Theme:

Title: **Requirements Identification for 4D Constraint-based Construction Planning and Control System**

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Abstract: *Construction planning and control are identified among the top potential areas needing improvements. A traditional technique known as the Critical Path Method (CPM) has been widely criticised in terms of its inability to cope with non-precedence constraints, difficulty to evaluate and communicate interdependencies, and inadequacy for work-face productions. Attempting to treat these deficiencies, substantial research efforts have resulted in a wide range of advancements including design of new planning and control methodologies and development of sophisticated computerised applications. However, these efforts have not effectively overcome all of the above CPM drawbacks and, therefore, have not yet provided a solution to the industry.*

This paper identifies requirements for the next generation of the planning and control as multi-constraints, visual, and lean-based system. In order to achieve this goal, important construction constraints and their characteristics are derived from previous literature. Various constraint detection and satisfaction techniques such as knowledge-based system, advanced computational algorithm, and 4D visualisation are also investigated. As a part of the Lean Enterprise Web-based Information System (LEWIS) presented in the companion paper, a developing prototype called 4D constraint-based planning and control system is briefly demonstrated. It is anticipated that successful implementation of this system will enable generation of reliable plans and constraint-free assignments, which will, in turn, reduce production risks and improve on-site productivity.

Keywords: *4D Simulation, Constraints, Lean Construction, Planning and Control, Scheduling*

Introduction

Construction planning and control are identified among the top potential areas needing improvements. A review of literature and a case study confirm typical problems regarding separation of execution from planning and after-the-fact variance detection (Sriprasert and Dawood, 2002). Many researchers agree that major causes of these problems are inadequacy of traditional project management theory and improper applications of information technologies (IT). As a major part of the LEWIS – Lean Enterprise Web-based Information System for Construction presented in the companion paper, this paper focuses on requirements identification for the next generation of planning and control systems. Based on the identified requirements, a developing prototype called 4D constraint-based planning and control system is briefly demonstrated. It is anticipated that successful implementation of this system will enable generation of reliable plans and constraint-free assignments, which will, in turn, reduce production risks and improve on-site productivity.

Critiques of CPM

A traditional project planning and control technique known as the Critical Path Method (CPM) was invented by the aerospace industry and has been adopted in the construction industry since late 1950s. The CPM applications have well served project managers in many aspects including 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; El-Bibany, 1997). However, because of unique nature of construction, its suitability has been widely criticised. Among the criticisms, three major drawbacks can be identified as follows:

1) *Inability to cope with non-precedence constraints* – In the real world, construction possesses various kinds of constraints ranging from physical constraints, contract constraints, to resources and information constraints. Unfortunately, CPM considers only time and precedence constraints among activities (Pultar, 1990; Shi and Deng, 2000). Its underlying network representation is proved to be inadequate to represent and integrate more problems in construction management (El-Bibany, 1997). Woodworth and Shanahan (1998) have shown that schedules based on time-oriented networks are exceeded by an average of around 38%.

2) *Difficulty to evaluate and communicate interdependencies* – The CPM schedule is graphically presented in either a form of Gantt chart (Bar chart with relationships) or a form of precedence diagram. To evaluate and communicate the time and construction sequences, project participants must mentally associate this schedule information with the description of the physical building. This has proven difficult especially when there is a need to analyse effects of changes to the overall sequence of construction (McKinney and Fischer, 1998).

3) *Inadequacy for work-face productions* – As projects enter their construction phase, detailed planning is delegated to engineers, superintendents, or foremen. Rather than employing the CPM, simple Bar chart or activity lists are dominant techniques for the work-face production planning (Mawdesley et al., 1997). Several studies provide convincing reasons why the CPM is not widely used. Levitt et al. (1988) stated that the existing CPM tools do not provide adequate support for analysis of constraints at operational level. Resource allocation, smoothing or levelling procedures are incapable of ensuring full continuity for a production crew or process (Jaafari, 1984). For complex projects, field personnel find the CPM schedules confusing and, therefore, less useful (Pultar, 1990). Large amount of efforts are required to replan and redraw the network each time it was updated (Jaafari, 1996). Furthermore, the CPM has inflexibility and lack of expressiveness to cope with the varied pattern of construction in the field (Jaafari, 1996; Choo et al, 1999).

Innovative Concepts and Advancements of Planning and Control Systems

To overcome deficiencies of the traditional planning and control, requirements for the next generation of planning and control can be identified as multi-constraints, visual, and lean-based system. The future system should have flexibility and agility to respond (both proactively and reactively) to various constraints. Advanced visualisation techniques such as 4D (3D + time) (McKinney and Fischer, 1998) and Virtual Reality (VR) (Retik and Shapira, 1999) should be utilised for more effective evaluation and communication of schedule information. In addition, the last planner methodology based on the lean construction concept should be incorporated so as to enhance reliability of the production planning at the work-face level (Ballard, 2000). As a ground towards this goal, this section identifies important constraints that should be addressed in the next generation of planning and control system. Based on current and previous research projects, advancements of planning and control systems are reviewed. Various constraint detection and satisfaction techniques are also discussed.

Identification of Constraints in Construction

In general, a constraint can be defined as “one that restricts, limits, or regulates” (Houghton Mifflin Company, 2000). In construction, a constraint can be understood as “one that restricts, limits, or regulates commencement or progress of work-face operations to achieve construction products within agreed time, cost, and quality”. Based on previous literature, important constraints in construction can be classified into three major groups including physical, contract, and enabler constraints. Examples of constraints of each group are detailed in Table 1.

Table-1: Important Constraints in Construction

Constraint	Examples
Physical Constraints	
- Technological dependencies	Topology – inter-component relationships of buildings such as separation, adjacency, connectivity, intersection, and containment (Nguyen and Oloufa, 2001) Construction method – uses of equipment, temporary facilities, and modular techniques i.e. prefabrication, and concerns of zones and execution patterns
- Space	Activity work area, storage area, staging area, access path, relative distant to access, etc.
- Safety	The Occupational Safety and Health Administration (OSHA) requires the installation of a temporary or permanent floor not more than two stories or 30 ft (9.14 m) below the actual frame erection operation.
- Environment	Ground condition, weather condition, sensitive-to-impact surrounding (i.e. hospital, school)
Contract Constraints	
- Time	Project start and finish date, imposed milestones
- Cost	Contract price, budget, cash flow
- Quality	Specifications (i.e. materials and workmanship)
- Special agreement	Requirement for client' s authorisation prior to commencement of specific activities
Enabler Constraints	
- Resources	Includes staff, technicians, labour, materials, equipment, tools, temporary facilities, etc.
- Requirement	Types and amount required at a certain period of time (i.e. 3 electricians (8 working hours/day) during week 3 and 4 of construction)
- Availability	Actual availability of the required resources at a certain period of time (i.e. only 1 electrician is actually available in week 3 and week 5 of construction)
- Capacity	Maximum productive output or capability of resources (i.e. bricklaying = 30 m^2/man-day or max. boom length of crane = 60.0 m)
- Perfection	Quality of materials, operability of equipment, etc.
- Continuity	Crew work continuity in repetitive projects (to reduce idle-time of resources)
- Information	Includes drawings, specifications, schedules, method statements, safety and risk assessments, authorisations to work, etc.
- Requirement	Types and contents required at a certain period of time
- Availability	Actual availability of the required information at a certain period of time
- Perfection	Accuracy, clarity, relevancy, and completeness of information

Constraint Characteristics

The different constraints identified above possess varied degrees of flexibility, controllability, uncertainty, dynamic, and impact. Some of these constraints are practically unavoidable, while others may be bypassed with an increase in construction cost, time, and risk. Understanding of these constraint characteristics will assist planners to prioritise project's needs, negotiate inherent risks, and produce feasible plans for all involved parties. These constraint characteristics can be described as follows:

1) *Flexibility* – a degree in which the activity sequencing imposed by this constraint can be practically modifiable with existing construction methods (Echeverry and Ibbs, 1991). In this case, topological constraints (i.e. supported by, covered by, and embedded in) and safety can be classified as *inflexible constraints*. A clear example of this is that if a beam is supported by a set of columns, the installation of the columns has to precede the installation of the beam. On the other hand, *flexible constraints* may consist of space and perfection of information. This is because congested work area and poor information will not affect activities to be re-sequenced though they may affect productivity and increase in the risk of rework.
2) *Controllability* – a degree in which this constraint can be controlled by those concerning the constraint. For instance, contractors certainly have less degree of controllability over resources of subcontractors or suppliers.
3) *Uncertainty* – a degree in which this constraint can be anticipated in advance. A clear example of *uncertain constraints* consists of the weather constraint and resource availability constraint (i.e. lack of resources because of strike of labour union or shortage of local materials)

4) *Dynamic* – a degree in which status of this constraint can be changed overtime. For example, topological constraint can be considered more static than space constraint and resource availability constraint.
5) *Impact* – a degree in which time, cost, and quality of construction will be impacted if this constraint is not satisfied prior to commencement of activity. For example, the lack of resources for a critical activity can create more impact than for a non-critical one.

Advancements of Planning and Control System

To identify room for improvement and realise the potential of various techniques in dealing with each type of constraint, a review of current and previous research projects in the area of planning and control systems is conducted. Concerned constraints and system techniques of each research project are presented in Table 2.

Table-2: Review of Key Research Projects in Planning and Control System

Concerned Constraints & System Techniques	Levitt et al. (1988); Kartam & Levitt (1990); Kartam et al. (1991); Darwiche et al. (1988)	Pultar (1990)	Waugh & Froese (1990); Cherneff et al. (1991)	Echeverry et al. (1991)	Kim (1991)	Alkayyali & Minkarah (1993)	Grobler et al. (1995)	Shaked & Warszawski (1995)	Fischer & Aalami (1996)	Jaafari (1996)	Lin & Hass (1996)	El-bibany (1997)	Moizuddin & Selim (1997)	Thabet & Beliveau (1997)	El-rayes & Moselhi (1998)	McKinney & Fischer (1998); Akinci & Fischer (2000)	Choo et al. (1999); Choo and Tommelein (2000, 2001)	Chua et al. (1999); Shen et al. (2000); Chua & Shen (2001)	Retik & Shapira (1999)	Shi & Deng (2000)	O'Brien & Fischer (2000)	Abeyasinghe (2001)	Dawood et al. (2001)
I. Concerned Constraints																							
Physical Constraints																							
- Technological dependencies	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
- Space				X							X			X		X	X						X
- Safety and regulations				X							X						X						
- Environment				X							X						X			X	X		
Contract Constraints																							
- Time	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
- Cost						X			X		X					X	X				X		
- Special agreement																	X			X			
Enabler Constraints																							
- Resources																							
- *Requirement*				X	X	X	X			X	X		X	X	X		X	X	X	X	X	X	
- *Availability*																	X	X		X	X		
- *Capacity*											X												
- *Perfection*																	X						
- *Continuity*															X								
- Information																							
- *Requirement*																	X	X					
- *Availability*																	X	X					
- *Perfection*																	X						
II. System Techniques																							
- Computational algorithm		X			X	X	X			X		X	X		X					X	X	X	
- AI and Knowledge-based system	X		X	X				X	X					X		X			X				
- Database						X					X						X	X					
- Visualisation																							
- *2D or 3D*											X												
- *4D*																X							X
- *VR*																			X				X

Unsurprisingly, all research projects concern technological dependencies and time constraints, which are the major constraints inherited in the traditional CPM technique. Resource requirement and cost constraints are also conventional constraints concerned in most projects. It is found that flexible and dynamic constraints such as availability and perfection of resources and information have later been introduced by a group of researchers in lean construction. Their idea is to consider physical flow between activities, which is neglected in the conversion model of the traditional project management theory. Other major constraints such as space, safety, and environment are also concerned in several research projects. However, only one piece of research appears to consider most types of constraint.

For system techniques, artificial intelligence (AI) and knowledge-based systems that can automatically generate plans based on pre-specified rules seems restrict to controllable, certain, and static constraints. Database, as a complementary technique, can be used to acquire information related to dynamic constraints (i.e. availability of resources and information) from responsible project participants. In term of constraint satisfaction, various network-based computational algorithms have been developed to mathematically solve the constraint networks. On the other hand, visualisation techniques such as 3D, 4D (3D + time) and Virtual Reality (VR) can assist planners to visualise and manually detect and solve constraints. In conclusion, these techniques should be synchronised so as to pursue the multi-constraints, visual, and lean-based system as required.

4D Constraint-based Planning and Control System: A Proposed Solution

System Framework

A developing prototype called 4D constraint-based planning and control system is proposed to fulfil the requirements of being multi-constraints, visual, and lean-based system. This system is a major part of the LEWIS – Lean Enterprise Web-based Information System for Construction presented in the companion paper (Sriprasert and Dawood, 2002). A framework of the system is illustrated in Figure 1.

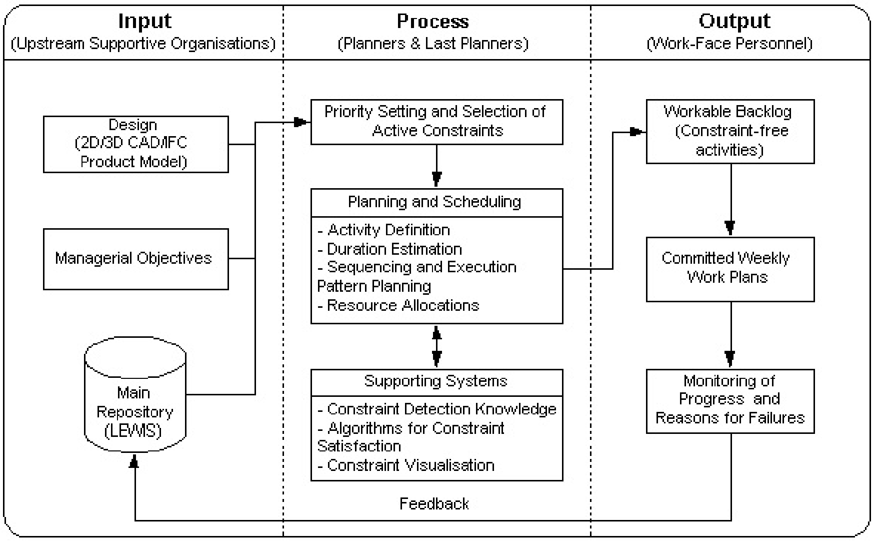

Figure-1: 4D Constraint-based Planning and Control Framework

Input of the system is information generated throughout the construction phase by upstream supportive organisations (i.e. designers, engineers, contractor head office, suppliers, and subcontractors). The information consists of: 1) design information (2D/3D CAD drawings or the IFC product model); 2) managerial objectives (i.e. to achieve least-cost, least-time, limited resource schedule or any feasible combinations of the three (Alkayyali and Minkarah, 1993)); and 3) information from the LEWIS main repository that gathers various constraint information and feedback from the work face. Based on the managerial objectives and available information, planners can set priority and select *active constraints* (subset of all constraints) to be concerned in the planning and scheduling process. With assistance from supportive systems (including constraint detection knowledge, algorithms for constraint satisfaction, and constraint visualisation), the planners can then generate the first feasible baseline plan. During construction, when more information is available, short-term look-ahead planning can be performed in order to check the active constraints and request co-operation from the supportive organisations to satisfy all the constraints prior to releasing activities into workable backlog (constraint-free activities). From the workable backlog, the last planners (i.e. foremen) can generate weekly work plans and commit on what they 'can' do rather than what they 'should' do. Finally, completion of the weekly work plans will be monitored and reasons for failures will be fed back to the LEWIS. The upstream supportive organisations will be informed of the actual status and, in turn, will be able to prioritise their deliverables to the work face in the just-in-time manner. In addition, the planners will be able to analyse impact against the baseline plan and update it accordingly.

A screen shot of the developing prototype is shown in Figure 2. The prototype has been developed using Visual Basic for Application (VBA) embedded in the Autodesk Architectural Desktop 3.3 (IFC 1.5.1 supported) environment. Currently, by utilising information from the LEWIS, sequence of activities and associated constraints can be simulated and visualised in the 4D and VR fashion. Details of the schedule, constraints, related information, and workable backlog can also be annotated. It should be noted that the authors are looking for a possibility to incorporate constraint satisfaction algorithms and AI technique in the prototype system.

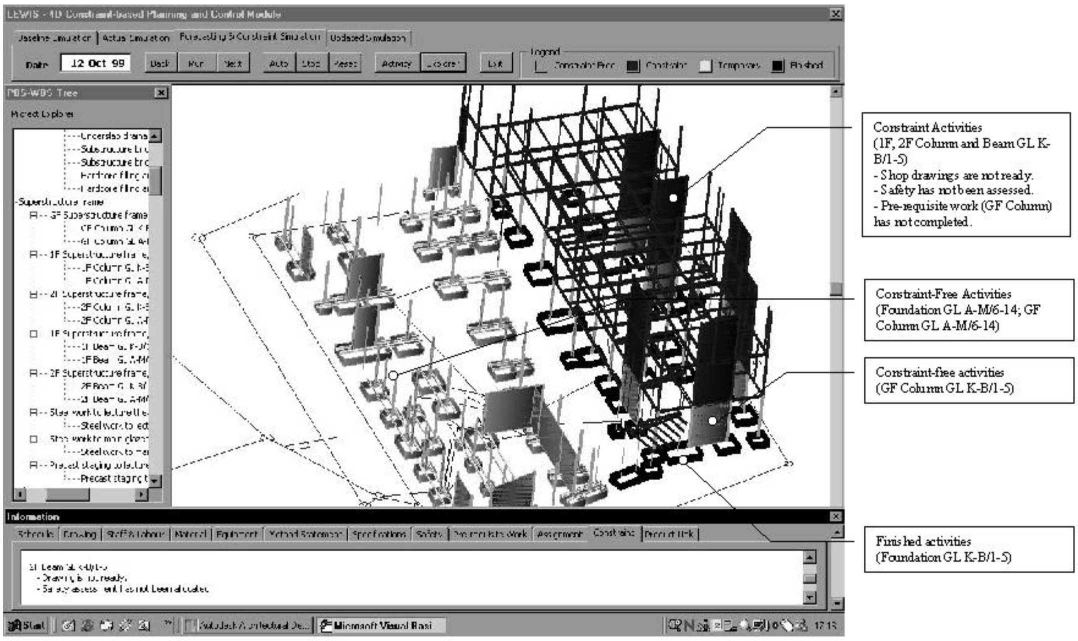

Figure-2: 4D Constraint-based Planning and Control Prototype System

Conclusions

Aiming to overcome deficiencies of the traditional planning and control concept and CPM technique, this paper identifies requirements for the next generation of planning and control as multi-constraints, visual, and lean-based system. As an important background, construction constraints and their characteristics are identified and various constraint detection and satisfaction techniques are reviewed. It is proposed that a synchronisation of database, 4D/VR visualisation, AI technique, and computational algorithms will lead to a solution system. To prove this concept, a prototype called 4D constraint-based planning and control system that possesses ability to simulate and visualise plans and various constraints has been being developed and briefly demonstrated in this paper. It is anticipated that successful implementation of this system will enable generation of reliable plans and constraint-free assignments, which will, in turn, reduce production risks and improve on-site productivity.

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