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ENHANCEMENT OF SCHEDULING RELIABILITY IN BUILDING PROJECT USING THEORY OF CONSTRAINT

Min-Lan Yang Tsung-Chieh Tsai
National Yunlin University of Science & Technology

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Abstract Most building projects neglect that despite minimizing the project duration, the uncertainty of constraints, such as the uncertainties of personnel, machine, or weather still jeopardizes the project scheduling reliability and influences the resources arrangement causing the project duration overrun. The contractor must combine the project scheduling with planning to reduce the uncertainty of the project activities and project duration. This study attempted to improve the relationship between activities, revise the uncertainty of activities, and reduce the uncertainty of schedule to enhance the reliability of building project scheduling by applying the concepts of Theory of Constraint (TOC). To demonstrate the effects on the reliability improvement in building project scheduling by the application of TOC, the authors take one high-rise building constructed in Taiwan as a case study to illustrate enhancement of scheduling reliability. The simulation results are compared to Program Evaluation and Review Technique (PERT) simulation. The comparisons illustrate that the DBR proposed model can enhance the reliability of schedule planning.

Keywords: Theory of Constraint, Drum-Buffer-Rope, project schedule, reliability, uncertainty

1. Introduction

The uncertainty in the project duration may lead to numerous schedule disruptions. In particular, in terms of time-control, building project activities are subject to considerable uncertainty, and the project delivery cannot reach the requirements as planned or as contracted. Most scheduling methods emphasize shortening the project duration and optimizing the arrangement of project activities [15]. However, the most important concerning for the contractor is processing the project smoothly, that is, completing the project as planned in construction phase under the constraints such as the contract budget, material, etc. Hence, the major objective of the contractor for the scheduling is to reduce the uncertainty of project activities and the project duration, in order to enhance the reliability of project scheduling.

Program Evaluation and Review Technique (PERT) extends critical path method (CPM) by introducing the concept of uncertainty in estimating activity duration that is widely used but which has two major limitations. First, it is based upon the central limit theorem that assumes all activities are independent. Second, it dose not accurately reflect the duration uncertainty concerning other paths influencing the total project duration [18]. Consequently, the PERT calculated mean project duration is always an underestimate of the true project mean [1]. Many researches have investigated the project scheduling efforts usually fail to achieve their requirements [2, 4, 9]. Because most project scheduling concerns resource assignment and leveling, and neglects the influence of the constraints of uncertainty on the variation of the total project duration, even the project duration fell. Due to the uncertainty of constraints, the real concern in jobsite for a contractor is how to manage the variation of project duration without reducing it.

The uncertainty existing in every project is the underlying main cause for most problems; it is the management of that uncertainty that is the key issue. Dr. Goldratt in 1986 presented the Theory of Constraint (TOC), which can be applied in the concept of scheduling management [13]. TOC production management uses the Drum-Buffer-Rope (DBR) principle to rectify the uncertainty of activities and, enhance the reliability of schedule. The slowest or least productive member (drum) in the system should first be properly identified and set up. The system should then carefully arrange the protection (buffer) that prevents the drum from influencing the total schedule, and the driving (rope) which expedites or improves the drum to meet the main purposes of a system. Cook (1994) indicated that DBR scheduling contained less variance of procedure time than traditional scheduling [8]. Additionally, Blackstone (1997) indicated that the delivery time achievement rate rose from 80–85% to 97% after using DBR [6], meant the uncertainty of the manufacturing procedure time can clearly be minimized.

The next step is the application of Monte Carlo Simulation (MCS) which has two advantages to overcome the deficiencies of PERT. First, MCS uses probability distribution, primarily beta distribution, to present an activity uncertainty. Beta distribution can be defined with three values for each input in this study: (1) the optimistic; (2) the most likely; and (3) the pessimistic. Second, MCS has no assumption of independence. Random numbers are used to extract a duration estimate from each activity duration distribution, resulting in one complete project run [5, 15, 17, 24]. Multiple runs are made, and MCS analysis output can be summarized in terms of probability statements about the event outcomes [5].

In this paper, the authors attempted to improve the relationship between activities, revise the uncertainty of activities, and reduce the uncertainty of schedule to enhance the reliability of building project scheduling by applying the concepts of Theory of Constraint. The main aims of this study are: (1) to discuss the application of TOC to construction project schedule and (2) to enhance the reliability in scheduling by adopting TOC. The scheduling of a steel-structure project was used as a case study to verify the validity of this model and demonstrate that it can be applied in a construction project.

2. Theory of Constraint

Theory of Constraint was introduced by Goldratt in 1986. TOC was initially introduced as a component of the Optimal Production Technology (OPT) software; the DBR represents the basic manufacturing planning and control system behind the TOC [21].

Goldratt (1986) attributed the project constraint, rather than the techniques, such as the construction concept, to the main issue of overdue projects. The main consideration of TOC and DBR is that the performance of each system is limited by constraints. According to TOC, each system has at least one constraint; else the system can produce manufactures without limits. Therefore, the constraints should be managed to improve the production efficiency in a system. DBR is used to solve the scheduling problem of production management in the TOC.

As revealed in Figure 1, the three major components of DBR are the drum, the buffer, and the rope. To fully protect and use the constraint resource or bottleneck, the constraint can be a resource, market demand or management policy, the project manager must arrange a proper production schedule drum. The most obvious application of the DBR is when plant performance is constrained by a lack of manufacturing capacity at a key workcentre. Hence, the entire production output of the plant is based on the capabilities of this Capacity Constraints Resource (CCR) or bottleneck. Both previous OPT and recent TOC focus on verifying bottlenecks to use the bottleneck activities fully and achieve the maximum production system output.

Additionally, an appropriate buffer should be provided to protect the project due date against the disruptions that may occur during project execution. As mentioned in the literature, the use of buffer in project scheduling is decidedly from the management of slack. Slack times occur randomly in a project plan and as such they are generally ineffective in limiting the effects of variations in activity duration [19]. Schragengein (1991) considered the size of buffer as three times the standard deviation of the average bottleneck lead time. The reason of three times comes from experience and the reliable lead time distribution assuming the lead time complies with the normal distribution [22]. Rohen and Starr (1990) defined the buffer as a quarter of the total lead time [20]. Ballard (1995), on the other hand, believed that buffer is based on the uncertainty level of the target or the sum of 50% of each activity duration [3]. Also Demmy (1994) respectively identified three buffer times in a manufacturing system (constraint buffer, assembly buffer and shipping buffer). Identification of buffer is to provide safeguard so that when there is activity variable it won't affect bottleneck activity and its successors. And buffer time decreases proportionally when the activity completion date falls behind the expected schedule [10].

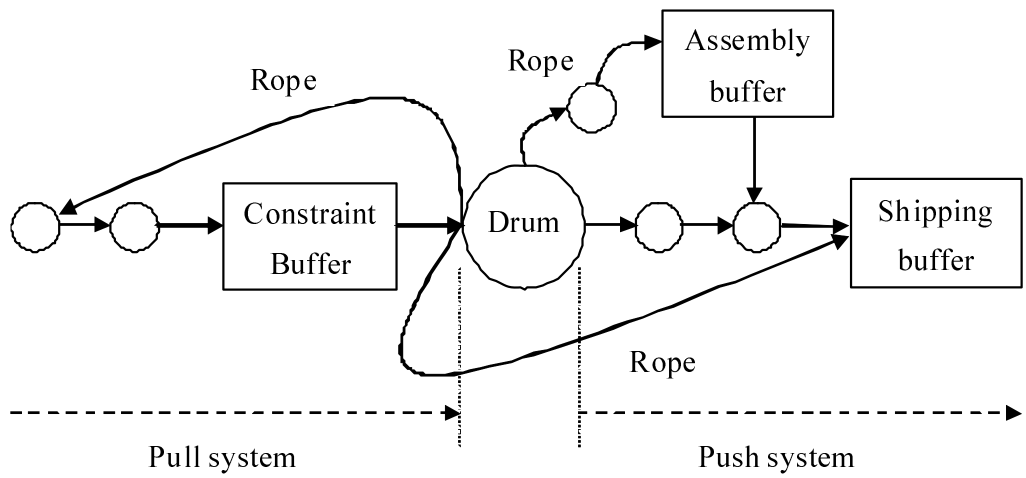

Figure 1: DBR concept [6]

Meanwhile, the adjustment of rope also improves the start time of the bottleneck. The rope is traced back as the length of time from the bottleneck to the lead time of the initial order. The major role of the rope is to calculate the appropriate time for the right material to arrive the site, ensuring that enough material is available to support the bottleneck activity. The rope determines an appropriate initial order time to enable the logistics to back up the bottleneck via non-bottleneck activities [14, 26, 23].

Apparently, drum has rectified the uncertainty of activities, buffer and rope have turned the independent activities into dependent activities, and consequently drum, buffer, and rope (DBR) all together have enhanced the reliability of project scheduling in this study.

3. Scheduling in DBR Model

The previous literatures about PERT indicates that most project durations or production completion dates did not meet the original planned schedule [4, 5], revealing that PERT must be improved to enhance schedule planning reliability. However, the key concept of scheduling (DBR) has been developed and applied to various fields in TOC since 1986. Related studies indicate that DBR significantly enhances the reliability of schedule planning [9, 8].

3.1. Structure of scheduling in DBR model

The way of scheduling of DBR is different with that of PERT. It is necessary to rectify DBR schedule. Figure 2 shows the analytical steps of the DBR model.

1) *Step1. Define the basic project network:*

Identifying and documenting the logical relationship and three-time values (the optimistic, the most likely, and the pessimistic) among schedule activities and diagramming the project network. Using Equations (1)–(6) to calculate the values of each activity in the project network. Parameters EF_i and LF_i can be calculated by forward pass calculation and backward pass calculation respectively. Additionally, developing the network allows the project manager to build the drum, buffer and rope to satisfy the actual requirements under various activity conditions.

$$Exp_i = (a_i + 4m_i + b_i)/6 \tag{1}$$

$$\sigma_i^2 = ((b_i - a_i)/6)^2 \tag{2}$$

$$T = \max\left\{ \quad t_i + d_i |\, i = 1, 2, \ldots, n \quad \right\} \tag{3}$$

$$T_e = \max\left\{ \quad t_i + Exp_i |\, i = 1, 2, \ldots, n \quad \right\} \tag{4}$$

$$t_j - t_i - d_i \geq 0, \forall_j \in S_i \tag{5}$$

$$TF_i = LF_i - EF_i \tag{6}$$

in which Exp_i = expected duration of activity i; a_i = optimistic duration of activity i; m_i = most likely duration of activity i; b_i = pessimistic duration of activity i; σ_i^2 = variance duration of activity i; T = project duration; T_e = expected project duration; t_i = starting time of activity i; d_i = duration of activity i; n = total number of activities; S_i = set of successors of activity i; TF_i: total float of activity i; LF_i = late finishing time of activity i; EF_i: early finishing time of activity i.

2)*Step2. Verify the bottlenecks:*

In project scheduling management perspective, bottlenecks can be scheduling uncertainty on the variation of the total project duration. So project duration is considered the major bottleneck of project in general [16]. Obviously the critical path (the path that determines project duration) of a scheduling largest influence the total project duration, and for a single project can be defines the critical chain [25]. Basically, the bottleneck activity can be improved by qualifying the schedule planning, which verification comprises three phases:

a. *When DBR is adopted in the construction scheduling, the activity on critical path can be viewed as bottleneck activity. If bottleneck activity has not been succeed in managed, the end lead to numerous schedule disruptions.*

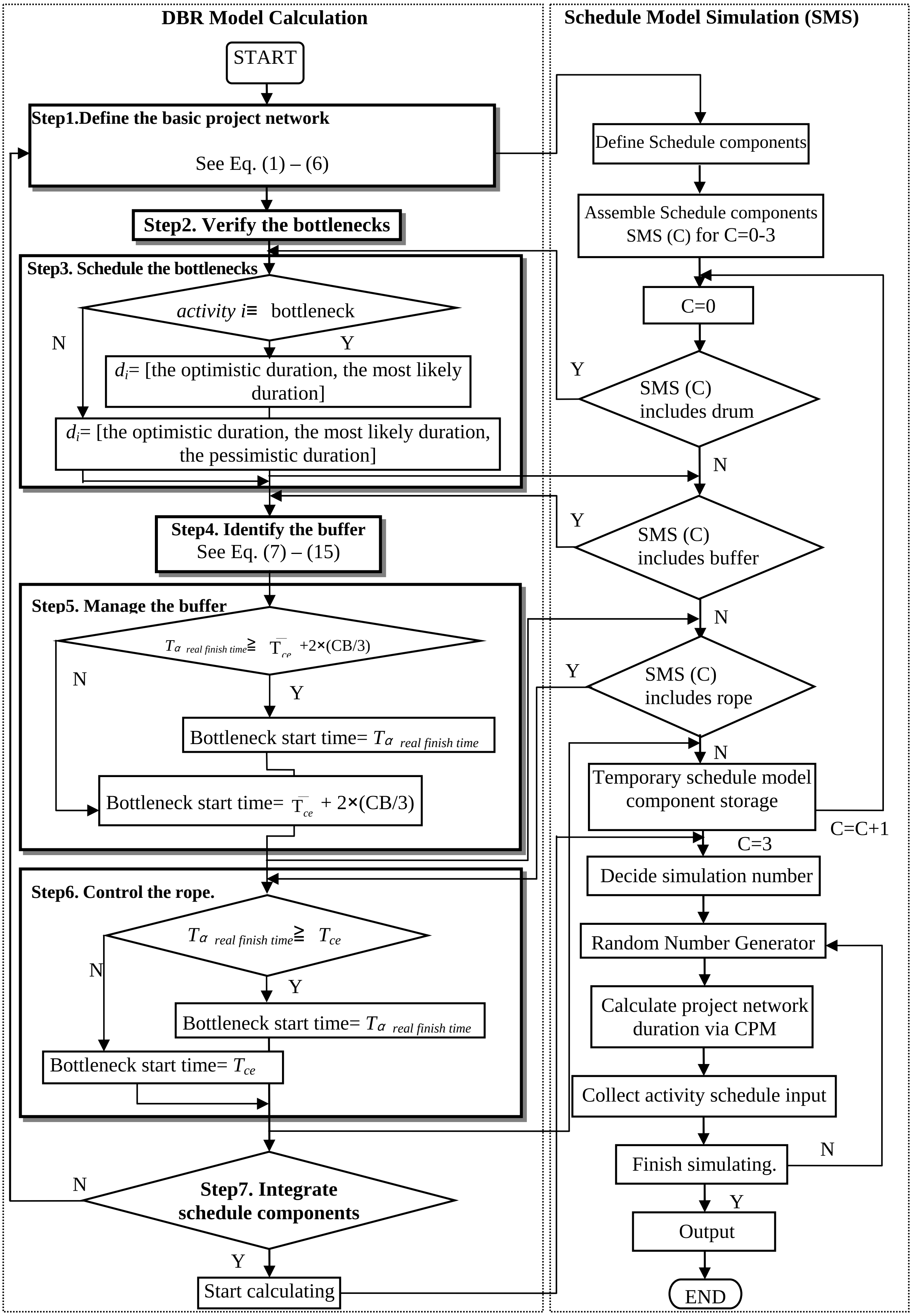

Figure 2: Flowchart of DBR model calculation and simulation applied in construction project scheduling (note: "C" is the number of DBR schedule components)

b. *Given the total float of activity on critical path is 0. If the activity being subjected to the uncertainty and causing delay, the precedence or afterward activities would be affected, and the project duration is unable to fulfill the scheduling planned in the early stage. That is, the activity with high uncertainty of activity duration can be regarded as the bottleneck of scheduling in the construction process. The uncertainty level of activity can also be estimated by the duration variance or standard deviation of the critical path activities, and therefore the activity with the highest variance or standard deviation may be the bottleneck.*
c. *There might be more than one activities with the higher variance or standard deviation, which means the higher uncertainty, where the project manager has to choose the bottleneck activity arbitrarily, and compares the scheduling simulation results of different activities with the same variance or standard deviation as the bottlenecks.*

3)*Step3. Schedule the bottlenecks:*

The drum in the OPT software, is determined by backward scheduling from customer orders. Other activity schedules obtain the expected duration of the total processing time from the drum scheduling [11, 12]. In other words, the entire production schedule is subject to bottleneck scheduling. To ensure that the bottleneck starts and finishes as estimated, the project manager must provide sufficient resources (e.g. people, machines and material). That means the uncertainty of constraints must be reduced to stop the pessimistic duration from occurring, delaying the predecessor activity duration or advancing the successor activity duration. Therefore, the most likely value is the late completion duration of the bottleneck activity. Estimation of other components, such as buffer or rope, is also based on bottleneck scheduling.

Bottleneck scheduling minimizes the uncertainty of the bottleneck activity duration, and forecasts the postponement or advance of non-bottleneck activities.

4)*Step4. Identify the buffer:*

Traditionally, duration estimates for individual activity contain some provision for contingencies. DBR scheduling aggregates these provisions into a project buffer. This implies that all due dates on individual activity and sub-projects are estimated. Buffer on the other hand are calculated to

reflect the uncertainty in the estimates of duration of tasks [25], construction activity is actually no precisely permanent rate of buffer time. Because activity has all the attributes such as customer order processing, client changes, construction areas and construction types. For example, formwork layout may take only half of one day, but concrete curing of slab may take 14 days. For each activity to have the same rate of buffer time is simply not practical. It is definitely going to affect the quality and safety of activity if the same rate is used. This study adopts dynamic buffer in which the buffer time is the statistical variance in the process. The bigger the variance is, the more the buffer is necessary. And the buffer time will be proportionally decreased, when the activity completion date falls behind the expected schedule [10].

a. *Constraint Buffer (CB): Equation (7) is used to calculate the CB time. Additionally, Chua and Shen (2002) stated that the bottleneck buffer must be placed in front of the critical path activity to minimize the resource limit and maximize the duration reliability [7]. Parameters T_{cb} and T_{ce} denote respectively the pessimistic and expected duration of all predecessor activities of CB, which are used in Equation (3) and Equation (4) to* *calculate the predecessor activity duration.*

b. *Assembly Buffer (AB): Equation (8) is used to calculate the AB time, which ensures that the bottleneck is not delayed by postponement of other activities when it is assembled. The PERT scheduling has assembly node duration variance resulting in an increase in project duration uncertainty. AB is therefore added to the assembly node where the bottleneck and non-bottleneck are merged. Parameters* T_{ab} *and* T_{ae} *denote respectively the pessimistic and expected duration of all predecessor activities of AB, which are used in Equation (3) and Equation (4) to calculate the predecessor activity duration.*

c. *Shipping Buffer (SB): Equation (9) is used to calculate the SB time to be set up in the shipping area. SB attempts to prevent by the processing variables from influencing the order delivery. The production process in the PERT scheduling uses a push system. Once the bottleneck duration is extended, the postponed duration causes breach of the contract, which is why SB occurs after a bottleneck. Parameters* T_{sb}*and* T_{se} *denote respectively the pessimistic and expected duration of all predecessor activities of SB, and are used in Equation (3) and Equation (4) to calculate the predecessor activity duration.*

$$CB_c = (T_{cb} - T_{ce})\big/2, \quad c \in S_{CB} \tag{7}$$

$$AB_a = (T_{ab} - T_{ae})/2, \quad a \in S_{AB} \tag{8}$$

$$SB_s = (T_{sb} - T_{se})/2, \quad s \in S_{SB} \tag{9}$$

in which CB_c = constraint buffer (day); AB_a = assembly buffer (day); SB_s = shipping buffer (day); T_{cb} = pessimistic duration of all predecessor activities of constraint buffer; T_{ce} = expected duration of all predecessor activities of constraint buffer; T_{ab} = pessimistic duration of all predecessor activities of assembly buffer; T_{ae} = expected duration of all predecessor activities of assembly buffer; T_{sb} = pessimistic duration of all predecessor activities of shipping buffer; T_{se} = expected duration of all predecessor activities of shipping buffer, S_{CB} = set of predecessor activities of constraint buffer;S_{AB} = set of predecessor activities of assembly buffer; S_{SB} = set of predecessor activities of shipping buffer.

The above three buffer time Equations (7)–(9), are similar but have different numbers of predecessor activities of bottleneck, so the buffer time varies. Equations (10)–(12) allocate each activity buffer time according to the ratios of expected duration of predecessor activity of the buffer to project expected duration. Parameter T_e is derived from Equation (6), and the buffer time is derived from each activity; Equations (13)–(15) subtract extra buffer time from each activity. The subtracted buffer time is then placed in the buffer zone, and can be used to manage the project uncertainty. Buffer management monitors the project schedule status and improves the scheduling reliability.

$$Buffertime_c = (b_c/T_e \times CB_c)\,, \quad c \in S_{CB} \tag{10}$$

$$Buffertime_a = (b_a/T_e \times AB_a)\,, \quad a \in S_{AB} \tag{11}$$

$$Buffertime_s = (b_s/T_e \times SB_s)\,, \quad s \in S_{SB} \tag{12}$$

$$\overline{b_c} = b_c - Buffertime_c \tag{13}$$

$$\overline{b_a} = b_a - Buffertime_a \tag{14}$$

$$\overline{b_s} = b_s - Buffertime_s \tag{15}$$

in which $Buffertime_c$ = buffer time of predecessor activity c before of bottleneck buffer; $Buffertime_a$ = buffer time of predecessor activity a before of assembly buffer; $Buffertime_s$

= buffer time of predecessor activity s before of shipping buffer; $\overline{b_c}$= pessimistic duration without buffer time of predecessor activity c before of constraint buffer; $\overline{b_a}$= pessimistic duration without buffer time of predecessor activity a before of assembly buffer; $\overline{b_s}$= pessimistic duration without buffer time of predecessor activity s before of shipping buffer;b_c = pessimistic duration of predecessor activity c before of constraint buffer; b_a = pessimistic duration of predecessor activity a before of assembly buffer; b_s = pessimistic duration of predecessor activity s before of shipping buffer;T_e = expected project duration; S_{CB} = set of predecessor activities of constraint buffer;S_{AB} = set of predecessor activities of assembly buffer; S_{SB} = set of predecessor activities of shipping buffer.

5)*Step5. Manage the buffer:*

Regarding project management, it is very important to make the project delivery as planned, while the setting of buffer to reduce the occurrence of uncertainty and enhance scheduling reliability can be a very effective tool. For the management of buffer time, Schragenheim (1991) suggested dividing the buffer time zone into three sections, overlooking, warning and overworking [22], the size of each section is allocated equally according to Equations (7)–(9). For instance, consider the constraint buffer as revealed in Equation (16). If the actual duration of predecessor activity of constraint buffer is longer than "the expected duration of all predecessor activities of constraint buffer without the buffer time ($\overline{T_{ce}}$)", then it means the project duration is not likely to meet the requirements of the planned duration, and, therefore, the constrain buffer needs sufficient time to absorb the extra project duration caused by uncertainties.

If the actual duration of predecessor activity of constraint buffer is within the overlooking section, the buffer time is still sufficient for the project manager to make use of the project duration while being monitoring it. If the actual duration of predecessor activity of constraint buffer is located within the warning section, then, the project manager should watch more closely on the progression of project duration to ensure the project can be completed as planned. If the actual duration of the building project is within the overlooking section or warning section, the project can be expected to complete in smooth processing with currently available resources before the end of the warning section; that is to say, given the starting time of the bottleneck of

adding 2×(CB/3), the temporal variances are in a range still acceptable for the project manager, thus posing no need of extra overworking resource to start the bottleneck activity ahead of the schedule, since it is more important for the manager keeping the project duration as planned than shortening it.

Conversely, if the actual duration is found within the overworking section, the manager has to increase overworking resources, such as manpower, machinery for construction or working hours, so as to start activities ahead of schedule for earlier completion, allowing bottleneck activity to commence as scheduled, so as not to jeopardize the starting time of succeeding project activities. If the actual duration should fail in meeting the duration planned, the time for succeeding operations would be extremely difficult to control. When confronting with potential problems of penalty for breach of contract and project delay, it is definitely necessary to add in certain amount of resources to shorten the operation time, and that, in the meantime, adds cost to the project.

$$\overline{T_{ce}} = \max\left\{t_i + \left(a_i + 4m_i + \overline{b_c}\right)\Big/6\right\} \tag{16}$$

in which $\overline{T_{ce}}$= the expected duration of all predecessor activities of constraint buffer without the buffer time; t_i = starting time of activity i; a_i = optimistic duration of activity i; m_i =

most likely duration of activity i; $\overline{b_c}$= pessimistic duration without buffer time of predecessor activity c before of constraint buffer.

6)*Step6. Control the rope:*

The expected start time of the bottleneck activity, or the completion time of the predecessor activity of bottleneck, can be calculated with PERT. The length of the rope is as same as the duration of the predecessor activity of bottleneck, which uses a pull system for concurrent production. The rope scheduling is the milestone for all bottleneck predecessor activities after the start of work. To enable the bottleneck to start as expected as in the buffer management, the total completion time of all predecessor activities must not exceed the rope scheduling.

When a constraint is broken, the next constraint will have to be found out and improved thus continuing the process of improvement.

3.2. Simulation of scheduling in DBR model

The right half of Figure 2 shows the logic operation procedure of computer simulation. As revealed in Table 1, the DBR model components in the schedule model are the drum, buffer and rope. For instance, when the schedule model simulations contains 2 schedule components (C=2), three possible types of DBR model exist, the Drum-Buffer schedule (No.5), Drum-Rope schedule (No.6) and Buffer-Rope schedule (No.7), and are compared with PERT simulation result (No.1). Therefore, a total of eight schedule models exist.

Table 1: DBR model components for MCS

No.	Schedule Components	Drum	Buffer	Rope
1.	PERT schedule			
2.	Drum schedule	■		
3.	Buffer schedule		■	
4.	Rope schedule			■
5.	Drum-Buffer schedule	■	■	
6.	Drum-Rope schedule	■		■
7.	Buffer-Rope schedule		■	■
8.	Drum-Buffer-Rope schedule	■	■	■

Note: Shaded sections indicate which DBR schedule components are utilized in the simulation

4. Case Study

4.1. Case background

The actual building project of the steel-structure building in the Taichung area of Taiwan was used to test the viability of DBR model. Table 2 shows all activities of the project.

The project includes steel structure manufacturing in the shop (activities 1-12), structure work on the site (activities 13-24) and the steel structure assembly (activities 25-27). The project has three phases in total, and all activities are related to each other by Finish to Start (FS). For instance, the successor activity of activity 7, "assembling", is activity 8, "check on".

Table 2: Activity duration information (*critical path)

Activity code i	Activity item	The optimistic a_i (day)	The most likely m_i (day)	The pessimistic b_i (day)	Precedence relation	Standard deviation SD. (day)
Shop work						
1.	Drawing	20	25	30	–	1.7
2.	Assessment & accept	7	10	15	1	1.3
3.	Layout	4	6	10	2	1.0
4.	Cutting	3	7	10	3	1.2
5.	Drilling	3	5	7	4	0.7
6.	Straighten	2	3	5	4	0.5
7.	Assembling	5	7	10	5,6	0.8
8.	Check on	2	3	5	7	0.5
9.	Welding	10	13	18	7	1.3
10.	Examination & adjustment	3	5	7	8,9	0.7
11.	Painting	5	7	10	10	0.8
12.	Transportation	3	5	7	11	0.7
Basement work						
13.	B1 earthwork*	5	7	10	–	0.8
14.	B1 horizontal support	3	5	7	–	0.7
15.	B2 earthwork*	5	7	10	13,14	0.8
16.	B2 horizontal support	3	5	7	13,14	0.7
17.	B3 earthwork*	7	10	15	15,16	1.3
18.	B3 horizontal support	3	5	7	15,16	0.7
19.	B4 earthwork*	7	10	15	17,18	1.3
20.	B4 horizontal support	4	6	10	17,18	1.0
21.	B4 structural construction*	14	24	38	19,20	4.0
22.	B3 structural construction*	14	24	38	21	4.0
23.	B2 structural construction*	14	24	38	22	4.0
24.	B1 structural construction*	15	25	39	23	4.0
Site work						
25.	Erection*	16	20	25	12,24	1.5
26.	Adjustment*	2	3	5	25	0.5
27.	Welding*	7	10	15	26	1.3

4.2. Case analysis

The case in this study is analyzed as follows according to the left half of DBR model in Figure 2:

1)*Step1. Define the basic project network:*

According to Table 2, the basic project network is diagramed and the values of each activity are calculated with Equations (1)–(6).

2)*Step2. Verify the bottlenecks:*

As shown in Table 2. The activities on the critical path are 13, 15, 17, 19, 21-27. The activities with the highest variation or standard deviation among all are activity 21-24, with the variation of 16 days, and the standard deviation of 4 days. As the result, activity 21-24 would be the bottleneck activities, and to built up a basis on the bottlenecks schedule and the buffer and the rope.

3)*Step3. Schedule the bottlenecks:*

The purpose of this step is to manage the variance of bottleneck activity duration. The construction resources must fully support bottleneck to stop the pessimistic duration from delaying the successor activities or the project completion date. Therefore, the most likely value is the late completion duration of the bottleneck activity, the assumed activity duration distribution is [20]. With complete support from project resources, the bottleneck is not delayed.

Table 3 and Figure 3 show the results of simulating the DBR and the PERT 2000 times by MCS. The mean completion time of simulating the PERT schedule (No.1) was 172.6 days. The mean completion time of simulating the PERT schedule (No.1) is not the longest duration, but the uncertainty of project duration reaches 10.6 days (SD.10.6 days, Min.136.9 days, Max.208.8 days). Obviously, PERT scheduling still has room for improvement. Figure 3 compared the results of simulation of the DBR model schedule components (No.2-No.8) with the PERT schedule (No.1). The uncertainty of bottleneck activities is reduced in the Drum schedule (No.2). Although the project completion time is reduced by 4.5 days, the uncertainty of project duration is only reduced by 1.2 days (SD.9.4 days, Min.139.7 days, Max.198.1 days). Due to the extra buffer time in the Buffer schedule (No.3), the project completion time rises by 10.4 days when the project duration uncertainty is reduced by 5.3 days (SD.5.3 days, Min.168.7 days, Max.200.9 days). In the Rope schedule (No.4), the project duration uncertainty is reduced by 2.2 days (SD.8.4 days, Min.155.7 days, Max.211 days).

In terms of the reliability of the duration in the above three schedule models, Buffer schedule (No.3) by central control of the buffer time has the lowest duration uncertainty but a longer duration. This helps reduce the idle time when the project manager mobilizes resources such as manpower and machinery. Conversely, the DBR schedule key component, drum still needs buffer and rope to enhance the reliability of schedule.

The Drum-Buffer schedule (No.5), Drum-Rope schedule (No.6) and Buffer-Rope schedule (No.7) were compared with the PERT schedule (No.1). The durations of the two-component schedules were slightly different, but the duration uncertainty fell. In particular, the uncertainty of project duration in the Buffer-Rope schedule (No.7) is reduced by 7.7 days (SD.2.9 days, Min.161.2 days, Max.180.3 days).

The Drum-Buffer-Rope schedule (No.8) reduces the uncertainty of project duration by 8.1 days (SD.2.5 days, Min.161.5 days, Max.176.2 days). When compared with the other seven schedule models, the project duration of 168.8 days is not bigger than others. As Cook (1994) and Blackstone (1997) indicated, the Drum-Buffer-Rope schedule reduces the duration effectively [6, 8].

Table 3: DBR simulation results versus PERT simulation results

No.	Simulation results				
	Mean	Standard deviation (SD.)	Range minimum (Min.)	Range maximum (Max.)	Difference in standard deviation compared with PERT
Simulation 1	172.6	10.6	136.9	208.8	Not applied (N/A)
Simulation 2	168.1	9.4	135.7	198.1	1.2
Simulation 3	183.0	5.3	168.7	200.9	5.3
Simulation 4	174.8	8.4	155.7	211.0	2.2
Simulation 5	178.8	3.6	168.2	190.2	7.0
Simulation 6	170.4	7.2	153.6	198.3	3.3
Simulation 7	169.3	2.9	161.2	180.3	7.7
Simulation 8	168.7	2.5	161.5	176.2	8.1

Unit: day

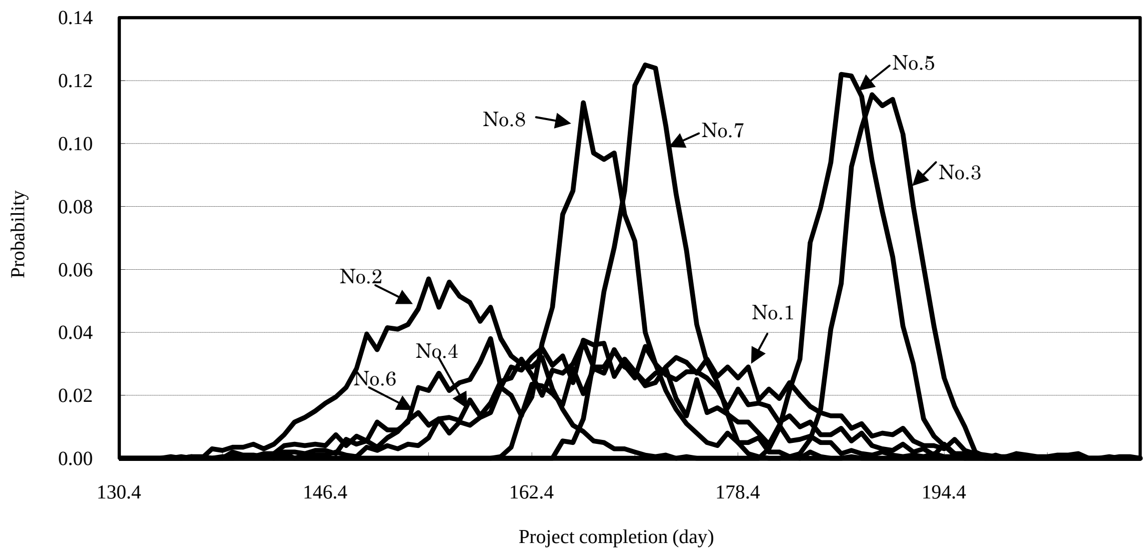

Figure 3: DBR simulation distributions versus PERT simulation distributions

5. Conclusions

TOC production management (DBR) enhances the reliability of schedule. Basically, following the numbers of schedule components were used (drum, buffer, rope) the range of finish date distribution is reduced. It means the DBR of TOC can reduce the uncertainties of scheduling, but not always means that they can shorten the project schedule.

The DBR model was tested on a steel-structure building; the result of each DBR schedule model (No.2-No.8) showed the improvement of the pertaining defect of project schedule and reduced the uncertainty of project duration. In terms of the reliability of the duration in the single-component schedule models (No.2, No.3, No.4), the buffer schedule using the central control of the buffer time has the lowest duration uncertainty but a longer duration, helping reduce the idle time when the project manager is mobilizing resources. Conversely, the drum without a buffer and rope must still be improved to reduce the uncertainty effectively.

The analytical results indicate that the project uncertainty of Drum-Buffer-Rope schedule (No.8) (SD. 2.5 days) is lower than that of the PERT schedule (No.1) (SD.10.6 days). The drum application helps the project manager with identify and schedule bottlenecks. The buffer helps remove extra protection time of each activity and controls it to manage uncertainty. Meanwhile, buffer management monitors the schedule status and increases the schedule stability. Scheduling based on PERT is a push system, since it uses forward pass calculation to calculate the activity start time. In case of delays in the critical path activity, the project duration falls behind the schedule and the reliability decreases. Rope can be used to control the starting time of project bottleneck, thereby reducing the influence of the successor activity uncertainty on the duration. Drum-Buffer-Rope working together constitutes a fair DBR schedule plan and emphasizes the advantages of the DBR schedule. Project manager can reduce the variance of the bottlenecks and non-bottlenecks by the drum and the buffer. On the other hand, the application of the buffer and the rope makes dependent relations on each activity. For example, the start time of the bottlenecks is limited by the length of the rope.

This study indicated that using the DBR schedule model can reduce the uncertainty and enhancing the reliability of project duration. There is still much work to be done, such as trade off between the values about reduction of the variance of project duration and the cost of the bottleneck confirmed starts on time. Additionally, the precedence relationships of the network, such as Start to Finish (SF), Finish to Start (FS) and Finish to Finish (FF) can be used in the further study.

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Tsung-Chieh Tsai
Department of Construction Engineering,
National Yunlin University of Science and Technology,
123 University Road, Section 3, Douliou, Yunlin 64002,
Taiwan, R.O.C.
E-mail: tctsai@ce.yuntech.edu.tw