A New Approach for a Finite Capacity Material Requirement Planning System

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Abstract

This paper aims to develop a practical finite capacity MRP (FCMRP) system using heuristics based on schedules of the bottlenecks to adjust release and due dates to ensure capacity feasibility. Effects of available options in the FCMRP system, including release or due date scheduling, priority-based rearrangement, and shifting forward or backward in time options on the performance measures are statistically analyzed using real data from an auto-parts factory. Statistical results show that the release or due date scheduling and shifting forward or backward options have significant effects on the performance measures. To analyze the effectiveness of the proposed FCMRP system, its performance measures are compared to those of the conventional FCMRP systems and the variable lead-time MRP (VMRP) system. The proposed FCMRP system offers a compromise solution between that of the VMRP (infinite capacity) and the conventional FCMRP system (forward and forward-backward scheduling systems).

Keywords: Material Requirement Planning, Finite Capacity, Shifting forward or backward, Theory of Constraints, and Application in Industry.

1. Introduction

Manufacturing Resources planning (MRP II) is a well-known methodology for production planning and control in discrete part manufacturing and assembly. The methodology is often unsuccessful in practice because most MRP II packages determine a production schedule under an assumption that work centers have infinite capacity (see McCarthy and Barber [1]). This may result in a capacity infeasible schedule.

Nagendra and Das [2] stated that some MRP II packages include a function called capacity requirement planning (CRP) which can indicate capacity problems on work centers. However, this system does not suggest alternative schedules to remedy the capacity problems. It depends on the user to resolve it by trial and error, which is very time consuming.

Another approach for solving the capacity problem is a shop floor control (SFC) system. Examples include single-pass forward scheduling (McCarthy and Barber [1]), single–pass backward scheduling (White and Hastings [3]), and a combination of forward and backward scheduling (Hastings and Yeh [4]). Taal and Wortmann [5] and Bakke and Hellberg [6] concluded that a SFC system is unable to solve the capacity problems. The a SFC system does not change the release and due dates for orders, which are generated by the MRP system. For example, if the MRP system releases too many orders for a particular period, the open shop orders create additional inventory. In an FCMRP system, release dates might be changed if capacity is exceeded in some periods. They also suggested that the capacity problems should be prevented at the MRP calculation stage using an integrated approach of MRP and finite capacity scheduling. Thus, the finite capacity material requirement planning (FCMRP) system has been developed to remedy the capacity problems.

A survey of literature reveals that research works in the FCMRP area can be classified into two approaches. The first one is an optimization approach. This approach tries to optimize related costs. This approach is difficult to understand by the users who have no experience about the optimization technique, but it can guarantee the optimal result. Research works adopting the optimization approach are as follows. Billington and Thomas [7] and [8] formulated a production planning model as a mixed integer linear programming model. The objective is to minimize the sum of inventory carrying, setup, overtime, and utilization costs, subject to capacity constraints of work centers. Adenso-Diaz and Laguna [9] proposed an optimization model to support a production planner in solving capacity problems. However, in order to keep the model small and simple, they ignored the effects of lot sizing and work in process. Tardiff and Spearman [10] developed a technique called capacitated material requirements planning (MRP-C). MRP-C uses fundamental relations between WIP and cycle time (Little's law) to optimize performances of the production system. Sum and Hill [11] presented a method that not only adjusts lot sizes to minimize set-up time but also determines the release and due times of production orders while checking the capacity constraints. They split or combine the production orders to minimize set-up and inventory costs. Wuttipornpun *et al.* [12] developed a goal programming model to determine the optimal start time of each operation to minimize the sum of penalty points incurred by exceeding the goals of total tardiness, total earliness, and average flow-time considering the finite capacity of all work centers and precedence of operations.

The second approach is a heuristic approach. This approach does not try to optimize related costs, but it is easy to understand by the user. The heuristic research works are as follows. Hastings *et al.* [13] applied a forward loading technique to schedule the orders on work centers. This technique guarantees feasible release dates for production orders, but it may generate some tardy orders. Pandey *et al.* [14] developed a FCMRP algorithm, which is executed in two stages. First, capacity-based production schedules are generated from the input data. Second, the algorithm produces an appropriate material requirement plan to satisfy the schedules obtained from the first stage. Wuttipornpun and Yenradee [15] developed a FCMRP system for assembly operations that is capable of automatically allocating some jobs from one machine to another and adjusting timing of the jobs considering a finite available time of all machines.

A survey of current production planning in Thailand shows that the capacity planning and production scheduling are performed separately. Therefore, planners need at least 1 day to solve the capacity problems created from both stages.

A conventional FCMRP system being used in industries is a combination of MRP and finite capacity scheduling systems. The MRP system generates production orders assuming infinite capacity of work centers. The production orders indicate part ID, quantity to produce, and recommended start and due times. Then, the production orders will be loaded into the finite capacity scheduling system, where the start and completion times of each order will be calculated considering finite capacity of work centers. There are three conventional FCMRP systems, namely, forward (F), backward (B), and forward-backward (FB) scheduling systems. These systems have a significant effect on system performances since they use different scheduling concepts. The F scheduling system tries to schedule orders as soon as possible. This may result in early or late completion of some finished products. The B scheduling system tries to complete all orders on their due dates. This may result in early completion and an infeasible release date of some orders. The FB scheduling system tries to reduce the earliness in the F system by trying to delay some early completion orders.

Currently, some ERP packages such as SAP or Oracle try to integrate the optimization technique into their packages. A module called the Advance Planning Optimization module (APO), which is an optimization tool, is integrated into the package in order to increase the efficiency of scheduling. Many constraints can be set in order to generate a schedule with the desired performance measures.

This paper is organized as follows. The algorithm of the proposed FCMRP system is explained in section 2. The algorithms of the conventional FCMRP systems are briefly described in section 3. There are two experiments in section 4. The first one is to analyze the effects of available options in the proposed FCMRP systems on performance measures. The second one is to compare the effectiveness among the proposed FCMRP systems, the conventional FCMRP systems and the variable lead-time MRP (VMRP) system. The experimental results are analyzed and discussed in section 5. Finally, the results are concluded in section 6.

2. Proposed FCMRP System.

This paper proposes a new FCMRP system, based on a heuristic approach that can be used in companies with multiple products, flow shop with assembly operation characteristics, and identifiable bottleneck work centers.

The manufacturing process under consideration produces many products. Some products may require both sequential operations and convergent operations that are common for assembly shops. Others may require only sequential operations that are common for fabrication shops. Note that each operation must be performed in a work center and the flow of material through the work centers is unidirectional, which is a characteristic of the flow shop with assembly operations (not the job shop). Customers place orders for finished products by specifying the required product, quantity, and due date of each order.

Overall mechanisms of the proposed FCMRP system are explained before detailed steps of the algorithm are presented. The FCMRP system has five main steps. First, the initial schedule is generated by a variable lead-time MRP (VMRP) system. An objective of this step is to break the order for finished product into the required manufacturing operations and determine the release and due dates of all operations. The exact release and due dates of all operations are specified (bucketless MRP). The planning horizon is long enough to cover all operations of all orders. In this step, the initial schedule is completely generated by exploding all levels and all items in the bill of materials in order to determine the schedule of all operations without considering finite capacity of work centers.

Second, all operations are scheduled to their first priority (the most appropriate one considering cost or processing time) work centers. An objective of this step is to check capacity problems on the first priority work centers. Third, the operations in the same day are rearranged by some priority rules in order to determine the operation sequence. Fourth, the schedule is adjusted considering finite capacity of all work centers by moving some operations from the first priority work centers to the second priority work centers (if possible). An objective of this step is to reduce the capacity problems on the first priority work centers. After the fourth step is completed, all operations are assigned to work centers considering finite capacity. Finally, the schedule of operations on all work centers is adjusted based on the schedule of the bottleneck work center.

The characteristics of the schedule obtained from the proposed FCMRP system is that the schedule of the bottleneck work centers has no idle time and overtime, which complies with the Optimized Production Technology (OPT) or Theory of Constraints (TOC) concept (see Goldratt [16], Fry *et al.* [17], and Yenradee [18]). However, the schedule of non-bottleneck work centers may have idle time and overtime in order to deliver the required parts to the bottleneck work centers whenever they are required. The proposed FCMRP system based on the heuristic approach is easier to use than a Drum-Buffer-Rope (DBR) scheduling system of the TOC concept. The DBR system requires the user to appropriately determine time buffer and rope (see Chakravorty [19], Schragenheim and Ronen [20]).

A block diagram of the FCMRP system is shown in Figure 1. The system is described step-by-step and illustrated by an example as follows.

<u>1. Generate production and purchasing plan using variable lead-time MRP system</u>

The production and purchasing plans are initially generated by the MRP system called TSPICs (Thai SME Production and Inventory Control system). TSPICs has been developed by Sirindhorn International Institute of Technology and implemented in some factories in Thailand. It is different from the conventional MRP system in that it assumes variable lead-times.

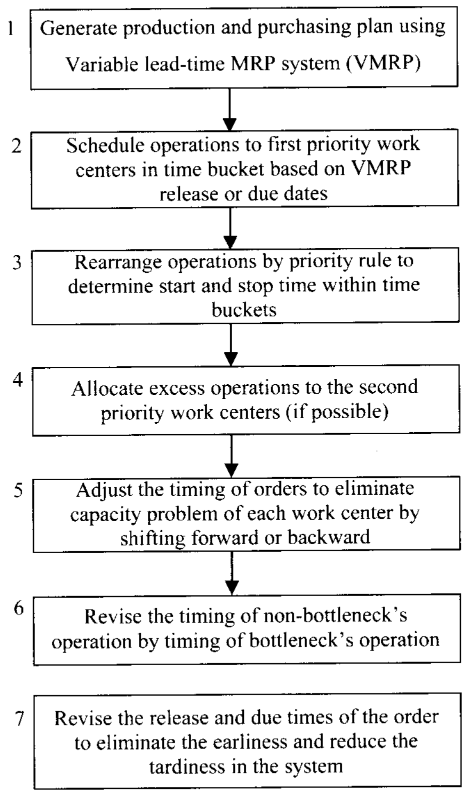


Figure 1. Block diagram of FCMRP system

The total lead-time in TSPICs is a function of lot size, unit processing time, and setup time. The release time of orders is calculated from the due date minus the total lead-time considering a detailed work calendar of the factory. Thus, the release time of orders from TSPICs is more realistic than that of the conventional MRP system.

An example of calculating the release date and time can be described by Table 1. It shows detail of all operations required to produce products for customers. The due time is assumed to be 5:00 pm. The release date and time of each operation is calculated using formulas (1) and (2) and presented in the last column of Table 1.

Release date and time =
Due date and time – Total lead-time(hrs) (1)

Total lead-time =
[Order quantity (pcs) x Unit processing time (hrs/pcs)] + Setup time (hrs) (2)

Note that the FCMRP system uses a lot-for-lot lot sizing rule since it is the simplest and results in the lowest inventory level.

2. Schedule operations to the first priority work centers by release or due date scheduling

Operations may be performed by more than one work center as shown in Table 1. The most efficient or most appropriate work center is called the first priority work center, and the next most appropriate one is the second priority work center. The aim of this step is to check the capacity requirement on each work center when operations are scheduled on the most appropriate work centers. There are two proposed methods to schedule the operations on the first priority work centers. The first one is to schedule the operations to be performed as per their release dates (denoted by SR method). The second one is to schedule the operations to be performed as per their due dates (denoted by SD

Table 1 Data of the required operations for producing products

Operation name	Due date/time	First priority work center	Sec. priority work center	Total Lead-time (hrs)	Release date/time
M1	1/5.00 p.m.	1	2	5.5	1/10.30 a.m.
N2	1/5.00 p.m.	1	2	3	1/02.00 p.m.
M3	2/5.00 p.m.	1	2	2.25	2/02.45 p.m.
P4	2/5.00 p.m.	1	2	2.04	2/02.57 p.m.
N5	3/5.00 p.m.	1	2	4.5	3/11.30 a.m.
P6	4/5.00 p.m.	1	2	11.5	3/01.30 p.m.
M7	4/5.00 p.m.	1	2	5.5	4/10.30 a.m.
S8	1/5.00 p.m.	2	1	2.7	1/02.18 p.m.
T9	2/5.00 p.m.	2	1	6.5	2/09.30 a.m.
S10	2/5.00 p.m.	2	1	2.5	2/02.30 p.m.
T11	3/5.00 p.m.	2	1	4.5	3/11.30 a.m.
T12	4/5.00 p.m.	2	1	2.7	4/02.18 p.m.
S13	4/5.00 p.m.	2	1	2.75	4/02.15 p.m.

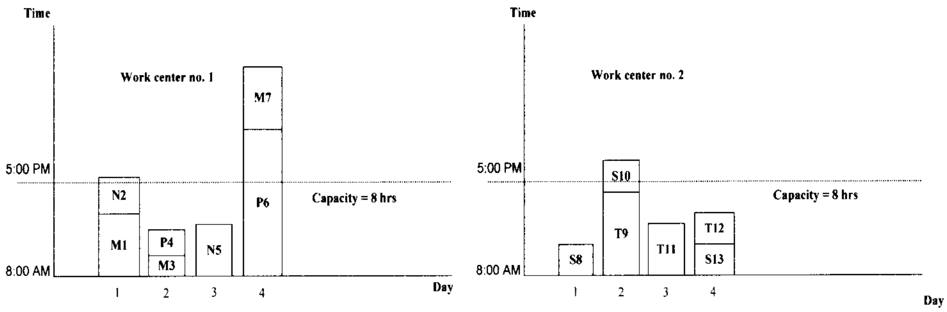
Table 2 Operation schedules based on SR and SD methods

Day	SR method		SD method	
	Work center 1	Work center 2	Work center 1	Work center 2
1	M1, N2	S8	M1, N2	S8
2	M3, P4	T9, S10	M3, P4	T9, S10
3	N5, P6	T11	N5	T11
4	M7	S13, T12	P6, M7	S13, T12

method). Based on the information in the last column of Table 1, the SR method determines the schedule as shown in Table 2. Similarly, the SD method uses the information in column 2 of Table 1 to determine the schedule as shown in Table 2.

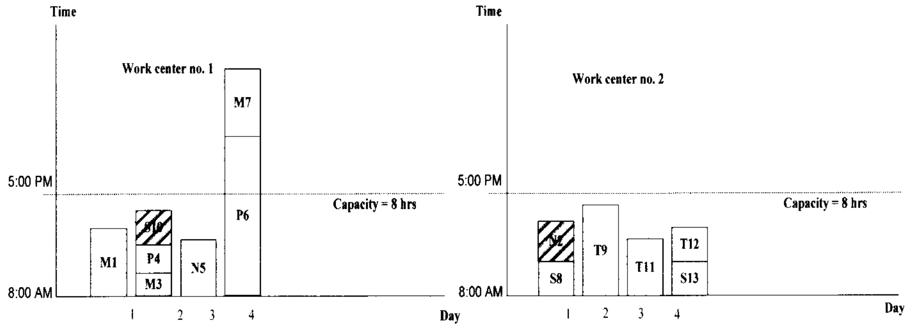
3. Rearrange operations scheduled on the same day by priority-based rearranging

It can be seen from Table 2 that there are two operations (M1 and N2) which are performed in day 1 in work center 1. Therefore, the sequence of operations scheduled on the same day can be determined by applying some priority rules. There are two priority rules under consideration, namely, earliest release time (ERT) and earliest due time (EDT). The ERT rule will perform the operation with earliest release time first and perform the operation with relatively late release time later. Thus, the operation with relatively late release time may exceed the available capacity of the work center. The operation that exceeds the capacity of the work center is called an "excess operation", which will be allocated to the second priority work enter in the next step. Similarly, the EDT rule will perform the operation with earliest due time first and perform the operation with relatively late due time later. If there are some operations which have the same release time (or due time) on the same day, the sequence of these operations can be determined arbitrarily.



(a) (b)

Figure 2. Load profile on work centers obtained from SD method and ERT rule



(a) (b)

Figure 3. Load profile on work centers after allocating excess operations to the second priority work center

Figure 2 shows the load profile on work centers 1 and 2 of the schedule obtained from the SD method and ERT rule. The X-axis shows the day and the Y-axis shows the time of day. Note that after applying the ERT rule, operations M1, N2, M3, P4, N5, P6, and M7 are performed sequentially in work center 1 and operations S8, T9, S10, T11, S13, and T12 are performed sequentially in work center 2, which are the first priority work centers for the operations.

<u>4. Allocate the excess operations to the second priority work centers</u>

This step tries to reduce capacity problem on the first priority work center by moving the excess operations from the first priority work center to the second priority work center on the same day if the movement will not make the operations become excess operations on the second priority work center. The whole operation may be moved (but not a fraction of the operation) to avoid additional setup. From Figure 2(a), the excess operation N2 on work center 1 in day 1 can be moved to work center 2 (see Figure 3(b)). Similarly, from Figure 2(b), the excess operation S10 on work center 2 in day 2 can be moved to work center 1 (see figure 3(a)). However, the excess operation M7 on work center 1 on day 4 cannot be moved to work center 2 since the slack capacity of work center 2 is not enough to accept the operation M7. At the end of this step, bottleneck work centers are identified by comparing the capacity requirement and available capacity of each work center. The bottleneck work centers have capacity requirements greater than, equal to, or slightly less than the available capacity on an average basis. They have no, or very little, idle time and may have overtime at some periods. Note that after step 4 is completed, the schedule of operations on all work centers is used as an initial schedule for the VMRP, conventional FCMRP, and the proposed FCMRP systems.

<u>5. Adjust the timing of operations to eliminate capacity problem of each work center by shifting forward or backward</u>

This step tries to eliminate capacity problem in all work centers by shifting forward or backward without changing the sequence of operations in the work centers. The flowchart of this step is shown in Figure 4.

There are two important steps in the flowchart. The first one involves moving operations to the left (shifting backward), which makes the operations start and complete earlier. The second one is to move the operation to the right (shifting forward), which delays the operation. The moving assumption in this step is different from step 4 since this step tries to move the operations scheduled on the same work center, whereas step 4 tries to move the operations from the first to the second priority work centers. The capacity problem can be solved by allowing some operations to be completed earlier than their due dates (increasing inventory holding costs) or allowing some operations to be completed later than their due dates (increasing late delivery to the customers).

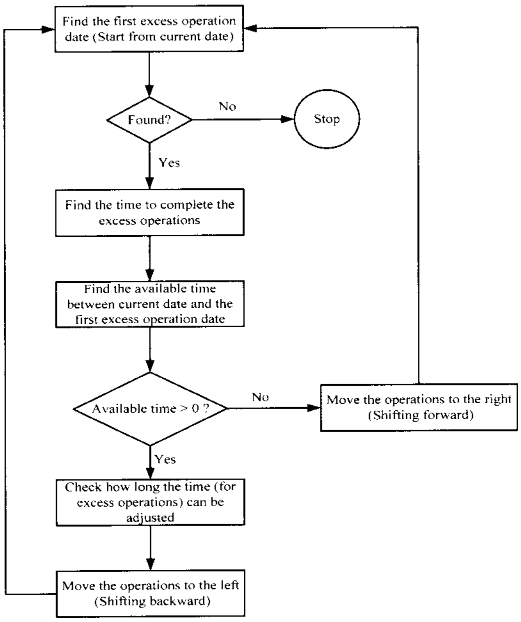


Figure 4. Flowchart for adjusting timing of operations to eliminate capacity problem

Although both are undesirable, completing the operation early is assumed to be better than completing the operation late. Therefore, the shifting backward step is applied first. If the shifting backward step cannot entirely solve the capacity problem, there are two alternatives. First, the leftover capacity problem may be solved by applying overtime. Second, if applying overtime is undesirable, the shifting forward procedure will be applied to solve the leftover capacity problem.

Figure 5(a) shows a load profile of work center 1. Suppose that there are seven operations in this work center. The first day that the excess operations (entire operation M7 and part of operation P6) occur is day 4. The slack capacity is available from day 1 to day 3, which allows the shifting backward procedure to be applied. After the shifting backward procedure is applied, the slack capacity on day 1 to day 3 disappears, but part of operation M7 is still an excess operation (see Figure 5(b)). This problem can be solved using overtime. However, if the overtime is undesirable, the shifting forward procedure is applied. Figure 5(c) shows the load profile after applying the shifting forward procedure. It can be seen that the capacity problem does not exist but operation M7 will be completed one day late. After applying these rules, the sequence of operations is not changed but their release and due times are changed. From Figure 5(c), operations P4, N5, and M7 seem to be fractional but actually they can be performed continuously with only one set-up time. For instance, in Figure 5(c), operation P6 is started on day 3 (after operation N5) and finished on day 4 (before starting operation M7).

The bottleneck work centers are normally operated for two shifts or three shifts during regular time. Therefore, it is inappropriate to add any overtime on the bottleneck work centers. Therefore, the shifting option that is appropriate for the bottleneck work center is a combination of shifting backward and shifting forward. However, if the bottleneck work centers are operated for a single shift, the overtime may be allowed and only shifting backward may be applied.

In this paper, the bottleneck work centers are operated for two shifts and the overtime is not allowed. For the non-bottleneck work centers, there are three possible cases, namely, apply none, apply only shifting backward, and apply both shifting backward and shifting forward. The applications of scheduling directions to bottleneck and non-bottleneck work centers can be summarized as follows.

1. Apply both shifting backward and shifting forward to only the bottleneck work centers.

2. Apply only shifting backward to the non-bottleneck work centers and apply both shifting backward and shifting forward to the bottleneck work centers.
3. Apply both shifting backward and shifting forward to all work centers.

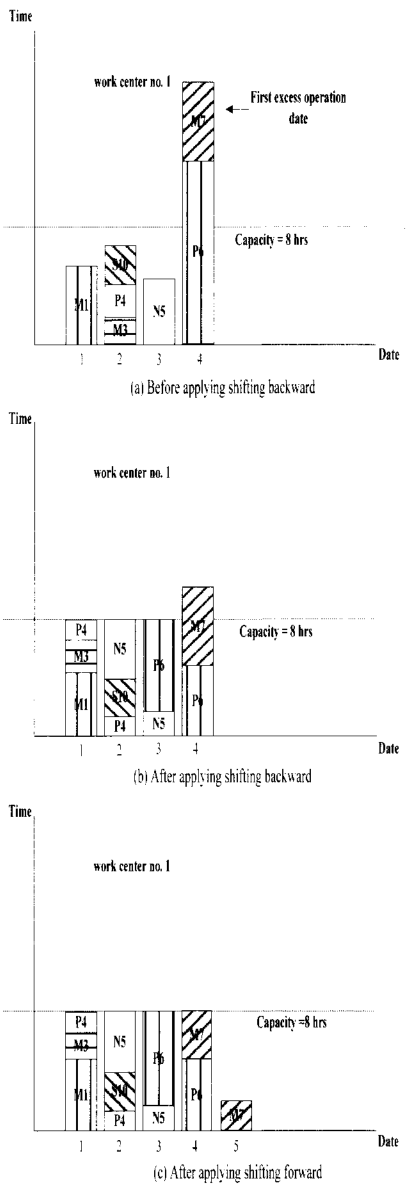


Figure 5. Example of applying shifting backward and shifting forward methods

<u>6. Revise the timing of non-bottleneck's operation by timing of bottleneck's operation</u>

In step 5, the timing of some operations on each work center has been adjusted independently without considering precedence relationships among the operations. Thus, it is possible that the release and due times of operations for producing parts of the same order (parts in the same BOM) are in conflict. This step tries to solve the conflict by revising the release and due times of some operations if necessary.

On a shop floor, some work centers are bottleneck work centers and others are non-bottleneck work centers. The schedule of operations on the bottleneck work centers should be fixed since it is very tight. The schedule of operations on the non-bottleneck work centers may be revised (to comply with that of the bottleneck work centers) since it has significant slack times. To make it more comprehensive, an example of BOM in Figure 6 is used to illustrate how the timing of operations is revised. A product requires 11 operations as presented in Table 3 and relations between the operations are shown in Figure 6. The release and due times of each operation are obtained from step 1 of the proposed FCMRP system. Suppose operation B is performed in the bottleneck work center and it has a release time of 13 and due time of 16.

The schedule of the operations performed in the bottleneck work center should be maintained and the schedule of operations performed on the non-bottleneck work center should be revised accordingly. The due times of operations D and E have no conflict with the release time of operation B, thus, they will not be revised. The due time of operation X (equals 12) is in conflict with the release time of operation D (equals 10). Therefore, the due time of operation X must be changed from 12 to 10. As a result, the release time of operation X must also be changed from 7 to 5 since the total lead-time of operation X is 5. Considering the precedence between operations B and A, operation A has the release time of 15 which is in conflict with the due time of operation B, which is 16. Thus, the release time of operation A must be revised from 15 to 16, which in turn changes the due time of operation A from 17 to 18 (total lead-time of operation A is 2 days).

Table 3. BOM related data and job schedule

Operation name	Total lead-time (days)	Release time	Due time	Work center
A	2	15	17	non-bottleneck work center
B	3	13	16	bottleneck work center
C	1	14	15	non-bottleneck work center
D	3	10	13	non-bottleneck work center
E	1	12	13	non-bottleneck work center
F	1	12	14	bottleneck work center
G	1	13	14	non-bottleneck work center
X	5	7	12	non-bottleneck work center
Y	5	7	12	non-bottleneck work center
Z	5	8	13	non-bottleneck work center
W	5	8	13	non-bottleneck work center

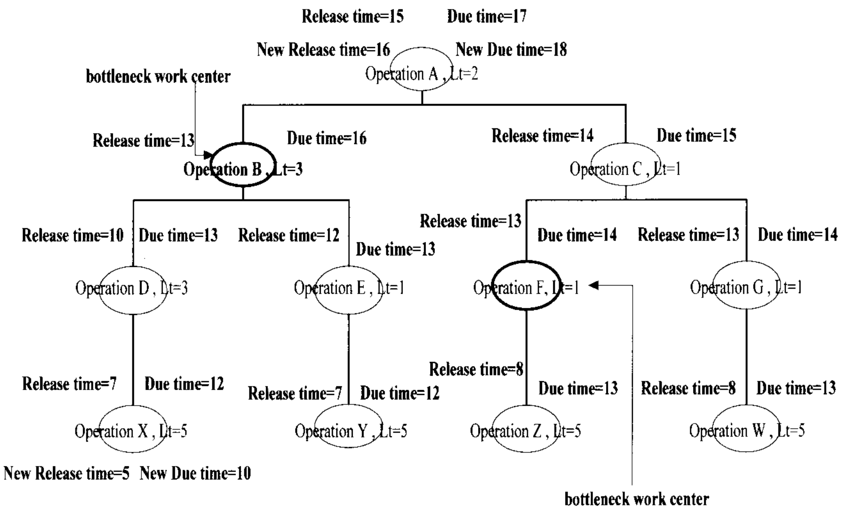


Figure 6. Example of revising the production and purchasing plans

Suppose operation F is also performed in the bottleneck work center and it has a release time of 13 and due time of 14. Similarly, the schedule of the operations performed in the bottleneck work center should be maintained and the schedule of operations performed in the non-bottleneck work center should be revised accordingly. However, the precedence constraints of operation F and other operations are not violated, thus release and due times of other operations will not be revised. Note that any operation on the bottleneck will be selected first and timing of its precedent operations will be considered level-by-level until the lowest level in the BOM. Then, the timing of its succeeding operations will be considered level-by-level until the highest level in the BOM. This procedure has a limitation. Suppose operations B and X are performed on bottleneck work centers. Both operations are in the same path of the BOM. In this case, the algorithm of this step cannot work well. If the schedule of operation B is fixed, the schedule of operation X must be revised accordingly. However, operation X is produced by a bottleneck work center, which means its schedule cannot be revised easily. Note that if there are some orders whose operations do not pass through any bottleneck work center, the schedules of their operations will be revised (if they are conflicting) based on the schedule of the operation at the highest level in the BOM to let the order complete as close to its due date as possible.

7. Revise the release and due times of the orders to eliminate the earliness and reduce the tardiness in the system.

After applying step 6, all operations will not have any conflict. However, the system may still have some earliness and tardiness. This procedure tries to revise the release and due times of each order to eliminate the earliness and reduce the tardiness in the system. The earliness and tardiness have been calculated by the difference between the customer due time and completion time of the order. To eliminate the earliness, the completion time of each order which is early will be moved to the due time of the customer order. Figure 7 shows an example of eliminating the earliness. Suppose operation B is performed on the bottleneck work center and it has a release time of 13 and due time of 16. After applying step 6, the release time of operation A will be revised from 15 to 16 and the due time of operation A will be revised from 17 to 18. Suppose operation A has a customer due time of 20. It shows that operation A will be completed 2 days early (new due time is 18). Thus, the new due time of operation A will be revised again from 18 to 20 which in turn changes the release time of operation A from 16 to 18 (total lead-time of operation A is 2 days).

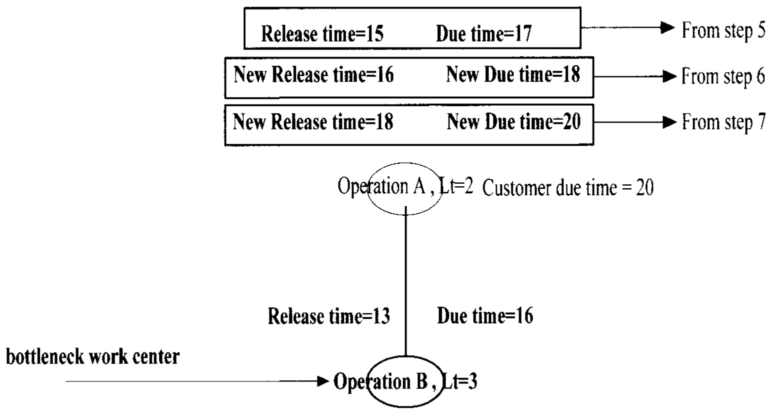


Figure 7. Example of eliminating the earliness

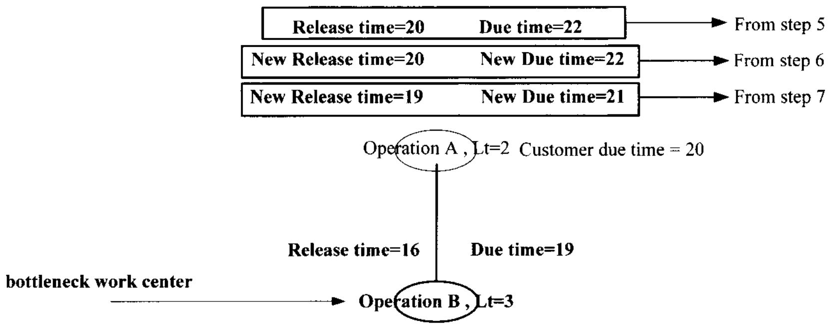


Figure 8. Example of reducing the tardiness

To reduce the tardiness, the completion time of each order which is tardy will be moved as close as possible to the customer's due time if the movement will not cause any conflict with other operations in the same BOM.

Figure 8 shows an example of reducing the tardiness. Suppose operation B is performed in the bottleneck work center and it has a release time of 16 and due time of 19. Operation A has a release time of 20 and due time of 22 (obtained from step 5). After applying step 6, the release and due times of operation A are the same since they are not in conflict with operation B. It shows that operation A will be completed late by 2 days (the customer's due time of operation A is 20). This step will move the completion time of operation A back to day 21. Therefore, the new due time of operation A will be revised from 22 to 21, which in turn changes the release time of operation A from 20 to 19 (total lead-time of operation A is 2 days). Note that the due time of operation A cannot be revised from 22 to 20 because the release time of operation A will be revised from 20 to 18 which is in conflict with the due time of operation B.

3. Conventional FCMRP Systems.

This section explains the concept of conventional FCMRP systems. Two conventional FCMRP systems, namely, Forward (F) and Forward-Backward (FB) scheduling systems, are considered. The algorithm of the F scheduling system is presented in figure 9. The first four blocks of the algorithm are the same as those of the proposed FCMRP system in order to generate the same initial schedule for a fair comparison between VMRP, F, FB, and the proposed FCMRP system. The remaining blocks of the algorithm try to schedule the production orders as early as possible to the available time on the work centers considering precedence relationships of the operations. The operations cannot be started if all precedence operations (operations for producing all required components and parts) are not completed.

Unlike the proposed FCMRP system, no overtime is allowed for the conventional FCMRP systems since it is impractical to determine in advance which work centers and in which periods, how many hours of overtime should be applied. However, if overtime is needed to be applied, a trial and error method, which is time consuming and may not give a good result, may be used.

Since the F scheduling system tries to schedule the operations as early as possible, some operations may be completed before their due dates, which incur an inventory holding cost. The FB scheduling system tries to alleviate this drawback by delaying the early-completed operations as much as possible without making the operations completed late. The algorithm of the FB scheduling system is presented in Figure 10.

4. Design of Experiments.

This section presents two experiments. The first one aims to analyze the effects of options available in the proposed FCMRP system. The second one is to evaluate the effectiveness of the proposed FCMRP system. To accomplish this, TSPICs has been further developed to integrate the features of the proposed FCMRP system.

4.1 Experiment to analyze the effects of options available in the proposed FCMRP system

The effects of the options available in the FCMRP system on the performance measures of the generated schedule will be analyzed. Results of the analysis will indicate how the options are selected to obtain the desirable performance. Independent and dependent variables of the experiment and experimental case are described as follows.

Independent variables

The independent variables of the experiment are the options available in the proposed FCMRP system. They are presented as follows.

1. Options for scheduling operations to the first priority work centers (release or due date scheduling options)

There are two options for scheduling operations to the first priority work centers as described in section 2, namely, SD and SR methods.

2. Options for rearranging operations scheduled on the same day (priority-based rearrangement option)

There are two options for priority-based rearrangement, namely, ERT and EDT.

3. Options for eliminating capacity problems (shifting forward or backward Options)

There are three options as follows:

3.1 Apply both shifting backward and shifting forward to only the bottleneck work centers.

3.2 Apply only shifting backward to the non-bottleneck work centers and apply both shifting backward and shifting forward to the bottleneck work centers.

3.3 Apply both shifting backward and shifting forward to all work centers.

Experimental case

The experiment is performed based on a real situation of a selected manufacturing company producing automobile steering wheels and gearshift knobs. The situation under consideration is briefly explained as follows:

1. The company is a multi-stage flow shop and has 25 items of finished goods with approximately 1,200 items of components.
2. Bill of materials (BOM) has 3 to 10 levels depending on the products.
3. There are 20 work centers and two of them are bottlenecks, namely work centers 13 and 15.
4. Some products can be produced in more than one work center.
5. The first and second priority work centers are specified by the planner.
6. The first and second priority work centers have the same unit processing time and setup time.
7. The bottleneck work centers are operated 16 hours a day and cannot have any overtime (company's policy).
8. The non-bottleneck work centers are operated 8 hours a day (can add overtime).
9. Time bucket is daily (other time bucket may be applied).
10. Overlapping of production batches is not allowed.
11. The lot-sizing technique being used is lot-for-lot since it results in a low inventory level and it is the most popularly used by MRP users (Haddock and Hubicki [21]).
12. Based on a goodness of fit test of historical demand in the past 12 months, the customer demand follows a uniform distribution, where the maximum and minimum demands are +/- 15% of the mean demand.
13. The actual demand of each product in a month is collected and used as the mean demand.

The experiment is conducted in 30 replications using 30 sets of randomly generated demands. A full factorial design of experiment technique is used to statistically analyze effects of the independent variables on the performance measures.

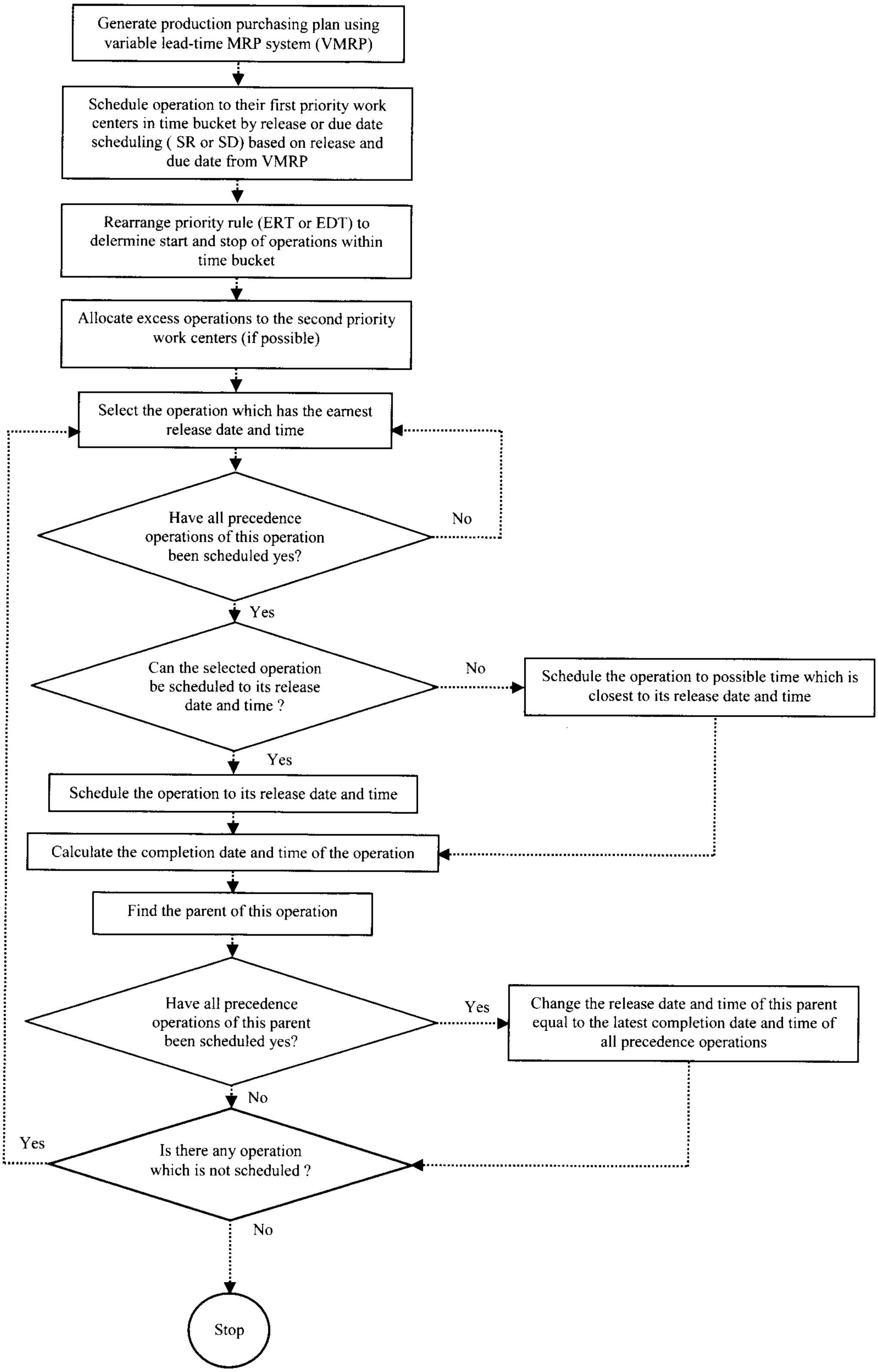


Figure 9. An algorithm of F system

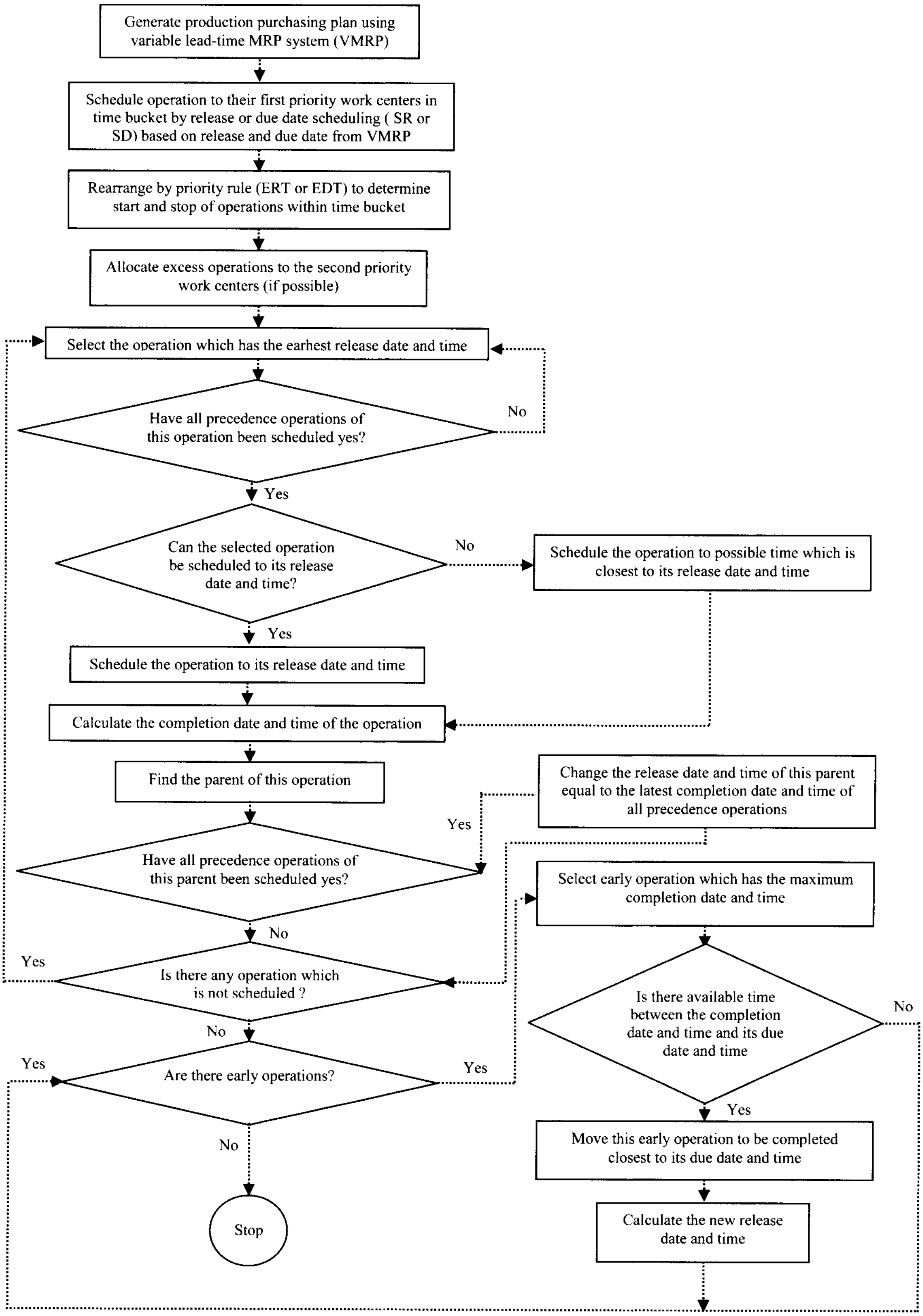


Figure 10. An algorithm of FB system

4.2 Experiment to evaluate the effectiveness of the proposed FCMRP system.

After analyzing the available options of the proposed FCMRP system as presented in section 4.1, possible settings of FCMRP options will be set. To analyze the effectiveness of the possible settings of FCMRP system, the performance measures of the schedules generated by it are compared to those of the schedules generated by a variable lead-time MRP (VMRP) and conventional FCMRP (F and FB) systems. The experimental case is already described in section 4.1. One-way ANOVA is used to statistically analyze the effectiveness of the possible settings of the FCMRP system.

5. Results and Discussion

The results and discussion are divided into two sections. The first one is the analysis on the effects of options available in the proposed FCMRP system. The second one is the analysis on the effectiveness of the proposed FCMRP system.

5.1 Analysis on the effects of options available in the proposed FCMRP system

The ANOVA results of the experiment to analyze the effects of options available in the proposed FCMRP system are shown in Table 4. They reveal that the release or due date scheduling option has a significant effect on all performance measures, namely, number of tardy orders, total tardiness, total overtime, and flow-time. The shifting forward or backward option has a significant effect only on total overtime and flow-time whereas the priority-based rearrangement option has no significant effect on all performance measures. The interaction effects between the release or due date scheduling and shifting forward or backward options for total overtime and average flow-time are significant but other two-way and three-way interactions are insignificant. Table 5 shows the average values of performance measures for only significant options. The ranking of the performance measures obtained by Tukey's test is shown in parentheses. The lower rank has better performance than the higher rank. From Table 5, it can be seen that the SD option outperforms the SR option for all performance measures (SD has rank 1). This occurs because of the following reason. Customers place orders for finished products based on their needs. The company reviews the orders based on production capacity. If the company is heavily loaded in some periods, the company may negotiate with the customers to change the due dates of the orders to alleviate the capacity problem. The due dates of the orders are regulated before accepting the orders. Therefore, when the orders are scheduled to be produced on the due dates (following SD), the load on the work centers is smoother than when the orders are scheduled on the release dates (following SR). For example, the load profiles on work center 20 after the orders are scheduled using SR and SD options are shown in Figure 11. It can be seen that the load profile of SD option is smoother and has a lower amount of excess orders. Starting from a better schedule obtained from the SD option, other steps of the FCMRP system tend to work better too. As a result, all performance measures of the SD option are better than those of the SR option.

Based on Table 4, the effect of priority-based rearrangement option is insignificant which can be explained as follows. After applying ERT or EDT option, the excess operations on the first priority machines will be allocated to the second priority machines on the same day if the second priority machines exist and have the available capacity. Based on the current data of the company, the second priority machines exist for only 15% of all orders. Therefore, most excess operations cannot be allocated to the second priority machines. As a result, the difference of the performance between the ERT and EDT options is insignificant.

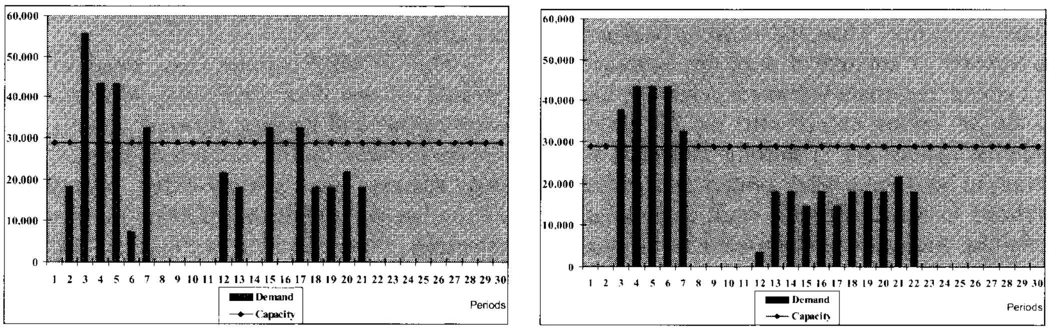
Table 4. Analysis of variance results

Factors	P-value			
	No. of tardy orders	Total tardiness	Total Overtime	Average Flow-time
Release or due date scheduling option (S)	*0.000	*0.000	*0.000	*0.000
Priority-based rearrangement option (R)	0.665	0.433	0.779	0.433
Shifting forward or backward option (SHIFT)	0.433	0.312	*0.000	*0.000
SxR	0.247	0.076	0.418	0.095
RxSHIFT	0.442	0.632	0.073	0.444
SxSHIFT	0.545	0.639	0.000*	0.000*
SxRxSHIFT	0.471	0.065	0.085	0.077

Note : * means the effect is significant at a significance level of 0.05

Table 5 Average values of performance measures for significant options
( ) Tukey's test performance ranks

Factors				
	No. of tardy jobs	Total tardiness (days)	Total Overtime(Hrs)	Flow-time (Hrs)
Release or due date scheduling options SR	53.62(2)	72.80(2)	262.11(2)	81.15(2)
SD	51.93(1)	65.80(1)	224.39(1)	70.70(1)
Shifting forward or backward options (SHIFT) Shifting backward/shifting forward for bottleneck work centers	77.88(1)	138.70(1)	362.09(3)	61.48(1)
Shifting backward for non-bottleneck and shifting backward/shifting forward for bottleneck work centers	77.98(1)	138.80(1)	279.98(2)	72.48(2)
Shifting backward/shifting forward for all work centers	77.88(1)	138.70(1)	124.42(1)	72.65(2)



(a) SR (b) SD

Figure 11. Load profile after applying SR and SD on work center no. 20

According to Table 5, when the shifting backward and shifting forward method is applied to only bottleneck work centers, total overtime is relatively high and flow-time is relatively low whereas there are no early orders. When the shifting backward is applied to non-bottleneck work centers (in addition to applying the shifting backward and shifting forward to bottleneck work centers), the total overtime can be significantly reduced but the flow-time is significantly increased. This occurs since the excess operations (except the ones that produce finished products) on the non-bottleneck work centers are produced early. As a result, the flow-time will be increased. When the shifting backward and shifting forward method is applied to all work centers, the total overtime can be further reduced but flow-time is not significantly increased. This is because the shifting forward method tries to delay the excess operations on the non-bottleneck work centers to reduce the overtime.

Since the interaction effects between the release or due date scheduling option and shifting forward or backward option for total overtime and average flow-time are significant, the effects of both options should be considered simultaneously to understand the interactions. The Graphs showing the interaction between both options on the total overtime, and average flow-time, and are presented in Figures 12 and 13, respectively. It can be seen that when the shifting forward or backward option is set in a way that results in relatively high total overtime and average flow-time the SD option outperforms the SR option. Considering the total overtime (see Figure 12), the interaction graphs show that when the shifting backward and forward is applied to only the bottleneck work center, the total overtime is relatively high and the SD option outperforms the SR option. While the options are 1) shifting backward and forward to bottleneck work centers and shifting backward to non-bottleneck work centers, and 2) shifting backward and forward to all work centers, the total overtime is relatively low and the SR and SD scheduling options result in the same level of performance measures.

Considering the average flow-time (see Figure 13), when shifting backward and forward is applied to all work centers, the average flow time is relatively high and the SD option outperforms the SR option. For the other two options on shifting forward or backward, the SD and SR options have the same average flow time.

It is interesting to evaluate the performances of the proposed FCMRP system when the demand pattern and number of bottleneck work centers are changed. Thus, two additional experiments are conducted. The first additional experiment is the same as the experiment previously reported in this section except the demand is seasonal, which is created by increasing the demand in weeks 1 and 3 by 50%. The experimental results are presented in Table 6. Since the demand in weeks 1 and 3 are increased, the tardiness, total overtime, and flow-time in Table 6 are higher than those in Table 5. By observing the ranking of performance measures in Table 6, the effects of scheduling options on the performance measures are still the same as those in Table 5. The second additional experiment is conducted by increasing the unit processing time of work center number 17 by 250 % and allowing this work center to be operated for 16 hours a day so that this work center is now a bottleneck work center. Note that the number of bottleneck work centers is increased from 2 to 3. The ranking of performance measures in Table 7 clearly shows that the effects of scheduling options on the performance measures are still the same as those in Table 5. Therefore, it can be concluded from additional experiments that the proposed FCMRP system still shows the same trend of performances when the demand pattern and number of bottleneck work centers are changed.

The FCMRP system has three options (release or due date scheduling, priority-based rearranging, and shifting forward or backward options). Based on the analysis of the results in this section, the priority-based rearranging option has no significant effect on performance measures, thus possible settings of FCMRP options can be set without considering this option. Table 8 shows six possible settings of FCMRP options.

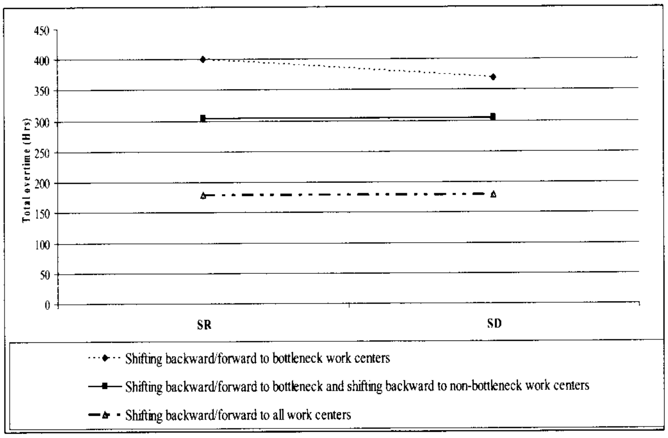


Figure 12. The interaction effect between release or due date scheduling and shifting forward or backward options on total overtime

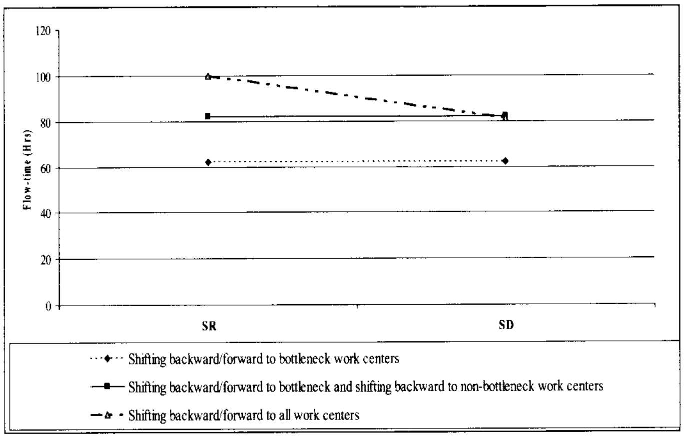


Figure 13. The interaction effect between release or due date scheduling and shifting forward or backward options on flow-time

Table 6 Average values of performance measures for significant options (increased demand at weeks 1 and 3 by 50%)

( ) Tukey's test performance ranks

Factors	No. of tardy jobs	Total tardiness (days)	Total Overtime(Hrs)	Flow-time (Hrs)
Release or due date scheduling options SR	75.67(2)	89.65(2)	288.44(2)	100.15(2)
SD	72.22(1)	83.45(1)	250.03(1)	93.29(1)
Shifting forward or backward options (SHIFT) Shifting backward/shifting forward for bottleneck work centers	99.12(1)	177.44(1)	392.22(3)	79.89(1)
Shifting backward for non-bottleneck and shifting backward/shifting forward for bottleneck work centers	99.32(1)	177.62(1)	301.01(2)	95.54(2)
Shifting backward/shifting forward for all work centers	99.12(1)	177.44(1)	139.11(1)	95.67(2)

Table 7 Average values of performance measures for significant options (increased number of bottleneck work centers from 2 to 3)

( ) Tukey's test performance ranks

Factors	No. of tardy jobs	Total tardiness (days)	Total Overtime(Hrs)	Flow-time (Hrs)
Release or due date scheduling options SR	64.23(2)	79.77(2)	270.19(2)	87.44(2)
SD	60.33(1)	72.85(1)	232.33(1)	79.99(1)
Shifting forward or backward options (SHIFT) Shifting backward/shifting forward for bottleneck work centers	89.55(1)	153.65(1)	375.69(3)	68.34(1)
Shifting backward for non-bottleneck and shifting backward/shifting forward for bottleneck work centers	89.61(1)	153.70(1)	287.88(2)	80.88(2)
Shifting backward/shifting forward for all work centers	89.55(1)	153.65(1)	132.44(1)	80.96(2)

Table 8. Possible setting of FCMRP options

FCMRP setting	Scheduling option	Scheduling Direction option
FCMRP 1	SR	Shifting backward/shifting forward for bottleneck work centers
FCMRP 2	SR	Shifting backward for non-bottleneck work centers and shifting backward/shifting forward for bottleneck work centers
FCMRP 3	SR	Shifting backward/shifting forward for all work centers
FCMRP 4	SD	Shifting backward/shifting forward for bottleneck work centers
FCMRP 5	SD	Shifting backward for non-bottleneck work centers and shifting backward/shifting forward for bottleneck work centers
FCMRP 6	SD	Shifting backward/shifting forward for all work centers

5.2 Analysis on the effectiveness of the proposed FCMRP system

In this section the performance of the schedules obtained from the FCMRP system will be compared to those of the schedules obtained from the variable lead-time MRP (VMRP) system and the conventional FCMRP (F and FB) system. To determine the performance measures of the schedule obtained from the VMRP system, the generated operations must be scheduled on the first priority work centers (the second step of the FCMRP system) using SR and SD options. Then, the excess operations are allocated to the second priority work centers if possible.

The average value of the performance measures and the ranking of the performance measures obtained by Tukey's test are shown in Table 9. The ranks are presented in parentheses. The lower rank has better performance than the higher rank. The performance measures with the same rank are not significantly different.

It can be seen from Table 9 that the VMRP system has no tardiness and earliness, but requires the highest overtime. As a result, its average flow time is very short. The reason is that the VMRP tries to satisfy the customer due dates by assuming infinite capacity of all work centers thus the required overtime is extremely high. The F system results in the highest tardiness because overtime is not allowed. The earliness is also high since the F system tries to complete operations as soon as possible. The FB system can reduce the earliness when compared to the F system while they have the same value of tardiness. The reason is that the FB system tries to delay early operations to be completed on their due dates (if possible). As a result, the average flow time of the F system is less than the FB system.

Based on Table 9, the performance measures of the proposed FCMRP systems (FCMRP 1, FCMRP 2, FCMRP 3, FCMRP 4, FCMRP 5, and FCMRP 6) are somewhere between those of the VMRP and the conventional FCMRP systems (F and FB). While the VMRP, F, and FB systems generate a schedule that is the best for some performance measures and the worst for others, the proposed FCMRP systems generate a compromised schedule that is moderate for all performance measures. It can be seen from Table 9 that the proposed FCMRP system can significantly reduce the tardiness from the F and FB systems, whereas the total overtime is increased.

Table 9. Means and ranks of performance measures
( ) Tukey's test performance ranks

Factors	Average value and rank of performance measures						
	No. of Early orders / % of all orders	Total earliness (days)	No. of tardy orders / % of all orders	Total tardiness (days)	Total Overtime(Hrs) / % of VMRP (SR) overtime	Flow-time (Hrs) / % of FB flow-time	Overall performance index
VMRP (SR)	00.00/00.00% (1)	00.00 (1)	00.00/00.00% (1)	00.00 (1)	785.56/100.00% (7)	12.20/9.76% (1)	135.62 (7)
VMRP (SD)	00.00/00.00% (1)	00.00 (1)	00.00/00.00% (1)	00.00 (1)	656.49/83.57% (6)	14.80/11.84% (2)	114.12 (3)
F	08.00/03.19% (2)	10.00 (2)	201.00/80.0% (4)	647.00 (4)	00.00/00.00% (1)	124.30/99.4% (7)	346.33 (10)
FB	00.00/00.00% (1)	00.00 (1)	201.00/80.08% (4)	647.00 (4)	00.00/00.00% (1)	125.00/100.00% (8)	344.75 (9)
FCMRP 1	00.00/00.00% (1)	00.00 (1)	80.40/32.03% (3)	145.70 (3)	399.35/50.84% (5)	65.20/52.16% (4)	151.82 (8)
FCMRP 2	00.00/00.00% (1)	00.00 (1)	80.45/32.05% (3)	145.80 (3)	275.70/35.10% (3)	75.70/60.56% (6)	132.64 (6)
FCMRP 3	00.00/00.00% (1)	00.00 (1)	80.40/32.03% (3)	145.70 (3)	124.88/15.89% (2)	75.91/60.73% (6)	106.98 (2)
FCMRP 4	00.00/00.00% (1)	00.00 (1)	75.35/30.02% (2)	131.70 (2)	324.43/42.77% (4)	57.57/46.06% (3)	130.79 (5)
FCMRP 5	00.00/00.00% (1)	00.00 (1)	75.50/30.08% (2)	131.80 (2)	273.25/34.78% (3)	69.25/55.40% (5)	124.13 (4)
FCMRP 6	00.00/00.00% (1)	00.00 (1)	75.35/30.02% (2)	131.70 (2)	123.96/15.78% (2)	69.44/55.55% (5)	98.73 (1)

Note : Total number of jobs = 251 orders

Focusing on different options of the proposed FCMRP system, some interesting points can be discussed. All FCMRP systems have no earliness (as a result of step 7 of the proposed FCMRP system), but have different performance on overtime and flow time. Considering FCMRP 1, 2, and 3 (based on SR rule), FCMRP1 (applies both shifting backward and shifting forward to only bottleneck work centers) requires the highest overtime, but has the lowest flow time. FCMRP 2 applies shifting backward to the non-bottleneck work centers in addition to FCMRP 1. Thus, some operations that need overtime may be produced earlier. This results in a schedule that has lower overtime but higher flow time compared to that of FCMRP 1. FCMRP 3 applies shifting forward to the non-bottleneck work centers in addition to FCMRP 2. Therefore, some operations that still need overtime after applying FCMRP 2 may be produced later. Note that the shifting backward and shifting forward will be applied to an extent that will not create an early order and an unnecessary late delivery of finished product to the customer (see step 7 in section 2). This results in a schedule that has lower overtime compared to that of FCMRP 2.

The release or due date scheduling option of FCMRP 1, 2, and 3 is SR while that of FCMRP 4, 5, and 6 is SD. From Table 5, SD outperforms SR for all performance measures. Therefore, FCMRP 4, 5, and 6 (using SD) are better than FCMRP 1, 2, and 3 (using SR), respectively for all performance measures. An overall performance index can be determined using a weighted average of some performance measures. Based on an opinion of the planner of this company, one hour of total overtime or one hour of average flow-time is as important as one day of total earliness while one day of total tardiness is as important as three day of total earliness. Thus, the weights of total tardiness, total earliness, average flow-time, and total overtime are 0.5, 0.17, 0.17, and 0.17, respectively. The overall performance indices are presented in Table 9. It indicates that FCMRP 6 results in the best overall performance index calculated based on the opinion of the planner of this company.

Note that an average calculation time required for all methods is 2 hours. It shows that the proposed FCMRP method can greatly reduce the calculation time compared with that of the current practice Thai industries, which is about one day.

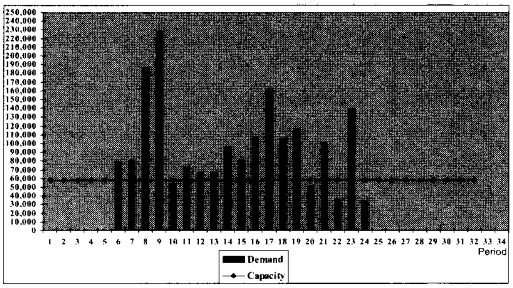
The characteristics of schedules generated by the proposed FCMRP systems are similar to those of the schedules obtained from the TOC concept. The characteristics of a TOC schedule is that the schedule on the bottleneck work centers has no idle time or overtime but the schedules on the non-bottleneck work centers may have idle time and overtime. As an example, the load profiles on the bottleneck work center of the VMRP, FB, and FCMRP 6 are shown in Figure 14. From Figure 14, the load profiles on the bottleneck work center obtained from the FCMRP 6 have no idle time or overtime, but those of VMRP have significant idle time and overtime, and those of FB have only idle time at the beginning of the planning horizon. The load profiles on a selected non-bottleneck work center of the VMRP, FB, and FCMRP 6 are shown in Figure 15. It clearly shows that the load profile of the FCMRP 6 is smoother than that of the VMRP system, however, it still requires overtime in some periods. The FB does not require overtime on the non-bottleneck work center.

6. Conclusions.

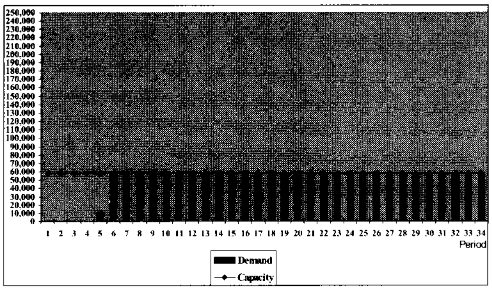
A new approach to FCMRP systems, which is applicable for real industrial problems, was developed. The developed FCMRP system has three options, namely, release or due date scheduling, priority-based rearranging, and shifting forward or backward options. The effects of the options on the performance measures are statistically analyzed based on the real data of an auto-part factory. Statistical results show that the release or due date scheduling option and shifting forward or backward option have significant effects on the performance measures.

The SD option outperforms the SR option for all performance measures since the company reviews the customer orders based on the production capacity and negotiates with the customers to change the due dates of the orders to alleviate capacity problems.

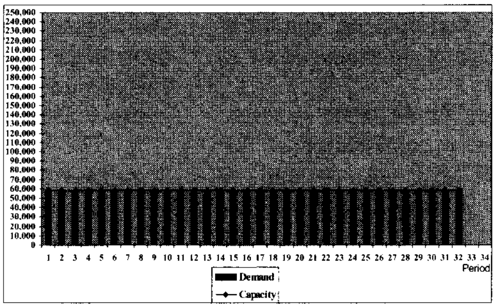
The shifting forward or backward option is effective in reducing the required overtime (but increases the flow-time). It tries to start some excess operations earlier (shifting backward) and to delay some excess operations



(a) VMRP

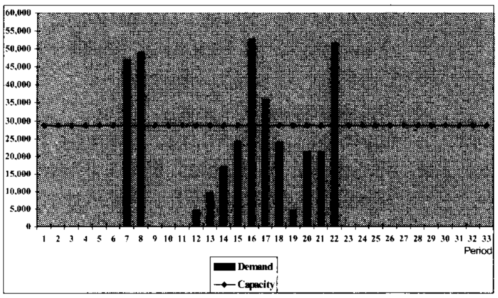


(b) FB

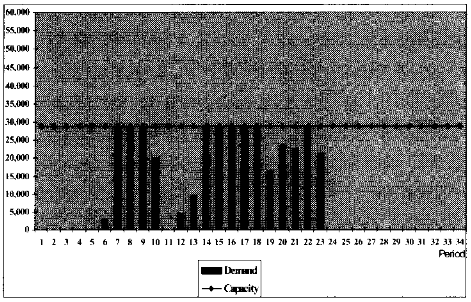


(c) FCMRP 6

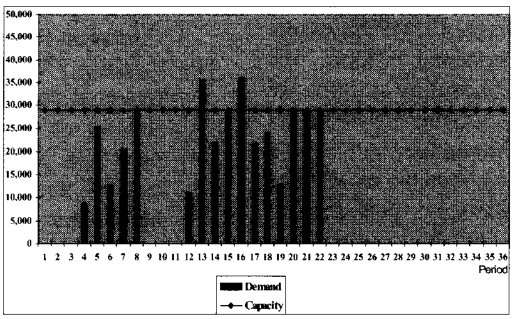
Figure 14. Load profile on bottleneck work center no. 15 of VMRP, FB and FCMRP 3



(a) VMRP



(b) FB



(c) FCMRP 6

Figure 15. Load profile on non-bottleneck work center no. 20 of VMRP, FB, and FCMRP 3

(shifting forward). Both shifting backward and shifting forward should be applied to all bottleneck work centers to eliminate the required overtime on them since they are operated two shifts or three shifts where overtime is not allowed in practice. The shifting backward and shifting forward options may be or may not be applied to non-bottleneck center work centers. If they are applied, the required overtime on the non-bottleneck center will be reduced but the flow-time will be increased. The priority-based rearranging option does not significantly affect the performance measures since most operations cannot be produced by a second priority machine.

There are six types of FCMRP systems, which are obtained from a combination of the significant options. FCMRP 4, 5, and 6 outperform FCMRP 1, 2, and 3, respectively, because the former ones use the SD option that outperforms the SR option being used by the latter ones. The performance measures of FCMRP 4, 5, and 6 are different because of the effect of shifting forward or backward options. FCMRP 6 has lower overtime but higher flow time than FCMRP 4 while FCMRP 5 is somewhere between FCMRP 4 and FCMRP 6.

Since the options of the FCMRP system can significantly affect the scheduling performance, the options should be carefully designed and selected to obtain the desirable scheduling performance. This leads to further research of developing and analyzing more options for the FCMRP system.

The proposed FCMRP system is a new method for generating production and purchasing schedules that offers compromised solutions between that of the VMRP (infinite capacity) and the conventional FCMRP systems (F and FB scheduling systems). Since the performance measures of scheduling systems are conflicting, there is no system that is best for all performance measures. The production planners tend to prefer a scheduling system, which can trade-off among conflicting performance measures. The proposed FCMRP system has selectable options, which the production planners can select to trade-off among the conflicting performance measures to obtain the best overall performance index. Thus, the proposed FCMRP system is a good alternative method for production scheduling for capacity constrained flow shops.

Characteristics of the schedule generated by the proposed FCMRP system comply with those generated by the TOC concept in that the bottleneck schedule is free of idle time and overtime. However, the non-bottleneck schedule may have idle or overtime in some periods to deliver parts to the bottleneck whenever they are required.

The proposed FCMRP system still has some limitations. The lot sizing policy under consideration is only lot-for-lot. The effect of the lot sizing policy has not been studied. The overlapping of production batches has not been considered. Thus, further research is needed to analyze and develop the FCMRP system to improve these limitations.

7. Acknowledgement

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