http://ansinet.com/itj

ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 10 (1): 40-50, 2011
ISSN 1812-5638

A Modification of Simplified Drum-Buffer-Rope for Re-entrant Flow Shop Scheduling

Y.C. Chang and W.T. Huang
Department of Industrial Engineering and Management, National Chiao Tung University,
Hsinchu 300, Taiwan, Republic of China

Abstract: This study proposes the layer production buffer to monitor the status of the buffer. A dispatching rule is applied to decide the priority of all orders by the buffer status deviation of each re-entrant layer with the consideration of the re-entry feature, termed as $\text{SDBR}_{\text{Reentry}}$, in a RFS environment. To show our $\text{SDBR}_{\text{Reentry}}$ in a RFS, this paper compares four methods, the abovementioned method, traditional SDBR, the applications of the company K and critical ratio in a simulated RFS environment. The resulting outcomes that compare to six approaches indicate that our proposed method improving performance in a RFS. Hence, this method has better performances when an increase in re-entrance orders of product mix result in the better performance of a RFS. Furthermore, the bottleneck machines operate at full capacity.

Key words: Drum-buffer-rope, re-entry, flow shop, scheduling, theory of constraints

INTRODUCTION

Goldratt and Cox (1984) develop the Theory of Constraints (TOC) based on the concepts of the constraint management which is the performance of a system is determined by constraints which are effectively managed by the Five Focusing Steps (5FS). That is, identifying and exploiting constrained resources, subordinating the non-constrained resources with the production pace of constrained resources, elevating throughput by increasing capacity to a constraint (if necessary) and finally preventing inertia to be the constraints of continual improvement. Moreover, the constraints can be divided into three categories: policy constraints, physical constraints and market constraints (Schragenheim and Ronen, 1991; Watson *et al.*, 2007). More precisely, the policy constraints can be interpreted as the capacity of the system limited by formal or informal rules. The physical constraints are to state that the resource capacity is less than demand. The market constraints also can be explained as the demand less than resource capacity.

For physical constraints, Drum-Buffer-Rope (DBR) can be utilized to fulfil the Capacity Constrained Resource (CCR) or bottleneck being exploiting and subordinating process (Goldratt, 1990; Schragenheim and Dettmer, 2001). Let us introduce the concepts of the DBR in the following. The drum which is a detailed schedule of the CCR from the present time to the future controls the pace of production. On the other hand, the buffer is the protection time. Furthermore, the buffer can be discussed in two manners: the CCR buffer and the shipping buffer. The CCR buffer can protect the integrity of the drum and the shipping buffer can protect the shipping schedule. The rope is the release plan based on the changes of the drum as shown in Fig. 1a (Schragenheim and Ronen, 1990; Wu and Liu, 2008). For market constraints, Simplified DBR (SDBR) is more suitable than DBR in solving issues of low demand and due date setting based on Schragenheim and Dettmer (2001). It is doubly important that even though the SDBR is similar with the DBR, there is a little difference among these two concepts. In SDBR, no detailed schedule (or the drum) is created for the CCR. We monitor the CCR with total load to ensure that there exits enough capacity to meet all due dates. The buffer is simplified into one single Production Buffer (PB), which is equivalent to the production cycle time. It allows that no delay of the due date occurs because of the system variations. The Buffer Status (BS) is defined as the percentage penetration into the PB (Schragenheim and Burkhard, 2007). It can be treated as the dispatching rule for prioritizing the orders on shop floor. It should be noted that the rope is the release plan which is generated by pushing back one PB of the promised due date of each order after considering the CCR with the future load. For visualization purpose, we depict the concepts of the SDBR as Fig. 1b.

Previous applications of dispatching rules of DBR and SDBR assume that each job visits CCR or bottleneck at most once (Schragenheim and Ronen, 1990; Schragenheim and Dettmer, 2001; Sirikrai and Yenradee, 2006). We utilize the Fig. 2a to explain the concept of CCR

Corresponding Author: Y.C. Chang, Department of Industrial Engineering and Management, National Chiao Tung University, Hsinchu 300, Taiwan, Republic of China Tel: 0886-3-5731815/7105 Fax: 0886-933960989

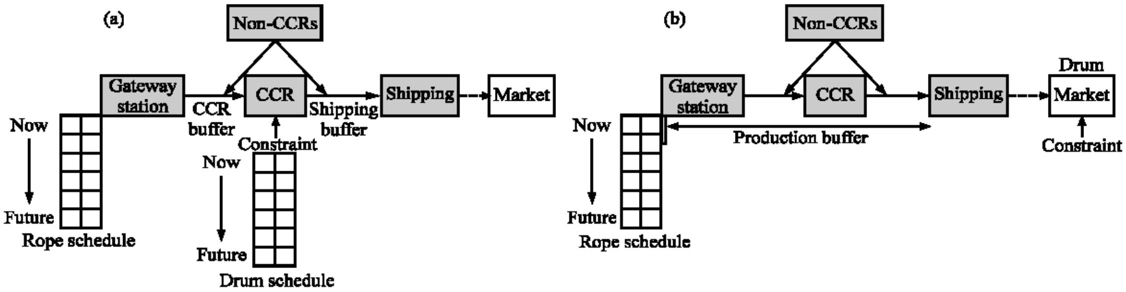

Fig. 1: Major concepts of DBR and SBDR (Wu and Liu, 2008). (a) DBR and (b) SDBR

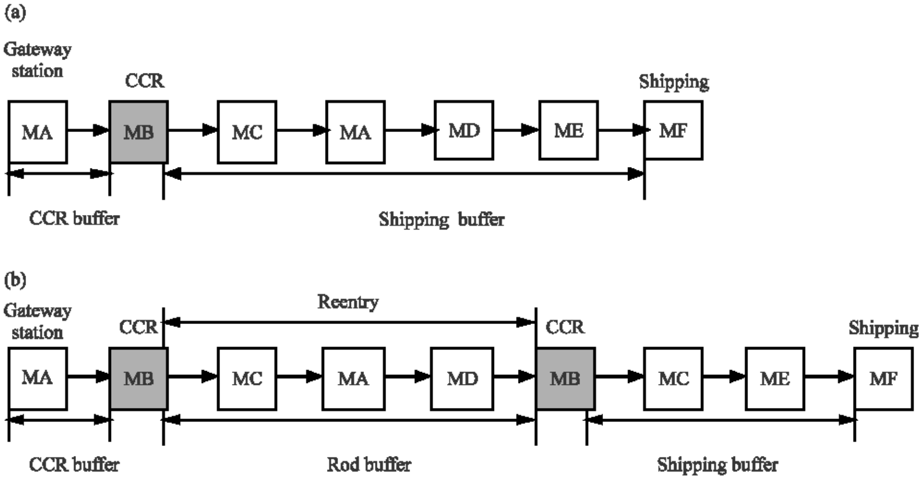

Fig. 2: Concept of the re-entrant flows. (a) Non-reentrant flow and (b) reentrant flow

which is denoted as the machine B (MB). Pan and Chen (2003) argue that re-entrant shops are common in practice. For example, at the photolithography stage in a semiconductor wafer foundry, in the array area of Thin Film Transistor-Liquid Crystal Display (TFT-LCD) manufacturing or in the production process of multilayer motherboards, a job needs to pass through CCR repeatedly to form a re-entrant process (Yan *et al*., 2000). Figure 2b illustrates the concept of a re-entrant process.

As to study of applying DBR to a re-entrant process, Goldratt (1990) proposes a method to add rod buffers into DBR in order to protect subsequent CCR operations. Later, Wu and Yeh (2006) examine the relationship between rod buffer and Operation Separation Time (OST) in applying DBR. Rod buffer refers to the estimated time when a lot leaves and then re-enters the CCR. In addition, OST refers to the time between two adjacent CCR operations in the drum schedule.

Indeed, the earlier study could not show us how to apply their methods in the real world environment. In this study, we consider a situation that often occurs in the reality. That is, Re-entrant Flow Shop (RFS). Chen *et al.* (2007) state that the RFS can be explained as follows: each job of a RFS can be decomposed into several layers containing several machines. We mention that the issue related to the efficient arrangement of the OST is crucial to the DBR that can be applied in a RFS. In a RFS problem, the performance measure plays a key role. Pan and Chen (2003) adopt the makespan as the measurement to solve the scheduling problem. Chen *et al.* (2007) introduce a hybrid tabu search technique to solve the scheduling problem of minimizing the makespan in a RFS. Yang *et al.* (2008) obtained a lower bound on the makespan considering a two machine in a RFS. Dugardin *et al.* (2010) use three multi-objective methods to solve the re-entrant hybrid flow shop scheduling problem. However, it is seldom application applied the SDBR to a RFS. It motivates us to propose a set of control mechanisms and dispatching rules in applying SDBR in a RFS. For simplicity, we denote $\mathrm{SDBR}_{\mathrm{Reentry}}$ as a set of control mechanisms and dispatching rules. To show our $\mathrm{SDBR}_{\mathrm{Reentry}}$ in a RFS, this study considers four types of dispatching rules, the $\mathrm{SDBR}_{\mathrm{Reentry}}$, the SDBR, the case-study approach and the critical ratio. This study adopts six performance indexes related to due date.

To our best knowledge, it is seldom study to apply the SDBR in a RFS and encourages us to fulfil the gap between the SDBR and RFS.

SDBR$_{\text{REENTRY}}$ MODEL

SDBR introduction: Before illustrating the SDBR$_{\text{Reentry}}$ model, it is needed to explain several terms used in applying SDBR method. The first term is touch time that represents the shortest processing time on a machine of a work order includes setup time and then the total touch time of a work order can be calculated by the summation of the shortest processing time on each machine where a work order passes through. The second term is Production Buffer (PB) that represents the time of a work order from the release date to the due date and is equal to cycle time. It should be noted that PB has a positive relationship with the touch time. The third term is Planned Load (PL). It intends to convert each work order into the number of capacity hours of CCR that is needed in the future. Combining the resulting outcome with the original CCR, we can derive the planned load. Hence, each work order has an accumulated point in CCR. The release point is obtained by moving backward each PL point subtracting the half of a PB. On the other hand, safe delivery is obtained by adding the half of a PB. Usually, promise due date can be estimated as additional buffer plus safe delivery. Then the manager can inform the customer about the promise due date. The fourth term is Buffer Management (BM) which is a mechanism that adopts the Buffer status (BS) to decide the urgency of a work order (Schragenheim, 2006). Lee *et al*. (2010) further define BS as the dispatching rule of CCR shown by Eq. 1.

$$\text{BS} = \frac{(\text{Production buffer} - \text{Remain days to due date})}{\text{Production buffer}} \qquad (1)$$

The numerator in Eq. 1 represents penetration that is the accumulated flow time of a specific work order on the shop floor from the release date until the CCR is reached. High penetration rate means that increasing consumption of PB leads to the possibility of delayed delivery. In other words, the order with the high value of the BS results in the higher sequence of the CCR. Figure 3 can aids us in introducing our model.

Drawback of SDBR dispatching rule in re-entrant flow shop: For simplicity, we can decompose Eq. 1. Hence, the BS is manipulated as the ratio between the flow time and the PB of a specific work order on the shop floor as shown by Eq. 2.

In a RFS, if the manufacturing plant uses Eqs. 1 or 2 to decide the priority of all work orders on shop floor, the dispatch of CCR can be improved in three aspects. Firstly, the work order of short production buffer time (or cycle time) is always prior to that of long ones. Consider the situation (a) in Table 1 as an example. The PB of work order 1 is shorter than that of work order 2. If it is also retained on the shop floor for 16 days, the dispatching rule of BS would arrange the work order 1 of a shorter PB prior to the work order 2 of a longer PB. If the situation (a) occurs, the number of the work order 1 is apparently larger than the number of the work order 2. It leads to an increase in the probability of the delay of the work order 2.

Table 1: An illustrated example of SDBR dispatching results

Situation	Order no.	PB	CCR layer	Total CCR layer	Total flow time	BS (%)	Priority
a	1	18	2	2	16	89	*
	2	24	2	3	16	67	
b	3	18	1	2	12	67	*
	4	24	2	3	16	67	*
c	5	24	3	3	16	67	*
	6	24	2	3	16	67	*

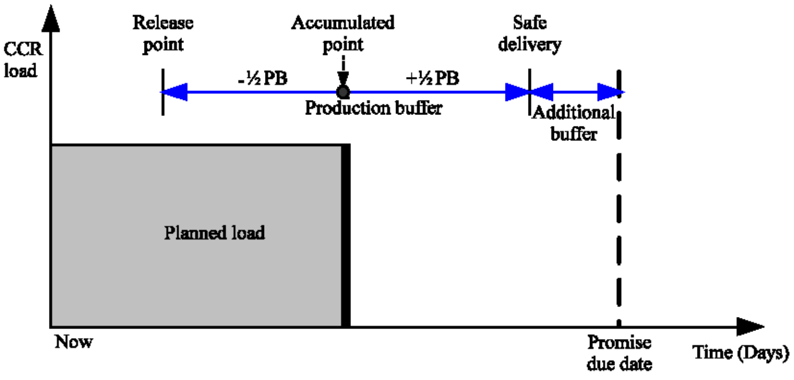

Fig. 3: The framework of SDBR system

$$\begin{aligned}\text{BS} &= \frac{(\text{Production buffer - Remain days to due date})}{\text{Production buffer}}\\ &= \frac{[\text{PB - (Due date - Today' date)}]}{\text{PB}}\\ &= \frac{[\text{Today' date - (Due date - PB)}]}{\text{PB}}\\ &= \frac{(\text{Today' date - Release date})}{\text{PB}}\\ &= \frac{\text{Flow time}}{\text{PB}}\end{aligned} \tag{2}$$

Secondly, when two orders belong to different products but have the same urgency of the due date occurs, SDBR cannot distinguish the differences among work orders that indeed generate the risk of delay. Take the situation (b) in Table 1 into consideration. Work order 3 and work order 4 belong to different products, but have the same BS. If the dispatching rule is not predefined for the second priority, SDBR would choose one of them arbitrary. If the system has the majority of work orders with the same BS, it would be unable to distinguish work orders that truly generate the risks of delay and reduce the due date performance.

Thirdly, when two orders belong to the same product and have the same urgency of the due date, SDBR cannot distinguish work orders that truly generate the risk of delay. Similarly, take the situation (c) in Table 1 as an example. Work order 5 and work order 6 belong to the same product and have the same BS but they are at different CCR layers. If the dispatching rule is not predefined for the second priority, SDBR would choose one of them arbitrarily. In practice, the risks of delay of work order 6 at layer 2 is higher than work order 5 at layer 3. Hence, if SDBR is prior to work order 5, it would increase the risk of delay of work order 6.

A modification of SDBR for re-entrant flow shop: The performance of traditional SDBR would be limited when it is applied to a re-entrant manufacturing environment due to its dispatching rule. The $\text{SDBR}_{\text{Reentry}}$ further considers re-entrant layers (layered control) in the buffer management mechanism of SDBR and decides the priority of all work orders by the buffer status deviation of each re-entrant layer. The $\text{SDBR}_{\text{Reentry}}$ model is described in the following. The notations used in this study as given below.

m : No. of orders

n_i : No. of orders of product i, for i = 1, 2, …, m

o_i : No. of re-entrant layers of product i, for i = 1, 2, …, m

BS_{ij} : The buffer status ratio of order j of product i, for i = 1, 2, …, m, j = 1, 2, …, n_i

PB_{ij} : The production buffer time of order j of product i from the release date to the due date, for i = 1, 2, …, m, j = 1, 2, …, n_i

LPB_{ijk} : Layer production buffer, the production buffer time of order j of product i at the kth layer, for i = 1, 2, …, m, j = 1, 2, …, n_i, k = 1, 2, …, o_i

LFT_{ijk} : Layer flow time, the flow time of order j of product i at the kth layer, for i = 1, 2, …, m, j = 1, 2, …, n_i, k = 1, 2, …, o_i

TFT_{ij} : Total flow time, the total flow time of order j of product i on the shop floor, for i = 1, 2, …, m, j = 1, 2, …, n_i

LBS_{ijk} : Layer buffer status, the buffer status ratio of order j of product i at the kth layer, for i = 1, 2, …, m, j = 1, 2, …, n_i, k = 1, 2, …, o_i

LTT_{ijk} : Layer touch time, the touch time of order j of product i at the kth layer for i = 1, 2, …, m, j = 1, 2, …, n_i, k = 1, 2, …, o_i

TTT_{ij} : Total touch time, the total touch time of order j of product i on the shop floor, for i = 1, 2, …, m, j = 1, 2, …, n_i

The PB of each product with re-entrant flows divided into layers based on the number of CCR. It follows that we can obtain an estimated value of PB for each CCR layer. We intend to analyze the urgency of each CCR layer accurately. Therefore, the BS should be adjusted to consider the deviations of overall urgency and urgency at different layers. The actual sequence should be determined based on their BS deviation. We summarize the above statement about the mechanism of $\text{SDBR}_{\text{Reentry}}$ as Fig. 4. In the following, we introduce the formula needed utilized in present study.

$$\text{BS}_{ij} = \frac{\sum_{k=1}^{o_i} \text{LFT}_{ijk}}{\text{PB}_{ij}} \times 100\%, \text{ for } i = 1, 2, ..., m, j = 1, 2, ..., n_i \tag{3}$$

$$\text{LPB}_{ijk} = \frac{\text{LTT}_{ijk}}{\text{TTT}_{ij}} \times \text{PB}_{ij}, \text{ for } i = 1, 2,...., m, j = 1, 2,...., n_i, k = 1, 2,...., o_i \tag{4}$$

$$\text{LBS}_{ijk} = \frac{\text{LFT}_{ijk}}{\text{LPB}_{ijk}} \times 100\%, \text{ for } i = 1, 2,...., m, j = 1, 2,...., n_i, k = 1, 2,...., o_i \tag{5}$$

$$\Delta\text{BS}_{ijk} = \text{BS}_{ij} - \text{LBS}_{ijk}, \text{ for } i = 1, 2,..., m, j = 1, 2,..., n_i, k = 1, 2,..., o_i \tag{6}$$

From Eq. 3 to 6, these concepts can be explained as follows: the BS_{ij} is the accumulated urgency of each work

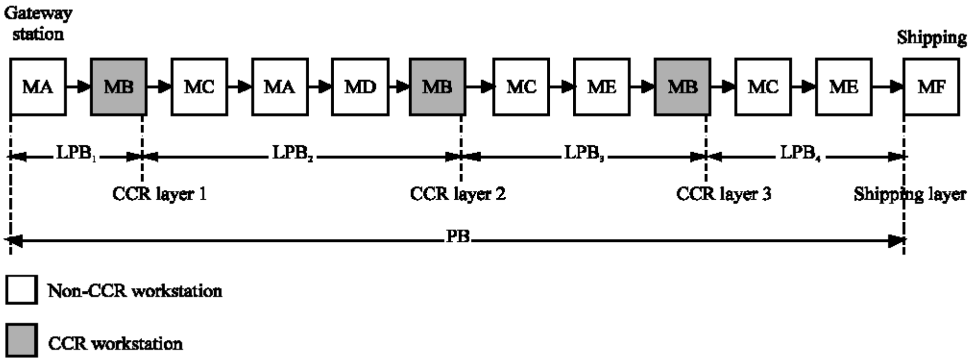

Fig. 4: Layered control diagram of re-entrant layers in $\text{SDBR}_{\text{Reentry}}$

Table 2: An illustrated example of $\text{SDBR}_{\text{Reentry}}$ dispatching results

								SDBR		$\text{SDBR}_{\text{Reentry}}$		
Situation	Order no.	PB	CCR layer	Total CCR layer	Total flow time	Layer flow time	LPB	BS (%)	Priority	LBS (%)	ΔBS (%)	Priority
a	1	18	2	2	16	5	8	89	*	63	26	
	2	24	2	3	16	3	8	67		38	29	*
b	3	18	1	2	12	1	4	67	*	25	42	
	4	24	2	3	16	1	8	67	*	13	54	*
c	5	24	3	3	16	1	6	67	*	17	50	
	6	24	2	3	16	1	8	67	*	13	54	*

order among layers. The LPB_{ijk} equals to the weight of different layers multiplied by the production buffer. The production buffer for different layers can be estimated by the LPB_{ijk}. In addition, LBS_{ijk} is used to judge the urgency of each work order among layers. The ΔBS_{ijk} is the deviation of the overall and actual urgency of each work order. High ΔBS_{ijk} implies that itself is with high priority. Non-CCR machines are dispatched following the First-In-First-Out (FIFO) rule.

Procedures of $\text{SDBR}_{\text{Reentry}}$: Here, we summarize the procedures of $\text{SDBR}_{\text{Reentry}}$ so as to be easy apply it to the practice as follows:

- **Step 1. Estimate the PB for each product in each CCR layer:** Calculate the touch time of each product respectively at the initial stage; the PB of each product with re-entrant flows should be divided into layers based on the number of CCR entries. Then we can derive the estimated PB in each CCR layer
- **Step 2. Calculate the PL of each CCR layer:** Once receiving a new order, the managers converts each work order into the number of capacity hours of each CCR layer that is needed in the future. Combining the resulting outcome with the original CCR, we can derive the planned load. Ensure that it will not exceed the due date after adding the half of a PB
- **Step 3. Decide the release schedule:** The work order is released into the shop floor according to the flow time it will works on CCR minus the half of a PB to get the release date. Then prioritize the release date of work orders from now to future, so that we can obtain the complete release schedule
- **Step 4. Decide the dispatching schedule:** Calculate the overall urgency BS_{ij} of each work order accumulates in front of the CCR, calculate the urgency LBS_{ijk} for each work order in each layer and rank the deviation rate ΔBS_{ijk} from high to low to obtain the complete real-time dispatching schedule for CCR layers. Non-CCR machines are dispatched following the FIFO rule

Example: To illustrate the proposed procedure of $\text{SDBR}_{\text{Reentry}}$, let us reconsider the example in Table 1. The resulting outcomes can be listed in Table 2. PB_{ij} is assumed to be twice as much the touch time for each product. BS_{ij} is the overall urgency of SDBR in Table 1. LBS_{ijk} which is the ratio between LFT_{ijk} and LPB_{ijk} can be used to judge the actual urgency of each work order among layers. ΔBS_{ijk} which records the difference between BS_{ij} and LBS_{ijk} is the dispatching priority of $\text{SDBR}_{\text{Reentry}}$, representing the deviation rate of overall urgency and actual urgency in different layers.

In Table 2, it can be seen that SDBR considers only the total flow time of work order 1 and work order 2 in situation (a). It leads the work order of a shorter PB to be prioritized over the longer PB. The reason is that BS_{ij} only represents the planned value of the overall urgency for a specific work order with re-entrant flows. Due to the complexity of re-entrant flows, we have to consider the urgency of a specific work order at each CCR layer. Hence, we can obtain the actual urgency of a specific work order. Calculate the LBS_{ijk} for each work order at each layer and prioritize the deviation rate ΔBS_{ijk} from high to low, then the work order 2 that can distinguish between the risks of delay under a RFS environment.

Moreover, work orders that truly generate the risks of delay could be distinguished when $SDBR_{Reentry}$ is applied to two or more work orders with the same urgency rate. For example, work order 3 and work order 4 in situation (b) of Table 2 involve different products but have the same urgency. BS_{ij} dispatching priority in SDBR will recommend choosing one of them arbitrarily. However, $SDBR_{Reentry}$ allows choosing work order 4, which truly generates risks of delay after measuring the deviation rate ΔBS_{ijk} of the planned and actual value of the overall urgency. Work order 5 and work order 6 in situation (c) of Table 2 are the same product and urgency, but belong to different layers. Under SDBR method, values of BS_{ij} are the same and can be chosen arbitrarily. However, it appears practically certain that work order 6 in layer 2 has higher risks of delay than work order 5 in layer 3. When choosing a specific work order with ΔBS_{ijk}, its allows $SDBR_{Reentry}$ to choose work order 6, which generates the risk of delay.

Note that the negative ΔBS_{ijk} represents a work order processed ahead of schedule in a specific layer under $SDBR_{Reentry}$. This can be used as an alarm for real-time dispatching on the shop floor. The value of ΔBS_{ijk} is approximate one represents the ratio that is a specific work order not been processed in a specific layer. It is the same as the order lags behind the planned value of the overall urgency in a specific layer. Hence, it can be regarded as the second alarm. Managers judge the necessity of launching the expediting mechanism.

COMPUTATIONAL EXPERIMENT

In order to compare the performance of $SDBR_{Reentry}$ and SDBR in a RFS, this paper establishes a simulation plant satisfying the actual manufacturing environment of a multilayer printed circuit boards plant in Taiwan. Because of the company property, we refer the company as the company K. The simulation plant implements in a Make to Order (MTO) environment. Since 2007, the company K has implemented the SDBR project. After measuring the performance of the SDBR implementation in 2008, the company K found that the SDBR was not applicable for a re-entrant process because the SDBR could not distinguish different products with the same urgency in delivery. Therefore, it motivates us to propose a set of control mechanisms and dispatching rules in applying the SDBR in a RFS simulated environment.

Table 3: Product routing in the simulated plant

	Product		
Step	P1	P2	P3
1	MA	MA	MA
2	MB	MB	MB
3	MC	MC	MC
4	MA	MA	MA
5	MD	MD	MD
6	ME	MB	MB
7	MF	MC	MC
8		ME	ME
9		MF	MB
10			MC
11			ME
12			MF

Table 4: Calculation results of the average load for machines in the simulated plant

	Machine					
	A	B[a]	C	D	E	F
P1	2	1	1	1	1	1
P2	2	2	2	1	1	1
P3	2	3	3	1	2	1
Sum	6	6	6	3	4	3
Avg.	2	3	2	1.5	2	1.5

[a]CCR machine which is identified by summing the processing times of all operations to be performed at a machine

Profile of simulation environment: The simulation plant produces three types of products: P1, P2 and P3. Each of them has re-entrant processes. Table 3 lists the product routing in the simulated plant. The simulation plant has six types of machines: A, B, C, D, E and F, with respective quantities of 3, 2, 3, 2, 2 and 2. The CCR for the simulation plant is calculated based on the method recommended by Russell and Taylor (2005). Furthermore, sum over total processing time of each product for each machine. The average load for each machine would be equal to the sum of total processing time divided by the number of machines. The machine B with the highest average load is CCR for the simulation plant as shown in Table 4. Therefore, P1, P2 and P3 require 0, 1 and 2 re-entrant layers, respectively. We assume that there is only one type of raw material provided for all three types of products. Also, each machine can process only one work order each day. We assume that all operations to be performed at a machine require the same processing time. We fix that one work order representing one lot, processing lot and transfer lot. The study assumes that the simulation plant has a zero defective rate of machine and the yield rates of three products are all 100%.

This study is simulated four dispatching and release rules, the $\mathrm{SDBR}_{\mathrm{Reentry}}$, the SDBR, the case-study method (we refer the method as the method K) and the Critical Ratio (CR). This study adopts six performance indexes related to due date. These are Throughput Dollar Day (TDD), Inventory Dollar Day (IDD), Due Date Slack Time (DDST), Due Date Performance (DDP), average queue length in front of CCR (Q_CCR) and Total Flow Time.

The notations used in the six performance indexes are described as below:

CD_{ij} : The completed date of order j of product i, for i = 1, 2, …, m, j = 1, 2, …, n_i
DD_{ij} : The due date of order j of product i, for i = 1, 2, …, m, j = 1, 2, …, n_i
O_{ijk} : Order j of product i is processed on CCR at the kth layer, for i = 1, 2, …, m, j = 1, 2, …, n_i., k = 1, 2, …, o_i
OV_{ij} : The value of the orders of order j of product i, for i = 1, 2, …, m, j = 1, 2, …, n_i
RD_{ij} : the release date of order j of product i, for i = 1, 2, …, m, j = 1, 2, …, n_i
U_{ij} : indicate whether order j of product i is completed by its due date. i.e., if $\mathrm{DD}_{ij} > \mathrm{CD}_{ij}$, then $U_{ij} = 1$; otherwise, $U_{ij} = 0$, for i = 1, 2, …, m, j = 1, 2, …, n_i
WV_{ij} : the value of the WIP of order j of product i, for i = 1, 2, …, m, j = 1, 2, …, n_i
Q_{ijkt} : =1, if order j of product i is queued in front of the CCR at time t; =0, otherwise, for i = 1, 2, …, m, j = 1, 2, …, n_i, k = 1, 2, …, o_i

The six performance indexes are calculated as Eq. 7 to 12.

$$\mathrm{TDD} = \frac{1}{m} \times \sum_{i=1}^{m} \sum_{j=1}^{n_i} \frac{\left[\mathrm{OV}_{ij} * \left\{\mathrm{Max}(0, \mathrm{CD}_{ij} - \mathrm{DD}_{ij})\right\}\right]}{n_i} \tag{7}$$

$$\mathrm{IDD} = \frac{1}{m} \times \sum_{i=1}^{m} \sum_{j=1}^{n_i} \frac{\left[\mathrm{WV}_{ij} * (\mathrm{CD}_{ij} - \mathrm{RD}_{ij})\right]}{n_i} \tag{8}$$

$$\mathrm{DDST} = \frac{1}{m} \times \sum_{i=1}^{m} \sum_{j=1}^{n_i} \frac{(\mathrm{DD}_{ij} - \mathrm{CD}_{ij})}{n_i} \tag{9}$$

$$\mathrm{DDP} = \frac{1}{m} \times \sum_{i=1}^{m} \sum_{j=1}^{n_i} \left(\frac{U_{ij}}{n_i}\right) \tag{10}$$

$$\mathrm{Q\_CCR}_t = \frac{1}{m} \times \sum_{i=1}^{m} \sum_{j=1}^{n_i} \sum_{k=1}^{o_i} \left(\frac{Q_{ijkt}}{n_i}\right) \tag{11}$$

$$\text{Flow time} = \sum_{i=1}^{m} \sum_{j=1}^{n_i} \left\{(\mathrm{CD}_{ij} - \mathrm{RD}_{ij}) + 1\right\} \tag{12}$$

In Eq. 7 to 12, TDD which is the summation of the value of the orders multiplied by the number of days by which their delivery is late and is typically tracked to guide managers to focus on improving throughput; IDD is the summation of the dollar value of the WIP multiplied by the time since the WIP entered the plant. It is usually used to guide managers to focus on reducing the plant's actual WIP and production cycle time (Ho and Li, 2004); DDP is tracked to guide managers to focus on ensuring no delay of each order; DDST which is represented by the number of days that the order is completed ahead of schedule depicts the ability to protect the due date; Q_CCR which is the total average of queuing work orders before CCR.

Test problem design: The test problem in simulation plant can be considered by two factors in practice:

- **Different utilization ratios of CCR:** Under different utilization ratios of CCR situations, different numbers of work orders need to be processed on and this has various impacts on the planned load of CCR among machines. Hence, we consider three utilization ratios of CCR by 70, 80 and 90%, respectively
- **Different layer mixes of CCR:** Due to the complexity of re-entrant flows and its dispatching rule, the performance of $\mathrm{SDBR}_{\mathrm{Reentry}}$ might be limited when it is applied to a RFS. So we take into account three combinational ratios of three layer mixes are simulated as: B-B-B (1 : 1 : 1), L-H-L (1 : 6 : 3), L-L-H (3 : 1 : 6). That the triplet can be interpreted as follows: B is Balance, L is Low and H is High. For example, L-L-H (3 : 1 : 6) represents P1 : P2 : P3 = 3 : 1 : 6. Table 5 shows the nine test scenarios of the two factors

Description of SDBR, critical ratio method and method K: In order to compare the performances of the $\mathrm{SDBR}_{\mathrm{Reentry}}$ under a RFS environment. This paper selected SDBR, CR and method K to evaluate its efficiency. The detailed steps are described as the following.

Table 5: The design of test problems

		Layer mix			Proportion		
Scenario	Utilization (%)	P1[a]	P2	P3	P1	P2	P3
1	70	B[b]	B	B	1	1	1
2		L	H	L	1	6	3
3		L	L	H	3	1	6
4	80	B	B	B	1	1	1
5		L	H	L	1	6	3
6		L	L	H	3	1	6
7	90	B	B	B	1	1	1
8		L	H	L	1	6	3
9		L	L	H	3	1	6

[a]The simulation plant produces three types of products: P1, P2 and P3. [b]The triplet can be interpreted as follows: B is Balance, L is Low and H is High

Procedures of SDBR

- **Step 1. Calculate the touch time of each product and estimate the PB:** Calculate the touch time of each product at the initial stage, then estimate PB of each product by the touch time multiplying the constant times on practical experience
- **Step 2. Calculate the PL of CCR:** When receiving a new order, the managers will convert each work order into the number of capacity hours of CCR that is needed in the future. Combining the resulting outcome with the original CCR, we can derive the planned load. Ensure that it will not exceed the due date after adding the half of a PB.
- **Step 3. Decide the release schedule:** The work order is released into the shop floor according to the flow time it will work on CCR minus the half of a PB to get the release date and prioritize the release date from now to future to obtain the complete release schedule.
- **Step 4. Decide the dispatching schedule:** Calculate the overall urgency BS_{ij} of each work order accumulates in front of the CCR. Then prioritize the BS_{ij} from high to low to obtain the complete real-time dispatching schedule for CCR. Non-CCR machines are dispatched under the FIFO rule

Procedures of CR

- **Step 1. Decide the CCR dispatching schedule:** Calculate the respective CR of each work order waiting before CCR according to Eq. 13. Then prioritize the CR ratio from low to high to obtain the real-time dispatching schedule of CCR

$$\begin{aligned} CR &= \frac{\text{Time remaining}}{\text{Work remaining}} \\ &= \frac{(\text{Due date - Today' date})}{\text{Remaining processing time}} \times 100\% \end{aligned} \tag{13}$$

- **Step 2. Decide the non-CCR dispatching schedule:** Non-CCR dispatching schedule based on the principle of FIFO rule

Procedures of method K

- **Step 1. Decide the release schedule:** The release point is obtained by moving backward each due date was assigned by the client subtracting one average Quoted Lead Time (QLT) of the market. Then prioritize them from the present time to the future to obtain the integrated release schedule
- **Step 2. Decide the dispatching schedule:** Calculate the Modified Critical Ratio (MCR) of each work order waiting before CCR according to Eq. 14. The difference between CR and MCR is the remaining processing time. That is, the part of numerator is the major difference. Then prioritize the MCR ratio from low to high to obtain the complete CCR real-time dispatching schedule

$$MCR = \frac{(\text{Due date - Today' date})}{(3 \times \text{Remaining touch time})} \times 100\% \tag{14}$$

- **Step 3. Decide the non-CCR dispatching schedule:** Decide the dispatching schedule of non-CCR under the FIFO principle

EXPERIMENTAL RESULTS

Simulation experiments in this plant start with an empty plant. Machines are at either up or idle states at the beginning. The length of time for each simulation is three times of touch time for each product. Each machine only processes one work order each day, operates seven days a week with one shift per day. To provide a consistent basis to comparison between four dispatching rules, the due date and release date are kept constant as three times of touch time for each product. Four dispatching rules are respectively executed ten times under nine scenarios. The resulting simulation outcomes are as follows.

Analysis of performance under different utilization ratios of CCR: Figure 5 shows the IDD of four methods under different utilization ratios of CCR. When PB is three times of touch time and layer mix is kept as constant, the IDD obtained from $SDBR_{Reentry}$ is the smallest under the three utilization ratios of CCR. Moreover, it has the largest

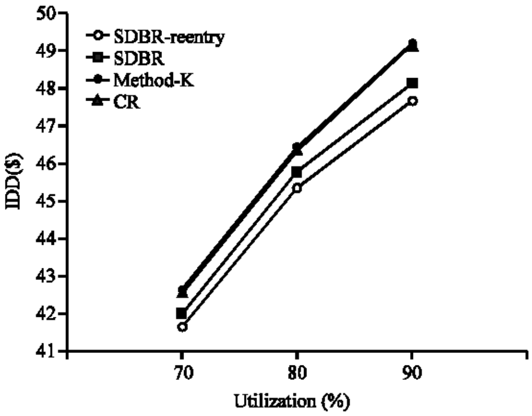

Fig. 5: IDD under different utilization ratios

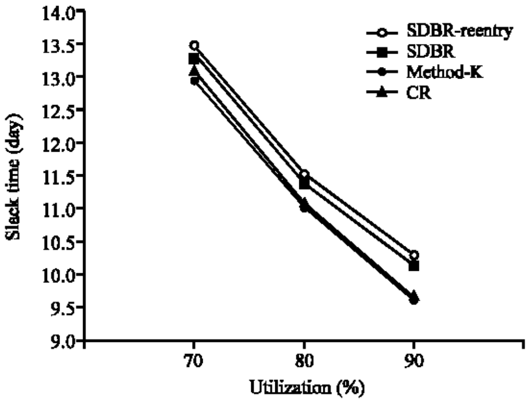

Fig. 6: DDST under different utilization ratios

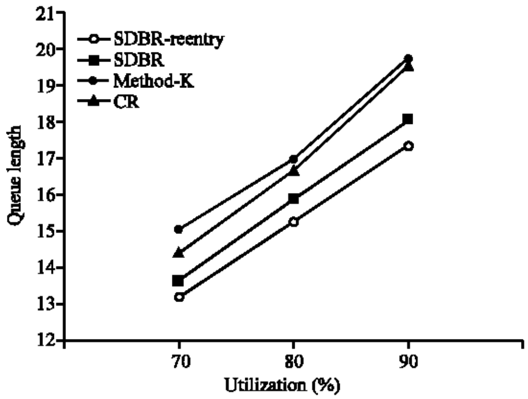

Fig. 7: Q_CCR under different utilization ratios

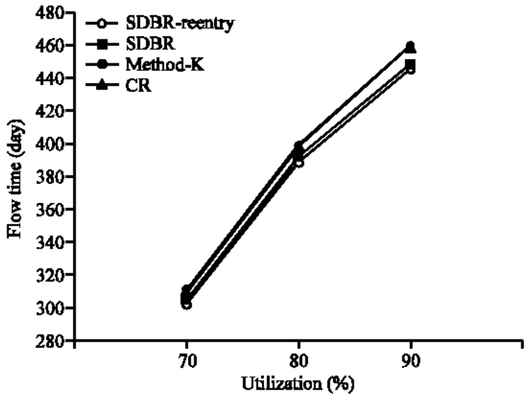

Fig. 8: Flow time under different utilization ratios

gap with the other methods if the utilization ratio of CCR is 90%. This study infers that it is driven by the deviation rate ΔBS_{ijk} of the layered control added into $SDBR_{Reentry}$.

Figure 6-8 show the DDST, the Q_CCR and the flow time obtained from four methods, respectively, when PB is three times of touch time and layer mix is kept as constant under different utilization ratios of CCR. It can be

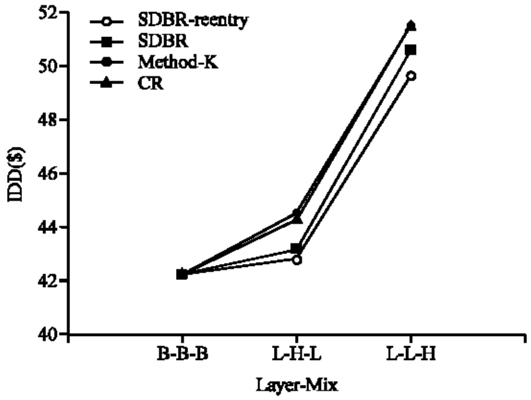

Fig. 9: IDD under different layer mixes

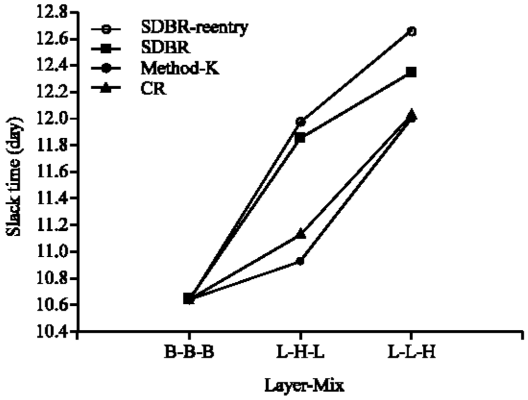

Fig. 10: DDST under different layer mixes

seen from Fig. 6 that the DDST obtained from $SDBR_{Reentry}$ is the largest under all three utilization ratios of CCR, represents the better protection of due date under $SDBR_{Reentry}$. Figure 7 shows that the Q_CCR is obtained from $SDBR_{Reentry}$. It leads to the Q_CCR is the smallest under different utilization ratios of CCR and to the biggest gap in comparison with other methods when the utilization ratio of CCR is 90%. This study shows that it results from the layered control by the deviation rate ΔBS_{ijk} for each re-entrant layer in SDBR $_{Reentry}$Figure 8 shows that the flow time obtained from $SDBR_{Reentry}$ is not significantly better than other three methods under three utilization ratios of CCR.

From the simulation result, it can be seen that the TDD of the four methods is 0 and the DDP is 100%. Therefore, we do not have further discussion about this matter.

Analysis of performance under different layer mixes of CCR: Figure 9-12 show that the changes of CCR resulting the four indexes. The change of CCR means that layer mix is changed and the rest of factors are the same as before.

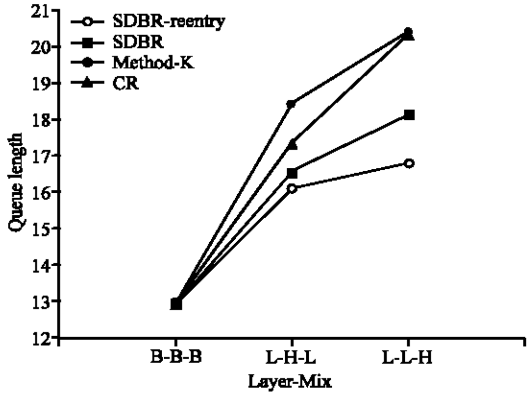

Fig. 11: Q_CCR under different layer mixes

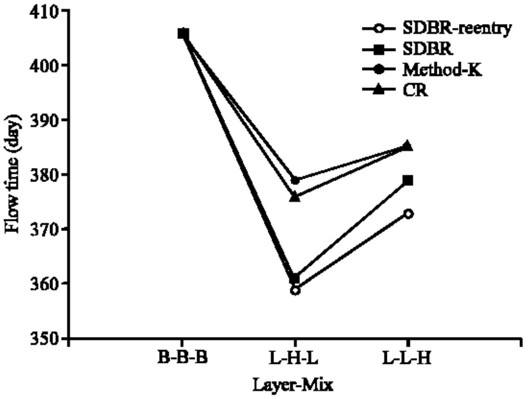

Fig. 12: Flow time under different layer mixes

In Fig. 9, 11 and 12, the IDD, the Q_CCR and the flow time obtained from SDBR$_{\text{Reentry}}$ are smallest under two layer mixes. SDBR$_{\text{Reentry}}$ has the biggest gap in comparison with SDBR method when work orders with 2 CCR reentries are in the majority (L-L-H indicates the ratio of 0 reentry, 1 reentry and 2 reentries), indicates better performance if the product portfolio has more multi-reentrant work orders.

Figure 10 demonstrates that SDBR$_{\text{Reentry}}$ has the largest gap with the DDST in other methods when work orders (L-H-L) with 1 CCR reentry playing the most parts. SDBR$_{\text{Reentry}}$ has the largest gap with SDBR when work orders with 2 CCR reentries are playing the most parts, indicates the better protection of due date. The above results show that the deviation rate ΔBS_{ijk} for layered control into SDBR$_{\text{Reentry}}$ has impact on the original SDBR in the positive direction.

DISCUSSION

As stated above, we attempt to explain why SDBR$_{\text{Reentry}}$ would perform better than SDBR in a RFS. In the example, SDBR uses the BS to decide the priority of all work orders while SDBR$_{\text{Reentry}}$ uses the ΔBS in a RFS (Table 2). Note that the BS represents the planned value of the urgency for a specific work order with re-entrant flows. When work orders have the same BS but they are at different CCR layers, SDBR cannot distinguish work orders that truly generate the risk of delay. By contrast, SDBR$_{\text{Reentry}}$ adopts the LBS to judge the actual value of the urgency of each work order among layers. Finally, after the deviation rate ΔBS is measured, SDBR$_{\text{Reentry}}$ will choose work orders which result in the risk of delay in a RFS.

In order to investigate the various impacts on the planned load of CCR among machines, we consider the utilization ratios of CCR from 70 to 90%, respectively. In comparison with the performance (such as protection of due date, the queue length in front of CCR and the flow time) between SDBR$_{\text{Reentry}}$ and SDBR, the results indicate that the larger the utilization ratios of CCR are, the better the performance of SDBR$_{\text{Reentry}}$ is.

For the sensitivity analysis, the number of work orders in Table 2 is increased and the results are displayed in Fig. 9 to 12, which show that the SDBR$_{\text{Reentry}}$ has the better protection of due date, the lower queue length in front of CCR and the lower flow time than those of SDBR. The plausible reason of the findings is that the SDBR$_{\text{Reentry}}$ takes ΔBS into consideration, but SDBR do not. However, most previous SDBR studies are to implement the SDBR in a non-RFS environment, but this paper pioneers to apply the SDBR with re-entry feature in a RFS environment. For example, Schragenheim and Dettmer (2001) develop the concept of SDBR in a non-RFS environment. Furthermore, they argue that in a RFS, a planned sequence of operations can be much better than an arbitrary sequence. By contrast, our findings are different from Schragenheim and Dettmer (2001) inference in a RFS environment. The possible reason is that the SDBR$_{\text{Reentry}}$ decides the priority of all orders with the consideration of the re-entry feature, but they do not. Schragenheim (2006) describes the MTO aspects of implementing the due date setting method of SDBR in a non-RFS environment. Further Lee *et al.* (2010) extend the work of Schragenheim (2006) and deal with whether CCR is located in the middle of the routing as assumed in SDBR or not.

From the viewpoint of a RFS environment, there are several studies which focus on minimizing the makespan of the scheduling problems in a RFS environment. For instance, Pan and Chen (2003) propose three extended mixed binary integer programming formulations and six extended effective heuristics for solving re-entrant permutation flow shop scheduling problems. Chen *et al.* (2007) introduce a hybrid tabu search technique to solve the scheduling problems in a RFS environment. Yang *et al.* (2008) obtain a lower bound on the makespan considering a two machine in a RFS environment. Dugardin *et al.* (2010) use three multi-objective methods to solve the re-entrant hybrid flow shop scheduling problem. By contrast, the $\text{SDBR}_{\text{Reentry}}$ of this research emphasizes the concept of CCR (or bottleneck) which reduces the complexity of scheduling problems from the entire machines to the CCR machine.

CONCLUSIONS AND FUTURE RESEARCH

The main contribution of this study is to propose $\text{SDBR}_{\text{Reentry}}$ $(\Delta \text{BS})_{jk}$ given the buffer management mechanism of SDBR is adopted in re-entrant environment. Calculating the future planned load of CCR for each work order can derive the promised due date, release date and conduct layered control according to the re-entrant layers. Also this can make the decision on the priority of all work orders based on the deviation rate for buffer status of each re-entrant layer.

This study compares six performance indexes related with the due date by applying four methods as mentioned earlier. The results show that the proposed modified method has better performance in the manufacturing environment with re-entrant characters when the product portfolio has a big ratio of multi-reentrant orders, or when the bottleneck machine of the system approaches full load with the utilization ratio above 90%. Because the study does not consider the machine setup time and machine failures situations, future research may consider these factors. In addition, further studies may perform two bottleneck machines on a system.

REFERENCES

Chen, J.S., J.C.H. Pan and C.K. Wu, 2007. Minimizing makespan in reentrant flow-shops using hybrid tabu search. Int. J. Adv. Manuf. Technol., 34: 353-361.

Dugardin, F., F. Yalaoui and L. Amodeo, 2010. New multi-objective method to solve reentrant hybrid flow shop scheduling problem. Eur. J. Operational Res., 203: 22-31.

Goldratt, E.M. and J. Cox, 1984. The Goal. North River Press, Croton-on-Hudson, NY, ISBN: 0884270610.

Goldratt, E.M., 1990. The Haystack Syndrome: Sifting Information Out of the Data Ocean. North River Press, Great Barrington, MA, ISBN: 0884270890.

Ho, T.F. and R.K. Li, 2004. Heuristic dispatching rule to maximize TDD and IDD performance. Int. J. Prod. Res., 42: 5133-5147.

Lee, J.H., J.G. Chang, C.H. Tsai and R.K. Li, 2010. Research on enhancement of TOC simplified drum-buffer-rope system using novel generic procedures. Expert Syst. Appl., 37: 3747-3754.

Pan, J.H. and J.S. Chen, 2003. Minimizing makespan in re-entrant permutation flow-shops. J. Operational Res. Soc., 54: 642-653.

Russell, R.S. and B.W. Taylor, 2005. Operations Management: Quality and Competitiveness in a Global Environment. John Wiley and Sons, New York, ISBN: 0471692093.

Schragenheim, E. and B. Ronen, 1990. Drum-buffer-rope shop floor control. Prod. Invent. Manage. J., 31: 18-23.

Schragenheim, E. and B. Ronen, 1991. Buffer management: A diagnostic tool for production control. Prod. Invent. Manage. J., 32: 74-79.

Schragenheim, E. and H.W. Dettmer, 2001. Manufacturing at Warp Speed: Optimizing Supply Chain Financial Performance. St. Lucie Press, Boca Raton, FL, ISBN: 1574442937.

Schragenheim, E., 2006. Using SDBR in rapid response projects. http://www.scienceofbusiness.com/free-stuff/free-toc-vv-articles.aspx.

Schragenheim, E. and R. Burkhard, 2007. Drum buffer rope and buffer management in a make-to-stock environment. http://www.scienceofbusiness.com/free-stuff/free-toc-vv-articles.aspx.

Sirikrai, V. and P. Yenradee, 2006. Modified drum-buffer-rope scheduling mechanism for a non-identical parallel machine flow shop with processing-time variation. Int. J. Prod. Res., 44: 3509-3531.

Watson, K.J., J.H. Blackstone and S.C. Gardiner, 2007. The evolution of a management philosophy: The theory of constraints. J. Operational Manage., 25: 387-402.

Wu, H.H. and M.L. Yeh, 2006. A DBR scheduling method for manufacturing environments with bottleneck re-entrant flows. Int. J. Prod. Res., 44: 883-902.

Wu, H.H. and J.Y. Liu, 2008. A capacity available-to-promise model for drum-buffer-rope systems. Int. J. Prod. Res., 46: 2255-2274.

Yan, H., S. Lou and S.P. Sethi, 2000. Robustness of various production control policies in semiconductor manufacturing. Prod. Operations Manage., 9: 171-182.

Yang, D.L., W.H. Kuo and M.S. Chern, 2008. Multi-family scheduling in a two-machine reentrant flow shop with setups. Eur. J. Operational Res., 187: 1160-1170.