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Developing and evaluating a framework of total constraint management for improving workflow in liquefied natural gas construction

JUN WANG[1]*, WENCHI SHOU[1], XIANGYU WANG[1,2] and PENG WU[3]

[1]*Australasian Joint Research Centre for Building Information Modelling, Curtin University, GPO Box U1987, Perth, WA 6845, Australia*

[2]*Department of Housing and Interior Design, Kyung Hee University, Seoul, South Korea*

[3]*Department of Construction Management, School of Built Environment, Curtin University, GPO Box U1987, Perth, WA 6845, Australia*

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Liquefied natural gas projects are complex and full of variability. Their plan reliability is affected by constraints arising from engineering, supply chains and construction site. Effective management of these constraints is critical to reducing project uncertainties and improve workflow. However, current approaches for constraint removal are fragmented and heavily rely on human's commitments because the underlying data for decision-making are static and outdated. In order to tackle this problem, this paper proposes a framework of total constraint management (TCM), which consists of three main parts: constraint modelling, constraint monitoring and constraint removal. Information technologies (i.e. building information modelling, radio frequency identification, barcoding, laser scanning and photogrammetry) are also discussed and incorporated into the TCM framework so as to make it more practical and effective. A laboratory-based experiment was developed to demonstrate and evaluate the framework. The results showed that successful implementation of TCM could significantly improve construction workflow and productivity.

Keywords: Advanced work packaging, last planner system, lean construction, theory of constraints, total constraint management, workface planning.

Introduction

Australia has benefited and will continue to benefit significantly from liquefied natural gas (LNG) investments underway (Ellis *et al.*, 2013). The Global Demand Forecast for LNG is 470 million tonnes per annum by 2030, which means more than 200 million tonnes of new capacity will be needed to fulfil increased demand (Ellis *et al.*, 2013). However, rising costs in Australia mean this country risks pricing itself out of the global LNG market. For instance, current LNG construction in Australian typically cost 2–3 times higher than in other countries (Ellis *et al.*, 2013). The major driver for the rising costs is the long-time project delay which was caused by the massive disputes and uncertainties during project execution (Ellis *et al.*, 2013). Past and current LNG projects have failed to deliver the desired outcomes through lost time, reworks, design errors, construction inefficiencies and life cycle performance failures. Reliable construction plans are vital for effective collaboration across design, procurement and construction so as to reduce schedule delay and cost overrun (Dawood and Sriprasert, 2006; Hamzeh *et al.*, 2015).

Reliability of construction schedules can be enhanced and improved through satisfying all potential constraints prior to site execution (Dawood and Sriprasert, 2006). Potential constraints can be incomplete drawings and

*Author for correspondence. E-mail: jun.wang15@postgrad.curtin.edu.au

specifications, shortage of workforce and materials, lack of temporary structures, limited work space, uncompleted preceding works, bad weather, lack of work permits and safety issues. A constraint is something that will happen while a risk is something that may happen. For example, the likelihood of rain in construction is usually a factor that needs to be considered. In Dubal, this is a risk because it rarely rains but may happen; however, in Melbourne, this is a constraint because it will always rains, especially in winter, and meteorological records provide a very good indication of the likely rainfall on a month by month basis, allowing project managers to make an appropriate action to reduce the impact. Once a constraint is not timely removed, it becomes an issue which needs to be resolved now so as to move forward. Current approaches for constraint removal have four shortcomings:

(1) Sluggish removal of constraints. Late implementation of constraint analysis leaves short lead time to remove constraints (Hamzeh, 2009).
(2) Low transparency of constraint status and over commitments from different sides including suppliers, consultant and some subcontractors (Alsehaimi *et al.*, 2009).
(3) Inefficient selection criteria and process for constraint-free tasks releasing (Nieto-Morote and Ruz-Vila, 2011; Lindhard and Wandahl, 2014).
(4) Poor foresight capacity of the look-ahead plan. While some constraints are identified and removed at the commitment/weekly work plan level, other constraints having a lead time beyond the weekly work plan window are not identified and removed in time (Hamzeh *et al.*, 2008).

To address the above issues, a novel approach, total constraint management (TCM), is developed to manage the various constraints in LNG construction. There are three main modules within the approach: constraint modelling, constraint monitoring and constraint removal. Information technologies, such as building information modelling (BIM), radio frequency identification (RFID), barcoding, laser scanning and photogrammetry, are also discussed to facilitate TCM framework implementation in practice. To illustrate the benefits of the proposed approach, the authors have applied the TCM framework to a lean simulation game of LNG compression.

Constraint management

Constraint management is one of the core issues in production planning and control. The concept of constraint was firstly introduced in 1984 as constraint management and the theory of constraints (Goldratt and Cox, 1984). It is defined as any condition, such as technical sequencing, temporal/spatial limitations and safety/quality concerns, which prevents work plans assigned to construction crews from being successfully executed in the field (Blackmon *et al.*, 2011). While the most common types of constraint, e.g. time constraint, can be managed using the traditional project control techniques, e.g. the critical path method (CPM), it is proven that these techniques are not adequate for effectively identifying and tracking detailed constraints in construction works (Pultar, 1990). For example, Pultar (1990) argued that CPM does not cover the full spectrum of constraint types and can only be created following the development of a fixed plan.

Lean construction, which originates 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; Koskela, 2000). Compared with traditional 'push-driven' approach, the main objective of a 'pull-driven' method is to produce finished products as optimally as possible in terms of quality, time and cost, so as to satisfy customer demand (Tommelein, 1998). To implement a pull-driven approach, selective control is needed and should be driven by both information about resources in the queues and work-in-progress and resources downstream (successor queues and activities) in the process (Tommelein, 1998).

Three types of planning methods had been developed to transform pull concept into the construction industry. The first one is last planner system (LPS) developed by Glenn Ballard and Greg Howell, which is a production planning system designed to produce predictable workflow and rapid learning in programming, design, construction and commissioning of projects (Ballard, 2000). The LPS was originally designed to address some shortcomings of the CPM method, a particular shortcoming of which, i.e. task continuity, was not addressed (Dave *et al.*, 2015). According to Winch (2006), the LPS is an important innovation, and anecdotal evidence of the use of lean construction. However, Winch (2006) has also argued that when using LPS, there is a lack of attention paid to the theory of constraints and its project-specific application in the critical chain. The critical chain concept provides a revolution to address the problem of slack in task execution time estimates when construction projects don't have infinite resources. The second one, workface planning (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 last one is advanced work packaging (AWP) 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). Constraint removal is one of the key processes among the three planning methods and is discussed in the following sections.

Constraint removal in LPS

LPS has been widely used on projects and within both design and construction firms across a multitude of different sectors in the building, mining and oil and gas industries. 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 (Höök and Stehn, 2008; Hamzeh *et al.*, 2015). An action research study conducted by AlSehaimi *et al.* (2014) indicated that the benefits of LPS included: improved construction planning, enhanced site management and better communication and coordination between the parties involved; and the barriers to release the full potential of LPS contained: lengthy approval procedure by client, cultural issues, commitment and attitude to time and short-term vision.

In LPS, the main task of the look-ahead process is to efficiently schedule the potential task assignments for the next 3–12 weeks. The number of weeks over which a look-ahead process extends is decided based on project characteristics, the reliability of the planning system and the lead times for acquiring information, materials, labour and equipment (Ballard, 2000). Once assignments are identified, they are subjected to constraints analysis to determine what must be done in order to make them ready to be executed. Only activities, in which all constraints have been removed and that they are in the proper sequence for execution, are allowed to enter into the workable backlog. Weekly work plans are then formed from the workable backlog, thus reducing the uncertainties and improving the productivity. If the planner is not confident that all the constraints can be timely removed, or of identifying a constraint (e.g. engineering drawings) that definitely cannot be removed in time, the assignment would not be allowed to move forward.

Different types of assignments have different constraints which vary from internal constraints (e.g. design information, materials, prerequisite work, space, equipment and labour) to external constraints (permits, inspections, approvals and weather). Nieto-Morote and Ruz-Vila (2011) applied LPS in a chemical plant construction, and two useful 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. Hence, good constraints analysis requires all relevant parties to actively manage their production and delivery, and provides the coordinator with early warning of problems, ideally with sufficient lead time to plan around them.

However, current process of constraint removal within LPS is sluggish and negative, such as the 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 cannot be identified and removed in time due to poor foresight capacity of the look-ahead plan (Hamzeh, 2009). In addition, paper-based constraint analysis and meeting-based constraint status updating and coordination are still the dominant approaches for constraint removal.

Constraint removal in WFP and AWP

WFP has been widely used in industrial projects (e.g. oil and gas plant) and is now a common requirement in the construction contracts in Alberta, Canada (Fayek and Peng, 2013). The main objective of WFP is to reduce schedule and cost overrun, and improve labour efficiency in mega projects (Fayek and Peng, 2013). High-level benefits identified from previous case studies include: improved project party alignment and collaboration, increased site productivity, reduced construction rework, improved project control, improved safety awareness, increased reporting accuracy and improved client satisfaction (O'Brien *et al.*, 2011).

Within WFP, three different levels of work packages are defined and used to describe different levels of project plans: construction work area (CWA), construction work package (CWP) and field installation work package (FIWP) (PMP, 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 a more complete work packaging system than WFP. It covers both the construction and the initial early stages of the project and allows a system more control over the breakdown of the project through its life cycle (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 similar shortcomings.

Research method

The development of the framework started with the reference and literature analysis of constraint management from previous studies. Subsequently, 13 industry experts were asked to examine and finalize the proposed framework. They all have experience of project planning and control and had been involved in several real LNG projects in the last few years. The review process started by giving an introduction about the purpose of this study. The proposed framework was then illustrated to the industry experts. All the 13 experts verified the framework and gave their feedbacks based on their expertise. Table 1 shows the profile of the interviewees and their contribution. As can be seen from Table 1, the selection of the industry experts covered the LNG project life cycle, including design, procurement, logistics and supply chain, engineering and construction management, as well as maintenance. All industry experts had a minimum of 10-year experience in developing, delivering and managing LNG projects. It is therefore expected that these industry experts can offer a fair and useful evaluation of the proposed framework.

In order to validate the proposed framework of TCM, a laboratory test is developed and implemented based on an LNG lean construction simulation game. The following questions are posed: Can the TCM framework improve the construction workflow? Can the productivity be increased with TCM implementation? Can the project duration and the impact of the long lead constraints be reduced?

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 has to be commissioned by testing for correct operation. Table 2 shows the number of people and roles needed to play the game. All the 40 volunteers are graduate students or visiting scholars who have very limited knowledge on lean and TCM. The age range of the volunteers is set for 15 years, which includes young adults and mature adults. Meanwhile, there are both male and female subjects, which align to the real project team. The volunteers are randomly split into two groups: Group A with TCM implementation and Group B without. In order to reduce the learn curve issues, there is a basic training session for both groups, and they are also guided to play once before starting the test. Two additional players are assigned to represent the clients of the LNG train. One selects design variations at regular time intervals through the game and delivers them to the project manager; the other checks completed tasks and issues permits to site managers.

Framework of TCM for LNG construction

This section describes a framework of TCM which aims to improve workflow in LNG construction. During the review stage of the proposed framework by the selected industry experts, the client and manufacturer pointed out that there were two different types of constraints in LNG construction, namely: long lead and short lead constraints, which needed to be distinguished. For instance, most of the project-specified instruments were long lead constraints because they were needed to be designed and fabricated overseas which took a long time to deliver. Standard materials and tools such as valves and bolts, could be short lead constraints if they are available in local market. There should be different management strategies to handle these two types of constraints. People from engineering company emphasized the alignment among engineering, procurement and construction plans. In addition, they mentioned constraint removal plan should be developed from a construction-centred perspective. The contractor highlighted the importance of identifying constraints like safety and permits because there were more rigorous standards in LNG industry. The delay of temporary structures was another type of constraint identified by the sub-contractor, which had a big negative impact on construction workflow. The lean consultancy confirmed the AWP process; however, he emphasized that the process was not constant and would be adjusted based on client's requirement. The technology providers demonstrated the capabilities of existing project planning software and tracking technologies. Their limitations were also emphasized, for example, the accuracy of RFID-enabled positioning method was very low in a metal environment.

Figure 1 shows the final version of the TCM framework. In the left part, AWP method is selected as a basis to express the workflow of the project execution in LNG industry. The underlying reasons are threefold: (1) AWP method is developed from and increasingly used in oil and gas industry when compared with LPS (Hamdi, 2013); (2) AWP method is an extension

Table 1 Profile of the 13 interviewees and their contribution

No.	Organization (types)	Expertise	Years of experience	Main contribution
1	Woodside (client)	Construction management	20+	Long lead constraints management
2		Logistics and supply chain	20+	Supply chain constraint monitoring
3		Turnaround maintenance	15+	Long lead constraints identification
4	WorleyParsons (engineering, procurement and construction)	Engineering management	10+	Engineering constraint monitoring
5		Logistics and supply chain	10+	Alignment between procurement and construction
6	Monadelphous (construction and maintenance)	Construction management	15+	Constraint identification for safety and permits
7		Site logistics	10+	Material constraint tracking
8	Track'em (software)	Supply chain management	10+	Supply chain constraint monitoring
9	AVEVA (software)	Engineering design	20+	Maturity index development for engineering constraint
10		Construction management and procurement	10+	Alignment of removal plans among engineering, supply chain and site constraints
10	Fremantle Steel (manufacturer)	Offsite fabrication	20+	Constraint modelling for offsite fabrication
11	KAEFER (contractor)	Construction management	15+	Constraint management for temporary structures
12	Bentley (software)	Construction management	15+	Site constraint monitoring
13	SECORA (lean consultancy)	Lean construction	10+	Pull planning

Table 2 The roles of the people in the game

Roles	Quantity
Project manager	1
Plant manager	1
Engineering manager	1
Procurement manager	1
Site manager	1
Module manufacturing	6
Civil contractor	2
Mechanical contractor	1
Pneumatic contractor	2
Electrical contractor	1
Major equipment installation	1
Shipping	1
Commissioning	1

of WFP which covers both construction and initial early stages of projects (Hamdi, 2013); and (3) AWP is an overall process flow of all the detailed work packages (CWPs, EWPs and IWPs), which is more close to the current practice of LNG construction (confirmed by the 13 industry experts). Three stages are defined within the workflow: preliminary planning, detailed engineering and construction. The left part of Figure 1 shows the detailed process of TCM, which can be further classified into three modules: constraint modelling, constraint monitoring and constraint removal. The level of detail of each module depends on the project stages. For instance, in detailed engineering stage, the level of detail of all the three modules is in CWP level. There are three loops existing between the project stages and the core modules. Each of them is explained in detail as follows.

Constraint modelling

Constraint modelling is key to allow project managers and engaged partners to have a thorough understanding of interconnections among activities. There are three processes within this module. The first one is constraint identification which needs to accurately detect all the constraints. The traditional process for constraint identification always happens once and close to the construction stage, and only important constraints are taken into consideration, such as material, workforce and equipment. In order to assure a full constraint identification, constraints in LNG construction are classified

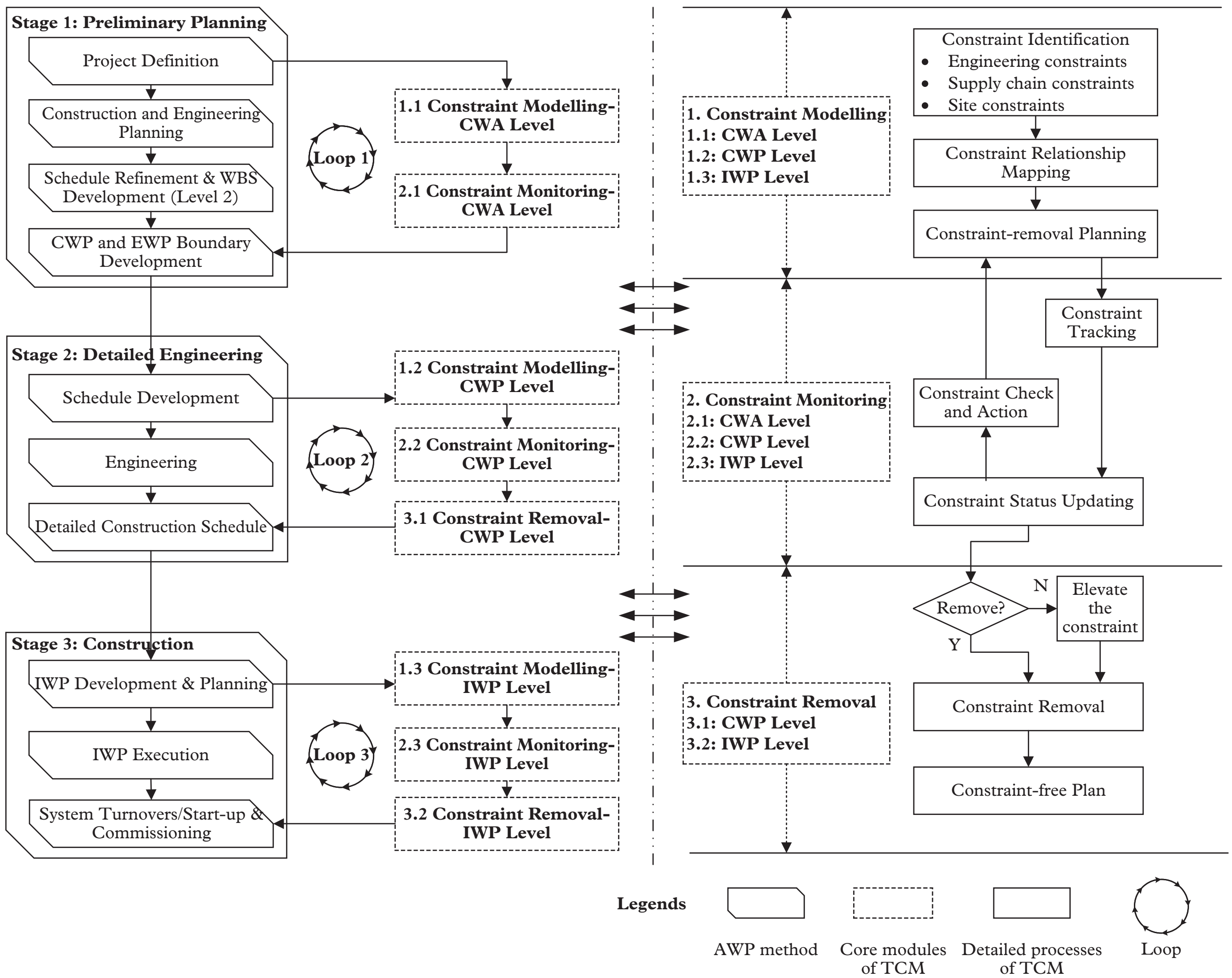


Figure 1 Framework of TCM for LNG construction

into three main categories (as shown in Figure 2): engineering, supply chain and site constraints. Constraints such as incomplete drawings, lack of assembly specifications and 3D models are engineering constraints, which decide the start time of procurement, fabrication and site installation. Supply chain constraints include the late procurement of bulk materials and project-specific instruments and equipment. Without timely purchasing and delivering these resources to the site, detailed construction activities cannot be planned and executed. Site constraints contain the shortage of workforce, lack of temporary structures, limited work space, uncompleted preceding works, bad weather, lack of work permits and safety issues. If these site constraints are not timely removed, construction work crews cannot perform their daily tasks. The underlying reasons for this type of classification are twofold: (1) most of LNG projects are delivered by the strategy of engineering procurement and construction (EPC); hence, it is easy to conduct constraint identification; and (2) work packages are widely used in LNG construction, such as EWP, CWP, IWP, procurement work package (PWP), inspection work package and commissioning work package. Therefore, it is easy to manage these constraints.

The second process is constraint relationship mapping. In real project situation, constraints are not independent and have interrelationships among each other. Hence, having a thorough understanding of these relationships is very helpful for removing constraint in time. Figure 3 shows a single example which contains only one EWP, one PWP, one CWP and one IWP. When the designers start to develop EWP, initial vendor data to perform detailed design need to be obtained, final vendor data are then needed to conduct production design and final approvals from the client are necessary to release the EWP to construction. An interesting finding is that both the two types of vendor

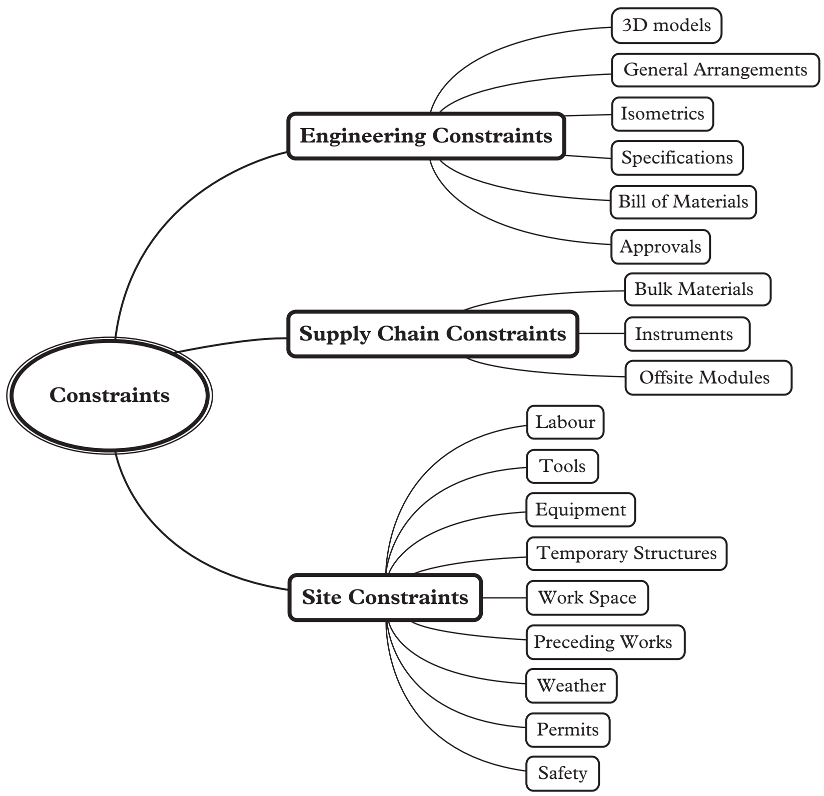


Figure 2 Constraint classification

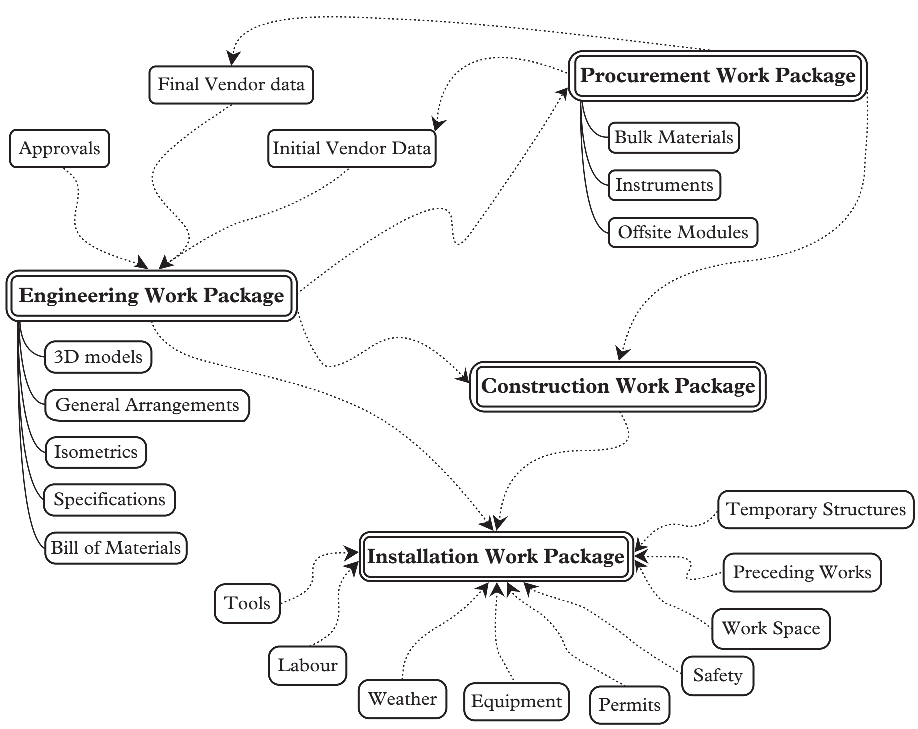


Figure 3 A simple example of constraint relationship mapping

data come from PWP, and the development of the PWP needs to rely on conceptual design outputs which come from the EWP. Therefore, any delay of the activities within the two work packages will result in late constraint removal, thus causing whole project delay. From the IWP perspective, before released to the site, it needs to satisfy all the different types of constraints including site constraints and constraints from EWP, CWP and PWP.

The last process is constraint removal planning. In order to assure all the constraints are timely removed, a detailed timeline for each constraint removal is needed to be pre-planned while considering the requirement of project completion. The pull-driven approach is applied to determine the deadline of each constraint. For example, when the sequence of the CWPs is decided and agreed by all project stakeholders, the planning of EWP and PWP should be aligned with the CWPs. In addition, each deliverable from EWP or PWP must be early defined and communicated so that engineering or procurement can be proceeded with a clear understanding of the level of detail.

Constraint monitoring

In a real LNG construction situation, the statuses of constraints change over time. The latest constraint information is important for project managers to assess progress and release constraint-free work packages. When project suffers delay, the up-to-date status of constraints can also be used as references for decision-making. There are three processes within the module of constraint monitoring. The first one is constraint tracking which focuses on tracking each individual constraint. The approaches for constraint tracking can be automated, semi-automated or manual which depend on project requirement and technology maturity. For example, material constraints can be automatically tracked by RFID (Navon and Berkovich, 2006), while safety constraints maybe still need to be manually checked by site workers.

The second process is constraint status updating which focuses on calculating the maturity of a task or a work package. The maturity index is intended to support both short-term decision-making by team leaders, before they commit to performing tasks, and also to support weekly planning activities (Sacks *et al.*, 2010). All the tracking data from the first sub-step are collected for the maturity index calculation. Table 3 shows an example of maturity index for a piping EWP.

The final process within this module is constraint checking and action, which focuses on comparing as-actual constraint status with an as-planned constraint removal plan. The frequency of constraint checking is dependent on the project stages and characteristics. For example, the frequency can be quarterly or monthly at project early stage, and then change to weekly or daily at construction stage. Different action strategies should be performed according to the checking results. If the results indicate several delays of constraint removal, catch up action needs to be conducted.

Table 3 An example of maturity index for a piping EWP

Tasks	Maturity (%)
EWP identified and mapped to CWP	5
Initial scope identified (line numbers)	20
Preliminary equipment data received	25
Initial routing of lines established	45
Initial bulk material to supply chain	55
Piping studies received for critical lines	60
Final vendor data received	70
Final routings completed	75
Process and instrumentation diagrams and line designation table issued for construction	80
Stress analysis for large bore completed	85
Bill of materials completed	90
EWP complete with all drawings/specs issued for construction	95
EWP accepted by construction	100

Constraint removal

Constraint removal is mainly executed in the stage of look-ahead planning. Constraints cannot be removed unless either of the following two conditions is satisfied: (1) the maturity index of the constraint is 100%; or (2) the maturity index can be updated to 100% based on forecasting or reliable commitment.

Loop 1

Loop 1 happens in project stage one and involves the modules of constraint modelling and monitoring in a CWA level. CWAs are manageable areas from a large project, and are developed according to the path of construction and requirement of integrated planning. The main objective of loop 1 is to identify and monitor long lead time constraints and align engineering and procurement plans to the construction plan. In project definition phase, it is important for design engineers to embrace a total project view in order to position the project for effective implementation of TCM. In construction and engineering planning phase, construction planning is key to establishing alignment with engineering. The sequence of construction activities should be established so as to ensure that engineering can sequence its work to support construction. This allows construction to drive the engineering plan which can realize the greatest potential of TCM to manage engineering constraints. The constraints of temporary structures (e.g. site traffic flow, temporary roads, general parking, laydown areas, site security, subassembly areas, field office locations, offsite storage and the related power, water and air requirement) should be identified and well managed because they can affect construction workflow. Engineering plan is developed based on the sequence of construction, and engineering feedbacks are also needed to refine the sequence. All major constraints should be addressed at this point, including any resulting from the contracting and procurement plan. In schedule refinement phase, key long lead time constraints of the supply chain should be identified and scheduled based on procurement expertise. In CWP and EWP boundary development phase, a list of deliverables for CWP and EWP has been developed. Constraints of labour and materials should be considered. Identifying at a high level the necessary workforce by discipline, including support craft services for each CWP, and then assessing the availability of these resources are key in this phase. The material requirement should be estimated based on material specification from engineering, and unique and/or long lead material items should be identified, such as certain alloy piping materials and many process equipment items.

Loop 2

Loop 2 happens in project stage two and involves all the three modules of constraint modelling, monitoring and removal in CWP level. A CWP defines a logical and manageable division of work within the construction scope and is typically aligned with a bid package. A typical CWP includes schedule, budget, environment requirements, quality requirements and special resource requirements. The objective of loop 2 is to manage constraints from a CWP-centred perspective, and continually involve owner, engineering, procurement and construction to find new constraints and detect potential constraint removal issues. Monitoring and removing constraints of engineering and long lead supply chain should be given high priorities in this loop. During the schedule development phase, detailed resource constraints should be considered with progressing for work packaging. There must be alignment with areas that plan to have an early start-up. Owner operations requirement should also be accommodated in this phase. In engineering phase, all engineering deliverables (i.e. engineering constraints for CWPs) need to be clearly mapped to EWPs and CWPs. Changes need to be managed to assess their impact on CWPs. In the detailed construction schedule phase, site constraints must be considered and reflected in the constraint relationship map.

Loop 3

Loop 3 happens in project stage three and involves all the three main modules within TCM in IWP level. An IWP is a deliverable that enables a construction work crew to perform work in a safe, predictable, measurable and efficient manner. The objective of loop 3 is to maintain, monitor and remove constraints from an IWP-centred perspective based on IWP look-ahead schedule. Modelling, monitoring and removal of detailed site constraints such as materials, equipment, tools, labour, safety, permits, weather and work space are the focus of this loop. Once the IWP scope is identified, a rough schedule and sequence can be developed. Foremen should be notified of the requirement to support this initial plan. After the initial allocations have been made, constraints should be monitored on the basis of the constraint removal plan. All the related constraints of an IWP should be removed prior to release of IWP to the field. Once issued, the superintendent should review and coordinate the execution of the work with the general foreman, foreman and craft. The superintendent, with support from the project planner, is responsible for follow-up on the execution and progress of the IWP. After IWP closeout, project team should continue to improve TCM process by looking for ways to increase accuracy, reduce information collection errors and redundancy and develop a specific continuous improvement/best practices plan to implement TCM in practice.

Information technologies incorporation

In a real project, there are thousands of IWPs, and for each IWP, there are more than 10 constraints. It is difficult for humans to manually manage these constraints. However, the integrity, consistency, transparency and traceability of constraints management are critical to release the greatest value of TCM. Information technologies such as BIM, RFID and laser scanning can greatly enhance the implementation of TCM. These technologies make it easier for planners and managers to identify, track, update and remove constraints (Isaac and Navon, 2014). Table 4 shows the positions of these technologies within TCM.

BIM is emerging as a method of creating, sharing, exchanging and managing the information throughout

Table 4 Information technologies incorporation

	Constraint modelling	Constraint monitoring
Engineering constraints	BIM	BIM
Supply chain constraints	BIM	Barcode/RFID/GPS
Site constraints	BIM	Barcode/RFID/GPS + laser scanning/photogrammetry

life cycle between all stakeholders (Fox and Hietanen, 2007; Demian and Walters, 2014; Wang *et al.*, 2015). Previous research had demonstrated significant benefits of BIM for project collaboration, design decisions-making, project constructability assessment, space constraint identification and so on (Mahalingam *et al.*, 2010; Shou *et al.*, 2015; Wang *et al.*, 2016). In order to facilitate TCM implementation in practice, BIM can be utilized to support the modelling process of all the three types of constraints, and engineering constraint monitoring. With the help of BIM, the project manager can simulate the overall construction process within the computer before field execution, and visually identify constraints based on the predetermined path of construction. In addition, some hidden constraints such as workspace and safety can be detected through 4D simulation. Constraint removal plan can be also validated with BIM. The most useful capabilities of BIM is to provide a collaborative platform for the project team to share their knowledge and experience to improve the overall performance of constraint modelling including integrity and consistency.

Tracking technologies such as barcoding, RFID and global position system (GPS) are increasingly used in LNG construction, and can significantly help project managers automatically monitor the status of supply chain and site constraints, especially for tangible objects tracking like materials, equipment and workers (Oloufa *et al.*, 2003; Ergen *et al.*, 2007; Hinkka and Tatila, 2013). Barcoding is an automatic identification technology that streamlines data collection (Li *et al.*, 2003). 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. GPS is a satellite-based navigation system that depends on the constellation of satellites orbiting around the earth (Pradhananga and Teizer, 2013). Take a supply chain constraint tracking of a special equipment as an example; barcode and RFID can be used to track equipment status during production stage while GPS is used to automatically locate the equipment during transportation stage and calculate the remaining time to destination (Wang *et al.*, 2007). Comparing with traditional labour-intensive approaches, the transparency and traceability of constraint monitoring can be improved through tracking technologies implementation.

Sensing technologies such as photogrammetry and laser scanning are useful to automatically or semi-automatically monitor the status of site constraints like limited work space, uncompleted predecessor work and construction defects (El-Pmari and Moselhi, 2008; Wang *et al.*, 2014). Laser scanning is an active sensor technique that captures geospatial information of a scene, delivering thousands of points with Cartesian (x-y-z) or spherical (Φ-θ-r) coordinates (Becerik-Gerber *et al.*, 2011; Bhatla *et al.*, 2012). Photogrammetry is another way to assess as-built construction conditions. Photogrammetry feeds the measurements from remote sensing and the results of imagery analysis into computational models in an attempt to successively estimate actual site environment (Brilakis *et al.*, 2011; Bhatla *et al.*, 2012). Both approaches allow the as-built environment to be visualized from different viewpoints. With the increasing level of the complex in LNG construction, integration of laser scanning and photogrammetry is preferred to provide a more cost-effective approach for automated site constraints monitoring.

Validation

According to the proposed TCM framework, 83 EWPs, 10 CWPs and 172 IWPs were developed for the simulation game. In order to simulate engineering works, all the drawings and specifications were taken into predefined engineering offices, respectively, according to different disciplines, such as mechanical, electrical, civil and piping. The released time for these drawings and specifications to the construction site was planned based on the design of the experiment. Twelve long lead constraints designed by the authors were incorporated into the game. Examples of long lead items in this experiment were equipment (i.e. compressor, convert, pressure, battery and power) that were designed and built specifically for the project, and tools (i.e. Allen keys) and materials (circuit board, bar, connector, metal pin, long pipe and switch) that were purchased in other countries. If the project team could not identify these constraints as early as possible, the game would suffer delay.

In the first round of play, simulating the TCM framework, the project manager of Group A was provided with a construction plan and a constraint relationship map. Detailed constraints for each IWP could also be checked (as shown in Figure 4). For example, when clicked 'IWP 6.2', the project manager could find all related constraints and their planned removal time. With TCM implementation, Group A found all the long lead constraints in the first 10 minutes, and developed action strategies to remove them timely. After the first five minutes of play had elapsed, the first client representative began selecting design variations at random for LNG modules and civil foundations in random sequence. Figure 5 showed an example of design variations in civil foundations. Two typical variations (B and C) were developed to the standard default design (A). Each design changes needed to be addressed; even the modules were delivered to the site or finished the installation. Moreover, only appropriate subcontractors could make the changes called for in the variation change order. In order to reduce rework, Group A changed the work sequence to follow the random sequence in which design variations were selected. Work was started on an LNG module only after its design variation had been selected.

Regarding constraint monitoring and removal, it was not feasible to implement the proposed technology solution of the TCM in this simulation game. However, in order to simulate the real-time constraint tracking and status updating, the project manager was allowed to walk around to get all the latest status of the constraints. The second client representative inspected each completed IWP and recorded the time. The play was finished after 31 min, and the performance of Group A was assessed in terms of progress, defective LNG modules, productivity and duration.

In the second round, simulating the conventional constraint removal approach, the following changes were made, while all other conditions remained as before:

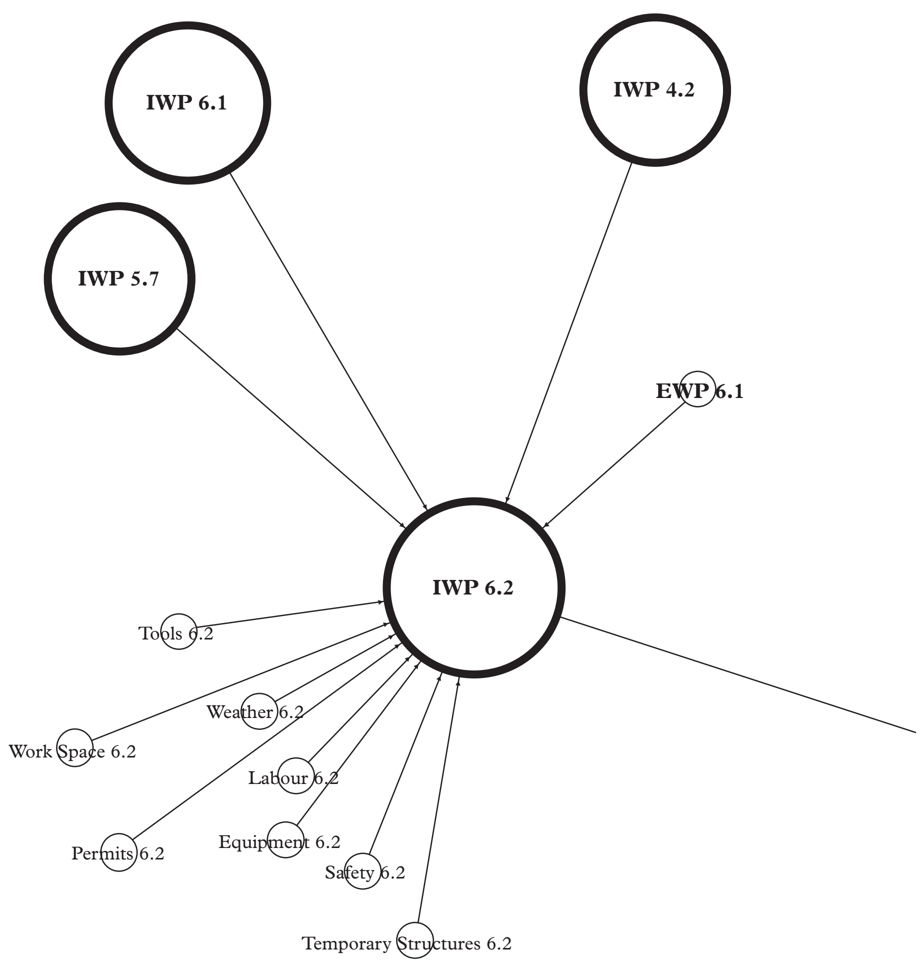
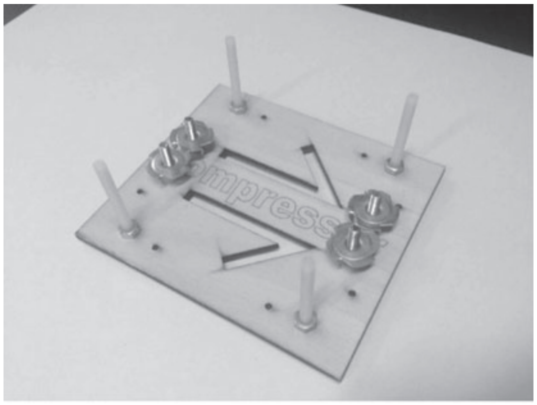
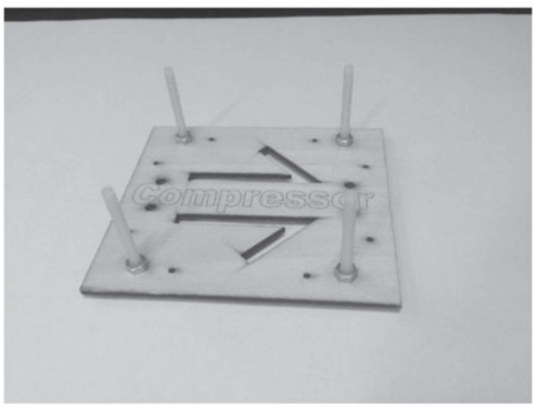


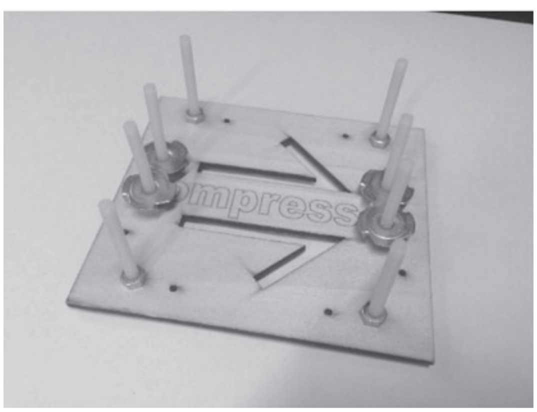
Figure 4 Detailed constraint check for each IWP



(a) Standard default design



(b) Design variation-1



(c) Design variation-2

Figure 5 An example of design variations in civil foundations

(1) Constraint analysis was late implemented and only happened at the IWP development stage. Currently, in most cases, constraint analysis started at the look-ahead planning phase, and was done by examining each activity that was scheduled to perform within the next six to eight weeks. In this regard, it was reasonable to assume the action of constraint analysis only happened at the IWP level, not CWP or higher level.
(2) Project manager of Group B was not allowed to walk around, and could only perform constraint removal in his own office based on progress reports and commitments. Most companies traditionally performed constraint removal based on their regular coordination meetings. Constraint status was manually updated according to paper-based reports and oral commitments. In this experiment, all the contractors and subcontractors worked within a small area. The action of 'walk around' could make the project manager get nearly real-time constraint information including status. Therefore, in order to largely reflect the real world experience, this assumption was formulated.
(3) Constraint relationship map and removal plan were not provided to Group B. In the conventional approach, constraint analysis and removal were conducted informally; thus, the experience, foresight and general capabilities of the managers made a great deal of difference. According to the feedbacks of the 13 industry experts, very few projects developed constraint relationship map and removal plan. The most common practice was identifying and listing all the constraints for each activity from a local perspective, not the globe.

Without TCM implementation, all the 12 long lead constraints were not timely found until the third 10 minutes. Delays were suffered at the end of the first 10 minutes because of materials and tools shortage. The performance of group B was also measured by the second client representative.

Results and discussions

After the two-round execution, the performance data of the two groups were calculated. The parameters of interest were the number of defective LNG modules, the actual duration, the actual progress for each time interval and the productivity for each trade. The first two were easily measured; the latter two were calculated according to the following two rules, respectively:

(1) Index of cumulative progress (CP) was developed to measure the actual progress at the end of each time interval. In this study, the time interval was set to 10 min. The formula was: $CP = A_1*A_{1w} + A_2*A_{2w} + A_3*A_{3w} + \ldots + A_n*A_{nw}$. The value of A_n was the actual progress of construction trade n, which could be measured

Table 5 The weight of each trade for CP calculation

Construction trades (n)	Descriptions	Weight (%) (A_{nw})
1	Site preparation	30 (A_{1w})
2	Off-site module manufacturing	10 (A_{2w})
3	Module installation	15 (A_{3w})
4	Pipework installation	28 (A_{4w})
5	Wiring installation	10 (A_{5w})
6	Major equipment installation	5 (A_{6w})
7	Commissioning	2 (A_{7w})

based on the finished quantity divided by the total quantity. A_{nw} was the weight of the trade n for CP calculation. The specified values of A_{nw} were listed in Table 5.

(2) The productivity index was calculated based on each construction trade. The formula was: $P_n = Q_n/(T_f - T_s)$. P_n: productivity of trade n; Q_n: total quantity of trade n; T_f: finish time of trade n; and T_s: start time of trade n.

Table 6 showed the actual duration and CP values of the two groups. Group B took 43 min to finish the whole construction works while Group A took 31 min, which meant 28% of the project duration was reduced. At the end of the second 10 minutes, the CP of Group A was 63%; however, the value for Group B was only 47%. The main underlying reason was related to the long lead constraints. Group B spent more time to wait for the constraints to be removed because of the late implementation of the constraint analysis.

Table 7 illustrated the number of the defective modules and productivity index of the two groups. The measurement of the defective module was based on a comparison between as-built and as-designed modules. If the difference(s) was found in a module which would be treated as a defective module, Figure 6(c) showed a defective module built by Group B which was in line with the original design (as shown in Figure 6(a)), and not the latest design (as shown in Figure 6(b)). The correct module was showed in Figure 6(d). The defective modules were significantly reduced in Group A when compared with Group B. The reason was that Group A could effectively reduce the impact of the design changes with TCM implementation. The values of productivity index of Group A were higher than Group B except commissioning because the commissioning was the last work of the simulation game, and the value of the productivity was only dependent on the operation proficiency. Productivity was dramatically improved in the works of off-site module manufacturing, module installation and major equipment installation because the workflow in Group A was more stable than Group B.

These results may present some normal degree of error and bias attributable to a number of reasons (Gonzalez *et al.*, 2015). Firstly, the nature of the simulation game revolves around human participation; some error may occur when measuring the performance metrics during each round. Various playing attitudes (i.e. positive and negative) or motivations can interfere with the accuracy of results. Secondly, there are biases between the two groups. Although participants were randomly allocated to groups, there is a chance of

Table 6 Actual duration and CP of the two groups

Groups	Actual duration (minutes)	CP at the end of the first 10 minutes (%)	CP at the end of the second 10 minutes (%)	CP at the end of the third 10 minutes (%)	CP at the end of the forth 10 minutes (%)	CP at the end of the fifth 10 minutes (%)
Group A	31	21	63	95	100	–
Group B	43	16	47	71	92	100

Table 7 The number of the defective modules and productivity index of the two groups

Construction trades	Defective modules		Productivity (unit/min)	
	Group A	Group B	Group A	Group B
Site preparation	0	1	1.315	1.214
Off-site module manufacturing	0	5	1.307	0.662
Module installation	0	3	4.348	1.887
Pipework installation	0	0	1.603	1.216
Wiring installation	0	0	2.384	2.096
Major equipment installation	0	1	0.352	0.263
Commissioning	0	0	15.625	15.214

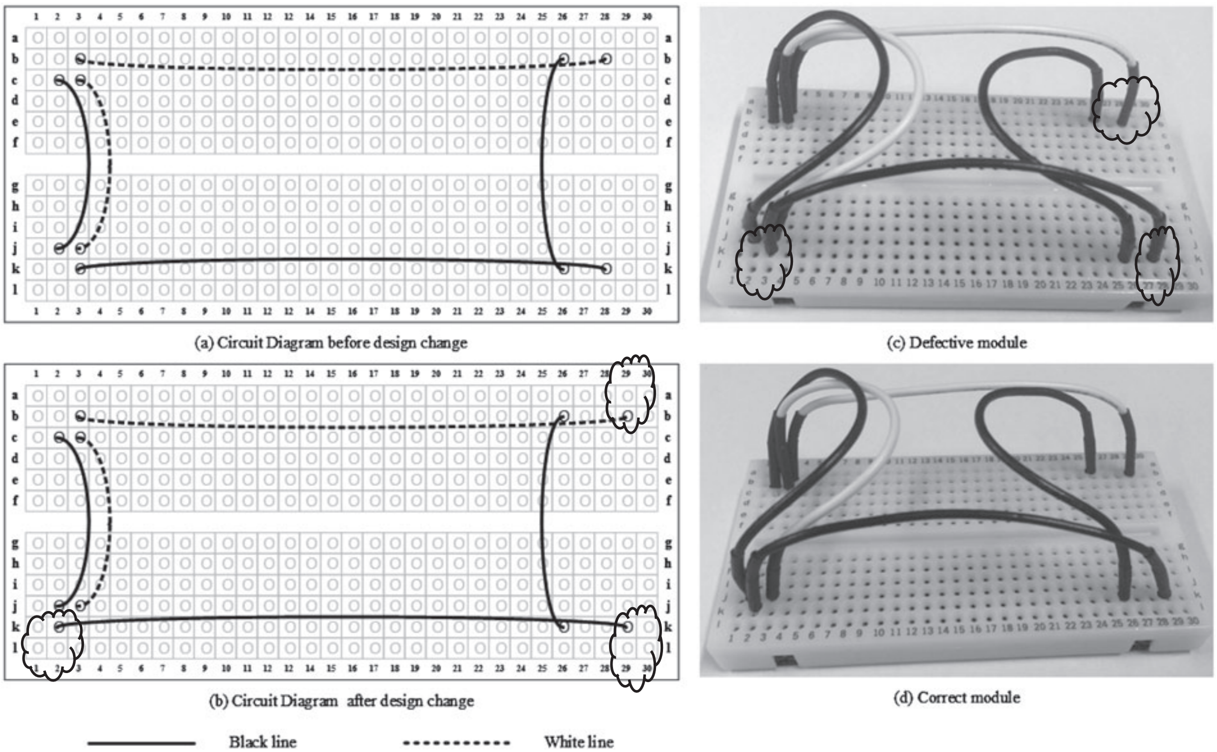


Figure 6 An example of defective module

uneven prior knowledge or learning ability. Enhanced prior knowledge would cause the simulation game to be easier for those people than completely new players. Finally, it is likely there is a learning curve effect for the two groups, which could impact the observed improvement. In general, the authors argue that some errors and biases may be present; however, the results still can validate the benefits of TCM implementation in LNG construction.

Conclusions and future work

The main contributions of the proposed TCM framework to the body of knowledge are twofold: (1) enhancing the role of constraint management within pull planning methods (i.e. AWP and LPS) and extending its contribution to workflow reliability. Traditionally, shielding assignments are the main approach to improving workflow. The action of constraint removal in this context is passive and always is late implemented. In this paper, it is assumed that the best way to improve workflow reliability is not only to shield assignments, but also to remove the constraints on time. In order to actively perform constraint removal, the proposed TCM framework consists of a completed process for constraint life cycle management from identification to removal. Constraint modelling module provides a global view of constraint relationships and interconnections, which is useful for identifying key constraints and calculating delay impact of each constraint; constraint monitoring includes a small cycle of constraint tracking, status updating and checking and action. It is key to realize the concept of 'Active' constraint management. Delay impact can be assessed in an early stage which leaves enough time for project teams to catch up; and (2) extending the process of constraint management beyond the look-ahead phase in a more structural and formal way. Due to the increased complexity and long duration of LNG construction projects, this paper proposes a hierarchical constraint management method across different project stages. Three loops of constraint management from CWA, CWP and IWP-centred perspectives, respectively, have been developed within the TCM framework, which are aligned with project progressing from initial planning stage to completion.

Results from the simulation game indicate a positive effect of facilitations when implementing the framework of TCM in LNG construction. Twenty eight% of project duration was reduced while no defective modules were found during TCM implementation. Productivity was also improved, especially in the works of off-site module manufacturing and module installation which increased by around two times. Information technologies were discussed to facilitate TCM implementation in practice because of the increased complexity of real LNG projects. BIM was proposed as a collaborative platform for the project team to share their knowledge and experience to improve the overall performance of constraint modelling including integrity and consistency. Tracking technologies such as barcoding, RFID and GPS were recommended to automatically monitor the status of supply chain and site constraints like materials, equipment and workers. Sensing technologies (i.e. photogrammetry and laser scanning) were introduced to automatically or semi-automatically monitor the status of site constraints like limited work space, uncompleted predecessor work and construction defects.

The size of the lean game is relatively small, and the duration is only within one hour. Although the observed improvement is clear, further validation should be conducted to draw more definitive conclusions as to this scale of improvement. Potential research includes engaging LNG industry experts to play the lean game and measuring their performance, and conducting several field tests to evaluate the improvement of TCM implementation. Field test is a validation method that brings proposals into the 'real world' to assess performance. When compared with a laboratory test, field test requires not only an upgrading of prototype design, in order to facilitate operation by field personnel, but also a thorough understanding of field practice. This way improvements in workflow and productivity with TCM can then be measured and quantified in a real project context. In addition, another three experiments will be developed to measure the performance of BIM for constraint modelling, integration of barcode, RFID and GPS for supply chain constraint tracking and laser scanning and photogrammetry integration for site constraint tracking, respectively.

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