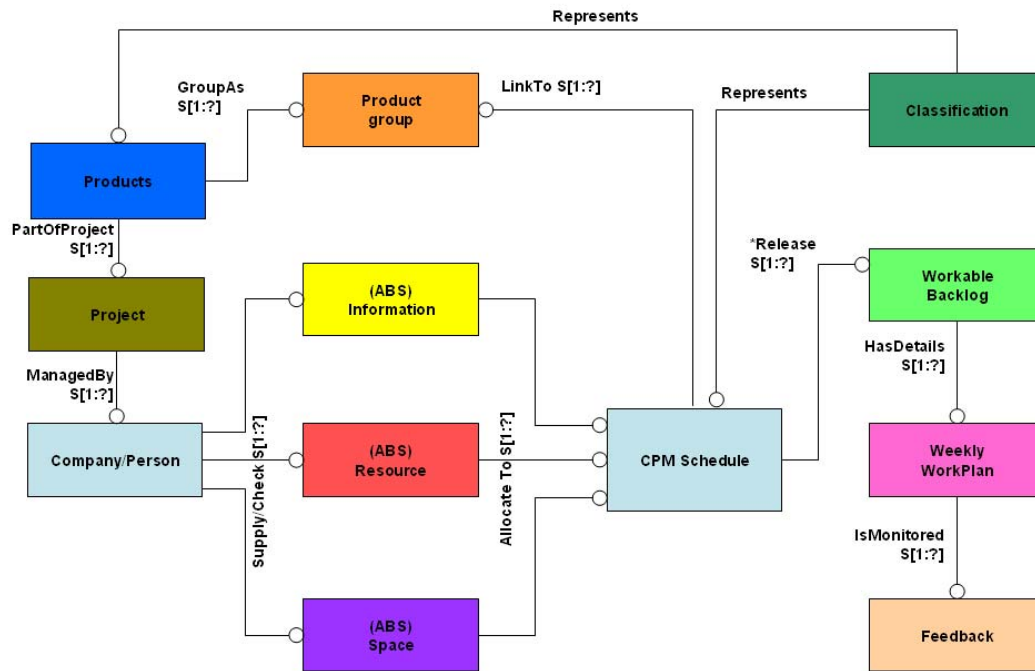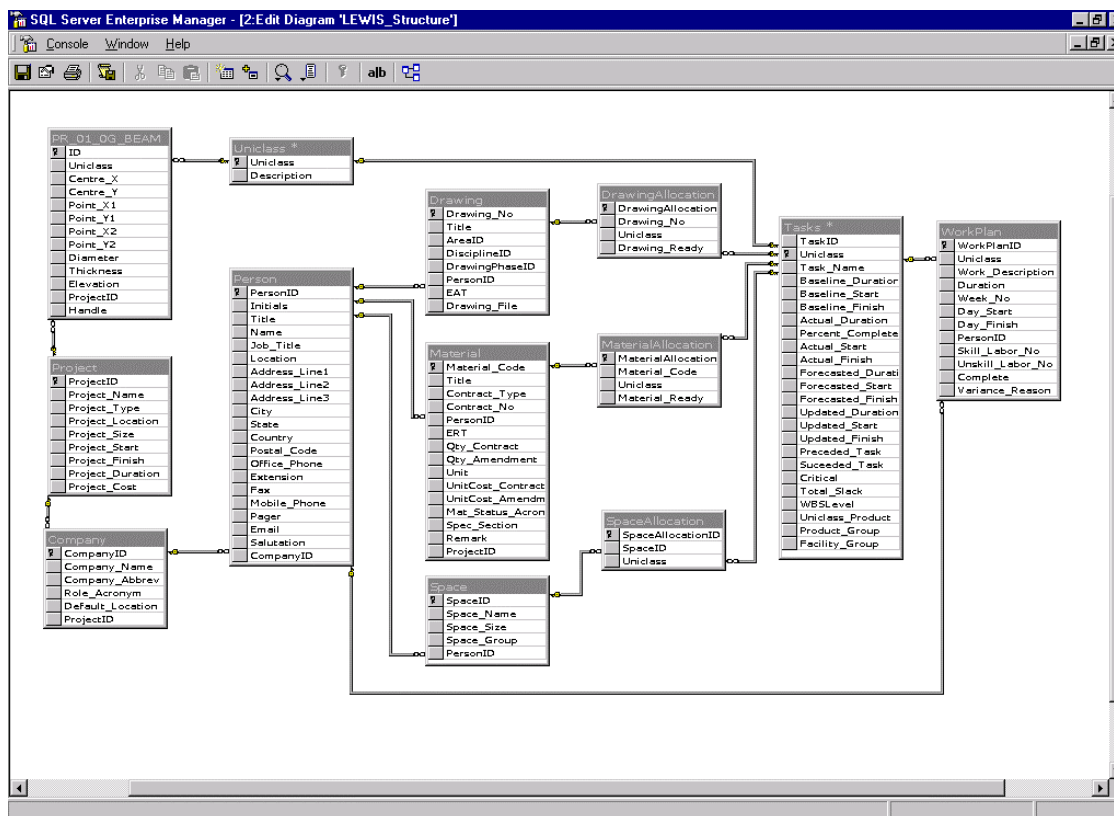
FIG. 3: EXPRESS-G data model for LEWIS.

FIG. 4: LEWIS database physical diagram at the abstract level.

7.2 LEWIS interfaces and data input
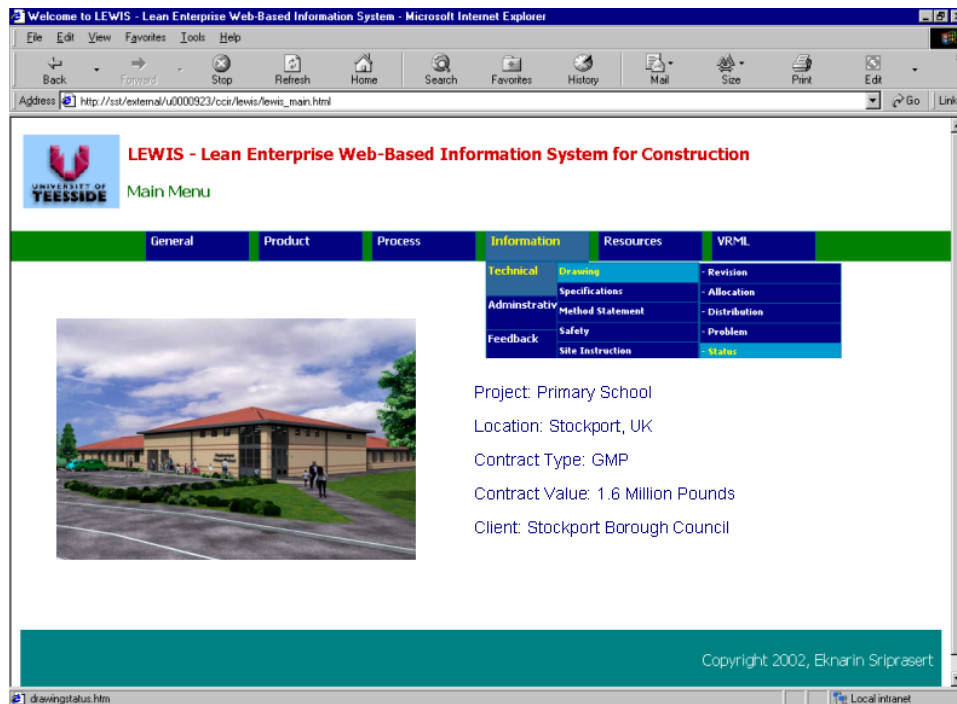
7.2.1 Main interface

FIG. 5: LEWIS main interface.

To achieve web-based functionality, several web programming languages including HTML, Active Server Pages, VB Script, and Java Script were employed. Fig. 5 illustrates the main interface of the LEWIS system.

The LEWIS main interface contains a set of pull down menus that enable direct access to different categories of project information. These categories are ranging from general project information, geometrical product data, CPM schedule and weekly work plan, project documents, resources information, to 4D simulation clips (AVI files) and VRML model presenting work progress and constraints in each period. Multiple constraints regarding physical, contract, information and resources of each activity can also be queried. A major advantage of the LEWIS over other commercial project information systems is that all information stored in the LEWIS have relationships with products and project schedule. Consequently, status of each constraint can be visualised in the 4D environment (elaborated in section 8) and start dates of activities that are associated with constraints can be updated automatically and accordingly. Furthermore, it is a platform that integrates higher level planning (CPM) with crew level planning (weekly work plan). It should be noted that another version of text-based interfaces has also been developed to be compatible with Internet Explorer for Pocket PC.

7.2.2 Data input

To set up the LEWIS, product and process data must be initially populated. An intelligent Visual Basic for Applications (VBA) macro called DataExtractMan was developed to automatically extract and populate 2D or 3D product data from CAD software (i.e. AutoCAD 2000 or Architectural Desktop 3.3). In a simpler way, the process data from project planning and scheduling software (i.e. MS Project or Primavera) can be extracted to the database using Open Database Connectivity (ODBC) and a built-in import/export template feature. The specification for organising the CAD and schedule data in compliance with the Uniclass and the British Standards of layering convention (BS 1192-5) is demonstrated in Dawood et al (2003b).

For other types of data input regarding information, resources, and weekly work plan, they can be input by each responsible supportive organisation as construction being progressed. Data Access Pages for each record set were developed to allow users to browse, modify, delete, filter, and organise the LEWIS data by using a robust navigation toolbar. Furthermore, the security feature in SQL Server was utilised to control different data access

rights for different users. Fig. 6 and Fig. 7 show examples for webtop and mobile interfaces for managing LEWIS data respectively.
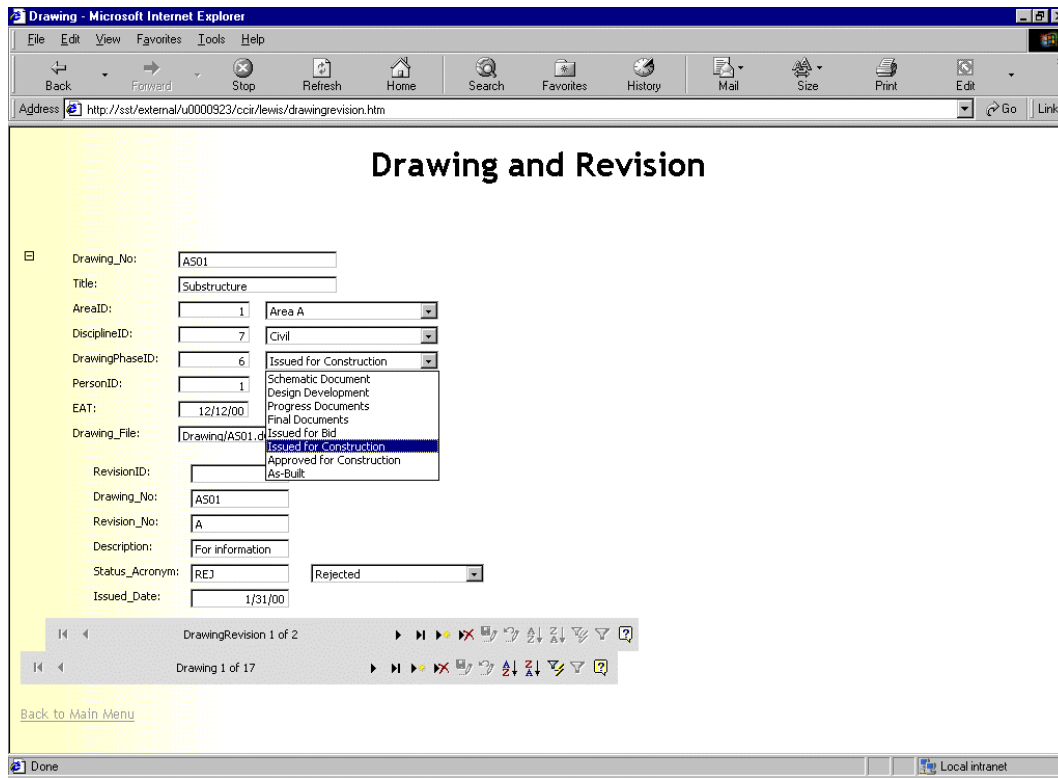

FIG. 6: An example of LEWIS interface for managing drawing and revision data set.

FIG. 7: An example of mobile interface for managing the LEWIS data.

7.3 Multi-constraint information analysis

Once project participants input the data into the LEWIS, look-ahead analysis regarding readiness of particular information, resources, and activities (workable backlog) at a specified period can be performed. In this development, two approaches including an interactive multi-dimensional query using On-Line Analysis Processing (OLAP) and a standard query using Structure Query Language (SQL) were implemented. Each of these approaches is demonstrated as follows.
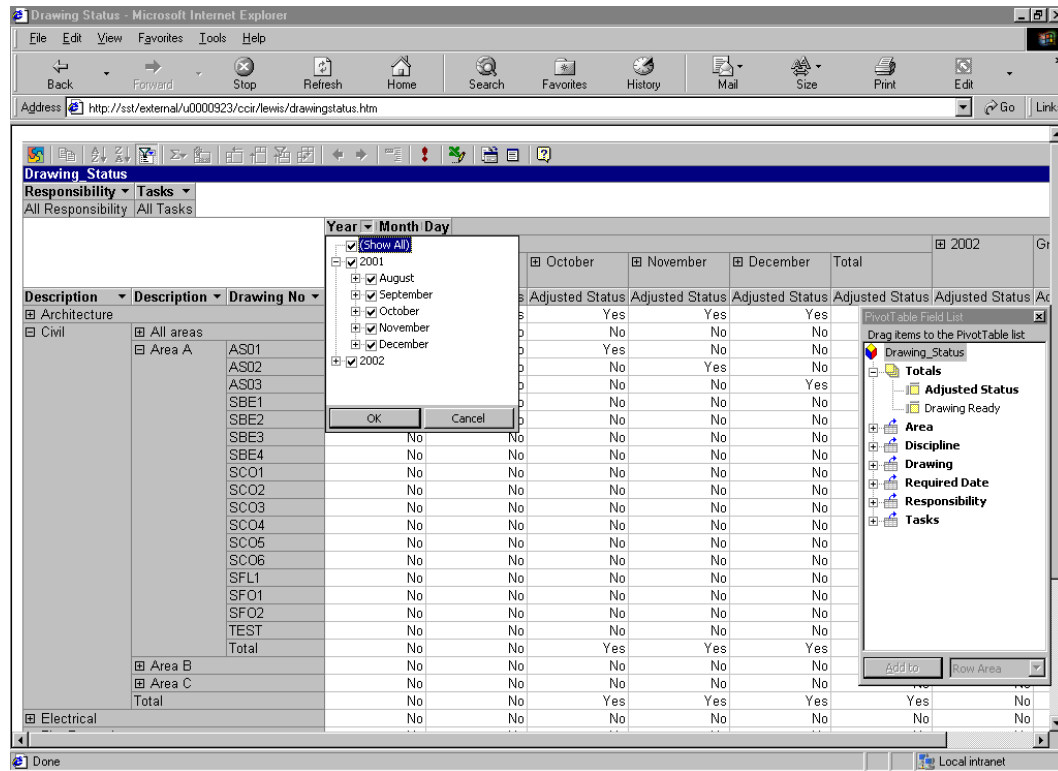
7.3.1 Interactive browser-based query

FIG. 8: An example of interactive browser-based query for drawing status.

To provide decision-makers with multi-dimensional and aggregated view of data, the concept of data warehouse coupled with OLAP tool was implemented. In this case, data cubes, dimensions, measures, hierarchies, levels and cells were logically constructed as the basis for the OLAP structure (Shumate, 2000). The OLAP is then connected to the Microsoft PivotTable thus allows the decision-makers to perform data analysis via the standard web browsers. An example of the interactive browser-based query is shown in Fig. 8. By using this feature, the decision-makers can interactively analyse the data such as checking drawing status based on multiple dimensions of time, work area, discipline, allocated task, and responsible person. Meaningful charts of the analysis results can then be generated in Microsoft Excel using PivotChart feature.

7.3.2 Standard query

Apart from the interactive browser-based query feature, a familiar search functionality for every data set is also provided. In this case, the decision-makers can either use pre-specified queries (hot links) or advanced search forms to reach at the required information. The underlying search mechanism is enabled by pre-coded Active Server Pages (ASP) script and standard Structure Query Language (SQL).

Fig. 9 illustrates an example of look-ahead analysis for activities that are scheduled to be executed next month (October, 1999). The example lists only activities that their associated drawings or method statements or materials are not ready. The blank data boxes indicate that drawings or method statements or materials have not been allocated to the activities and their statuses have not been confirmed. It should be noted that the users have full control over the set of constraints, period, and data fields that they want to see in the results.

All Constraint Activities Next Month

October, 1999

Uniclass	Task_Name	Drawing_No	Drawing_Ready	Method_No	Method_Ready	Material_No	Material_Type	Material_Ready	TaskID
D72111-G21-G21:G311-JE053	Insitu path to lecture theatre (for precast)	AS01	False	MS006	False	5	Concrete	False	22
D72111-G21-G21:G311-JR12	Underslab drainage	AS02	False	MS007	False				23
D72111-G21-G21:G311-JF10z1	Substructure brick and block work GL 1-5	AS03	False						24
D72111-G21-G21:G311-JD2-Z1	Hardcore filling and blinding to underside slab GL								26
D72111-G26-F137:G261:G311-JG10z1	2F Column GL K-B/1-5	SCO5	True						36
D72111-G26-F137:G261:G311-JG10z2	2F Column GL A-M/6-14	SCO6	True						37
D72111-G26-F13601:G262:G311-JG10z1	1F Beam GL K-B/1-5	SBE1	True	MS004	True	4	Steel	False	39
D72111-G26-F13601:G262:G311-JG10z2	1F Beam GL A-M/6-14	SBE2	True	MS004	True	4	Steel	False	40
D72111-G26-F137:G262:G311-JG10z1	2F Beam GL K-B/1-5	SBE3	False	MS004	True	4	Steel	True	42
D72111-G26-F137:G262:G311-JG10z2	2F Beam GL A-M/6-14	SBE4	False	MS004	True	4	Steel	True	43

FIG. 9: An example of look-ahead analysis for all constraint activities using standard SQL query.

7.4 Work-face information

According to the system architecture described in section 6, three categories of work-face information are demonstrated as follows.

7.4.1 Commitment planning

Commitment planning is a key to shield operation from constraints and improve plan reliability. Fig. 10 illustrates the weekly work plan interface in the LEWIS system. To generate a work plan, the last planner (foreman or job superintendent) can simply add sub-activities under a constraint-free activity (workable backlog). Other details such as week number, day start, and day finish can then be added using drop-down lists.

7.4.2 Work-face instruction

Information such as drawings, specifications, method statements, work instructions, and testing regulations are needed for the work-face operation (De la Garza and Howitt, 1998). Based on a recent trial, site staffs are more than ready to adopt mobile technology to assist their works (Bowden and Thorpe, 2002). Fig. 11 illustrates an example of work-face instruction and VR assembly model retrievable via wireless mobile devices. However, two problems regarding the availability of electronic information from the upstream organisations and the cost of data retrieval should be investigated. Primarily, our test in UK found that the flow of electronic information usually comes to an abrupt halt when it reaches the construction work face. Furthermore, the cost of wireless data retrieval is quite considerable. Based on the wireless access via GSM/GPRS network in which the charge is applied on the amount of data retrieval not on the duration of connection, the incurred cost is £0.50/Megabytes. (Vodafone Company).

7.4.3 Feedback

Based on the lean construction concept and the last planner method, weekly percent plan completion, which is the number of finished activity over the number of planned activity, is regarded as a new key performance indicator for project control. The more the PPC, the less the inflow variability is experienced on construction site. Fig. 12 shows the percent plan completion (PPC) for the first ten weeks of the project. Additionally, the LEWIS also allows reasons for variances on committed activities to be captured (see Fig. 10).
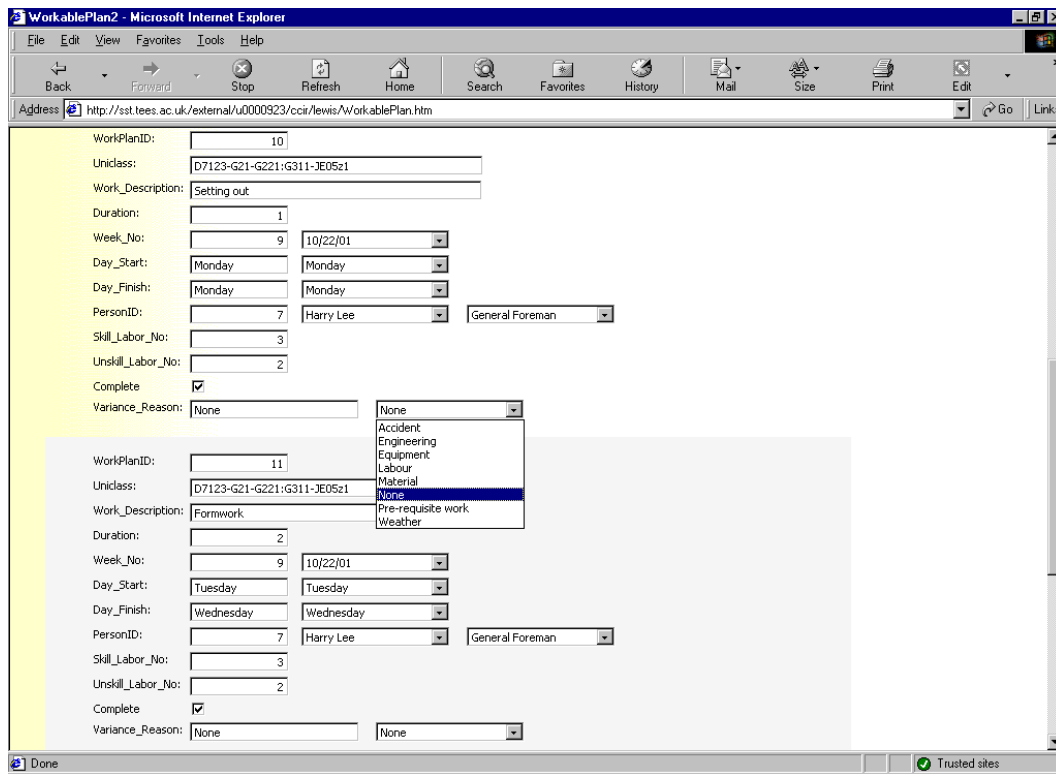
FIG. 10: An example of weekly work plan.

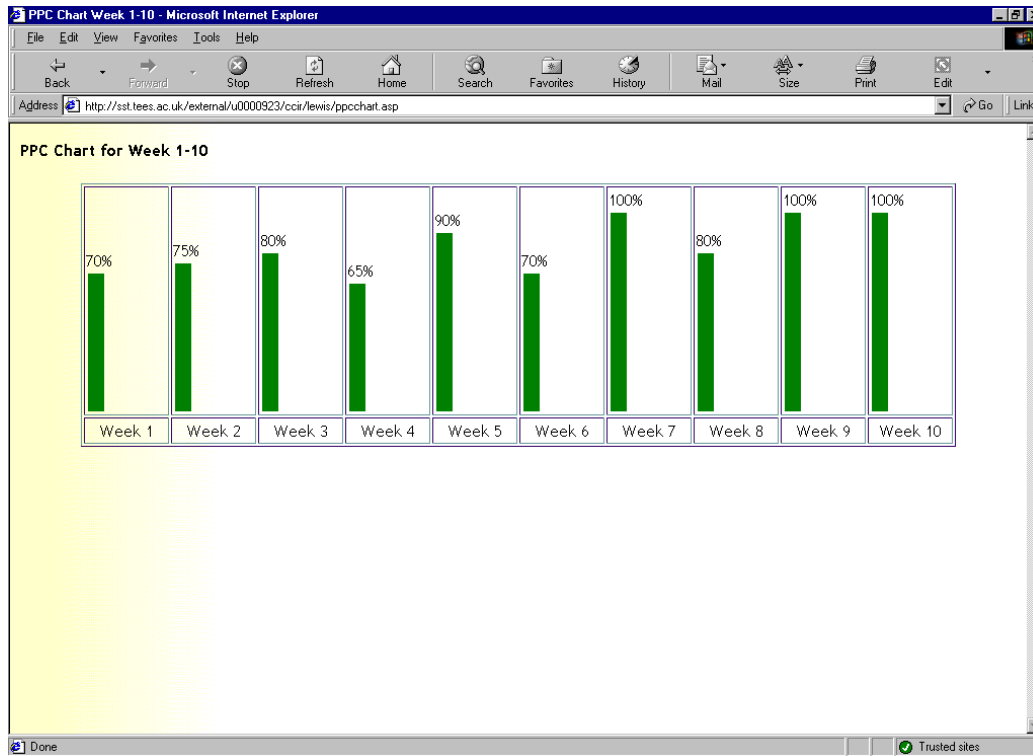FIG. 11: Work instructions and assembly VR model via Pocket PC.

FIG. 12: Percent plan completion chart for week 1-10 of the project.

8. MULTI-CONSTRAINT VISUALISATION

Abstract representation and complexity of CPM schedule create difficulty and inconsistency for project members to evaluate its completeness and correctness of logic. Several research efforts have developed 4D CAD (3D + time) and Virtual Reality models to enable visual evaluation of physical constraints i.e. technological dependency (McKinney and Fischer, 1998, Koo and Fischer, 2000), space (Akinci et al, 2002; Dawood et al, 2002a), and safety (Hadikusumo and Rowlinson, 2002). In this research, a new system called *4D constraint-based planning and control prototype* has been developed to cater for not only physical constraints but also contract, resource and information constraints. The system is developed using Visual Basic for Application (VBA) embedded in the AutoCAD 2000 and the Autodesk Architectural Desktop 3.3 (IFC 1.5.1 supported) environments. To generate the 4D constraint-based models, the CAD objects are firstly grouped and linked to associated activities in MS Project or Primavera. Secondly, other related constraints of each activity are allocated and determined within the LEWIS. As a result, sequence of activities and associated constraints can be simulated and visualised. Details of the schedule, constraints, related information, and workable backlog can also be annotated. The prototype has been primarily tested with real product and process data from an £8 million, School of Health Project at the University of Teesside and a £1.6 million, Primary School at Stockport. Since the prototype is emerged after the completion of these projects, data regarding availability of information and resources is assumed in the primary models. Results of the experiments are selectively demonstrated below.

8.1 Visualisation of physical constraints

8.1.1 Visualisation of product clashes

Product clashes are often caused by poor co-ordination between the design of architectural components and building services. Based on the Primary School project, product clashes between roof trusses and cable trays were detected and visualised in Fig. 13. Currently, this ability of product clash detection is well advanced and commercially available. A commercial 3D-design review product like NavisWorks has efficient algorithms and features to detect and manage clashes. The software allows users to save, search, add descriptions, and email clashes information to project participants. In addition, history and current statuses of each clash (i.e. unsolved, being reviewed, and solved) can be retained (http://www.psisoftware.co.uk).
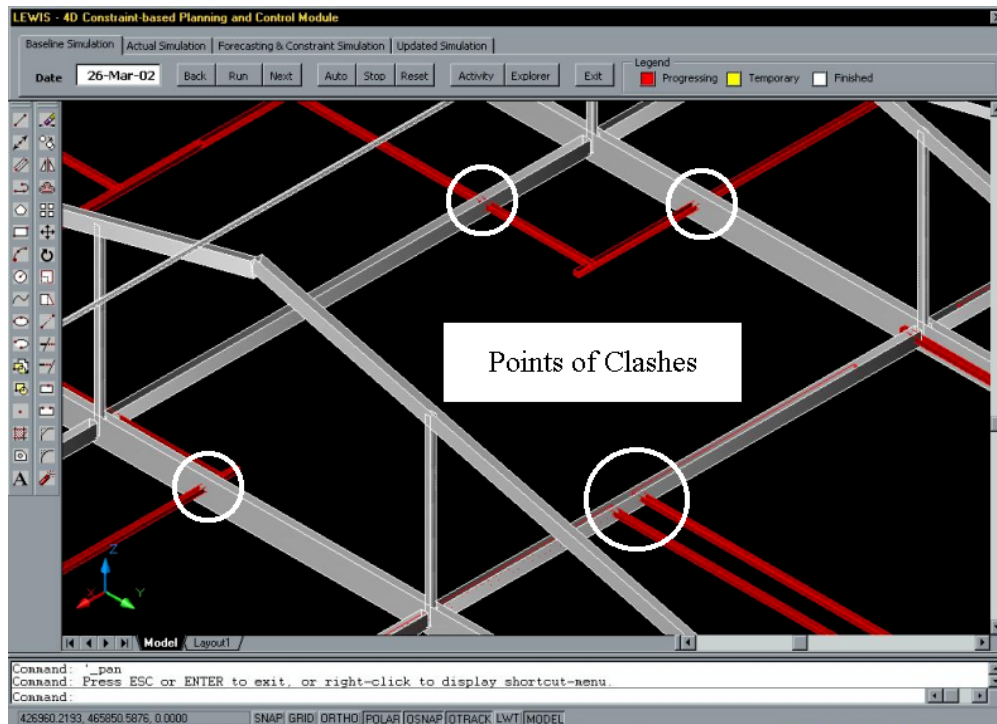
FIG. 13: Visualisation of product clashes between roof trusses and cable trays.

8.1.2 Visualisation of illogical relationships

Current 4D models present the project schedule by animating sequence of constructed products through time. This approach, however, do not convey all the information (i.e. predecessor-successor relationships) required to evaluate the schedule (Koo and Fischer, 2000). Similar to recent development of CIFE iRoom (Fischer et al., 2002), a new feature called *3D-LogicTracer* was, therefore, developed in this research to facilitate a thorough examination of the CPM relationships in the desktop environment. Basically, this feature allows users to visualise predecessors and successors of each selected activity in 3D environment. Fig. 14 illustrates a visualisation example of illogical relationships found in the Primary School project. By considering the west roof covering activity, the predecessor of this activity should be an installation of the underneath roof trusses rather than the central wall partitioning. Furthermore, the successor of this activity should be internal wall partitioning or lighting under the roof rather than the covering of the other side of the roof.

The critical chain scheduling method suggests that the construction of CPM relationships should be purely based on technological dependency (i.e. supported-by rule). Other criteria such as availability and continuity of resources should be evaluated separately using the resource aggregation/levelling feature. However, from both case studies, it is found that planners tend to take resource availability and continuity into consideration when they assign the relationships thus rendering CPM network misrepresented.

8.1.3 Visualisation of space congestion

In addition to displaying the logic (technological dependency) among activities of a schedule, the 4D model shows spatial constraints on the site and in the building. Whereas CPM schedules can only convey *what* is built *when*, the 4D model shows *what* is being built *when* and *where*. It therefore allows users to verify whether a component can be physically placed or whether crews can work in a certain location (Koo and Fischer, 2000). From the case studies, we were able to anticipate several space congestion circumstances. Space congestion occurs when work crews of different trades working on concurrent activities have to share a common workspace and therefore interfere with each other. This can decrease their productivity as well as prevent the execution of one or more affected activities (Thabet and Beliveau, 1997). Fig. 15 shows the visualisation of space congestion between internal partitioning wall and cable tray installation activities in the Primary School project.
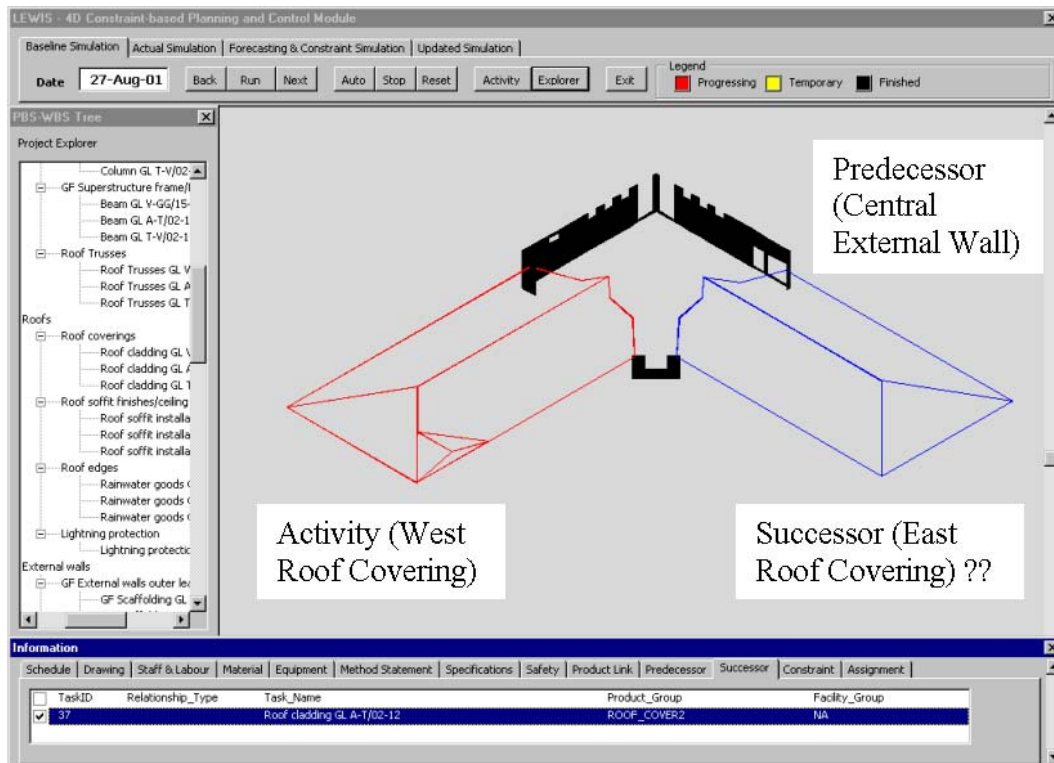
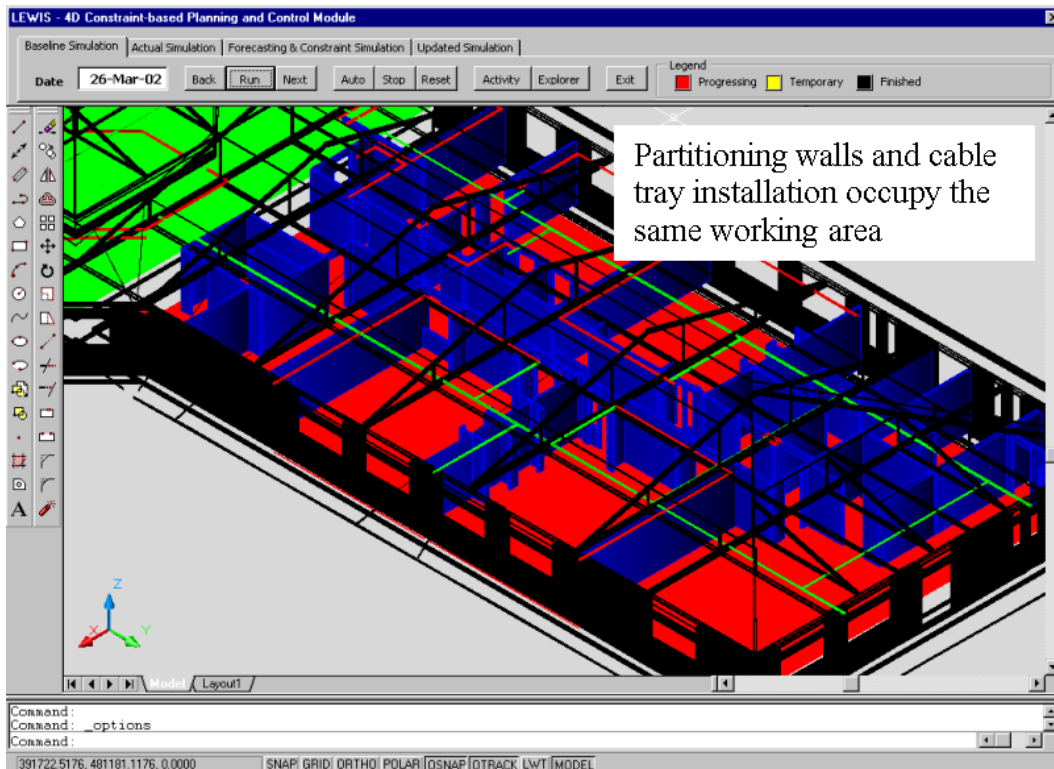FIG. 14: Visualisation of illogical relationships.

FIG.15: Visualisation of process clashes (space congestion).

8.2 Visualisation of enabler constraints

Enabler constraints are referred to contract constraint and resource and information readiness problem. The contract constraint represents imposed milestone, allowable budget, and special agreement such as a requirement for client's authorisation prior to commencement of specific activities. The *readiness* definition covers two main aspects including availability and perfection of resources and information. Several studies (e.g. Ballard, 2000, Tilley, 1997) point out that resource and information readiness problem is the most frequent problem occurring in the construction project and, perhaps, the most severe problem causing project delay. In this study, clients can input the contract constraints and upstream organisations can input estimated readiness time (ERT) of resources and information for each scheduled activity. These constraints of each activity are then aggregated and linked to the 4D model. For example, an activity that has two ERTs including (1) 1 Dec 02 for under-reviewed drawing; and (2) 7 Dec 02 for non-delivered material will have an aggregated ERT of 7 Dec 02. This means that this activity will not be able to start earlier than 7 Dec 02 or until all required resources and information are ready. Fig. 16 presents a visualisation example of the enabler constraints.
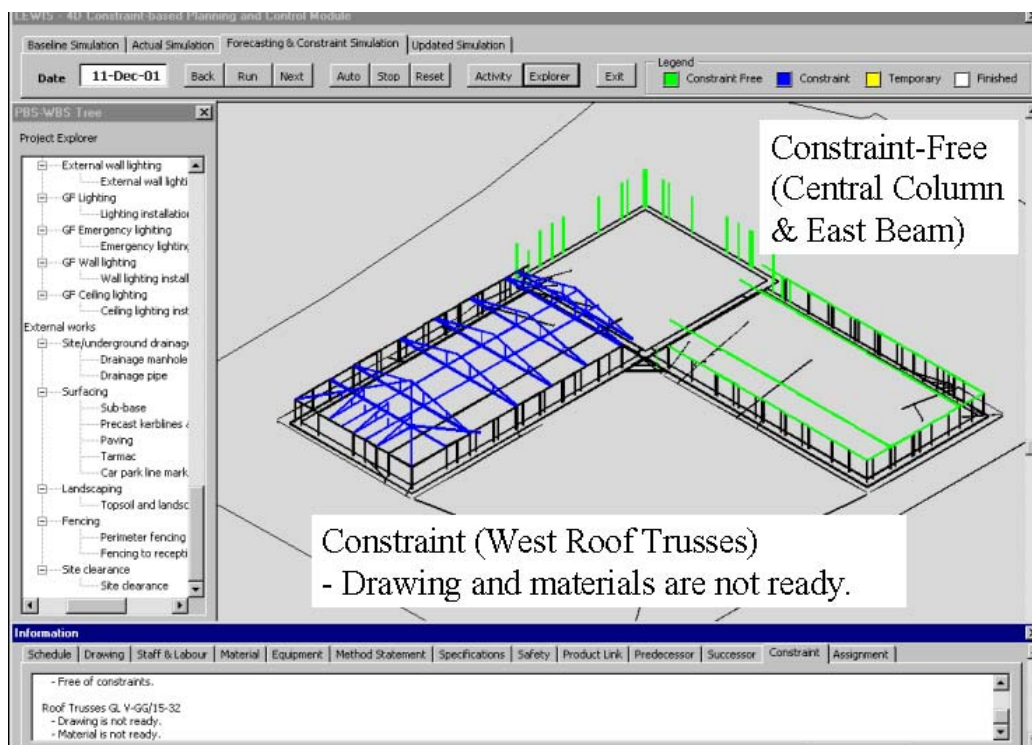

FIG. 16: Visualisation of enabler constraints.

It is worth mentioned that both the physical constraints and enabler constraints can be visualised and assessed at the same time. Considering the space congestion problem illustrated in Fig. 15, the system also highlights the readiness of the cable tray installation activity (green colour) in contrast to the remaining constraints of the wall partitioning activity (blue colour). Therefore, planners can make a decision to proceed with the cable tray installation and postpone the wall partitioning. Alternatively, the multi-constraint optimisation algorithm can be utilised to arrive at a new constraint-free schedule (Sriprasert and Dawood, 2003).

8.3 Visualisation of project status

Fig. 17 illustrates the prototype interfaces including 4D-simulation console, list of progressing and finished activities, browser of product-based work breakdown structure, and annotation window for schedule information and constraints. A sample comparison among baseline, actual, and forecasted 4D models of the School of Health project is also presented. This approach is very useful for planning and control purpose and can be supplemented with the presentation of S-curve in the project meeting.
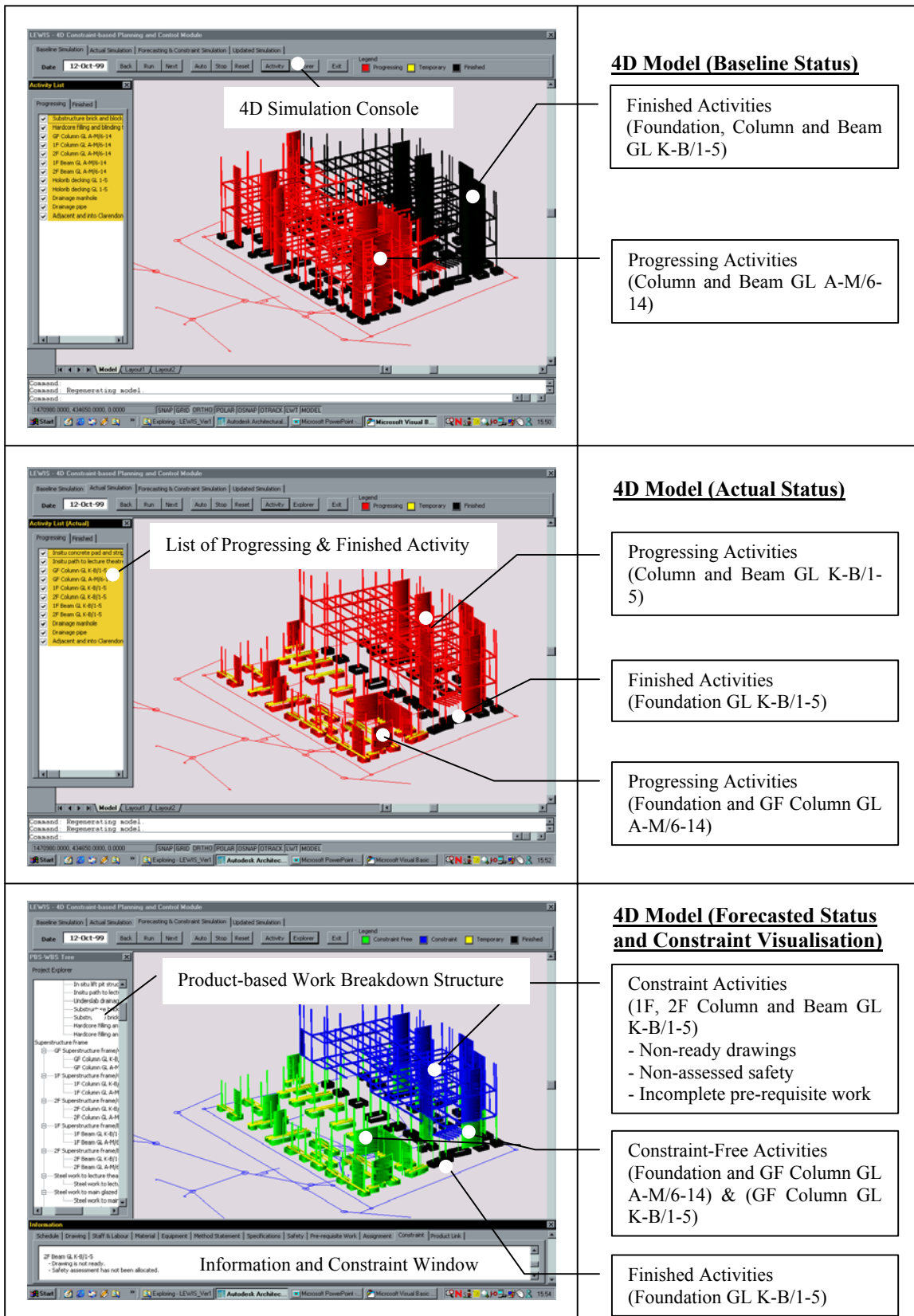
FIG. 17: Visualisation of project statuses.

9. FUTURE WORKS

To primarily evaluate the system, the concept of multi-constraint planning and the integrated DSS prototype were demonstrated to 15 senior planners of leading UK contractors. An industrial-day presentation in the *Reality is Virtual* workshop organised by the UK Institute of Civil Engineering (ICE) was also conducted. It was found that most planners were impressed by the advancement and potential of the system, in particular, the multi-constraint visualisation feature. They realised that the system could be used to communicate with clients as well as other project participants on the site. A senior planner has expressed his interests and commitment to implement this system in his company.

However, to implement the system fully and successfully, further development works need to be carried out:

1. Integration of LEWIS and SEEK to allow semi-automatic communication between LEWIS and various heterogeneous applications/databases;

2. Implementation of LEWIS in a reliable server with additional features including file management, document version checking, and data encryption and decryption;

3. Improvement of user-friendliness of LEWIS webtop and mobile interfaces;

4. Incorporation of safety and environmental constraints in the model;

5. Minimising efforts to generate 4D model by replacing basic grouping and linking method with work rate simulation (Mallasi and Dawood, 2003);

6. Extension of visualisation capability to cover various types of buffer and to highlight differences between various plan statuses; and

7. Enhancing interactivity of the VIRCON space planning tools (Dawood et al, 2003a).

Apart from the above list of required developments, organisational issue such as the readiness to adopt new business process and system implementation issue such as training and system supports must be concerned.

10. CONCLUSION

With an impetus to remedy the critical problem of separation of execution from planning, this paper highlights fragmentation of construction planning techniques and introduces a new methodology called *multi-constraint planning*. This proposed technique was developed to meet several requirements including: (1) collaborative and multi-level planning; (2) multi-constraint consideration; (3) effective handling of uncertainty; (4) appropriate visual representation; and (5) practicable optimisation. To enable implementation of this technique, an integrated decision support system for information management, visualisation, and optimisation of multiple constraints was developed and the two modules of information management and visualisation are demonstrated in the paper. The use of multi-facet based classification system such as Uniclass has made the integration of product and process data possible. The system was verified using real case data and was presented to senior planners of leading UK contractors. It was found that most planners realised the benefits of the system and, in particular, the visualisation feature. One of them has already committed to implement this system in his company. However, to implement the system fully and successfully, further enhancements to both the information management and the visualisation system are suggested. Furthermore, organisational issue such as the readiness to adopt new business process and system implementation issue such as training and system supports must be concerned. It is envisaged that successful implementation of this system will enable generation of reliable plans and constraint-free assignments, in turn, reduce production risks and improve on-site productivity.

11. ACKNOWLEDGEMENTS

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