A FRAMEWORK OF TOTAL CONSTRAINT MANAGEMENT FOR IMPROVING WORK FLOW IN LIQUEFIED NATURAL GAS CONSTRUCTION

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In complex and concurrent construction project, numerous constraints which come from engineering, supply chains and construction work face are the main factors affecting plan reliability. Effective management of these constraints is critical to improve planning reliability and work flow. However, current constraint management approach is very fragmented and heavy relies on human's commitments and static data in constraint identification, tracking, assessment and removal. To tackle this problem, this paper proposes a framework of Total Constraint Management (TCM), which possesses four superior characteristics including: (1) collaborative constraint identification; (2) real-time constraint status tracking; (3) dynamic constraint removal; and (4) visual constraint representation. Advanced technologies, such as Building Information Modelling, barcode, and Radio Frequency Identification, are discussed to enable TCM implementation in practice. A controlled experiment was developed to demonstrate and evaluate the framework. The results showed that successful implementation of TCM could significantly improve plan reliability and construction productivity.

Keywords: planning reliability, total constraint management, work flow.

INTRODUCTION

Australia has benefited and will continue to benefit significantly from Liquefied Natural Gas (LNG) investments underway. Global Demand Forecast for LNG is 470 million tonnes per annum by 2030, which means more than 200 million tonnes in new capacity will be needed. However, rising costs in Australia mean this country risks pricing itself out of the global LNG market. For instance, current Australian project costs of LNG construction are typically 2-3 times higher than for other countries. Reliable construction plans are vital for effective collaboration across design, procurement and construction so as to reduce schedule delay and cost overrun. Numerous constraints which come from engineering, supply chains and construction work face are the main factors affecting plan reliability.

Lean construction, which comes from lean production philosophy, is a new approach to design construction systems to facilitate material and information flow, thereby minimizing waste of materials, time and effort, and improving productivity (Koskela 1992, 2000). In order to implement lean concept in practice, three different types of methods had been developed to improve construction work flow in LNG construction: Last Planner System (LPS), WorkFace Planning (WFP), and Advanced Work Packaging (AWP).

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LPS is a production planning and control tool developed to increase the reliability of planning and thereby improving construction performance (Ballard 2000). In essence, LPS enables the collaborative management of the network of relationships and communications needed to guarantee effective programme coordination, production planning and project delivery (Ballard 2000, O. Alsehaimi, Tzortzopoulos Fazenda and Koskela 2014, Priven and Sacks 2015). The process of removing constraints within LPS is sluggish and negative, such as late implementation of constraint analysis and short lead time for constraint removal (Hamzeh 2009). Another problem is that constraints which have a lead time beyond the weekly work plan window are not identified and removed in time due to poor foresight capacity of the look ahead plan (Hamzeh 2009).

Nieto-Morote and Ruz-Vila (2012) had applied LPS in a chemical plant construction. For each week, a list of constraints was identified, and, after the second week, the constraints were classified as actions or no actions. Project leaders would only be given constraints classified as actions. Two conclusions related to constraint analysis were made: (1) identifying constraints of the planned work had a positive impact on the percentage and quality of completed activities; and (2) the process of constraint identification should be conducted by all of the project leaders, supervisors and contractors. Another action research had been conducted by O. AlSehaimi, *et al*. (2014) in two large state-owned construction projects. The findings identified benefits of LPS including improved construction planning, enhanced site management and better communication and coordination between the parties involved. They also described barriers to release the full potential of LPS, including lengthy approval procedure by client, cultural issues, commitment and attitude to time, and short-term vision.

WFP developed by Constructions Owners Association of Alberta (COAA), is the process of organizing and delivering all elements necessary before work is started, to enable craft persons to perform quality work in a safe, effective and efficient manner (Slootman 2007). The main objective of WFP is to reduce schedule and cost overrun, and improve labour efficiency in mega project (Fayek and Peng 2013). The deliverables of WFP are three different levels of work packages: Construction Work Area (CWA), Construction Work Package (CWP) and Field Installation Work Package (FIWP) (Ryan 2009). Each package cannot be released until all the related constraints are removed. Examples of constraints for work packages are: drawings, workforce, materials, equipment, work space, permission and a scope definition of the work package to be executed. However, the constraint removal process of WFP has three shortcomings: (1) short time for planners to optimize scarce resources; (2) negative attitude for constraint removal due to the lack of constraint tracking, and (3) limited understanding of identification and classification of the full range of constraints.

AWP is developed by a joint venture between the Construction Industry Institute (CII) and the COAA, which aims to align engineering, procurement and fabrication with the sequencing needs of site installation and turnover to operations (Hamdi 2013). AWP is a more complete work packaging system than WFP. It covers not only construction but also the early stages of project and adds to the system more control over the breakdown of the project through its lifecycle (Hamdi 2013). The three key deliverables of AWP are CWP, Engineering Work Package (EWP) (Hamdi 2013) and Installation Work Package (IWP). Regarding constraint removal within AWP, although the scope of constraints is extended to engineering and procurement when compared with WFP and LPS, the constraint removal process within AWP is still similar to WFP, and has the same shortcomings.

Four case studies of WFP or AWP application were conducted by CII and COAA (2013) so as to summarize their benefits, difficulties and lessons learned. Four main benefits were identified: low employee turnover, safety performance improved, lower weld reject rates, and fewer changes during execution. Two difficulties were found: lack of management buy-in, and paper IWP management system. Five lessons were learned: IWP benefits, IWPs development and support, electronic IWP management, constraint analysis, and integration of IWPs into engineering. Regarding constraint management and removal, total constraint analysis was strongly recommended to perform because currently, only the basic constraints—e.g., critical material availability and engineering completion—were monitored prior to IWP release.

In order to address these shortcomings within constraint removal, this paper developed a framework of Total Constraint Management (TCM) to improve plan reliability and construction work flow by synchronising the concepts of strategy-pull and technology-push. The proposed TCM consists of three main parts: constraint modelling, constraint tracking and constraint removing. In the modelling phase, project constraints are identified, classified and structured; in the tracking phase, a streamlined tracking process is developed to assure the real-time updating of the status of constraints; in the removing phase, different types of constraints are removed according to different removal strategy.

FRAMEWORK OF TOTAL CONSTRAINT MANAGEMENT

This section describes a framework of TCM for improving work flow in Liquefied Natural Gas (LNG) construction (as shown in Figure 1). On the top of the Figure 1, eight phases of LNG project lifecycle are listed in sequence from asset definition to decommissioning. Under the line of the project phases, process of TCM is developed which consists of six sub-processes: constraint identification, constraint-removal planning, constraint tracking, constraint removal, constraint status updating, and implementation. Each of them is explained in detail as follows.

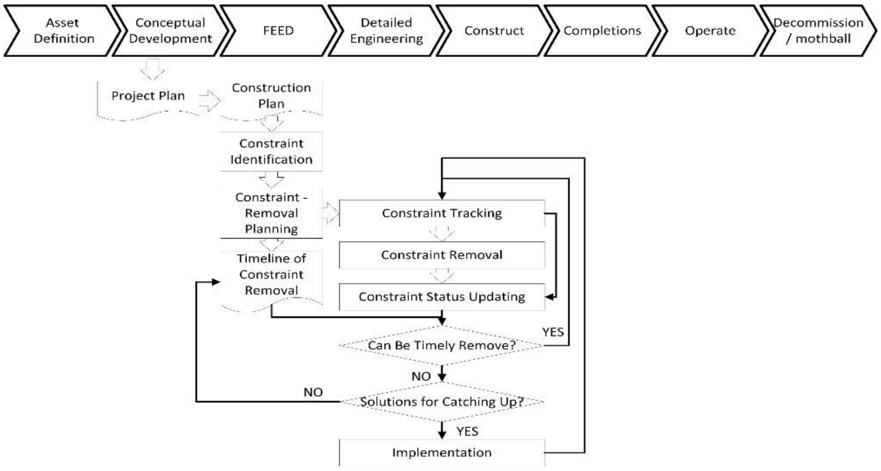

Figure 1: Framework of total constraint management

Constraint identification

LNG construction is very complicated. Numerous constraints comes from engineering, supply chains, onsite and offsite fabrication, and construction site.

Constraint modelling is a key step to enable project partners having a thorough understanding of interconnections among activities.

Traditional approaches for constraint identification are heavily rely on human's knowledge and experience. Moreover, only basic constraints are taken into consideration. In order to conduct a full constraint identification, three tools are developed: (1) constraint checklist. All the constraints are classified into three main categories: engineering, supply chains, and construction. Engineering constraints include drawings, specifications, instructions and plans. Supply-chain constraints consist of materials, equipment, and onsite and offsite fabrication. Construction constraints contain predecessor works, safety and health, work permits, temporary structures, weather conditions, workforce, construction machinery, tools, workspaces, and storage spaces; (2) Constraint relationship model. In real project situation, constraints are not independent. There are lots of connections among constraints. For instance, activity A has seven constraints which named from A1 to A7, activity B also has seven constraints which named from B1 to B7, if activity A is the predecessor work of activity B, the constraints A1-7 will have a connection to constraint B1-7; and (3) Virtual simulation, which is used to evaluate the completeness and correctness of the constraint relationship model.

Constraint-removal planning

After sub-process of constraint identification, timeline for each constraint removing need to be generated. There are two main tasks needed to be implemented during constraint planning. The first one is constraint-relationships modelling. For each construction work package, there are more than ten constraints need to be removed before releasing. These constraints are not independent and have inter-relationships among each other. Hence, having a thorough understanding of these constraints is very useful for constraint removing. The second one is deciding deadline of removal for each constraint so as to assure construction work flow and reduce time overrun.

Constraint tracking

According to the types of the constraints, different tracking processes are developed to assure the real-time monitoring requirement. There is a need to streamline the constraint tracking process by investigating: (1) the persons who are responsible for managing these different constraints; (2) the frequency of updating the constraint by the persons who are in charge; and (3) the correct ways that the updated constraint should be reported. An effective integration of virtual models and the physical construction has important implications for constraint tracking (Akanmu *et al*. 2014). A number of data acquisition technologies can be utilized in integrating virtual models and the physical construction including barcodes, wireless sensing technologies, photography, 3D laser scanners and photogrammetry (Akanmu *et al*. 2014).

Constraint removal

Constraint removal mainly executed in the stage of the four-week look-ahead planning. Constraints which have already satisfied the removal criteria or can satisfy the criteria based on forecasting, will be removed. The former on is named directly removal, the latter one is called indirectly removal.

Constraint status updating

In real LNG construction situation, the status of constraint is changed over time. The latest constraint information is very important for decision-making and constraint-free work releasing. According to different tools for constraint tracking, the way of constraint status updating can be concluded into three types: automated, semi-automated, and manual updating.

Implementation

In real project situation, there are lot of uncertainties impact the constraints being successfully removed. When we find some constraints cannot be timely removed, solutions need to be proposed to catch up the overall progress. For example, constraints like predecessor-work delay that can be timely removed by assigning extra resource. After the solutions approved, we need to implement our ideas and evaluate the final performance.

INCORPORATING EMERGING TECHNOLOGIES INTO THE PROPOSED FRAMEWORK OF TCM

In recent years, emerging information technologies have demonstrated their capabilities in improving performance of project management. This section discusses three technologies: Building Information Modelling (BIM), barcode, and Radio Frequency Identification (RFID), and how they can be incorporated into the proposed framework of TCM.

BIM for constraint identification and removal planning

BIM is emerging as a method of creating, sharing, exchanging and managing the information throughout life cycle between all stakeholders (Eastman *et al.* 2011, Pour Rahimian *et al.* 2014, Wang *et al.* 2014). A 4-Dimention (D) model results from the linking of 3-D model to the fourth dimension of time In the 4-D model, the temporal and spatial aspects of the project are inextricably linked, as they are during the actual construction process (Koo and Fischer 2000). Previous research had demonstrated significant benefits of BIM for project collaboration, design decisions-making, project constructability assessment, space constraint identification and so on (Mahalingam, Kashyap and Mahajan 2010).

With the help of BIM, project team can easily simulate overall construction process before field construction, and identify constraints based on the logic of the project schedule. In addition, some hidden constraints such as time-space conflicts and accessibility issues can also be detected through 4-D simulation. . In addition, BIM provides a collaborative platform for project team to share their knowledge and experience so as to improve the performance of the process of constraint identification.

BIM is also useful for constraint-removal planning. Within BIM, internal relationships of constraints can be visualized and further checked by project team. Moreover, the reasonability of timeline for constraint removing can be also validated in BIM.

Integration of barcode and RFID for constraint tracking and status updating

Barcode is an automatic identification technology that streamlines identification and data collection, and the technology of barcode has been applied to construction industry since the late 1980s, such as warehouse inventory management, field material control, site equipment management, and construction document management (Hong-Ying 2009, Li, Chen and Wong 2003). RFID uses radio frequency waves to transmit data between readers and tags. A typical RFID system includes an antenna, a transceiver (RFID reader) and a transponder (Radio Frequency tag). The antenna generates an electromagnetic zone where the tag detects the activation signal and responds by sending the stored data from its memory through radio frequency waves. RFID has recently attracted significant attention in construction areas such as material tracking, quality control, equipment monitoring and inspection, and asset maintenance (Hinkka and Tätilä 2013, Shin *et al.* 2011, Wang, Lin and Lin 2007).

Automated constraint tracking and status updating can significantly improve construction work flow and site productivity. Bar coding is widely used for tracking purpose during material fabrication stage while RFID focuses on material transportation from vendor sites to site storage locations to the final installation locations at the workface with GPS integration. Comparing with the traditional labour-intensive approaches, barcode and RFID can significantly improve the quality of constraint monitoring, and reduce the time.

With the increasing level of competition in the global LNG market, worldwide supply chain management become critical to project success. Therefore, integrated approach of barcode and RFID can provide real-time constraint tracking and updating, which is very useful to facilitate TCM implementation in practice.

VALIDATION

In practice, it is difficult to have access to construction sites and their facilities due to confidential issues and safety concerns. Therefore, it is not quite feasible to choose a real construction project to implement the proposed framework of TCM. In this study, a laboratory test was developed and implemented based on the LNG lean construction simulation game (as shown in Figure 2) to test and validate the framework of TCM. A hypothesise was developed for the experiment: Successful implementation of TCM can improve plan reliability and construction productivity. The validation of the emerging technologies mentioned above was not included in this paper.

The objective of the simulation game is to build an LNG train. The construction tasks consist of: site preparation, module installation (the modules are manufactured off-site), pipework installation, wiring installation, and major equipment installation. Finally, the LNG train need to be commissioned by testing for correct operation.

Figure 2: the LNG lean construction simulation game

The human subjects were graduate students and teachers from a wide range of backgrounds such as computer science, construction, mathematics, architecture, and engineering. Although most of the participants had no experience of construction management, site installation, and isometric drawing, they were all trained to understand the rules of the lean game. The age range of the research students was set as 15 years, which included young adults and mature adults. Meanwhile, there were both male and female subjects, which align to the real project team.

Experiment design

Two groups were selected to implement the experiment: A and B. The formal one applied TCM and the latter one not. There were 18 volunteers in each to perform all the roles in the simulation. Table 1 showed the roles of the people in the game. There was a basic training session for the both groups before the real test.

Table 1: The roles of the people in the game

Roles	Quantity
Project Manager	1
Plant Manager	1
Site Manager	1
Module Manufacturing	6
Civils Contractor	2
Mechanical Contractor	1
Pneumatic Contractor	2
Electrical Contractor	1
Major Equipment Installation	1
Shipping	1
Commissioning	1

In order to make the simulation game more close to the real environment, different types of interferences were added during the execution. Table 2 showed the interferences for different construction tasks.

Table 2: The interferences for different construction tasks.

Construction tasks	Weight for construction progress calculation	Interferences
Site preparation	30%	Bad weather
Off-site module manufacturing	10%	Design change
Module installation	15%	Quality unqualified
Pipework installation	28%	Material shortage
Wiring installation	10%	Labour shortage
Major equipment installation	5%	Late delivery of the equipment
Commissioning	2%	Delay of the work permit

Development of Key Performance Indicators

Two main indicators was developed to cater for TCM evaluation. The first one was Cumulative Progress (CP), which could be an indicator of actual progress. The second one was Total Construction Time (TCT), which could be used for measuring construction productivity.

Data collection and analysis

Initially, the performance of group B was measured by CP and TCT. An array of data was set up as the baseline. Next, the proposed TCM method was implemented by group A in the same experimental condition. Therefore, after the experiments, the performance data of the two groups were able to be compared so as to quantitative measure the benefits and improvement. All the data from the experiments was collected by dedicated recorders. Figure 3 showed the execution of the simulation game.

Figure 3: Execution of the LNG lean construction simulation game

Table 3 showed the final results. Group B took 53 minutes to finish the whole construction without TCM implementation. When compared with Group B, Group A only took 31 minutes, which meant 28% of TCT was reduced.

Table 3: results of the experiment

Groups	TCT (minutes)	CP1 (in the first ten minutes)	CP2 (in the second ten minutes)	CP3 (in the third ten minutes)	CP4 (in the fourth ten minutes)	CP5 (in the fifth ten minutes)
Group A	31	21%	63%	95%	100%	
Group B	43	16%	47%	71%	92%	100%

CONCLUSIONS AND FUTURE WORK

This paper developed a framework of Total Constraint Management (TCM) to improve plan reliability and construction work flow by synchronising the concepts of strategy-pull and technology-push. The proposed TCM consists of six sub-processes: constraint identification, constraint-removal planning, constraint tracking, constraint removal, constraint status updating, and implementation.

BIM was discussed to enhance constraint identification and the development of constraint-removal planning. Barcode and RFID were proposed for providing an integrated solution for real-time constraint tracking and status updating.

A controlled experiment devised to assess the discrepancies between the traditional method and TCM was undertaken. Results from the experiment indicate a positive effect of facilitations when implementing the framework of TCM in the LNG lean construction simulation game. The findings showed: 28% of TCT was reduced by Group A as compared with Group B. The successful implementation of TCM could significantly improve plan reliability and construction productivity.

Field Test is a validation method that brings proposals into the *"real world"* to assess performance (Bernold and Lee 2010). When compared with laboratory test, field test requires not only an upgrading of prototype design, in order to facilitate operation by field personnel, but also the thorough understanding of field practice (Bernold and Lee 2010). Future work will hopefully lead to the implementation of the TCM into a real LNG construction project. The real improvements in performance and productivity with TCM can then be measured and quantified in a real project context. In addition, another two experiments will be developed to measure the performance of BIM for constraint identification, and integrated solution of barcode and RFID for real-time constraint tracking. Australian LNG industry will benefit from this effective solution to mitigate the significant cost and schedule overruns in resource projects, particularly in mega-projects.

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