Simulation and Implementation Study of Robust Drum-Buffer-Rope Management System to Improve Shop Performance

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Abstract

The Drum-Buffer-Rope (DBR) method is the production application of Theory of Constraints (TOC), a global managerial methodology that helps the manager to concentrate on the most critical issues. Three management phases, i.e., planning (scheduling) phase, executing phase and control phase, are required to implement the DBR on a manufacturing plant. Although the DBR method has been studied in some literatures, major focus is only on one management phase. For DBR to gain acceptance as a viable planning and control system, a robust DBR management system is not investigated yet. The purpose of this study is to provide a robust DBR management system and to describe significance and the relationship among these phases. A prototype was also provided by the eM-Plant simulation model to demonstrate the significance and feasibility of this robust DBR management system. This study especially facilitates the managers who want to implement the DBR system for improving shop performance of manufacturing plants.

***Keywords**:* Drum-Buffer-Rope, DBR Management System, Theory of Constraint, Shop performance

1. Introduction

Most of the fabs resort to production scheduling/dispatching as a means to enhancing production efficiency. The commonly seen methods of production scheduling/dispatching at the present time are devised to meet single performance indicators. Few methods take into account multiple, or even conflicting performance indicators. Therefore, different production control managers adopt different criteria (Lin *et al*., 2008). The Drum-Buffer-Rope (DBR) method is the production application of Theory of Constraints (TOC), a global managerial methodology that helps the manager to concentrate on the most critical issues (Goldratt and Cox, 1984; Umble *et al*., 2006; Watson *et al*., 2007; Huang *et al*., 2008). Schragenheim and Ronen (1990) described the TOC as a comprehensive management methodology that can be used to improve shop performance. The five focus steps to implement TOC (Goldratt and Cox, 1984; Schragenheim and Ronen, 1990) are: (1) Identify the system constraint(s); (2) Decide how to exploit the constraint(s); (3) Subordinate everything else to the above decision; (4) Elevate the system constraint(s); (5) If, in the previous steps, a constraint has been broken, go back to step (1), but not let “inertia” become the system constraint. The DBR represents a set of rules for implementing the first three steps in TOC. The constraints in a manufacturing plant may be market demand, plant capacity, and material limitations. The most obvious application of the DBR is when plant performance is constrained by a lack manufacturing capacity at a key workstation.

Hence, the entire production output of the plant is based on the exploitation and subordination of this capacity constrained resource (CCR) or bottleneck. The DBR basically is a mechanism to fulfill the CCR exploitation and subordination process. As shown in Figure 1, the three major components of DBR are the Drum, the Buffer, and the Rope. The Drum is a detailed schedule of the CCR in order to ensure the exploitation of it. The Buffer is a protection time to protect the CCR when raw materials are delayed by previous processing procedures. Finally, the Rope which can be measured by offsetting the Buffer from the Drum is a detailed schedule for releasing raw material into the shop floor to force all the parts of the system to work up to the pace dictated by the Drum and no more. That is the Drum is the action plan for the CCR exploiting decisions and the Buffer and Rope are mechanisms to subordinate all non-CCRs to the Drum (and thus to the CCR exploiting decisions). The CCR exploiting and subordinating mechanism in DBR has two fold benefits. The first is it can squeeze and protect CCR potential throughput so as to improve the system throughput. The second is it restricts unlimited release of material into the system so as to prevent the growth of inventory and an associated increased in lead time. These improvements have been verified by some real cases (Schragenheim and Ronen, 1990; Corbett and Csillag, 2001).

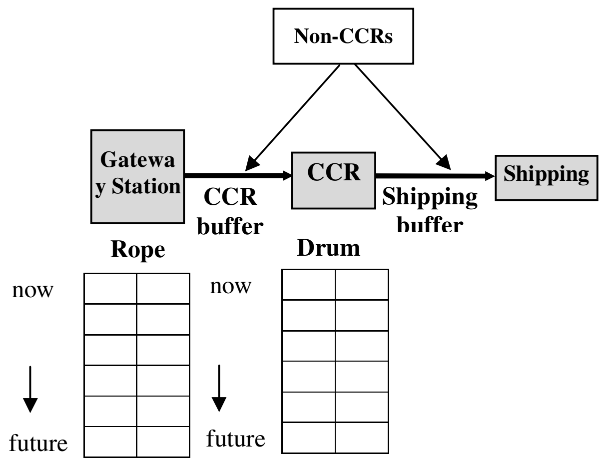

Figure 1: Three major components of DBR

However, three management phases, i.e., planning (scheduling) phase, executing phase and control phase, are required to achieve these improvements in implementing the DBR on a manufacturing plant. The planning phase plans how to exploit the CCR (i.e., Drum) and subordinate it (i.e., Buffer and Rope). The Drum and Rope are CCR exploiting and subordinating plans (scheduling output) on a shop floor after the planning phase. These plans will eliminate mishandling manufacturing order (MO) for CCR workers or releasing wrong raw material at gateway station. However, these plans will succeed only if all workmen in the shop floor can follow and subordinate to them. Therefore, the executing phase concerns how to successfully implement the plans in the shop floor. That is the subordinating behavior or rules for the workmen or stations on the shop floor must be set up to implement the plans. Besides, inevitable disruptions and variances are existed in any manufacturing process. Disruptions and variances might occur from a variety of sources: machine breakdowns, fluctuations in setup time or process time, personnel problems, unreliable vendors, or quality issues, etc. The purpose of control phase is thus to provide a control mechanism to diagnose if some order has been attacked by any unexpected fluctuations in the shop floor and if expediting it.

The control mechanism in DBR is called Buffer Management (BM) (Schragenheim and Ronen, 1990; Goldratt and Cox, 1986). If the executing phase and control phase is ignored, the performance of CCR exploiting and subordinating plans in planning phase will be diminished. That is the throughput of the CCR or manufacturing plant will become worse. For the fulfillment of the exploiting and subordinating CCR in the five focus steps of TOC completely, therefore, a DBR system must consist of these three management phases. A DBR system with these three management phases is referred as a robust DBR management system in this paper.Most researchers study the DBR methods which are located on the DBR planning phase, such as Schragenheim and Ronen (1990), Guide (1996), Tsai and Li (1997), Atwater *et al.* (2002) and Wu *et al.* (1994). Simulation study is usually used in these papers to demonstrate the presented DBR scheduling model. The working policies are required to be incorporated into the simulator to run it. Although the working policies simulate behavior or rules for the workmen or station on the shop floor, they are only used to drive the simulator but not formally to examine how to subordinate to CCR or support the DBR schedule. The papers related to the topics of DBR executing phase or control phase are little. Daniel and Guide (1997) first formally discussed the priority dispatching rules used at non-CCR to best support DBR.

Russell and Fly (1997) studied which order review/release policy is best suited for a DBR. Goldratt and Fox (1986) and Schragenheim and Ronen (1990, 1991) discussed the use of BM to monitor the execution of the schedule in an environment where the DBR method has been implemented. Although the DBR method has been studied in these literatures, however, major focus is only on one management phase. For DBR to gain acceptance as a viable planning and control system, a robust DBR management system is not investigated yet. The purpose of this study is to provide a robust DBR management system and to describe significance and the relationship among these phases. This study especially facilitates the managers who want to implement the DBR system for improving shop performance of manufacturing plants.

2. The Structure of a Robust DBR Management System

The fulfillment of the exploitation and subordination process in a shop floor requires a mechanism or a robust management system. The structure of a robust DBR management system is shown in Figure 2. This robust DBR management system composes three management phases, i.e., DBR planning phase, DBR executing phase and DBR control phase. The DBR planning phase plans the CCR exploiting decision and the subordinating plan. The DBR executing phase executes the decision or plans in the DBR planning phase. Finally, the DBR control phase monitors and controls the difference between the performance of executing phase and the planning performance of planning phase. The detailed functions of each management phase will be described detailed in the followings.

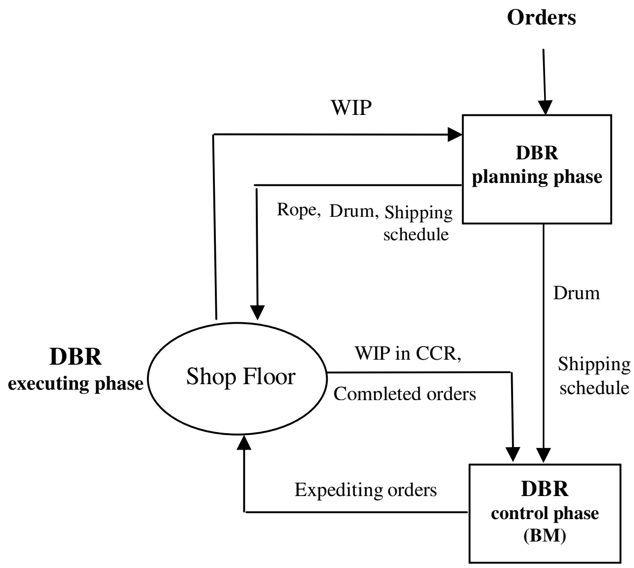

Figure 2: The structure of a robust DBR management system

3. Functions of a Robust DBR Management System

3.1 The DBR planning phase

Three basic functions are for daily application in the DBR planning phase:

1. Develop a Drum (schedule in CCR)

Less waste and more value-added performance in CCR help better exploit CCR or make more throughput for the plant. However, if the decision of obtaining these less waste or more value-added performance in CCR is made when CCR is dispatching jobs in shop floor or in executing phase, this decision is made too hurry and difficulty for less decision time and related information for shop floor being always in busy state. The more possibility of making mistake or wrong decision will be in a hurry and short of data situation. Besides, if the CCR exploiting decision is made until CCR is required to dispatch jobs in shop floor or in executing phase, this decision is difficult to real-time communicate to all non-CCRs. In this situation, the subordination of non-CCRs to this decision is impossible. Therefore, the CCR exploiting decision must be made in planning phase before the CCR is required to dispatch jobs in shop floor or in executing phase to full exploit the CCR. This CCR exploiting decision process is performed by the work of the Drum design in scheduling DBR. Therefore, the Drum design is the first step when scheduling in DBR (Schragenheim and Ronen, 1990). The less waste and more value-added performance in CCR can be used as the general guides for design a more profitable Drum. Or the design process of Drum proposed by Goldratt (1990) can be utilized. Therefore, a Drum which is the final result or documents after this CCR exploiting decision is the optimized processing sequence for all MOs at CCR.

2. Plan the Rope (material release schedule)

The Rope which is a material release schedule is a basic subordinating mechanism in DBR. The release time of a MO is measured by offsetting the CCR buffer from the start time of this MO in Drum. With this Rope subordinating mechanism, the system will be forced to contain only material that is scheduled by a Drum. Therefore, the Rope mechanism can avoid non-CCRs from processing the materials which are not required by CCR. This will ease the non-CCRs dispatching or subordinating decision in the following executing phase.

3. Plan the shipping schedule (SS) The purpose of SS is to ship the MOs completed by CCR as soon as possible. The shipping time of a MO is measured by adding the shipping buffer to the end time of this MO in Drum. With this SS, the work related to shipping function (such as shipping documents or transporter booking) can be prepared. Besides, this SS will activate the subordination of non-CCRs in the executing phase and control phase. Therefore, the functions of DBR planning phase first develop the Drum to make the best CCR exploiting decision and then plan the Rope and SS to subordinate to the Drum. The Drum, Rope and SS are the output or documentations of DBR planning phase. These documents will be the input to DBR executing phase. That is these plans must be launched into shop floor to be further followed and performed. Otherwise, the efforts in the DBR planning phase are nonsense.

3.2 The DBR executing phase

The DBR executing phase performs the plans (CCR exploiting and subordinating decisions) in the DBR planning phase. Because DBR does not develop detailed schedules for every station in the shop, the executing (dispatching) behavior or discipline at different station is various.

1. CCR station

Since a more profitable Drum has been planned in the DBR planning phase, CCR station must carry out works according to the MO sequence scheduled in Drum. Otherwise, the throughput of system will be destroyed. Therefore, the behavior of a CCR station is to subordinate itself to Drum. That is the CCR station must dispatch work according to the MO sequence in Drum. Unless a MO which is dispatched now is absent, the following MO can substitute for it to avoid CCR from being idle.

2. Gateway station

Since the Rope has been planned to best subordinate to Drum, the raw material released at gateway station must follow the plan in Rope, including types, quantity and release time. The traditional material release policy which is based on the idle status of gateway station is prohibitive.

3. non-CCRs station

Since DBR system has no schedule at non-CCRs in DBR planning phase, a non-CCR station cannot dispatch works based on a prescheduled plan. Therefore the foreman or technician at a non-CCR station is authorized to make the MO dispatching decision. In general, the more WIP inventories piled at a station the more difficulty of work dispatching decision. Since the Rope is in line with Drum, the WIP inventories piled at a non-CCR station are limited. That is the work dispatching decision in a non-CCR station will not be difficult. The findings by Daniel and Guide (1997) indicated that the simple priority dispatching rules, such as first-in, first-out or earliest due-date, at a non-CCR station work best to support DBR.

4. Other supporting departments

Any auxiliary resource required by an operation of a MO at a station must be prepared by supporting departments before this operation is operated. For example, the material must be kitted ready before material is released at a gateway station. Or if a tooling or jigs/fixtures is required for an operation of a MO at a station, this tooling or jigs/fixtures must be ready before this operation start to be processed. Preparation of these auxiliary must meet the required time of the operations, not too early and not too late. Although DBR does not develop detailed schedules for every station in the shop, a referenced time is provided for different operation. The referenced time at different operations of a MO can be divided into three situations. The first situation is for the operations before CCR station and the referenced time is the MO release time in Rope. The second situation is for the operation at CCR station and the operations after CCR operation and the referenced time is the MO start time in Drum. The third situation is for the operations upon or after MO completion and the referenced time is the MO completed time in SS. For example, the shipping documents must be ready before the MO completed time in SS.

3.3 The DBR control phase

Although in the DBR planning phase, CCR buffer and shipping buffer are utilized to protect Drum and SS respectively. However, inevitable disruptions and variances are existed in any manufacturing process. The progress of MOs will be interfered with these inevitable disruptions and variances in the shop. The purpose of DBR control phase is thus to provide BM control mechanisms to diagnose if some order has been attacked by any unexpected fluctuations in the shop floor and if expediting it.

The DBR system utilizes different BM to monitor the progress of MOs in the protected regions within different buffer (Schragenheim and Ronen, 1990; Goldratt and Cox, 1986). The progress status of a MO in the protected region within a CCR buffer (or a shipping buffer) is monitored by the CCR BM (or shipping BM). If a MO has been attacked by an unexpected fluctuation in a station within the protected region of the CCR buffer, the MO cannot arrive at the CCR station. The remaining time for this MO to be processed at CCR is the start time of this order in Drum minus current time. If this MO is absent at CCR station and the remaining time of this order is greater than one third of CCR buffer, there is still enough time until this MO is needed by the Drum.

However, if this MO is absent at CCR station and the remaining time of this order is less than one third of CCR buffer, this order is due very shortly at CCR station. In this situation, only a very short time remains to bring this MO in on time. Therefore, BM will highlight this emergent MO to managers to trigger corrective action, usually expediting. Many expediting actions can be taken by managers in a shop, such as speeding up the machining process, taking overtime for stations, operation overlapping(transfer batches), operation splitting (more batches processed simultaneously on machines), or giving dominant priority et al. If a MO is identified via BM as an expediting MO, this MO must be taken care at all non-CCR stations until it arrives at CCR station (CCR BM) or it is completed (shipping BM). The functions and methods for different management phases are summarized in Table 1. The relationship between these contents and TOC five focus steps is also shown in Table 1.

Table 1: Summary of functions and methods for different DBR management phase

Management phase	Functions	To perform the step in TOC five focus steps	Methods
	Drum	**Step 2**	A Drum is developed according to t he rules of less waste and more value-added for CCR.
Planning phase	Rope	Step 3	Material is scheduled to be released in line with Drum.
	SS	Step 3	The MOs completed by CCR are planned to be shipped out as soon as possible.
	CCR	Step 3	MO is dispatched according to sequence in Drum.
Executing phase	Non-CCRs	Step 3	MO is dispatched according to FIFO or decision of the foreman or technician.
	Gateway station	Step 3	Material is released according to the schedule in Rope.
	Supporting departments	Step 3	The required time of any auxiliary resource is according to Rope, Drum or SS.
Control phase	CCR BM	Step 3	CCR BM protects CCR from losing orders required by Drum.
	Shipping BM	Step 3	Shipping BM monitors the orders completed by CCR to be shipped out as soon as possible.

4. A Simulation Prototype and Demonstration

The application of the robust DBR management system is illustrated by the simulation system shown in Figure 3. This system is modeled using eM-plant^{TM}.

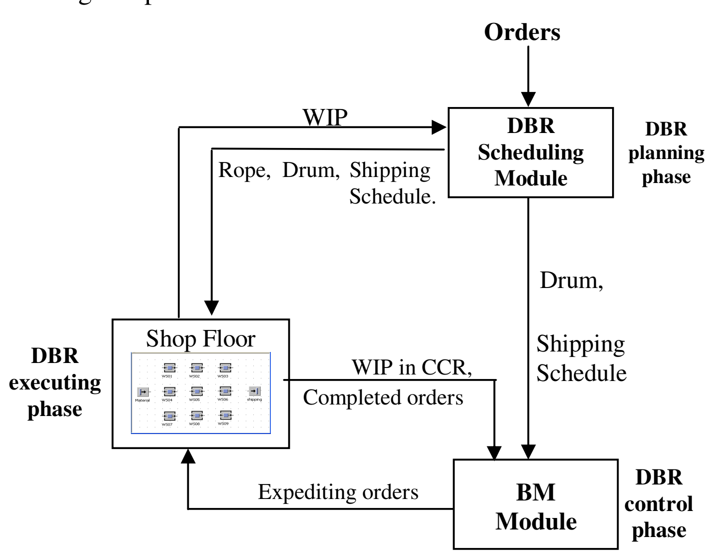

Figure 3: A simulation model for the robust DBR management system

The DBR scheduling module (for the development of Drum, Rope and Schedule everyday) for the planning phase and BM modules (CCR BM and shipping BM) for the control phase are developed utilizing SimTalk provided by eM-plant. The shop floor system (the execution of plans in planning phase) for executing phase is modeled using Tool box function provided by eM-plant.The shop floor system in the model includes nine workstations and nine products. Table 2 provides the processing time distribution for the workstations and Table 3 provides the different routings for these nine products.

The working hours in the system are 24 hours per day. Order arrival rate is 12 orders per day and randomly in a day. The product required by an arriving order is assigned randomly. To ensure steady-state conditions, the initial condition is set after running 365 days. The utilization levels described in Table 2 represent the initial condition for the operation used in the simulation model. WS05 is apparently observed as a CCR in this system. The CCR buffer and shipping buffer are set to be 21 hours and 13 hours which are the average of triple TWK of average processing time of non-CCRs in the protected region of a Buffer for different product.

Table 2: Workstation processing times and utilization

	Processing Time			
Workstation	Distribution	Mean	SD	Mean Utilization
WS01	Uniform	1:36	5.77	79.70%
WS02	Uniform	1:40	5.77	83.13%
WS03	Uniform	1:36	5.77	79.73%
WS04	Uniform	1:45	8.66	81.97%
WS05	Uniform	1:58	2.88	97.88%
WS06	Uniform	1:45	8.66	83.03%
WS07	Uniform	1:36	5.77	79.77%
WS08	Uniform	1:36	5.77	79.87%
WS09	Uniform	1:40	5.77	82.97%

Table 3: Product routing

Product	Routing
A	1, 2, 3, 4, 5, 6, 7, 8, 9
B	7, 8, 9, 1, 5, 2, 3, 6
C	1, 4, 3, 8, 6, 5, 7, 9, 2
D	2, 6, 9, 7, 5, 8, 1, 3
E	8, 6, 2, 9, 5, 1, 7, 4, 3

4.1 Operations in DBR planning phase

To be near the requirement for practical application in a plant, the planning phase is operated at 12:00 everyday. The new orders, old orders and WIP in the shop are input data for this planning phase. The new orders are those arrived yesterday. The old orders are those had scheduled yesterday but their material had not be released yet. The WIPs are those material had be released. The Drum is developed firstly to best exploit the capacity of WS05 (CCR) based on these input and the design process of Drum proposed by Goldratt (1990).

However, the sequences of WIPs in the Drum are fixed and are not rescheduled for their materials are released and other required auxiliary resources are also ready. The Rope and SS are then planned. As an example shown in Table 4, the Drum , Rope and SS are the output after rescheduling process at 12:00 2005/2/12. Among 23 MOs in Table 4, 10 MOs (Seq. 1~10) are WIP for their materials has been released, MO# 4892 (Seq. 20) are old MO and the others are new coming MOs. After the planning operations have been performed, the Drum, Rope and SS will be utilized in executing phase and control phase.

Table 4: Examples of Drum, Rope and SS
Rescheduling time: 12:00 2005/2/12

	Basic data				Rope	Drum	SS
Seq.	Order #	Product	Due-date		Material Released time	Start Time	Completed time
1	4875	3	2005/2/13 10:00		-	2005/2/12 13:42	2005/2/13 4:43
2	4894	4	2005/2/13 18:00		-	2005/2/12 15:43	2005/2/13 6:38
3	4885	2	2005/2/13 18:00		-	2005/2/12 17:38	2005/2/13 8:38
4	4896	4	2005/2/14 10:00		-	2005/2/12 19:38	2005/2/13 10:32
5	4895	4	2005/2/14 10:00		-	2005/2/12 21:32	2005/2/13 12:28
6	4893	5	2005/2/14 10:00		-	2005/2/12 23:28	2005/2/13 14:24
7	4891	2	2005/2/14 10:00		-	2005/2/13 1:24	2005/2/13 16:21
8	4890	3	2005/2/14 10:00		-	2005/2/13 3:21	2005/2/13 18:20
9	4888	1	2005/2/14 10:00		-	2005/2/13 5:20	2005/2/13 20:21
10	4887	5	2005/2/14 10:00		-	2005/2/13 7:21	2005/2/13 22:23
11	4908	4	2005/2/14 18:00		2005/2/12 12:00	2005/2/13 9:23	2005/2/14 0:16
12	4907	3	2005/2/14 18:00		2005/2/12 14:00	2005/2/13 11:16	2005/2/14 2:10
13	4906	4	2005/2/14 18:00		2005/2/12 16:00	2005/2/13 13:10	2005/2/14 4:06
14	4904	4	2005/2/14 18:00		2005/2/12 18:00	2005/2/13 15:06	2005/2/14 6:03
15	4903	1	2005/2/14 18:00		2005/2/12 20:00	2005/2/13 17:03	2005/2/14 8:01
16	4902	2	2005/2/14 18:00		2005/2/12 22:00	2005/2/13 19:01	2005/2/14 10:00
17	4900	2	2005/2/14 18:00		2005/2/12 0:00	2005/2/13 21:00	2005/2/14 12:01
18	4898	5	2005/2/14 18:00		2005/2/13 2:00	2005/2/13 23:01	2005/2/14 14:03
19	4897	2	2005/2/14 18:00		2005/2/13 4:00	2005/2/14 1:03	2005/2/14 16:06
20	4892	3	2005/2/14 18:00		2005/2/13 6:00	2005/2/14 3:06	2005/2/14 18:09
21	4905	4	2005/2/15 10:00		2005/2/13 20:00	2005/2/14 17:00	2005/2/15 7:58
22	4899	4	2005/2/15 10:00		2005/2/13 21:00	2005/2/14 18:58	2005/2/15 10:00
23	4901	3	2005/2/15 18:00		2005/2/14 5:00	2005/2/15 2:57	2005/2/15 18:00

4.2 Operations in DBR executing phase

In this simulation system, the material is released according to the Rope at gateway station. The order dispatching priority at WS05 (CCR) is according to Drum. As an example shown in Table 5, MO #4887 is being processed and MO# 4908, 4907 and 4902 are waiting to be processed at WS05 at 8:10 2005/2/13. The priority of these three waiting MOs are based on the Drum in Table 4. The order dispatching priority at all non-CCR workstations (WS1~WS4 and WS6~WS9) is based on the first-in, first-out rule. Table 5 shows the dispatching sequence in the queue at different workstations. For example, MO# 4893 arrived at WS03 earlier than MO# 4891, therefore, the priority of MO# 4893 is higher than MO 4891.

4.3 Operation in DBR control phase

A CCR BM window and a shipping BM window are provided in this simulation system for the planners or shop managers. If a MO is identified via BM as an expediting MO, the expediting action in this simulation system is to give this MO dominant priority over others at any non-CCR station until it arrives at CCR station or is shipped out. As shown an example in Table 6, MO# 4904 and 4906 are identified as an expediting MO. As shown at WS09 in Table 5, although the entering time of MO# 4904 is later than MO# 4890, the priority of MO# 4904 is higher than MO# 4890. And as shown in Table 7, MO# 4904 still has dominant priority in its next process at WS07.

Table 5: A snap for the MO priority at the queue of different stations
Observed time: 8:16 2005/2/13

WS	MO	Entering time	priority	Is CCR operation completed?
WS01	-	-	-	-
WS02	-	-	-	-
WS03	*4903 4893 4891	2005/2/13 6:15 2005/2/13 7:41 2005/2/13 7:48	- 1 2	No Yes Yes
WS04	*4892	2005/2/13 7:38	-	No
WS05 (CCR)	*4887 4908 4907 4902	2005/2/13 13:30 2005/2/13 2:58 2005/2/13 6:32 2005/2/13 8:07	- 1 2 3	No No No No
WS06	*4888 4898	2005/2/13 7:10 2005/2/13 7:30	- 1	Yes No
WS07	+*4906	2005/2/13 6:35	-	No
WS08	*4897	2005/2/13 6:27	-	No
WS09	*4900 +4904 4890	2005/2/13 6:26 2005/2/13 8:10 2005/2/13 8:07	- 1 2	No No Yes

*: the MO is processed in that workstation; +: Expediting MO via BM.

Table 6: A snap for CCR BM
Observed time: 8:16 2005/2/13

	MO	Start Time	Arrived at CCR
Expediting Zone	4908 4907 4906 4904	2005/2/13 9:23 2005/2/13 11:16 2005/2/13 13:10 2005/2/13 15:06	Yes Yes No No
Mentioned Zone	4903 4902 4900	2005/2/13 17:03 2005/2/13 19:01 2005/2/13 21:00	No Yes No
Ignored Zone	4998 4897 4892	2005/2/13 23:01 2005/2/14 1:03 2005/2/14 3:06	No No No

Table 7: A snap for the MO priority at the queue of WS07
Observed time: 9:50 2005/2/13

WS	MO	Entering time	Priority	Is CCR operation completed?
WS07	*4906	2005/2/13 6:35	-	No
	+4904	2005/2/13 9:44	1	No
	4888	2005/2/13 9:37	2	Yes

*: the MO is processed in that workstation; +: Expediting MO via BM.

5. Conclusions

The DBR method is the production application of TOC, a global managerial methodology that helps the manager to concentrate on the most critical issues. The DBR represents a set of rules for implementing the exploiting and subordinating to CCR in TOC five focus steps. Three management phases, i.e., planning (scheduling) phase, executing phase and control phase, are required to implement the DBR on a manufacturing plant. For the fulfillment of the exploiting and subordinating CCR in the five focus steps of TOC completely, therefore, a DBR system must consist of these three management phases. A DBR system with these three management phases is referred as a robust DBR management system in this paper. Although the DBR method has been studied in these literatures, however, major focus is only on one management phase.

For DBR to gain acceptance as a viable planning and control system, a robust DBR management system is not investigated yet. In this paper, a robust DBR management system was discussed. Besides DBR scheduling method (for planning phase), executing rules (for executing phase) to implement the DBR schedule in the shop floor and a control mechanism (for control phase), i.e., BM, were also detailed described. A prototype was also provided by the eM-Plant simulation model to demonstrate the significance and feasibility of this robust DBR management system. This study especially facilitates the managers who want to implement the DBR system for improving shop performance of manufacturing plants.

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