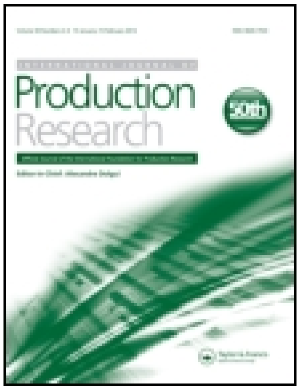

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Yung-Chia Chang[a] & Wen-Tso Huang[a]
[a] Department of Industrial Engineering and Management, National Chiao Tung University, Hsinchu, Taiwan, ROC
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An enhanced model for SDBR in a random reentrant flow shop environment

Yung-Chia Chang* and Wen-Tso Huang

Department of Industrial Engineering and Management, National Chiao Tung University, Hsinchu, Taiwan, ROC

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This study proposed an enhanced simplified drum-buffer-rope (SDBR) model to be applied in a reentrant flow shop (RFS) in which job processing times are generated from a discrete uniform distribution and machine breakdowns are subject to an exponential distribution. In this enhanced SDBR model, the due-date assignment method, order release rule and dispatching rule were improved. The due dates and release dates of orders were determined by considering the total planned load of the capacity-constrained resource (CCR) in a random RFS. The deviation rate of buffer status is used as a dispatching rule to eliminate the influence of machine breakdowns. Simulations based on a real case company are used to evaluate the effective of the proposed model. The experimental results showed that our approach yields better performance than the other methods in terms of six due-date-related indexes when the product mix is with a large proportion of multi-reentrant orders and when the utilisation of CCR increases from 60 to 90%.

Keywords: simplified drum-buffer-rope; due-date assignment; reentrant flow shop; random environments

1. Introduction

This research enhanced the simplified drum-buffer-rope (SDBR) method to be applied in a random reentrant flow shop (RFS). In a RFS, job processing times are deterministic, and machines are subject to randomly breakdown. In most cases, the constraint in a make-to-order (MTO) environment is market demand, and the order due date represents the market demand. Schragenheim and Dettmer (2001) introduced the SDBR method that can be easily applied in most MTO environments when other methods seem to be complicated in practice. SDBR is a management structure which includes not only the due-date assignment method but also order release rule and dispatching rule. In SDBR, the drum is treated as the due-date assignment method, and the rope is treated as the order release rule. Furthermore, the buffer is treated as the dispatching rule for a bottleneck machine on shop floor. The detail of SDBR method is described in Subsection 2.1. We found that when SDBR method was implemented in a random RFS (such as machine breakdowns) in practice, two potential drawbacks may be found. The first potential drawback is about the due-date assignment method (i.e. the drum) and the order release rule (i.e. the rope). The SDBR method utilises the planned load on one bottleneck machine to determine both the due dates and the release dates of all orders. The planned load of an order depends only on when it is arrived without considering if the process flow has re-entry property or the random breakdown situations on the bottleneck machine. The second potential drawback is about the dispatching rule (i.e. the buffer). The SDBR method (hereby referring as the 'conventional SDBR') utilises the priorities based on buffer status (BS) to dispatch jobs. Two jobs may receive the same priorities even when they are at different reentrant layers. The priorities may also be distorted when random breakdowns occur on the bottleneck machine.

In order to improve the due-date assignment method and the order release rule used by the conventional SDBR, this paper proposed a model (hereby referring as the 'enhanced SDBR') that can overcome the above-mentioned drawbacks. Different from the conventional SDBR, we added a new measure called total planned load (TPL) to consider the number of CCRs re-entries. Moreover, in order to improve the dispatching rule, our approach introduced a weighted layer BS (called LBS) to represent the weighted BS at different reentrant layer. The priority of jobs is determined by the difference between BS and LBS.

In this paper, we address a random RFS that often occurred in reality. In a RFS, all jobs have the same production route over machines in the shop and may return to the same machine once or several times before completion (Graves et al. 1983). For instance, in semiconductor manufacturing, a wafer needs to visit certain machines several times for processing (Vargas-Villamil and Rivera 2001). For the reentrant environment, some studies applied the concept of

*Corresponding author. Email: yungchiachang@mail.nctu.edu.tw

drum-buffer-rope (DBR) or the theory of constraints (TOC) on production and dispatching, such as those by Tyan, Chen, and Wang (2002), Kim, Davis, and Cox (2003), and Wu and Yeh (2006). Tyan, Chen, and Wang (2002) proposed a TOC-based state-dependent (TSD) dispatch rule for a near-real-world fabrication model. The idea of the TSD is to apply a revised two-boundary dispatching rule to capacity-constrained resource (CCR) or bottleneck which consider works in process deviation and surplus deviation for each part type at each layer. The non-CCR or non-bottleneck is dispatched following the modified shortest expected processing time rule until its next visit to the same CCR to expedite the reentrant lots to avoid starvation for CCR. However, due-date assignment method, order release rule and uncertainties such as machine breakdowns were not taken into account in their study. Kim, Davis, and Cox (2003) explored the use of material release, dispatching rule and flow control policy in a semiconductor wafer fabrication. They concluded that the first-in-first-out (FIFO) dispatching rule provides less total deviations of output product mix than the other ones. In contrast, for the total output measure, the shortest processing time rule performs better than the FIFO rule. Still, they did not take the due-date assignment method and uncertainties into consideration. Wu and Yeh (2006) examined a drum (i.e. CCR) development algorithm based on descriptions of ruin generation and ruin levelling method when applying DBR to a reentrant process. A ruin evaluates the relative production priority of different CCR operations of different lots, and a forward levelling process is adopted in this levelling method. Their method not only ensured proper sequencing of CCR operations, but also provided sufficient time between adjacent CCR operations for a lot within a drum. Nevertheless, they still did not consider the due-date assignment method and uncertainties. The above-mentioned papers could not show us how to apply a management structure which includes not only the due-date assignment method but also order release rule and dispatching rule in a random RFS.

Indeed, there exists few research discuss the issues of due-date assignment method when applying SDBR method in a random RFS in practice. For example, some studies discussed the due-date assignment method in a non-RFS environment such as Conway, Maxwell, and Miller (1967), Eilon and Chowdhury (1976), Ragatz and Mabert (1984), Lawrence (1995), Philipoom, Wiegmann, and Rees (1997), Soroush (1999), Hopp and Sturgis (2000), Song, Hicks, and Earl (2002) and Moses et al. (2004). Moreover, Vinod and Sridharan (2011) investigated the interaction between due-date assignment methods and scheduling rules in a dynamic job shop environment. Their objectives were to minimise the flow time as well as the tardiness of jobs. However, order release rule and uncertainties such as machine breakdowns were not taken into account. Koulamas (2011) analysed a number of due-date assignment problems with the weighted number of tardy jobs objective and shows that single-machine and parallel machines problems can be solved by dynamic programming. Nevertheless, he still did not take the re-entry and uncertainties into consideration. Azaron, Fynes, and Modarres (2011) presented a constant due-date assignment method in repetitive projects where the objective was to minimise the expected sum of the due-date cost, tardiness cost and earliness cost. They did not model reentrant layers and uncertainties in their study. Therefore, this paper is aimed at determining a reliable due-date assignment to customers. In practice, the due-date performance (DDP) is an index utilised to indicate the percentage of orders completed by due dates. A reliable due-date assignment means DDP is kept at least 80%. Schragenheim and Dettmer (2001), Schragenheim (2006) and Lee et al. (2010) stated that by adopting the conventional SDBR method, high DDP can be achieved in a non-RFS environment. However, the above-mentioned drawbacks made the conventional SDBR not efficient when applied to a random RFS and motivated this research.

In order to evaluate the effective of the enhanced SDBR, a simulation environment was created based on a true setting of a case company. Numerical experiments were conducted under different test scenarios which cover a range of CCR utilisations, and also, various product mixes per different number of reentrant layers. The experimental results of the enhanced SDBR were contrasts to the conventional SDBR and to the method used by the case company.

The remainder of this paper is organised as follows. In Section 2, we describe the details of the enhanced SDBR and give an example to illustrate the solution procedure and numerical analysis. The profile of simulation environment and the design of computational experiment are described in Section 3. Section 4 presents the analysis of simulation results. Section 5 concludes this paper and illustrates relevant study topics.

2. The enhanced SDBR for the conventional SDBR

2.1 *Concept of the PL in the conventional SDBR and its critical issues*

The core concept of the conventional SDBR is PL and due-date assignment method. Schragenheim and Dettmer (2001) first introduced the concept of the PL. They defined the PL as the accumulation of the derived load on the CCR for all the firm orders that have to be delivered within certain horizon of time (e.g. 7 days). In other words, it intends to convert each order into the number of capacity hours of CCR that is needed in the future to ensure that there is enough capacity to meet all due dates. Combining the resulting outcome with the original CCR, we can derive the PL.

For example, if both orders 1 and 2 require two hours of work on the CCR, respectively, the PL is 4 h. Moreover, Schragenheim (2006) extended the work of Schragenheim and Dettmer (2001) to further define the due date of a specific order to be obtained by adding half of a production buffer (PB) to PL. This is also known as the due-date assignment method in conventional SDBR. Figure 1 depicts the concept of PL. Furthermore, Lee et al. (2010) extended the work of Schragenheim (2006) and defined that if CCR is located in the front end of the routing, the order due date is equal to the PL plus PB multiplied by $(1-\alpha)$, where α is a positive number below 0.5. They also defined that if CCR is located in the back end of the routing, the order due date is equal to the PL plus PB multiplied by $(1-\beta)$, where β is a positive number between 0.5 and 1.

However, we think this kind of due-date assignment modification in conventional SDBR might have some problem that reduces the DDP of orders in a random RFS. We use Figure 2 to illustrate the potential problem. Consider an example in which there are four orders belong to three products that require 0, 1 and 2 re-entries on the CCR, respectively. The permutation which indicates the sequence to determine the due dates of orders by CCR is as presented in the Figure 2(a). Suppose we need to determine the due dates among products A, B, C, and the setting method of PL is used. After applying PL, one possible permutation can be formed arbitrarily. Therefore, 99% DDP may not be easy to achieve when applying the PL to a random RFS environment. For example, if the random breakdown situations on CCR inevitably happened after processing product A with non-re-entry first, product C with two re-entries on the CCR might not meet its due date since the finish time of this product is not getting earlier than the other two products. In a random RFS, the multi-reentrant orders (such as product C in our example) dedicated more capacity on CCR at different reentrant layers. This motivates us to reindex all products based on the non-increasing permutation of its PL in Figure 2(b). We are interested in knowing, in the due-date assignment problem, if the DDP can be kept at least 80% when applying the enhanced SDBR to a random RFS environment. This is the motivation of this research.

In order to enhance the improvement of DDP by the proposed model, this paper proposes not only due-date assignment method but also order release rule and dispatching rule. Regarding the order release rule in conventional SDBR, Schragenheim and Dettmer (2001) stated that since the market demand is always a constraint, the buffer in conventional SDBR is simplified into one single shipping buffer (SB) that represents the time of an order, from the release date to the due date, and is equal to the cycle time. Therefore, they defined the order released into the shop floor according to the due-date minus a SB to get the release date. Even though their order release method incorporated PL characteristic, they did not consider the re-entry flows or uncertainties (such as machine breakdowns). Furthermore, Schragenheim (2006) presented that the SB is equal to the cycle time in conventional SDBR, termed as PB and further defined the release date of a specific order as subtracting half of a PB from PL in Figure 1. They still did not take the re-entry and uncertainties into consideration. Moreover, Lee et al. (2010) defined that if CCR is located in the front end of the routing, the order release date is equal to the PL minus PB multiplied by α, where α is a positive number below 0.5. They also defined that if CCR is located in the back end of the routing, the order release date is equal to the PL minus PB multiplied by β, where β is a positive number between 0.5 and 1. However, only two kinds of CCR's locations are modelled, and uncertainties such as CCR breakdowns and re-entry were not taken into account.

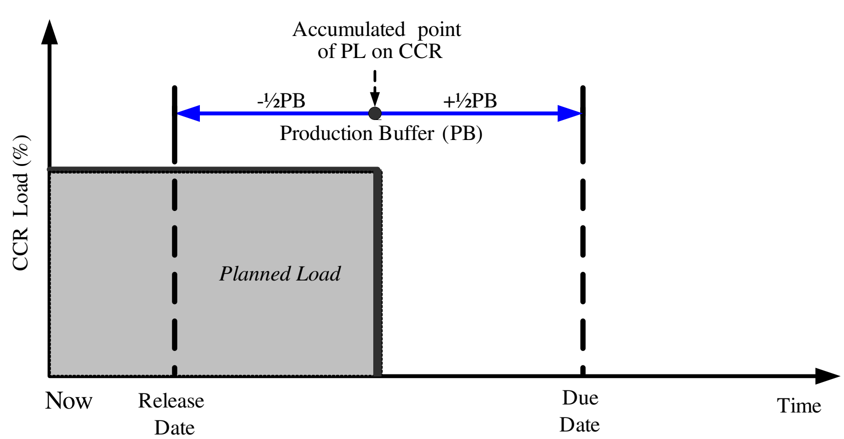

Figure 1. The PL of the conventional SDBR.

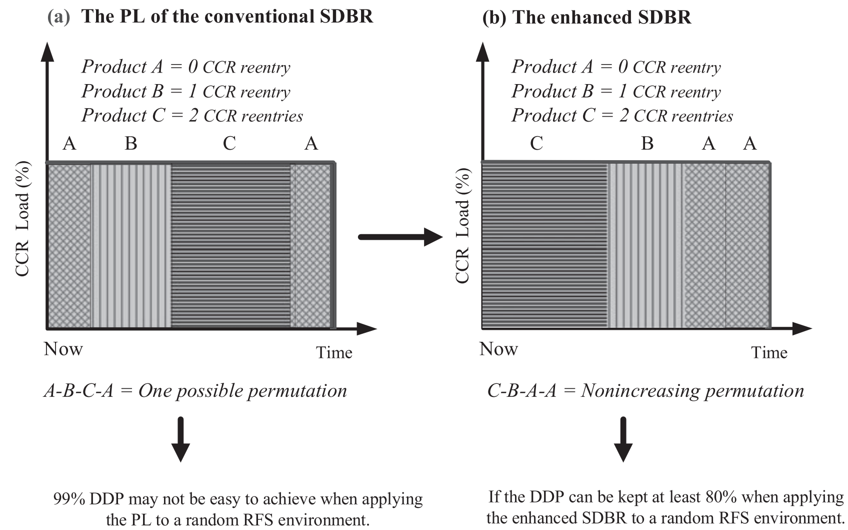

Figure 2. Motivation of the enhanced SDBR.

In addition to the conventional SDBR, the buffer is treated as the dispatching rule on shop floor. Schragenheim (2006) and Schragenheim and Burkhard (2007) introduced the buffer management (BM) which is a mechanism that adopts the penetration rate to decide the urgency of an order. In BM, the PB is divided into three equal areas. The term 'penetration' is defined as the accumulated flow time of a specific order on 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. However, high penetrations between multi-reentrant orders in front of CCR are not modelled, and uncertainties were not taken into account. Lee et al. (2010) further defined BS as the dispatching rule of CCR. In other words, the order with the high value of BS results in a higher sequence of CCR. Nevertheless, they still did not take the re-entry and uncertainties into consideration. We summarised the studies of the due-date assignment method, the order release rule and the dispatching rule of the conventional SDBR as Table 1.

The details of the enhanced SDBR are given in the subsequent section.

2.2 *The enhanced SDBR*

A major improvement made to the conventional SDBR is described in the following. In order to improve the due-date assignment method and order release rule used by the conventional SDBR, we reindex planned load of each order of each product based on the number of CCRs re-entries to obtain TPL and to reconstruct due-date assignment method and order release rule. Then, we utilise the TPL of each order of each product to determine both due dates and release dates of all orders. The TPL means the aggregated machine loading concept that this study utilises to assign due dates. In other words, the proposed enhanced SDBR model is in fact ignored the number of machines loaded in CCR station to a random RFS environment. Finally, in order to improve the dispatching rule, our approach uses the deviation rate between the BS and a weighted layer BS as a modified dispatching rule to eliminate the influence of the accumulated downtimes, and the machine downtimes at a specific layer and decides the priority for each job in front of the CCR.

Table 1. Summary of drum-buffer-rope in conventional SDBR.

The authors	Drum	Buffer	Rope
Schragenheim and Dettmer (2001)	Planned load (PL)	Shipping buffer (SB)	Release date = Due date – SB
Schragenheim (2006)	Due date = PL + 0.5 PB	Production buffer (PB) Buffer management (BM)	Release date = PL – 0.5 PB
Lee et al. (2010)	Due date = PL + (1 – α)PB Due date = PL + (1 − β)PB	Buffer status (BS) $= \frac{(PB - \text{Remain Days to Due Date})}{PB}$	Release date = PL – α × PB Release date = PL – β × PB

The notations used in this paper are given as follows:

i	Index of product.
j	Index of order.
l	Index of reentrant layer number.
m	Number of products.
n_i	Number of orders of product i.
p_i	Number of reentrant layers of product i.
M	Number of orders, where $M = \sum_{i=1}^{m} n_i$.
Q_{ijlt}	=1, if order j of product i is queued in front of CCR at layer l at time t; = 0, otherwise.
BS_{ijt}	The buffer status ratio for order j of product i at time t.
CD_{ij}	The completed date for order j of product i.
DD_{ij}	The due date for order j of product i.
DT_{ij}	The date of today for order j of product i.
U_{ij}	Indicate whether order j of product i is completed by its due date, that is, if $DD_{ij} > CD_{ij}$, then $U_{ij} = 1$; otherwise, $U_{ij} = 0$.
OV_{ij}	The value of order j of product i.
PB_{ij}	The production buffer time for order j of product i.
PL_{ij}	The planned load for order j of product i on CCR.
RD_{ij}	The release date for order j of product i.
WV_{ij}	The WIP value for order j of product i.
PTC_{ij}	The processing time for order j of product i on CCR.
RNT_{ij}	The remaining net processing time for order j of product i.
LBS_{ijlt}	The buffer status ratio for order j of product i at layer l at time t.
LDT_{ijlt}	The down time for order j of product i at layer l at time t.
LFT_{ijlt}	The flow time for order j of product i at layer l at time t.
LPB_{ijl}	The production buffer time for order j of product i at layer l.
LPT_{ijl}	The actual processing time for order j of product i at layer l.
MCR_{ijt}	The modified critical ratio for order j of product i at time t.
TPL_{ij}	The total planned load for order j of product i on CCR.
MULT	Constant buffer size multiplier.
MTBF	The mean time between failures of any machine.
MTTR	The mean time to repairs of any machine.

Our model is described in the following.

(1) The due-date assignment method:
First, we discusses every product at different reentrant layers include the number of reentrant layers (p_i) and the variable processing times on CCR (PTC_{ij}). Therefore, the PL_{ij} is calculated by multiplying p_i by the PTC_{ij}, calculated by Equation (1).

$$\mathrm{PL}_{ij} = p_i \times \mathrm{PTC}_{ij}, \quad i = 1, 2, \ldots, m, \ j = 1, 2, \ldots, n_i \tag{1}$$

We reindex all orders of all products based on the non-increasing order of PL_{ij}, $\forall i, j$. That is, a product with more CCR re-entries has a larger index than a product with fewer CCR re-entries. Furthermore, TPL_{ij} is calculated by Equation (2) which represents the accumulated PL_{ij} of different orders of different products.

$$\mathrm{TPL}_{ij} = \mathrm{TPL}_{i,j-1} + \mathrm{PL}_{ij}, \quad i = 1,\ 2,\ \ldots,\ m,\ j = 1, 2, \ldots, n_i. \tag{2}$$

The accumulated $\mathrm{TPL}_{i,\ j\text{-}1}$ is obtained by inheritance from TPL_{i-1,n_i}, as described in Equation (3).

$$\mathrm{TPL}_{i,j-1} = \mathrm{TPL}_{i-1,n_i}, \quad i = 1,\ 2,\ \ldots,\ m,\ j = 1, 2, \ldots, n_i. \tag{3}$$

The initial status of Equation (3) is given in Equation (4).

$$\mathrm{TPL}_{i,j-1} = \mathrm{TPL}_{0,n_1} = 0, \quad \text{for all } j \tag{4}$$

Therefore, a reliable due date for order j of product i, DD_{ij}, with the consideration of the re-entry feature and the variable processing times on CCR of the enhanced SDBR can be obtained by adding half of a PB_{ij} to TPL_{ij} using Equation (5).

$$\mathrm{DD}_{ij} = \mathrm{TPL}_{ij} + 0.5\mathrm{PB}_{ij}, \quad i = 1,\ 2,\ \ldots,\ m,\ j = 1, 2, \ldots, n_i. \tag{5}$$

(2) The order release rule:
Our rule releases order into a RFS at a timing determined by TPL_{ij} of the CCR. TPL_{ij} is used to determine release dates of orders. RD_{ij} is obtained by subtracting half of a PB_{ij} from TPL_{ij}, as described in Equation (6). Note that RD_{ij} is obtained by subtracting one PB_{ij} from DD_{ij} and the complete release schedule is obtained by prioritising the release dates of orders from now to future.

$$\mathrm{RD}_{ij} = \mathrm{TPL}_{ij} - 0.5\mathrm{PB}_{ij}, \quad i = 1, 2, \ldots, m, \ j = 1, 2, \ldots, n_i. \tag{6}$$

(3) The dispatching rule:
The dispatching rule, called SDBR_$D_{\text{Re-entry}}$, used in our proposed approach is adopted from the one introduced by Chang and Huang (2011). First, we introduced a weighted layer PB of order j of product i at layer l (LPB_{ijl}) which is obtained by distributing the PB_{ij} of each order j of each product i based on the number of times passing CCRs. The estimated value of LPB_{ijl} includes the influence of processing times among machines and machine downtimes at different reentrant layers, as shown in Equation (7).

$$\mathrm{LPB}_{ijl} = LPT_{ijl} \times \left(1 + \frac{\mathrm{MTTR}}{\mathrm{MTTR} + \mathrm{MTBF}}\right) \times \mathrm{MULT}, \tag{7}$$

where $i = 1, 2, \ldots, m$, $j = 1, 2, \ldots, n_i$, $l = 1, 2, \ldots, p_i$.

Then, the estimated value of PB_{ij} includes the influence of processing times among machines and machine downtimes at different LPB_{ijl}. PB_{ij} is then represented by the sum of LPB_{ijl}, as shown in Equation (8).

$$\mathrm{PB}_{ij} = \sum_{l=1}^{p_i} \mathrm{LPB}_{ijl}, \quad i = 1, 2, \ldots, m, \ j = 1, 2, \ldots, n_i. \tag{8}$$

In a random RFS, we may need to determine the sequence of orders accumulating in front of the CCR at different reentrant layers. Therefore, we used the LBS_{ijlt} to estimate the actual urgency at each reentrant layer in real time. It is measured by the ratio of LFT_{ijlt} to LPB_{ijl} at any particular reentrant layer. Usually, LFT_{ijlt} denotes the flow time at any particular layer of the CCR on the shop floor, calculated by Equation (9).

$$\mathrm{LBS}_{ijlt} = \frac{\mathrm{LFT}_{ijlt}}{\mathrm{LPB}_{ijl}} \times 100\%, \quad i = 1, 2, \ldots, m, \ j = 1, 2, \ldots, n_i, \ l = 1, 2, \ldots, p_i \tag{9}$$

On the other hand, we also need the planned values of the overall urgency for the orders accumulating in front of the CCR. BS_{ijt} is used to estimate the overall urgency of the due date in real time. It is measured by the ratio of accumulated LFT_{ijlt} to PB_{ij}, calculated by Equation (10).

$$\mathrm{BS}_{ijt} = \frac{\sum_{l=1}^{p_i} \mathrm{LFT}_{ijlt}}{\mathrm{PB}_{ij}} \times 100\%, \quad i = 1, 2, \ldots, m, \ j = 1, 2, \ldots, n_i. \tag{10}$$

When we need to determine the priorities of orders accumulating in front of the CCR, $\Delta\mathrm{BS}_{ijlt}$ can be used to eliminate the distortions of both BS_{ijt} and LBS_{ijlt} when random breakdowns occur on CCRs, calculated by using Equation (11). $\Delta\mathrm{BS}_{ijlt}$ is essentially the difference between BS_{ijt} and LBS_{ijlt} after eliminating the influence of the accumulated machine downtimes and the influence of machine downtimes at different reentrant layers. A higher $\Delta\mathrm{BS}_{ijlt}$ implies a higher priority. Ranking the $\Delta\mathrm{BS}_{ijlt}$ from *high* to *low* would then create a complete real-time dispatching schedule for CCR. Non-CCR machines are dispatched following the FIFO rule.

$$\Delta\mathrm{BS}_{ijlt} = \mathrm{BS}_{ijt} \times \left(1 - \frac{\sum_{l=1}^{p_i} \mathrm{LDT}_{ijlt}}{\mathrm{PB}_{ij}}\right) - \mathrm{LBS}_{ijlt} \times \left(1 - \frac{\mathrm{LDT}_{ijlt}}{\mathrm{LPB}_{ijl}}\right), \tag{11}$$

where $i = 1, 2, \ldots, m$, $j = 1, 2, \ldots, n_i$, $l = 1, 2, \ldots, p_i$.

2.3 *Procedures of the enhanced SDBR*

This following summarises the proposed enhanced SDBR into 11 steps.

Step 1. Calculate the PL of each order of each product by Equation (1).
Step 2. Calculate the summation of the PL of all orders of all products to obtain the TPL by Equation (2–4).
Step 3. Calculate the due date of each order by Equation (5).
Step 4. Calculate the release date of each order by Equation (6).
Step 5. Calculate the LPB of each order by Equation (7).
Step 6. Calculate the PB of each order by Equation (8).
Step 7. Calculate the actual urgency among the layers for each order by Equation (9).
Step 8. Calculate the overall urgency of each order by Equation (10).
Step 9. Calculate the ΔBS by Equation (11) to determine the priority of orders accumulating in front of CCR.
Step 10. Rank the ΔBS from high to low to obtain a complete real-time dispatching schedule for CCR.
Step 11. Dispatch orders on non-CCR machines by the FIFO rule.

Table 2. An illustrative example of due date assignment method and order release rule of the enhanced SDBR in a random RFS.

(1) Product i	(2) Order j	(3) PB_{ij}	(4) p_i	(5) PTC_{ij}	(6) PL_{ij}	(7) TPL_{ij}	(8) DD_{ij}	(9) RD_{ij}
1	1	100	3	8	=3 × 8=24	=0[a] + 24=24	=24+0.5 × 100=74	=24–0.5 × 100=(–26)
1	2	100	3	8	=3 × 8=24	=24+24=48	=48+0.5 × 100=98	=48–0.5 × 100=(–2)
1	3	100	3	8	=3 × 8=24	=48+24=72	=72+0.5 × 100=122	=72–0.5 × 100=22
2	1	50	2	8	=2 × 8=16	=72+16=88	=88+0.5 × 50=113	=88–0.5 × 50=63

[a]Where 0 denote the initial values of $TPL_{0,}n_1$.

2.4 *Example of the enhanced SDBR*

We use an example to illustrate the procedure of our approach. The inputs and the resulting outcomes are listed in Table 2. In Table 2, columns (3)–(5) are given as the settings of this example and ranked the order in the non-increasing order of PL_{ij} shown in column (6). Columns (1)–(4) represent the orders 1, 2 and 3 of product 1 with three CCR layers, order 1 of product 2 with two CCR layers. In Table 2, columns (6)–(9) are calculated by using Equations (1)–(6). The PL_{ij} shown in column (6) is obtained from Equation (1). The TPL_{ij} shown in column (7) is obtained by using Equations (2)–(4), which represents the accumulated PL_{ij} of different orders of different products. The DD_{ij} shown in column (8) is obtained by Equation (5), which represents the due-date schedule (or drum) of our approach. The RD_{ij} shown in column (9) is obtained by Equation (6), which represents the release schedule (or rope) of our approach. Note that the negative value of RD_{ij} means that order j of product i must be released into the shop floor immediately. From this example, we can see how the due-date assignment method and the release rule could be implemented when our approach is applied to two or more products in a random RFS.

We then adopted the dispatching rule, $SDBR\_D_{Re\text{-}entry}$, introduced by Chang and Huang (2011) to complete the mechanism of the conventional SDBR as Table 3. In Table 3, columns (2)–(13) are given as the settings of this example, and columns (14)–(18) are calculated by using Equations (7)–(11). In Table 3, the BS_{ijt} shown in column (14) is calculated by using data in columns (6)–(8) from Equation (10); the LBS_{ijlt} shown in column (16) is also calculated by using data in columns (6)–(8) from Equation (9); the ΔBS_{ijlt} shown in column (17) is then calculated by using data in columns (9)–(16) from Equation (11). Moreover, in Table 3, orders 1 and 2 in situation (a) are taken from Table 2 which are of the same product and have the same overall urgency but are at different CCR layers. Per the conventional SDBR method, since the corresponding BS_{ijt} values are the same for both orders, either one can be chosen arbitrarily. However, it appears that order 2 of product 1 in layer 2 has a higher risk of delay than order 1 of product 1 in layer 3. Based on the proposed approach, order 2 of product 1 is given a higher priority than order 1 of product 1 since $\Delta BS_{1,2,2,70} > \Delta BS_{1,1,3,70}$. On the other hand, order 3 of product 1 and order 1 of product 2 in situation (b) are taken from Table 2, which involve different products but have the same overall urgency. When the influence of machine breakdown is not taken into consideration (i.e. using the conventional SDBR), both orders have the same priority thus can be selected arbitrarily since $BS_{1,3,82} = BS_{2,1,41}$. However, our approach recommends to choose order 3 of product 1 since it generates a higher risk of delay than order 1 of product 2 after measuring the deviation rate ΔBS_{ijlt}. From this example, we can see how the due-date assignment method, release rule and dispatching rule of our approach could be implemented when we applied it to two or more products in a random RFS. In addition, we can also see that the influence of CCR machine downtimes for orders that generate a risk of delay could be distinguished when our approach is applied to more orders with the same overall urgency rate in a random RFS.

3. Computational experiment

In order to compare the performance of our approach and the conventional SDBR in a random RFS, this paper adopts a simulated plant designed by Chang and Huang (2011) based on the actual manufacturing environment of a multilayer printed circuit boards plant of Company K in Taiwan. In year 2007, Company K implemented the conventional SDBR approach in due-date assignment and job releasing. The company is interested in knowing if the conventional SDBR can be applied to a more realistic situation in which the DDP index can be kept at least 80% while processing times are varied and machines randomly breakdown.

3.1 *Profile of the simulation environment*

Company K produces three types of products called A, B and C, respectively. Table 4 lists the product routing in this simulated plant. The simulated plant has six types of machines: M1, M2, M3, M4, M5 and M6. The numbers of M1,

Table 3. An illustrative example of dispatching rule of the enhanced SDBR in a random RFS.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14) Conventional SDBR	(15)	(16) Enhanced SDBR	(17)	(18)
Situation	Product i	Order j	p_i	Current CCR Layer	LFT_{ij1t}	LFT_{ij2t}	LFT_{ij3t}	LDT_{ij1t}	LDT_{ij2t}	LDT_{ij3t}	LPB_{ijl}	PB_{ij}	BS_{ijt} (%)	Priority	LBS_{ijlt} (%)	ΔBS_{ijlt} (%)	Priority
(a)	1	1	3	3	19	24	27	3	8	11	35	100	70	*	77	2	
	1	2	3	2	21	49	0	5	33	0	50	100	70	*	98	10	*
(b)	1	3	3	2	33	49	0	17	33	0	50	100	82	*	98	8	*
	2	1	2	2	18	23	0	2	7	0	25	50	82	*	92	1	

Table 4. Product routing in the simulated plant.

	Step											
Product	1	2	3	4	5	6	7	8	9	10	11	12
A	M1	M2	M3	M1	M4	M5	M6					
B	M1	M2	M3	M1	M4	M2	M3	M5	M6			
C	M1	M2	M3	M1	M4	M2	M3	M5	M2	M3	M5	M6

M2, M3, M4, M5 and M6 are 3, 2, 3, 2, 2 and 2, respectively. Table 5 shows that the machine M2 with the highest average load is the CCR in the simulated plant per the approach developed by Russell and Taylor (2005). Therefore, product A, B and C require 0, 1 and 2 reentrant layers, respectively. We assume that PB is three times of net processing time. In addition, we assume that there is only one type of WIP provided for all three types of products. The WIP values of three different products are 1, 2 and 3 units, respectively. Also, the order values of three different products are 2, 4 and 6 units, respectively. One order represents one lot, a processing lot or a transfer lot. This paper assumes that the processing time of each of the non-CCR machines (i.e. M1, M3, M4, M5 and M6) follows a uniform distribution with a range between 3 and 12 h. Also, the processing times of the CCR machines (M2) follow a uniform distribution ranging between 10 and 20 h. Furthermore, we assume that the time required to repair a machine follows an exponential distribution with a mean of 2 h. Once the repair of a machine is completed, the time until the next breakdown of the machine also follows an exponential distribution with a mean of 40 h. The above data in the simulated plant are derived from the actual manufacturing environment of the company K as shown in Table 6.

This paper intends to compare the following three approaches involving the due-date assignment, the dispatching rule and the release rule: the proposed approach, the conventional SDBR and the method K used by Company K. Six indexes related to the due dates calculated by Equations (12)–(17) are used as performance indexes in our comparison. The DDP is tracked to guide managers to focus on ensuring no delay exists for each order, as shown in Equation (12) (Chang and Huang 2011):

Table 5. Calculation results of the average load for machines in the simulated plant.

	Machine					
Product	M1	M2[a]	M3	M4	M5	M6
A	2	1	1	1	1	1
B	2	2	2	1	1	1
C	2	3	3	1	2	1
Sum	6	6	6	3	4	3
Average load	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.

Table 6. Machine operation data in the simulated plant.

Machine	Quantity	λ[a]	MTBF	MTTR	System availability
M1	3	0.025	40[b]	2	0.95[c]
M2	2	0.025	40	2	0.95
M3	3	0.025	40	2	0.95
M4	2	0.025	40	2	0.95
M5	2	0.025	40	2	0.95
M6	2	0.025	40	2	0.95

[a]λ is the failure rate of the machine;
[b]MTBF = $1/\lambda = 1/0.025 = 40$;
[c]System availability = MTBF/(MTBF + MTTR)=40/(40 + 2)=0.95.

$$\text{DDP} = \frac{1}{M}\sum_{i=1}^{m}\sum_{j=1}^{n_i} U_{ij} \tag{12}$$

The due-date slack time (DDST) is represented by the number of hours that the order is completed ahead of schedule, which depicts the ability to protect the due date, as shown in Equation (13) (Chang and Huang 2011):

$$\text{DDST} = \frac{1}{M}\sum_{i=1}^{m}\sum_{j=1}^{n_i} (\text{DD}_{ij} - \text{CD}_{ij}) \tag{13}$$

The throughput dollar day (TDD) is the summation of the value of the orders multiplied by the number of hours that their delivery is late (Ho and Li 2004), as shown in Equation (14)

$$\text{TDD} = \frac{1}{M}\sum_{i=1}^{m}\sum_{j=1}^{n_i} [\text{OV}_{ij}\{Max(0, \text{CD}_{ij} - \text{DD}_{ij})\}] \tag{14}$$

Equation (14) indicates that the manager can focus on the increase of the throughput by the TDD. The inventory dollar day (IDD) is the summation of the dollar value of the WIP multiplied by the time since the WIP entered the plant (Ho and Li 2004), as shown in Equation (15):

$$\text{IDD} = \frac{1}{M}\sum_{i=1}^{m}\sum_{j=1}^{n_i} [\text{WV}_{ij}(\text{CD}_{ij} - \text{RD}_{ij})] \tag{15}$$

Equation (15) is used to guide managers to focus on reducing the plant's actual WIP and production cycle time. The average queue length in front of the CCR (Q_CCR) is the total average of queued orders in front of the CCR, as shown in Equation (16) (Chang and Huang 2011):

$$Q\_\text{CCR} = \frac{1}{M}\sum_{i=1}^{m}\sum_{j=1}^{n_i}\sum_{l=1}^{p_i} Q_{ijlt} \tag{16}$$

The flow time is calculated by Equation (17) (Chang and Huang 2011):

$$\text{Flow Time} = \sum_{i=1}^{m}\sum_{j=1}^{n_i} \{(\text{CD}_{ij} - \text{RD}_{ij}) + 1\} \tag{17}$$

3.2 *Design of test problem*

The test problem in the simulated plant was considered using two factors in practice:

(1) Different utilisation ratios of the CCR: The basic assumption behind the conventional SDBR is that the internal resources often have excess capacity. Hence, this paper considered four distinct non-full load utilisation ratios of the CCR: 60, 70, 80 and 90%, respectively.

(2) Different layer mixes of the CCR: Due to the complexity of the reentrant environment being exacerbated by reentrant processing (Yan, Lou, and Sethi 2000), the performance of our approach might be limited when it is applied to a random RFS. Therefore, this paper took into account three combinational ratios of layer mixes, which were denoted as M-M-M, L-H-L and L-L-H, in which H represents high, M represents medium and L represents low. The permutation indicates the sequence of the three products as A, B and C require 0, 1 and 2 reentrant layers, respectively. Medium represents the weight of product mix for the three products is equal. Low represents the weight of the products as 30 and 10%, respectively, while high represents 60%. For example, L-L-H (3:1:6) is used to represent a weight of A:B:C = 3:1:6. Table 7 shows the 12 test scenarios generated by these two factors.

3.3 *Description of the conventional SDBR and method K*

The due-date assignment method and the release rule of the conventional SDBR and the method K are the ones used by Schragenheim (2006), and the dispatching rule of the conventional SDBR is developed by Lee et al. (2010). In addition, the dispatching rule of the method K is so-called the *Modified Critical Ratio* (MCR) rule which was derived from the actual manufacturing environment of Company K (Chang and Huang 2011). The detailed steps of the conventional SDBR and the method K are described as follows:

Table 7. The design of the test problems (Chang and Huang 2011).

Scenario	Utilisation (%)	Layer mix			Proportion		
		A[a]	B	C	A	B	C
1	60	M[b]	M	M	1	1	1
2		L	H	L	1	6	3
3		L	L	H	3	1	6
4	70	M	M	M	1	1	1
5		L	H	L	1	6	3
6		L	L	H	3	1	6
7	80	M	M	M	1	1	1
8		L	H	L	1	6	3
9		L	L	H	3	1	6
10	90	M	M	M	1	1	1
11		L	H	L	1	6	3
12		L	L	H	3	1	6

[a]The simulation plant produces three types of products: A, B, and C;
[b]The triplet can be interpreted as follows: M is Medium, L is Low, and H is High.

(1) Procedures of the conventional SDBR:

Step 1. Calculate the PL of each order of each product.
Step 2. Estimate the PB by the net processing time multiplying the constant times on practical experience.
Step 3. Decide the due-date schedule by Equation (18).

$$\mathrm{DD}_{ij} = \mathrm{PL}_{ij} + 0.5\mathrm{PB}_{ij}, \quad \forall\, i, j. \tag{18}$$

Step 4. Decide the release schedule by Equation (19).

$$\mathrm{RD}_{ij} = \mathrm{PL}_{ij} - 0.5\mathrm{PB}_{ij}, \quad \forall\, i, j. \tag{19}$$

Step 5. Calculate the BS by Equation (20), and rank the BS from high to low to obtain the complete dispatching schedule for CCR. Non-CCR machines are dispatched under the FIFO rule.

$$\mathrm{BS}_{ijt} = \frac{(\mathrm{PB}_{ij} - \text{Remain days to } \mathrm{DD}_{ij})}{\mathrm{PB}_{ij}}, \quad \forall\, i, j. \tag{20}$$

(2) Procedures of method K:

Step 1. Calculate the PL of each order of each product.
Step 2. Estimate the PB by the net processing time multiplying the constant times on practical experience.
Step 3. Decide the due-date schedule by Equation (18).
Step 4. Decide the release schedule by Equation (19).
Step 5. Calculate the *Modified Critical Ratio* (MCR) according to Equation (21). Rank the MCR ratio from low to high to obtain the complete dispatching schedule. Decide the non-CCR dispatching schedule under the FIFO principle.

$$\mathrm{MCR}_{ijt} = \frac{(\mathrm{DD}_{ij} - \mathrm{DT}_{ij})}{3\mathrm{RNT}_{ij}} \times 100\%, \quad \forall\, i, j. \tag{21}$$

4. Experimental results

To the best of our knowledge, the order release rule and the dispatching rule incorporated into a due-date assignment problem of a random RFS have never been addressed before in depth for the conventional SDBR. In this experiment, unlike prior studies such as Schragenheim and Dettmer (2001), Schragenheim (2006) and Lee et al. (2010), the 12 scenarios (see Table 7) in Section 3.2 were replicated and were extended to include the three reentrant product routings. The computational experiments were performed on a personal computer with an Intel Pentium P6200 2.13 GHZ with

2.00 GB of memory. The simulation experiments began with an empty plant. Machines were either in up or idle states at the beginning. Each machine only processed one order each time, while operating 24 h per day, seven days per week. If a machine breakdown occurred during processing an order, the order needs to be start processing again after the machine's maintenance was completed. The three methods were respectively executed 10 times under 12 scenarios. The resulting simulation outcomes were discussed in the following subsections.

4.1 *Analysis of performance under different utilisation ratios of CCR*

Figures 3–8 show the DDP, DDST, TDD, IDD, Q_CCR and flow time obtained from the three methods, respectively. The layer mix was kept constant under different utilisation ratios of CCR. It can be seen from Figure 3 that the DDP obtained from the proposed approach was the largest under different utilisation ratios of CCR. The DDP had the biggest gap in comparison with the conventional SDBR when the utilisation ratio of CCR is 90%. On the other hand, when the utilisation ratios of CCR increased from 70 to 90%, the DDP obtained by the proposed approach was kept at least 80% while the ones obtained by the other methods were kept below the 60%. It should be noted that when the utilisation of CCR increased from 60 to 90%, our approach is more suitable than the conventional SDBR in solving issue of on-time delivery in a random RFS. This study inferred that this promising result was driven by reindexing all orders of all products based on the non-increasing order of PL_{ij} on due-date assignment and the deviation rate ΔBS_{ijlt} added into our approach. It can be seen from Figure 4 that the DDSTs obtained from the proposed approach were the largest under all four utilisation ratios of CCR which represented a better protection of the due date under a random RFS.

It can be seen from Figure 5 that the TDD under the four utilisation ratios of CCR obtained from the proposed approach was the smallest among the three methods. Moreover, it had the largest gap with the other methods if the utilisation ratio of CCR was 60%. When the utilisation ratios of CCR increased from 70 to 90%, the gap between the proposed approach and the conventional SDBR also increased. Figure 6 describes the IDD obtained by using the three methods under different CCR utilisations. It can be seen from Figure 6 that the IDD obtained from the proposed approach under the four utilisation ratios of CCR was the smallest among the three methods. The IDD had the biggest gap in comparison with the conventional SDBR when the utilisation ratio of CCR is 90%. In addition, when the utilisation had changed from 80 to 90%, the IDD of the proposed approach was decreased while the conventional SDBR and the method K were increased.

Figures 7 and 8 show the Q_CCR and the flow time obtained by the proposed approach under the different utilisation ratios of CCR were the smallest among the three methods. The Q_CCR has the biggest gap in comparison with the conventional SDBR when the utilisation ratio of CCR is 90%. Moreover, when the utilisation had changed from 80 to 90%, the flow time of the proposed approach was decreased while increased in other methods.

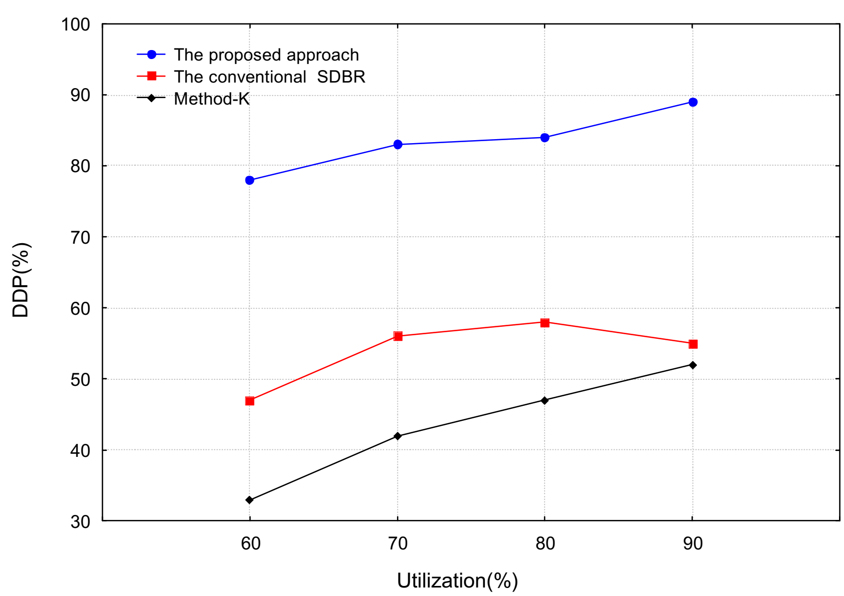

Figure 3. DDP under different utilizations.

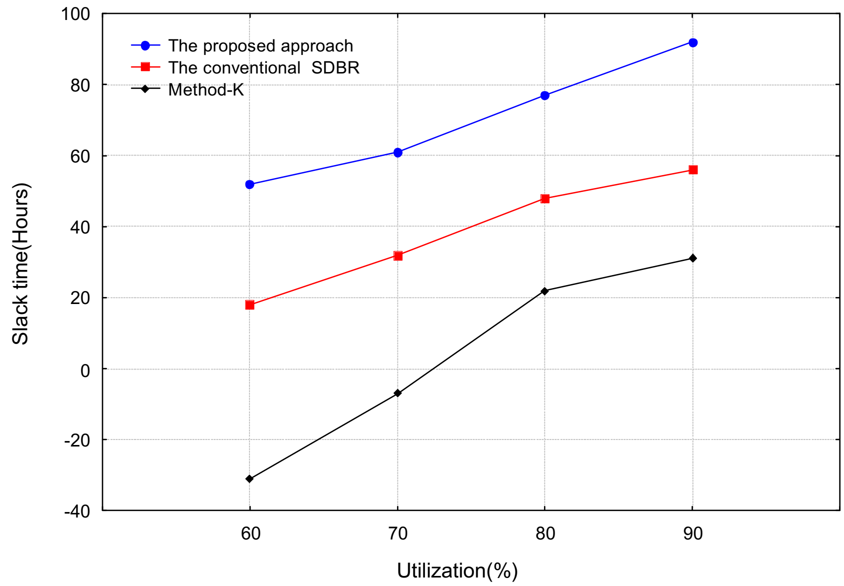

Figure 4. DDST under different utilizations.

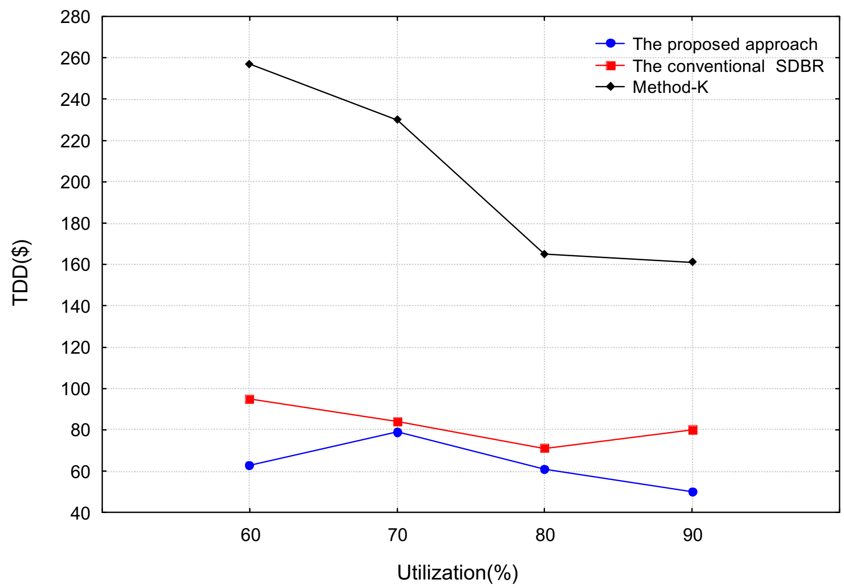

Figure 5. TDD under different utilizations.

4.2 *Analysis of performance under different layer mixes of CCR*

Figures 9–14 show the changes of the CCR resulting from the six indexes. A change of the CCR showed that the layer mix had changed, but the rest of the factors were the same as before. Figure 9 shows that the DDP obtained from the proposed approach under the different layer mixes of CCR was kept at least 80% among the three methods. By contrast, the DDPs of the other methods were kept below the 60% except that the one obtained from the conventional SDBR under the particular layer mix (L-H-L). Thus, we can observe that even when the layer mixes had changed among the three products, the proposed approach is more suitable than the conventional SDBR in solving issue of on-time delivery in a random RFS. The above results showed that reindexing all orders of all products based on the non-increasing order of PL_{ij} on due-date assignment and the ΔBS_{ijlt} added into the proposed approach can improve the performance when compared with the conventional SDBR.

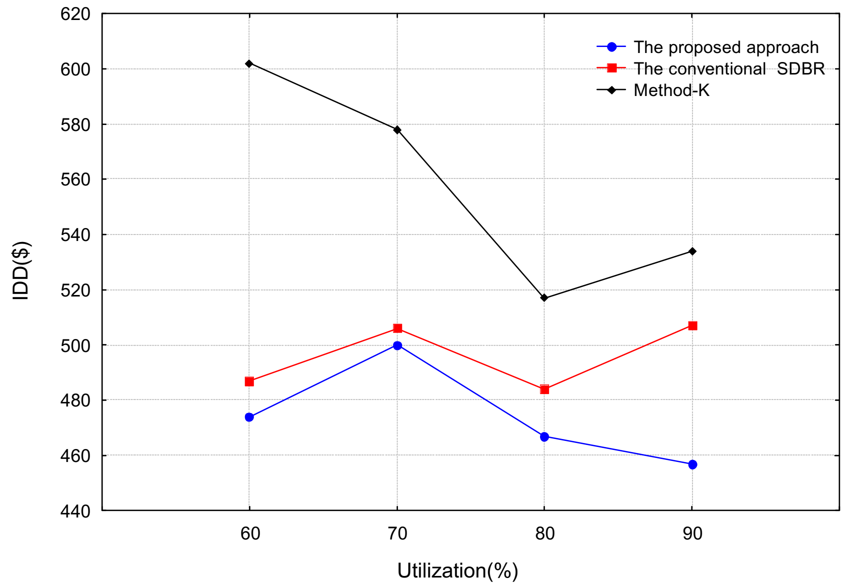

Figure 6. IDD under different utilizations.

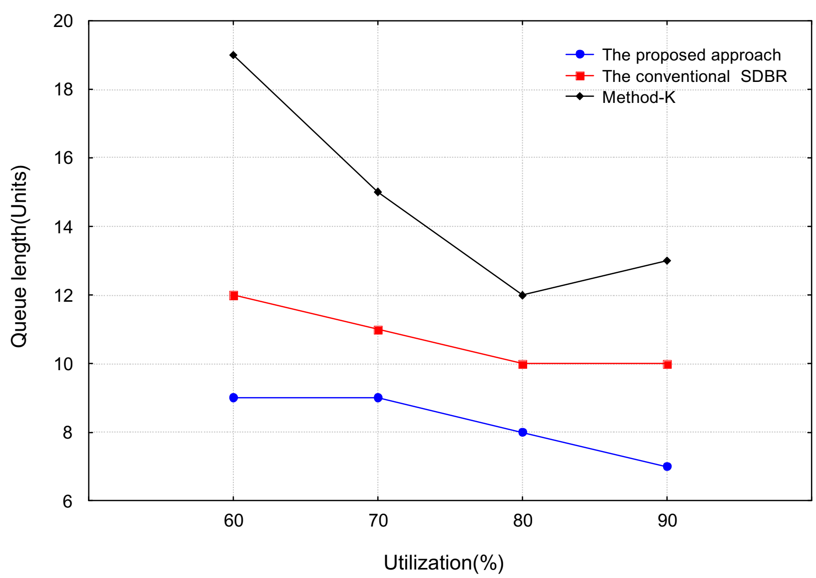

Figure 7. Q_CCR under different utilizations.

Figure 10 demonstrates that the DDSTs obtained from the proposed approach under all three different layer mixes were the largest among the three methods. This result shows that the proposed approach provided a better protection of the due date under a random RFS. In Figure 11, the TDDs obtained from the proposed approach under the two layer mixes (i.e. M-M-M and L-L-H) were the smallest among the three methods. On the other hand, the TDD obtained from the conventional SDBR under the particular layer mix (L-H-L) was the smallest. In Figure 12, the IDD obtained from the proposed approach under the two layer mixes (i.e. L-H-L and L-L-H) was the smallest. However, the IDD obtained from the conventional SDBR under the particular layer mix (M-M-M) was the smallest.

In Figures 13 and 14, the Q_CCR and the flow time obtained from the proposed approach under the three layer mixes were the smallest among the three methods.

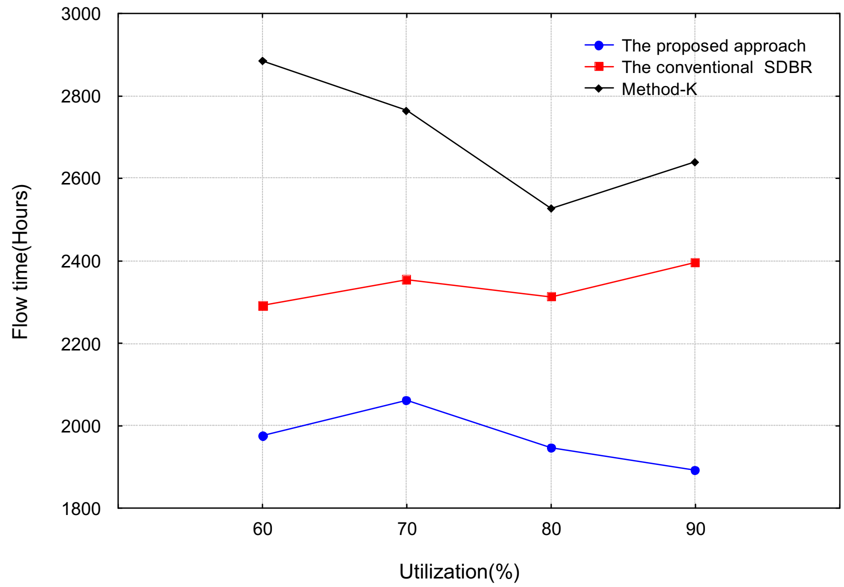

Figure 8. Flow time under different utilizations.

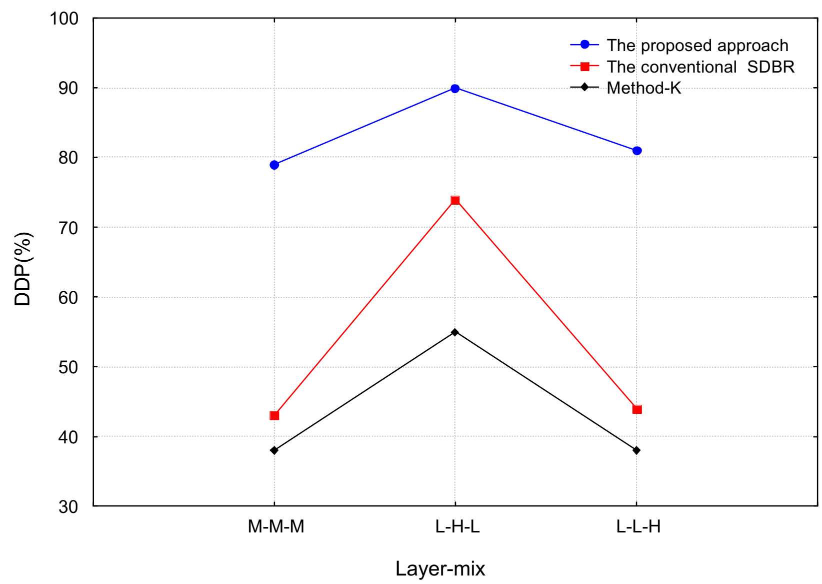

Figure 9. DDP under different layer mixes.

4.3 *Discussion*

In this section, we first discuss the difference between the conventional SDBR and the proposed enhanced SDBR regarding the due-date assignment method and the order release rule. Also, we then stated why the proposed approach could perform better than the conventional SDBR in a random RFS. Finally, we illustrate the difference the proposed approach from prior studies and the changes to practice should be made as a result of this paper.

First, the major difference of due-date assignment method (called drum) and order release rule (called rope) between the conventional SDBR and the proposed enhanced SDBR is the PL concept. Schragenheim (2006) introduced that the conventional SDBR utilises PL to determine both the due dates and the release dates of all orders. The PL of an order depends only on when it is arrived without considering its re-entry property or the random breakdown situations on

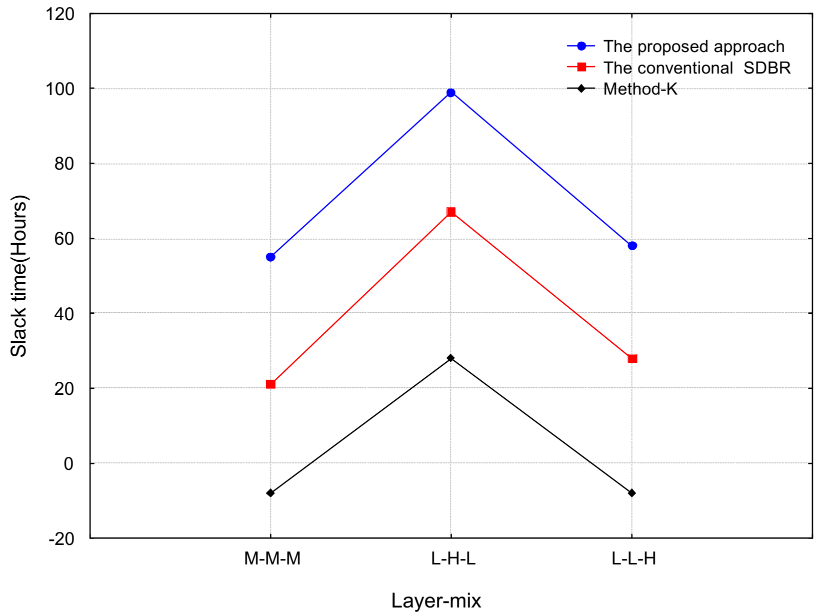

Figure 10. DDST under different layer mixes.

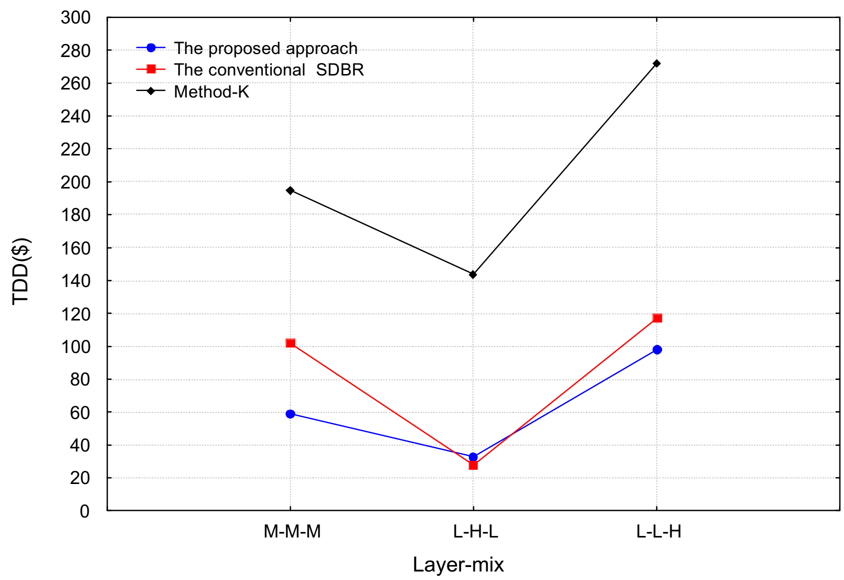

Figure 11. TDD under different layer mixes.

CCRs. As mentioned earlier, the DDP might be difficult to reach 99% as managers expected, sometimes even dropped to 30 or 40% when applying the conventional SDBR method in a RFS in practice. The DDP curve of the conventional SDBR in Figures 3 and 9 confirmed this. On the other hand, the proposed approach further considers the re-entry property of orders and reindexes all orders of all products based on the non-increasing order of their corresponding PL before deciding the due dates and release dates of orders. Thus, Figures 3 and 9 confirmed that the DDP curve of the proposed enhanced SDBR can be kept at least 80%. Second, in terms of the dispatching rule (called buffer), the conventional SDBR used the overall urgency (i.e. the BS) of a due date for a specific order to determine its priority without considering the re-entry feature and the influence of a random machine breakdown. By contrast, the proposed approach used the LBS to obtain the actual urgency at each reentrant layer. In order to distinguish the influence of machine

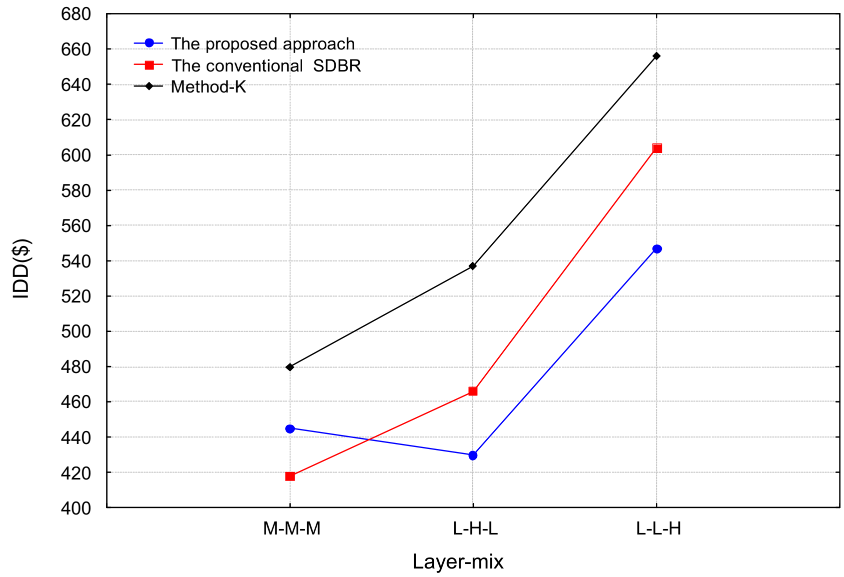

Figure 12. IDD under different layer mixes.

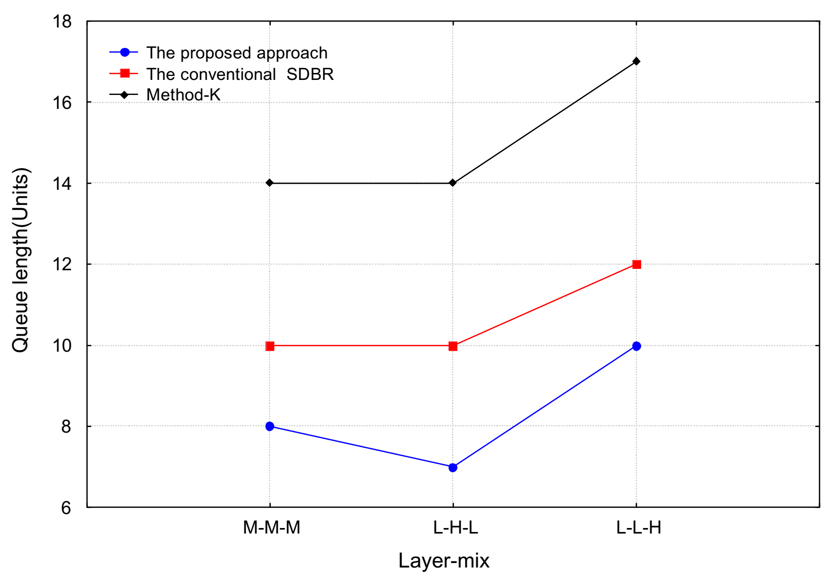

Figure 13. Q_CCR under different layer mixes.

downtimes for orders that generate a risk of delay, the proposed approach utilised the deviation rate of BS of each order to eliminate the influence of the accumulated machine downtimes and the influence of machine downtimes at different reentrant layers. Finally, our findings are different from the studies made by Schragenheim and Dettmer (2001), Schragenheim (2006) and Lee et al. (2010). In their studies, they claimed that 99% DDP can be easily achieved by using the conventional SDBR. Our study showed that the conventional SDBR is not that effective when being applied to a RFS subject to machine breakdowns compared with the proposed enhanced SDBR. The probable reason is that our method arranged due dates and release dates of orders with the consideration of the sequence of multi-reentrant orders among the PL of CCRs. We also take the deviation rate of BS into account to decide the priority of all orders in a random RFS while the previous studies made by Schragenheim and Dettmer (2001), Schragenheim (2006) and Lee et al. (2010) did not.

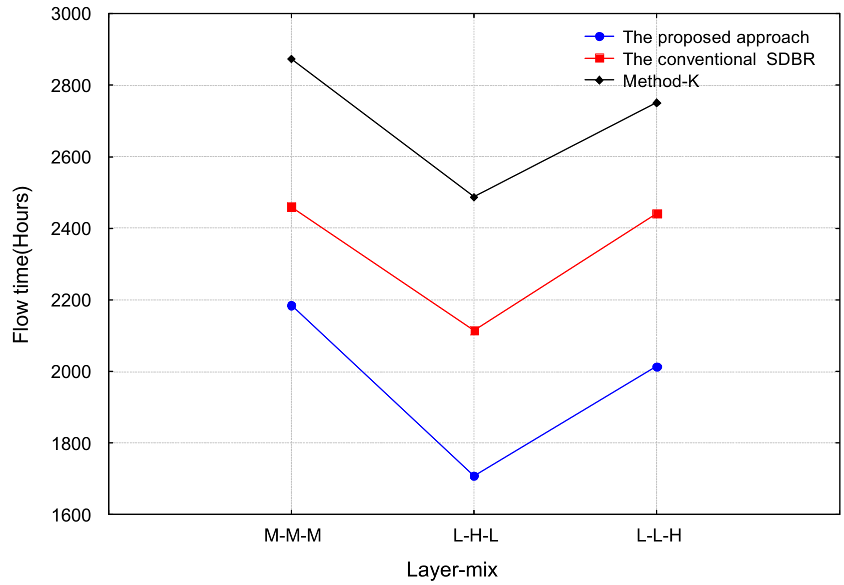

Figure 14. Flow time under different layer mixes.

5. Conclusions and future research

The proposed model provides a simple yet effective way to determine due dates and release dates of orders and dispatch jobs. Shop managers could easily use our proposed model to effectively managing their orders to meet customers' requirements. In order to improve the conventional SDBR to determine a reliable due date to customer in a random RFS environment, this paper proposed an enhanced SDBR model to overcome the two drawbacks found in the conventional SDBR. Regarding the due-date assignment method and order release rule, we proposed a new measure called the TPL to consider the number of CCR re-entries required to overcome the first potential drawback of the conventional SDBR. In addition, regarding the dispatching rule, we introduced a weighted layer dispatching rule to deal with the random breakdown situations on CCRs in order to conquer the second potential drawback. The efficiency of the proposed enhanced SDBR has been evaluated through different test scenarios which cover a range of CCR utilisations and also various product mixes per different number of reentrant layers. The results indicate that our approach yields better performance than the other methods in terms of the six due date related indexes when the product mix with a large proportion of multi-reentrant orders and when the utilisation of CCR increases from 60 to 90%. Due to the complexity of the reentrant environment being exacerbated by reentrant processing, the situation for precise multiple machines are in CCR is one of the future research directions. To solve the multiple machines are in CCR, it may taken the impact of a specific planned load that dedicates the capacity on a specific CCR at a specific layer into account. As this study did not consider the two or more machine bottleneck situations, future research should investigate this. In addition, it is also possible to consider the bottleneck shiftiness in a random RFS in future studies.

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