A Framework of Critical Resource Chain in Project Scheduling

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Abstract

To analyze a schedule is beneficial to understand and organize a project. Project schedules, in which time plans are created based on the Critical Path Method (CPM) or on Resource-Constrained Project Scheduling Problem (RCPSP) optimization, are targets herein. According to the concepts of the Theory of Constraints (TOC), a schedule is treated as a system. Schedule elements are suspected constraints. Moreover, a goal depends on the policy of schedule creation. Schedules are further analyzed herein to recognize its bottlenecks. Additionally, resource information is surveyed to identify true constraints. To integrate identified constraints on a schedule, a framework is proposed and the concept named the critical resource chain is introduced. Three scenarios are employed to illustrate the proposed framework under different scheduling considerations. Issues of project understanding can then be explained and discussed through identified constraints.

1. Introduction

A schedule guides a project, and it is also an index of project performance. In order to create schedules, the Critical Path Method (CPM), which is a scheduling method familiar to most project planners, is employed. According to the concepts of CPM, schedules are created by arranging activities and identifying at least one Critical Path (CP). As an extension of CPM, the Resource-Constrained Project Scheduling Problem (RCPSP) which states that schedules are created under resource limitations has been investigated for years. Whether using CPM or RCPSP, optimization operations have been applied to solve scheduling problems. Thus, optimized schedules are possible to lead projects.

Although a schedule offers a sketch of a project with activities, activity information can not totally satisfy the requirements for project understanding. Further investigation on schedules is required. Thus, this study examines resource information, which is schedule elements other than activities, using the Theory of Constraints (TOC). Resource related constraints can be recognized, and resource importance can then be explained. Moreover, Issues of project understanding can be further discussed.

2. Theories

Necessary concepts of TOC and RCPSP optimization are reintroduced to support and lead to the proposed method.

2.1 TOC and critical chain

The theory of constraints (TOC), which was proposed by (Goldratt, 1984), is a problem analysis tool. Based on the concepts of TOC, problems can be analyzed in terms of three basic fundamentals: system, goal, and constraint(s). In order to refine a system, a goal must be set, and constraint(s) must be found. The entire analysis process of TOC can be defined as follow: 1. Identify constraint(s); 2. Decide how to exploit the constraint(s); 3. Subordinate everything else to the above decision; 4. Elevate the constraint(s); 5. If in any of the previous steps a constraint is broken, go back to step 1. Briefly, TOC analysis is a process of system refining by removing constraint(s) based on a set goal. Moreover, constraint identification is the key foundation to support the five-step analysis process.

CPM based schedules can certainly be analyzed by the concepts of TOC. According to CPM rules, schedules are built from activities, activity durations, and relationships between activities. These elements are considered as bases to create a schedule "system," and some of them may be "constraint(s)" withal. The "goal" of such a schedule system is minimized overall schedule duration because of a CP in which a group of activities are connected to organize an "irreducible" total activity duration. Constraints of schedules are clearly implied in CP activities. In order to apply TOC in project management, critical chain (CC) and buffer management are proposed.

CC is the CP where schedules are created with consideration of resource insufficiency. For example, if a mutual resource is required by several activities at the same time, some of these activities may be postponed till the resource is available again. Such a resource insufficiency results in adding finish-to-start activity relationships among activities. These activity relationships are named resource dependencies in TOC. Furthermore, the CP is renamed CC when at least one resource dependency occurs in the CP. In other words, resource dependency is considered a constraint if the term CC is adopted.

Buffer management is applied to risk issues. An activity buffer is identified as an extension of activity duration considering overall risk evaluation of an activity. As TOC proposed, activity buffers that belong to identical activity paths are integrated in a path buffer, and this path buffer is located at the end of a path. Furthermore, project buffer and feeding buffer are two types of path buffer that are introduced in TOC. A project buffer is the buffer of CP (CC), and feeding buffers which belong to non-CP (CC) paths. Moreover, buffers also indicate the degree of risk being considered in a schedule. As an example of project buffer, risks are ignored in a project if no project buffer exists. A long project buffer implies that risks are possible and there is concern they may cause delays in the overall schedule duration.

Schedules considering TOC should be created using exact activity durations, and risk issues ought to be integrated in buffers. However, several questions are not answered in TOC: how can planners create schedules given resource insufficiency and how to validate a resource dependency are not specified.

2.2 RCPSP optimization

RCPSP optimization offers solutions to the above questions. RCPSP optimization has been widely discussed and identified for project scheduling issues. (Herroelen, 1998) and (Brucker, 1999) collected and classified RCPSPs and proposed optimization models. RCPSPs inherit most CPM rules but not resource assumptions. First, resource limitations are concerned in RCPSPs. Activities may be postponed when a resource insufficiency occurs. Second, various productivity options are usually allowed for each activity. Each productivity option corresponds with a combination of resource usage to present related activity duration. A productivity option for each activity must be determined to create a schedule. Finally, RCPSP allows restrictions other than schedule elements if they are required. Thus, RCPSPs are more complex than CPM scheduling problems. In order to solve RCPSPs, optimization operations have been well investigated. Optimization operations are not further explicated herein since the reader can refer to references mentioned before.

Comparing RCPSP optimization with CPM scheduling, resource importance is concerned. Resources are more effective than activities for producing schedules. Though activities are still elements of schedules, activities cannot dominate an entire schedule as they do in CPM, such that activities are assumed to drive resources. Not only does resource availability affect start time of activities, but productivity options determine for how long an activity will be performed. Therefore, any unit of resource may influence an entire schedule.

Schedules based on RCPSP optimization can be foundations for TOC analysis. RCPSP optimization and TOC have many characteristics in common. When RCPSP optimization creates a schedule with an objective function, an equal goal exists in TOC. Furthermore, RCPSP optimization is also a schedule improvement process to approach perfect scheduling. Dominated schedules are screened out during optimization. Once an optimal solution is found, the refined schedule is assured. Thus, identification of constraints can be performed based on the secure five-step of TOC schedule.

Buffer management is adopted for all schedules in this study for risk issues. First, schedule elements can be estimated accurately in RCPSP optimization and CPM scheduling for exact schedules. Constraints can then be defined accordingly. Next, the length of a buffer can represent the overall evaluation of both risk possibility and effect as duration extension. Furthermore, project buffer and feeding buffers further integrate individual activity buffers. A project buffer and feeding buffers can offer an overview of the risk issues facing a project. In order to clearly define feeding buffer and project buffer in this study, float time of non CP (CC) as defined as in CPM and is integrated in feeding buffers. Moreover, a project buffer is equal to the project duration minus the overall schedule duration if contractual project duration exists.

To refine a schedule through the five-step TOC analysis, what are constraints is still the key question. Based on the concepts of CPM, CP (CC) activities imply constraints on a schedule. According to RCPSP optimization, activities and resources interact. Thus, resource information is required to recognize constraints.

3. Method

3.1 Constraint Identification

In order to recognize constraints for an optimized schedule, the minimized project duration is assumed as the goal used to identify constraints. Optimization is employed to schedule creation of both a CPM schedule problem and RCPSP to ensure secure schedules. Based on these assumptions, constraint identification can be discussed as follows:

1. Resource Limitation and Critical Resource

Resource limitation is a clue to constraints. Resource limitation can cause resource insufficiency and further constraints of resource dependency. However, resource dependency constraints have resulted in translation from CP to CC, and they cannot further contribute to TOC analysis. Thus, the reason for resource insufficiency, resource limitation, needs to be surveyed. By drawing resource diagrams of a created schedule, it can be investigated whether resource limitations can be labeled constraints whenever resource usage reaches resource limitation. Especially, these resources are employed by CC activities at that moment. If additional resources are considered, the schedule may have a chance to be refined. Therefore, resource limitation at that moment is considered as a suspected constraint. Moreover, Max usage of resources plays a role similar to resource limitation. Although CPM schedules assume unlimited resources, an oversupplied resource does not worth anything to a project, and the max usage of a resource has a high probability of being the final resource quantity of a project when performing schedules. Thus, Resource limitation and max usage are two criteria to identify suspected constraints herein.

Whenever a suspected constraint of resource limitation is recognized, this resource is identified as a critical resource. In order to differentiate suspected constraints, information on a critical resource contains when the constraint occurs, what is the corresponding resource, and information on resource limitation or max usage. Furthermore, although CP (CC) activities can extend through the entire schedule, not all resources are employed by CP (CC) activities. In other words, some critical resources are not constraints. Thus, critical resources need to be further defined as follows: Whenever a resource is totally occupied by CP (CC) activities, the term of superior critical resource is adopted. On the contrary, the term inferior critical resource is adopted whenever a resource is used up regardless of CP (CC) activities. The definitions of all types of critical resource are shown as Figure 1. Based on these definitions, superior critical resources must be constraints.

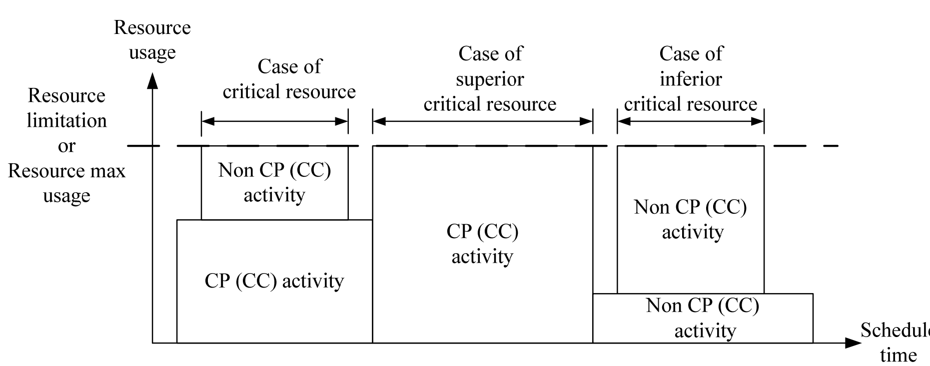

Figure 1. Sample of critical resource identification

2. Productivity Constraints

CP (CC) activities imply constraints. Although CP (CC) activities lead to minimized overall schedule duration, projects are not restrained by activity durations of CP (CC) activities but by productivity options. If a productivity option with a short corresponding activity duration is offered for a CP (CC) activity, the overall schedule duration can be directly shortened. Therefore, productivity options that CP (CC) activities adopt are treated as constraints herein. In order to present a productivity option constraint, activity name, corresponding activity duration, and quantity of resource usage are elements to differentiate other options. When an activity is identified as CP (CC) activity, the employed productivity option of the activity must be a constraint.

Productivity options imply additional constraints. It is a foundational assumption of CPM that resources offer a certain productivity for activities. That is why activity durations can be estimated according to resource usage. In other words, whether resources constitute a productivity option or even any individual resource is assumed to perform with steady productivity, they are natural constraints of schedules.

3.2 Critical Resource Chain Framework

A framework is proposed to integrate constraint information as figure 2. The framework is structured with all kinds of critical resources, productivity options for each CP (CC) activity, and project buffers. The concept of critical resource chain is then proposed since such resource related constraint information is shaped as a chain to restrain the entire schedule.

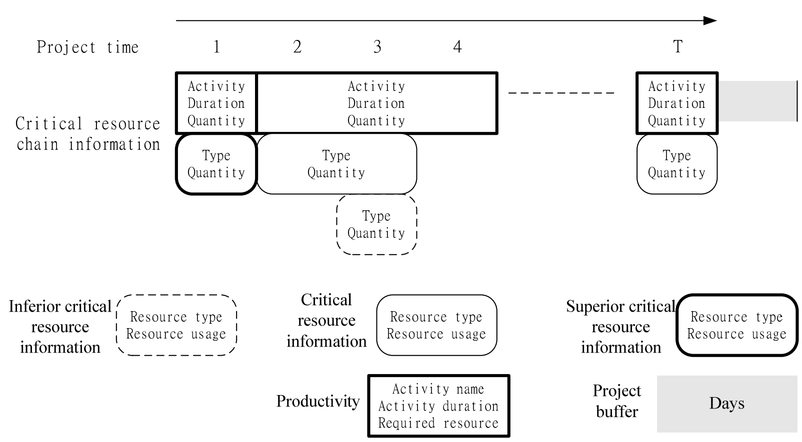

Figure 2. Sample of critical resource chain

3.3 Resource importance

Based on constraint identification as above, resource importance can be further discussed. First of all, a superior critical resource occurs with CP (CC) activities to indicate that a resource limitation directly restrains the schedule. The resource limitation is definitely a constraint on the schedule at that moment. In order to refine the schedule by removing this constraint, additional resources can be helpful. Contrarily, if any shortage occurs such as machine failure, the schedule will be also directly influenced. Thus, the resource that a superior critical resource indicates is a key resource. The required quantity of resource must be satisfied at that moment according to its classification as a superior critical resource. Second, critical resource status indicates the lower level of resource importance than superior critical status. In this case, there are chances to avoid impacts of resource variance by postponing non CP (CC) activities. Finally, inferior critical resource information is regardless of the goal. However, critical resources and inferior critical resources relate to other project management issues.

Resource productivity can also represent resource importance. In order to refine the schedule, considering various productivity options is beneficial. Although a selection of productivity options has been made during optimization, productivity options can be further examined in TOC analysis if a constraint on a productivity option is considered to be broken to refine the optimized schedule. When all resource productivity options of CP (CC) activities are scheduled, resources are crucial to offer their expected productivity with corresponding resource usage. Not only is resource usage of these productivity options required, but variance of productivity offering, especially a low productivity, must be prevented.

4. Scenario experiment

A case experiment is employed to implement the proposed critical resource chain framework. Two scenarios are considered as follows: Scenario 1 is a CPM scheduling problem. The minimized overall schedule duration is set as the goal, and resource limitation is not involved. Moreover, each activity adopts the shortest duration of productivity options to meet the goal. Scenario 2 represents a RCPSP optimization case with the goal as in scenario 1. Additionally, resource limitation is considered, and various productivity duration options are allowed. Comparing scenario 1 with scenario 2, constraint difference between CPM and RCPSP based schedules can be demonstrated. Project information and optimized output of these three scenarios are listed as Table 1.

Resource dependency behaviors can be easily discovered. The activity path A-C-G-H-I is the CP in scenario 1. The order of activities matches activity relationships to successors. The activity relationship A-C demonstrates that activity C is one of the successors of activity A as well as other relationships in CP are. In scenario 2, two activity paths, A-B-C-E-G-H-I and A-D-G-H-I, compose the minimized overall schedule duration: 41 days, and both these two paths can be CP or CC. Several resource dependency cases can be observed. B-C, C-E, E-G and D-G are additional activity relationships that are not set in project information. Thus, the CC is ascertained.

Various productivity options are beneficial and necessary in an RCPSP based schedule. By setting the goal of the minimized overall schedule duration, activities have no reason to adopt productivity options other than the one with the shortest duration. However, activities C, D, F, G, and H in scenario 2 adopt a productivity option other than the shortest one under the same goal. This situation is based on interactions of schedule elements. Nevertheless, the shortest activity duration of productivity options of each CP (CC) activity cannot guarantee the minimized overall schedule duration for sure in the RCPSP based schedule. Another investigation of activity H is significant. Activity H has two productivity options: 2-day case requiring $4,700 and 3-day case requiring $5,250. The 3-day case is dominated by the 2-day case no matter whether activity duration or usage cost is the measure considered. However, it is beneficial in scenario 2 to consider activity H as a CC activity. Restate, various productivity options is required while scheduling.

Critical resource chain frameworks of scenario 1 and 2 are implemented with related resource diagrams as Figure 3. Information of non CP (CC) activities is added above critical resource chain frameworks in order to offer an overview of schedules. Comparing scenario 1 with scenario 2, overall schedule duration is extended, and constraints are massively increased. The CC in scenario 2 contains more activities than CP in scenario 1. Most activities are CC activities except for activity F in scenario 2. Thus, productivity constraints are increased. Additionally, critical resources and, especially, superior critical resources exist everywhere in scenario 1. Contrarily, there is no superior critical resource in scenario 1.

Project planners can meditate on the necessity of considerations to a schedule. The further resource considerations such as resource limitation and productivity options may be required for practical schedules. It can be investigated what happens if the optimized schedule in scenario 2 is tightened: (1) Resources are well utilized; (2) activities are well arranged by considering various productivity options; (3) resource insufficiency can be recognized. However, such a schedule is very sensitive. Any change of schedule elements may affect the whole schedule. Based on the proposed critical resource chain framework, constraints can be recognized. It also can be investigated whether constraints are massively increased from scenario 1 to scenario 2. The sensitive schedule must be kept by observing constraints while performing the schedule. To remind what and where constraints are can be important to schedule performers. Nevertheless, the more considerations when scheduling, the more constraints may be incurred to keep sensitive schedules. The proposed framework is feasible to differentiate constraints for project planners and performers.

Table 1. Project information

Input			
Project indirect cost	$ 1000 / day		
	R1	R2	R3
Daily limit	13 units	10 units	1 units
Cost / unit	$ 200 / day	$ 250 / day	$ 300 / day

Project information						Output: Scenario 1		Output: Scenario 2	
Act.	Successor(s)	Dur.	R1	R2	R3	Start	CP	Start	CC
A	B、C、D、E	3	10	5	1	0	*	0	* #
B	G	6	3	2	0				
		3	5	5	0	3		3	*
C	F、G	12	8	4	0			6	*
		7	12	6	1	3	*		
D	H	20	5	3	0			3	#
		15	7	5	0				
		12	10	8	1	3			
E	--	5	7	3	1	3		18	*
F	I	17	5	2	0				
		15	8	4	0			23	
		13	10	5	0				
		10	13	7	0	10			
G	H	13	5	5	1			23	* #
		11	7	6	1	10	*		
H	I	3	5	3	0			36	* #
		2	8	3	0	21	*		
I	--	2	1	1	1	23	*	39	* #
Overall schedule duration:						25 (days)		41 (days)	
Total resource usage cost:						$ 195,550		$ 174,750	

*: Critical chain 1 #: Critical chain 2

5. Conclusions

This study has proposed a framework of schedule constraints named critical resource chain framework. Schedule constraints are identified and integrated into the proposed critical resource chain framework based on the concepts of TOC, CPM, and RCPSP optimization. Two scenarios of schedules including a CPM based schedule and an RCPSP based schedule with the goal of minimized overall schedule duration are successfully analyzed using the proposed framework. The proposed framework helps planners to understand projects by recognizing constraints. Moreover, further project management issues may be investigated as discussed.

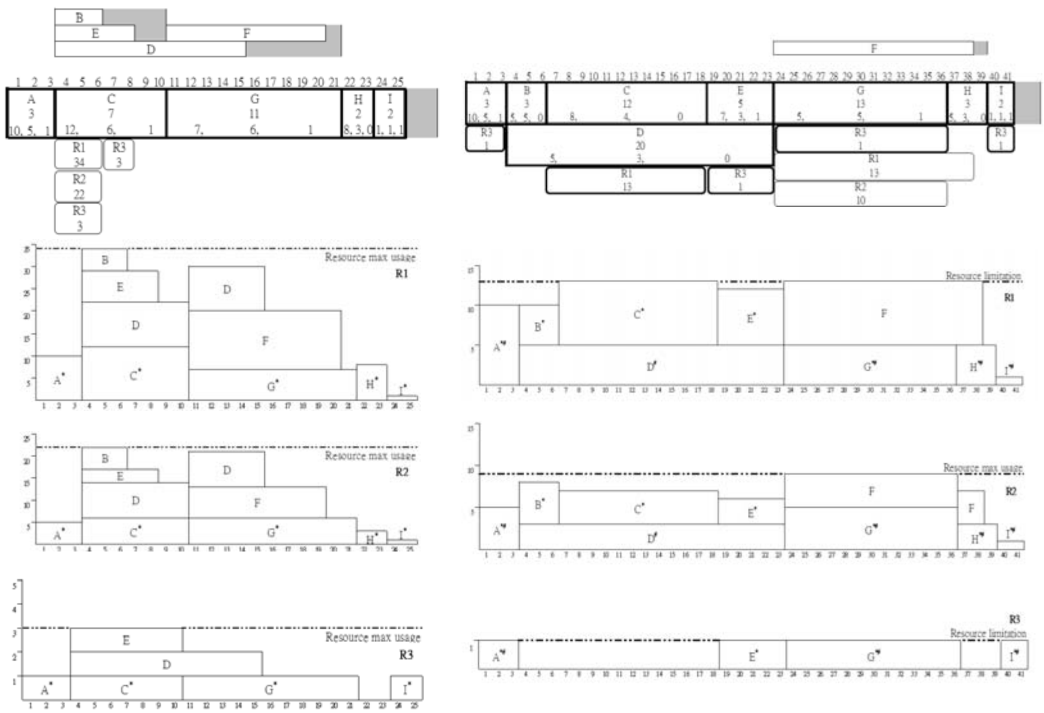

Figure 3. Critical resource chain and resource diagrams of scenario 1 and 2

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