AN INVESTIGATION OF CRITICAL CHAIN AND LEAN PROJECT SCHEDULING

Lijun Shen[1] and David K.H. Chua[2]

ABSTRACT

Critical chain and lean construction are two inspiring initiatives aiming at dramatically improving project performance through attacking the traditional management methods. The critical chain approach advocates improving throughputs to shorten task duration estimates and deploys various schedule buffers (i.e., project, feeding, resource, and capacity) to protect the project due date. The lean construction principles emphasize on eliminating waste by reducing non-value adding activities and managing hidden flows to improve the reliability of planning and production control. This paper investigates both practices and suggests that it is feasible, and necessary, to balance between aggressiveness (critical chain) and reliability (lean). A combination of critical chain and lean principles may provide benefits of both perspectives, with which critical chain is employed at relatively higher level to set up aggressive goals on task durations and deliveries of prerequisites, while lean works at low level to minimize the impact of flow uncertainties. An illustrative case study is provided to depict the effect of planning and control applying both the critical chain and the lean approaches.

KEY WORDS

critical chain, lean construction, constraint, reliable plan, buffer management

INTRODUCTION

Critical chain (CC) method is a relatively new application of Goldratt's Theory of Constraints (TOC) on project management (Goldratt 1990; Goldratt et al 1993; Herman 2000; Kuo et al 2008; Rand 2000). It adopts a unique technique to enhance both speed and reliability of project delivery through attacking several psychological problems commonly found in project and business practices, e.g., Student Syndrome (starting a task at the latest possible moment before a deadline, which waste any buffers built into individual task duration estimates), Parkinson's Law (work expands to fill the time available for its completion, which loses the opportunity to finish a task earlier to absorb delays in other processes), and multi-tasking (shifting back and forth among multiple projects, which effectively multiplies project lead times). According to CC, the built-in safety times in the traditional task duration estimates are generally wasted and often failed to protect project end date. They should be removed and replaced with a global buffer mechanism deployed at

[1] Research Fellow, Dept. of Civil Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260, (65) 68744643, FAX (65) 67791635, cveslj@nus.edu.sg

[2] Associate Professor, Dept. of Civil Engrg., National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260, (65) 68742195, FAX (65) 67791635, cvedavid@nus.edu.sg

strategic points to protect critical tasks and non-critical task that feed them. The revised schedule turns out considerably aggressive but still feasible. This method has been widely spread due to the reason that it is 'simple' to achieve 20~30% potential improvement just by re-distributing the buffers. However, it is necessary to have a clear understanding on the uncertainties and risks involved, which are crucial for scheduling and buffer management.

In this paper, we compare critical chain with lean project management, in particular, the Last Planner methodology, and suggest an enhancement that incorporates critical chain (at high level) with lean (at low level) to seek a balance between aggressiveness and reliability. First, the process of critical chain method is elaborated and several issues that may impede the implementation are discussed. Second, the lean construction principles are depicted and a comparison between critical chain and lean is made. Third, an enhanced model that adopts the best of both methods is proposed. We also recommend an additional performance index called Percent Plan Impacted (PPI), besides the Percent Plan Completed (PPC), for measuring plan reliability. An illustrative example, based on a computerized simulation model, is shown to demonstrate the effect of critical chain scheduling and the impact of uncertainties on project performance.

THE CRITICAL CHAIN METHOD

The Critical Chain scheduling begins with removing hidden safety to obtain new task duration estimates. How much amount to be reduced is, however, difficult to be quantified due to the diversity of management experience, skills, and confidence varying from one project to another. There are two basic approaches available for use. One is the Cut and Paste Method (C&PM), with which a fixed percentage cut is made on every task. The other is Root Square Error Method (RSEM), which uses two estimates (i.e., the safe estimate and the average estimate) for each task to determine buffer sizing (Tukel 2006). C&PM, due to its simplicity, has been extensively adopted in the current practice. The following is a brief summary of the process of critical chain scheduling based on C&PM:

Step 1: Reduce task duration estimates by 50% (common practice), while expecting the probability of exceeding the target duration to be increased. As the safety margins are greatly reduced, the project teams are required to work at full speed and use system buffers to alleviate the impact of task delays.

Step 2: Calculate project schedule backwards in time to obtain a late start schedule from the target end date. The late start schedule provides many benefits, such as minimizing work-in-progress, deferring actual cost until necessary, focusing on critical tasks first, and improving work efficiency and quality attributed to the early learning process (Scitor Corporation, 2000). A downside of late start schedule is that the entire network becomes critical. However, this problem can be solved by adding system buffers as depicted later.

Step 3: Adjust the project network by moving some tasks earlier in time to resolve any resource constraints and eliminate multi-tasking.

Step 4: Identify the critical chain as the longest path doubly constrained by task precedence relationships and resource dependencies.

Step 5: Insert buffers into project network, including (1) a Project Buffer (PB) at the end of the critical chain to protect project end date. The size of PB is set at 50% of project duration, equivalent to 50% of total reduced safety time; (2) any number of feeding buffers (FB) at points where non-critical tasks intersect with the critical chain. The size of FB is set at 50% of length of time of the feeding chain; (3) any number of capacity buffers to shield the usage of key resources from being interrupted in multi-project environment; and (4) any number of resource buffers to prevent delay of task schedule due to resource unavailability problem.

Step 6: Start the project and track project progress but do not set milestones. Once commenced, a task is required to be finished as soon as possible.

Step 7: Monitor the consumption of various buffers, especially the PB, and expedite tasks, when necessary, to reduce the impact of delays on the buffers.

No doubt the critical chain method provides an insightful solution attacking some very obscure problems related to human behavior (the student syndrome and the Parkinson's Law). However, several issues must be noted, ignoring which may impede the success of its implementation. First, it is not likely to obtain optimal sizing for tasks and buffers with a fixed percentage cut on task durations. The C&PM is over simplified and should only be used for illustrative purpose. In real-life project environment, a 50% cut on task duration estimates may be too aggressive for low risk projects (where the designed safety time is low) or research and development projects (where uncertainty is high). Second, there is not sufficient guidance for the practitioners to follow so as to reduce the risk of delays. It is certainly not easy to adopt a very different mentality from scratch, such as surrendering individual safety time and working on a late start schedule. Third, although the buffer management provides an overall picture about the impact of uncertainties, it does not adequately offer a localized view within a smaller scope, e.g., weekly or monthly. It could be helpful if such information is provided as an addition. Fourth, the critical chain method represents a holistic approach that requires a fundamental change of mindset to cope with many subsequent changes at both management and crew levels. This accordingly requires a good means of communication as well as continuous effort to achieve the goals.

In short, we may expect a number of opportunities arising from this refreshing management technique. Meanwhile, improvement can be made to make it more powerful and adaptive.

THE LEAN CONSTRUCTION PRINCIPLES

Lean philosophy (a.k.a. just-in-time manufacturing) represents another set of principles that challenge the paradigm of mass production. The lean thinking has been successfully introduced in construction management since the 1990s. One of the key principles found in lean philosophy is reducing waste. Waste can be found in many forms such as idling and rework. In fact, any process that does not add value to the final product could be deemed as waste. The hidden safety time in a task, for example, is essentially an instance of waste and should be minimized. This indicates a similarity between lean and the TOC, which is the theoretical background for critical chain method, though they are often discussed from different perspectives. Another key principle in lean philosophy is enhancing reliability, which was initially demonstrated by the Toyota pull-driven production system and lately found in the Last Planner system (Ballard and Howell, 1998). The reliability issue in the context of lean generally refers to the robustness of planning and control at production level. In contrast, it is interpreted as the robustness of meeting project end date, in the context of critical chain. This difference, however, can be deemed as an opportunity, rather than a conflict, in designing an enhanced approach that inherits the best of both worlds.

The theory of lean thinking significantly expands the vision on the otherwise limited view of construction. According to Koskela (1992 and 2000), the construction processes can be viewed from at least three perspectives: transformation, flow, and value (TFV). The transformation view is a process of converting input (e.g., materials) to output (e.g., products); the flow view represents a stream of resources being transported and processed in a system; the value view focuses on maximizing value-adding activities and minimizing non value-adding activities. The traditional construction paradigm, however, only supports the conversion view; hence it is no surprise that many important flow processes are neglected, which makes it difficulty to improve the overall production performance.

- This problem found in the mass production paradigm may possibly happen in the critical chain management. The hidden safety time designed in the traditional task duration is a form of buffer used to absorb the impact of uncertainties due to task and flow variability. Simply removing the buffers without adopting additional measures to shield the tasks from uncertainties may be disastrous to the production plan. It is generally impossible for the crew to envisage and eliminate such disruptive impediments, as it is beyond the scope of task management. We need to supply the project manager a systematic tool and a set of disciplines for analyzing the hidden flows and taking preemptive actions to solve any potential problems in advance. The Last Planner is one of such systems demonstrating five lean design criteria (Koslela 1999).

- The first principle is that the assignments should be sound regarding their prerequisites. This principle pursues the minimization of work in suboptimal conditions.

- The second principle is that the realization of assignments is measured and monitored. This focus on plan realization diminishes the risk of variability propagation to downstream flows and tasks.

- The third principle dictates that causes for non-realization are investigated and those causes are removed. Thus, in fact, continuous, in-process improvement is realized.

- The fourth principle suggests maintaining a buffer of tasks which are sound for each crew. This principle is instrumental in avoiding lost production (due to starving) or reduced productivity (due to suboptimal conditions).
- The fifth principle suggests that in look-ahead planning (with time horizon of 3-4 weeks), the prerequisites of upcoming assignments are actively made ready. This, in fact, is a pull system (Ballard 1999) that is instrumental in ensuring that all the prerequisites are available for the assignments.

It can be seen that these design criteria for lean production control system may be complementary to the critical chain implementation because they provide detailed principles in handling assignments, flows and constraints to minimize the impact of uncertainties. As a matter of fact, higher reliability could improve schedule estimates and increase the chance of fulfilling target dates. On the other hand, the holistic and aggressive means of critical chain scheduling and buffer management could help reduce system constraints that are difficult to be solved technically. The synergy between TOC and lean can certainly facilitate delivering improved system approaches (Moore and Scheinkopf, 1998).

INTEGRATION OF LEAN PRINCIPLES IN CRITICAL CHAIN SCHEDULING

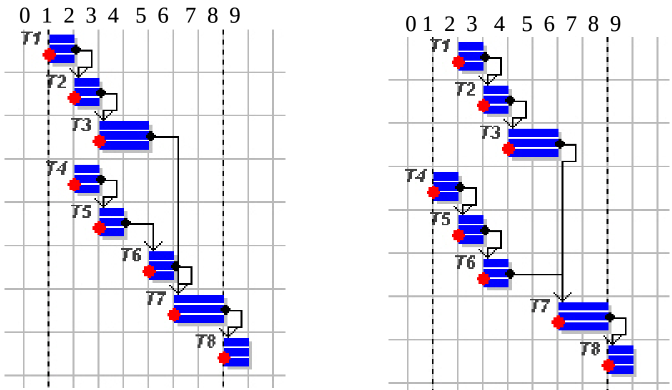
With the above analysis, we suggest a modification on the generic critical chain approach by incorporating the lean principles. The revised process is depicted as follows:

Step 1: Estimate task durations applying both critical chain and lean principles. Instead of cutting 50% fixed percentage, the reduction should account for the soundness of assignments and the matching of SHOULD to CAN. This is to prevent massive re-scheduling due to unshielded schedule.

Steps 2~5: Remain unchanged.

Step 6: Start the project and track project progress but do not set milestones. Once commenced, a task is required to be finished as soon as possible. Meanwhile, constraints that possibly impede work continuity should be identified and notified in weekly meetings.

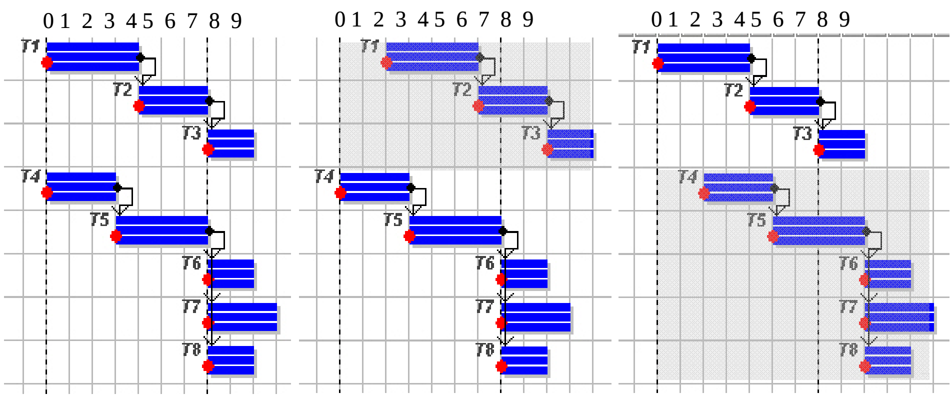
Step 7: Monitor the consumption of various buffers, especially the PB, and expedite tasks, when necessary, to reduce the impact of delays. The reliability of work plan is measured as Percent Plan Complete (PPC), which is the number of planned activities completed, divided by the total number of planned activities, and expressed as a percentage. However, PPC is essentially an after-the-effect evaluation and may fail in circumstances illustrated in Figs 1 and 2. In Figure 1(b), there is a schedule change of paths T1-T2-T3 and T4-T5-T6. Although the PPC remains unaffected between Fig 1(a) and 1(b), 6 tasks as well as the supporting resources have to be re-scheduled. In Fig 2(a), delaying T1 or T4 results in the same PPC (3 out of 4 tasks are completed so the PPC is 75%) but a different impact on the downstream. Delaying T1 only causes 3 tasks to be rescheduled (Figure 2(b)) while delaying T4 causes 5 tasks to be re-scheduled (Figure 2(c)). As a result, we propose another metrics called Percent Plan Impact (PPI) as an additional measure for plan reliability. Similar to PPC, PPI is the number of impacted activities, divided by the total number of planned activities, and expressed as a percentage. The PPI is capable of providing instant feedback on schedule changes. This would greatly help the project manager to compare various options in determining the most suitable plan.



(a) Original plan

(b) PPC and productivity remain same but 6 tasks are re-scheduled

Figure 1: PPC and productivity are same, but 6 out of 7 tasks are rescheduled in (b)



(a) Original plan assuming 6 working days

(b) PPC = 75% and 3 tasks are re-scheduled

(c) PPC = 75% but 5 tasks are re-scheduled

Figure 2: PPC are same, but PPI in (b) and (c) are different

CASE STUDY

A simulation model based on the Integrated Production scheduler (Chua and Shen, 2003 and 2005; Shen and Chua, 2005) is used to demonstrate the effect of critical chain scheduling. It is assumed that two types of variables exist in the schedule, one is task duration and the other is the delivery time of prerequisite. At the beginning of every week, work assignments and deliveries of prerequisites are scheduled. After executing the assignments, the schedule will be updated and a new assignment plan is made for the next week. This process will be repeated until the project is completed. After 1000 cycles for each simulation case, statistic data on project duration, PPC, and PPI will be generated.

The case study consists of 23 tasks, 15 in the critical chain and the rest 8 are equally split into 4 feeding chains. The original task durations (with hidden safety time) are estimated at 2 days each. The probability data of task duration and delivery time are shown in Table 1. ***a***, ***b***, and ***c*** stand for optimistic, most-likely, and pessimistic durations or delays of prerequisite, respectively. There are a total of three cases. Case 1 represents a traditional production system which falls into the pit of Parkinson's Law (work expands to fill the estimated 2 days). The mean and standard deviation are calculated using PERT (assuming a beta probability distribution). Meanwhile, three sub-cases are created. '*A*' stands for an ideal situation where no delay of prerequisite will happen; '*B*' stands for a relatively reliable system where the deliveries are generally on time (μ_P equals to 0) but subject to uncertainties (early or late by maximum 1 day); '*C*' stands for a worse scenario where deliveries are always delayed (μ_P equals to 1 day) and subject to uncertainties (early or late by maximum 1 day). Case 2 represents a critical chain schedule with medium-aggressive duration estimates. The most-likely durations is shorter (1.5 days); while the pessimistic and optimistic durations remain unchanged. The project buffer B_{PB} is 7.5 days (30-1.5x15=7.5days) and the feeding buffer B_{FB} is 1.5 days each (half the size of feeding chain). Similarly, case 3 represents another critical chain schedule with high-aggressive duration estimates (a 50% cut on the most-likely duration to 1 day). The B_{PB} is 15 days (30-1x15=15days) and the B_{FB} is 1 day each.

Table 1: Probability data of task duration and uncertainty of prerequisite

Simulation Case	Variation of Task Duration					Variation of Prerequisites		
	a, c, b (day)	μ_T	σ_T	B_{PB} (day)	B_{FB} (day)	*a, c , b*	μ_P	σ_P
Baseline CPM	2	2	0			0	0	0
Case 1A	0.75, 2, 2.25	1.833	0.204	0	0	0, 0, 0	0	0
Case 1B						-1, 0, 1	0	0.236
Case 1C						0, 1, 2	1	0.236
Case 2A	0.75, 1.5, 2.25	1.5	0.204	7.5	1.5	0, 0, 0	0	0
Case 2B						-1, 0, 1	0	0.236
Case 2C						0, 1, 2	1	0.236
Case 3A	0.75, 1, 2.25	1.167	0.204	15	1	0, 0, 0	0	0
Case 3B						-1, 0, 1	0	0.236
Case 3C						0, 1, 2	1	0.236

PROJECT DURATION

The simulation results are shown in Table 2 and Fig 3. Here are some findings. First, case 1 (the traditional instance) shows a consistent time overrun (+1.1%, +3.6%, and +18.2% in case 1A, 1B, and 1C, respectively), while Cases 2 and 3 (the critical chain instances) both achieve shorter project durations (-20.7%, -18.5%, and -6.0% in case 2A, 2B, and 2C; -39.6%, -38.1%, and -28.8% in case 3A, 3B, and 3C), even though they all have the same optimistic and pessimistic duration estimates. Second, if everything else is the same, the higher aggressiveness of task duration, the shorter project duration can be achieved. This clearly demonstrates the effect of critical chain scheduling. Third, within the same case, the higher variability of prerequisite availabilities, the longer project duration is found. For example, 2B (with uncertainties of prerequisites) results in longer mean project duration, 24.45 days, comparing with that of 2A (no uncertainties), 23.80 days. Meanwhile, delays of prerequisites would lead to a considerable increase of project duration, e.g., from 24.45 days in case 2B (low risks of delay) to 28.20 days in case 2C (high risk of delay). This indicates that it is important to minimize uncertainties, no matter what method is used. Note that we assumed an ideal situation where a task could start as soon as its predecessors are finished and the prerequisites are delivered. In reality, such delays may cause disruptive consequence on the downstream schedules, which further increase the project duration. Fourth, delays and uncertainties of prerequisite availabilities would drive up the variability of project duration, denoted by the standard deviation σ_D.

Table 2: Effect of variability on project duration

Simulation Case	**Project Duration**			
	Mean μ_D **(Day)**	**Increase** $(\mu_D - \mu_{D0}) / \mu_{D0}$	**Standard deviation** σ_D **(Day)**	**Coefficient of variation** v_D
Baseline CPM	30	0	0	0
Case 1A	30.33	+1.1%	0.18	0.6%
Case 1B	31.08	+3.6%	0.37	1.2%
Case 1C	35.46	+18.2%	0.83	2.3%
Case 2A	23.80	-20.7%	0.59	2.5%
Case 2B	24.45	-18.5%	0.69	2.8%
Case 2C	28.20	-6.0%	0.94	3.3%
Case 3A	18.11	-39.6%	0.87	4.8%
Case 3B	18.56	-38.1%	0.88	4.7%
Case 3C	21.36	-28.8%	1.17	5.5%

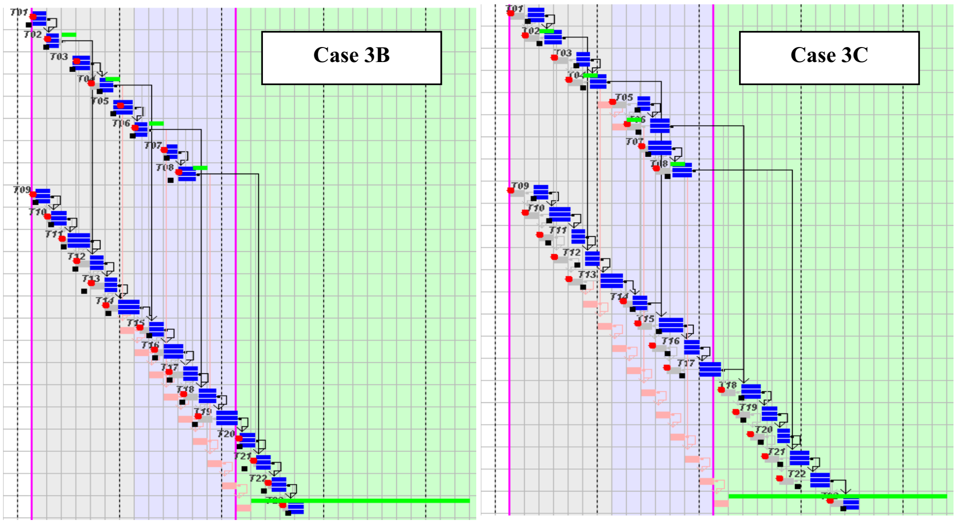


Figure 3: Sample simulation cycles taken from Case 3B (left) and Case 3C (right)

Percent Plan Complete (PPC) and Percent Plan Impacted (PPI)

Table 3 shows the results of PPC and PPI as two independent measures of plan reliability. Each PPC value is obtained by calculating the average of first three weeks. PPI has two values: one is for the current working week, and the other is for the coming next week. In this case study, we calculate PPI by only accounting for schedule changes that are more than 1 day.

Findings describe that, first, within the same case, the uncertainties of prerequisite availabilities reduce PPC (comparing 1B with 1A, 2B with 2A, and 3B with 3A). Meanwhile, delays of prerequisite deliveries reduce PPC (comparing 1C with 1B, 2C with 2B, and 3C with 3B). This indicates that flow variability has a notable negative effect on plan reliability. Second, the uncertainties of prerequisite deliveries increase PPI in the current working week, e.g., from 19.0% in case 3A to 33.3% in case 3B. Meanwhile, delays of prerequisites (average 1 day) cause a greater impact on PPI, e.g., from 33.3% in case 3B to 85.3% in case 3C. Third, same as the last finding, delays and uncertainties of flow variability significantly increase PPI in the next week schedule. Generally speaking, the impact of flow variability can be more visible in PPI than that of PPC.

Table 3: Effect of variability on PPI and PPC in the weekly plan

Case	PPC	PPI (>1 day) in Working Week	PPI (>1 day) in Next Week
Case 1A	92.0%	0	0
Case 1B	86.7%	11.7%	22.0%
Case 1C	69.0%	80.3%	98.7%
Case 2A	85.0%	5.3%	19.7%
Case 2B	82.7%	18.7%	47.3%
Case 2C	69.7%	78.7%	99.3%
Case 3A	88.7%	19.0%	74.0%
Case 3B	87.3%	33.3%	83.5%
Case 3C	78.0%	85.3%	99.5%

To sum up, the above findings indicate that critical chain method, when successfully implemented, may significantly shorten project duration. On the other hand, delays and uncertainties of prerequisite availabilities will negatively affect project performance, in terms of increased project duration, increased PPI, and reduced PPC.

CONCLUSIONS

In this paper, we investigated the critical chain scheduling method and the lean principles, and suggested adopt both practices to take advantage of the aggressiveness in critical chain and the reliability in lean. We also employed a probability simulation model called Integrated Production Schedule to demonstrate the effect of critical chain scheduling in a Last Planner alike production control system. The results show that critical chain approach can greatly improve project performance, in terms of shorter project duration. Meanwhile, it is also important to minimize delays and uncertainties, which would help reduce project duration, reduce Percent Plan Impacted (PPI), and increase Percent Plan Complete (PPC).

REFERENCE

Ballard G, and Howell G (1998). “Shielding production: essential step in production control.” Journal of Construction Engineering and Mgmt, ASCE, 124(1), 11-17.

Chua, K. H. D., Shen, L. J., and Bok, S. H. (2003). “Constraint-based planning with Integrated Production Scheduler over Internet.” Journal of Construction Eng. and Mgmt. 129(3), 293-301.

Chua, KHD and Shen LJ (2005). “Key constraint analysis with Integrated Production Scheduler.” Journal of Construction Engineering and Management, July issue.

Goldratt EM (1990). What is this thing called the theory of constraints? NY: The North River Press, 1990.

Goldratt EM (1993), Cox J. The goal, 2nd ed. Aldershot, England: Gower, 1993.

Herman S (2000). “An investigation into the fundamentals of critical chain project scheduling.” International Journal of Project Management, 19(6):363–9.

Koskela L (1992). “Application of the new production philosophy to construction.” Tech Report No. 72, Center for Integrated Facility Engineering, Dept. Of Civil Engineering, Stanford University, CA.

Koskela L (1999). Management of Production in Construction: A Theoretical View. Proceedings of 7th Annual IGLC Conference, University of California, Berkeley.

Koskela L (2000). An exploration towards a Production Theory and its Application to Construction. VTT Technical Research Center of Finland.

Kuo TC, Chang SH, and Huang SN (2008). Due-date performance improvement using TOC’s aggregated time buffer method at a wafer fabrication factory. Expert Systems with Applications, doi:10.1016/j.eswa.2007.12.038

Moore, R., Scheinkopf, L. (1998), “Theory of constraints and lean manufacturing: friends or foes?” http://www.tocca.com.au/uploaded/documents/Lean%20and%20TOC.pdf

Rand GK (2000). Critical chain: the theory of constraints applied to project management. International Journal of Project Management 18 (2000) 173-177

Scitor Corporation (2000). Critical Chain Concepts. Available online at: http://www.civiles.org/publi/Gestion/Critical-Chain-Concepts.pdf

Shen, LJ, and Chua KHD (2005). "Key Constraint Analysis: Achieving Lean Processes with the Application of TOC." *Construction Research Congress 2005*, April 5-7, San Diego, CA.

Tukel OI, ROM WO, and Eksioglu SD (2006). An investigation of buffer sizing techniques in critical chain scheduling. European Journal of Operational Research 172, 401–416.