World Academy of Science, Engineering and Technology
International Journal of Industrial and Manufacturing Engineering
Vol:4, No:10, 2010

An Algorithm of Finite Capacity Material Requirement Planning System for Multi-stage Assembly Flow Shop

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Abstract**—**This paper aims to develop an algorithm of finite capacity material requirement planning (FCMRP) system for a multi-stage assembly flow shop. The developed FCMRP system has two main stages. The first stage is to allocate operations to the first and second priority work centers and also determine the sequence of the operations on each work center. The second stage is to determine the optimal start time of each operation by using a linear programming model. Real data from a factory is used to analyze and evaluate the effectiveness of the proposed FCMRP system and also to guarantee a practical solution to the user. There are five performance measures, namely, the total tardiness, the number of tardy orders, the total earliness, the number of early orders, and the average flow-time. The proposed FCMRP system offers an adjustable solution which is a compromised solution among the conflicting performance measures. The user can adjust the weight of each performance measure to obtain the desired performance. The result shows that the combination of FCMRP NP3 and EDD outperforms other combinations in term of overall performance index. The calculation time for the proposed FCMRP system is about 10 minutes which is practical for the planners of the factory.

Keywords**—**Material requirement planning, Finite capacity, Linear programming, Permutation, Application in industry.

I. INTRODUCTION

ENTERPRISE resource planning (ERP) is an integrated computer-based system used to manage production and inventory control, internal and external resources including tangible assets, financial resources, accounting, and human resources. There is a main function called material requirement planning (MRP) consisted in various ERP packages. This function allows users to generate production and purchasing plans based on orders input to the system. The main concept of MRP in generating these plans is a fixed lead-time (infinite machine capacity). This concept results in a main drawback of MRP since it generates an infeasible production plan (Nagendra and Das [1], McCarthy and Barber [2]). A capacity requirement planning (CRP) and a shop floor control (SFC) concepts are then introduced in order to remedy the capacity problem after the MRP stage to obtain a feasible production plan (McCarthy and Barber [2], White and Hastings [3], and Taal and Wortmann [4]).

Although the CRP and SFC can solve the capacity problem but they do not attack the problem at the MRP stage. The appropriate way to solve the capacity problem at this stage is to determine the production schedule using an integration of MRP and finite capacity scheduling (Bakke and Hellberg [5]). Thus, a finite capacity material requirement system (FCMRP) then has been developed to attack the problem at the MRP level. There are many researches related to the FCMRP system. They can be classified into two main groups.

The first group is FCMRP systems with non-extension capacity. Pandey, Yenradee, and Archariyapruek [6] proposed an FCMRP algorithm that is executed in two stages. The first stage is to generate capacity-based production schedules based on data input to the system. The second stage is to calculate a capacitated material requirement planning to satisfy the schedule obtained from the first stage. The proposed algorithm guarantees a feasible schedule for the user. Wuttipornpun and Yenradee [7] developed an FCMRP system for a flow shop with assembly operations that is capable of allocating jobs from one machine to another and also adjusting timing of the jobs by considering the finite available time of all machines. This algorithm provides both non-extension and extension capacity solutions. Nagendra and Das [1] proposed a finite capacity scheduling system with lot size restrictions. This algorithm is called progressive capacity analyzer (PCA). In this algorithm, the capacity constraint and lot sizing are considered concurrently with the BOM explosion process. The result shows that the PCA procedure offers a better solution that addresses the practical scenario of finite scheduling for multiple products, capacitated resources, and lead-times for any periods. Wuttipornpun, Yenradee, Buellens, and Oudheusden [8], [9] developed an FCMRP algorithm for a multi-stage automotive-part assembly flow shop. In this system, the weight of each performance measure is assigned in order to obtain a desired solution. The result shows that the assigned weights are significantly affected to all performance measures. The user can change the weights in order to get the desired performance.

The second group is related to FCMRP systems with extension capacity. This group offers a solution with an

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essential overtime to reduce the tardiness in the system. Wuttipornpun and Yenradee [10] proposed an FCMRP system that generates a compromised solution among key performance measurers. This system is a modification of the algorithm developed in 2004 [7] by integrating the theory of constraint (TOC) and an FCMRP system called TOC-FCMRP. The result shows that the TOC-FCMRP system requires higher overtime than conventional FCMRP systems, whereas the tardiness and flow-time obtained from the proposed system are lower. Ozdamar and Bozyel [11] proposed a finite capacity system called the capacitated lot sizing problem (CLSP). This model offers a solution considering inventory, overtime, and setup time simultaneously. Since the problem is considered as a non-polynomial problem (NP), Genetic Algorithm (GA) and Simulated Annealing (SA) are then introduced to determine a solution. The result shows that SA outperforms GA in both performance measures and computational time. Rajagopalan and Swaminathan [12] proposed an effective solution in order to determine the required overtime. The result shows that the increase of product variety may not result in excessive inventory and also the increase of machine set up times or holding cost may not result in the increase of the total cost. Ornek and Cengiz [13] developed a capacitated lot sizing with alternative routing and required overtime. This algorithm incorporates the finite capacity scheduling and the MRP concept in order to avoid the capacity problem at the shop floor level. The algorithm offers a feasible schedule with appropriate lot size and overtime. Rong, Takahashi, and Morikawa [14] proposed MRP rescheduling heuristics with capacity extension under deterministic demand. The result shows that increasing overtime in the system obtains a better performance measure in cost since the overtime cost is lower than the setup or tardiness costs.

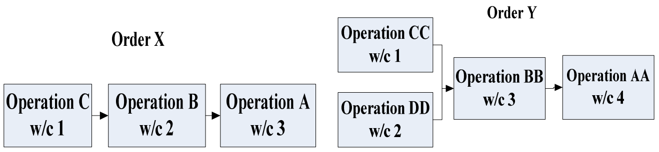
It is obviously seen that two categories of FCMRP system reviewed above are of interest. Therefore, this research also aims to propose a new FCMRP system which is a compromised solution among five key performance measures, namely, the total tardiness, the number of tardy orders, the total earliness, the number of early orders, and the average flow-time. The proposed FCMRP system has four main steps adapted from the research conducted by Wuttipornpun and Yenradee in 2005 and 2006 [8], [9]. The first three steps are to generate a sequence of orders and operations by proposed heuristics and the last step is to determine the optimal solution of the sequence generated from the previous steps by a linear programming model. The proposed system is evaluated based on real information from the selected factory so that it can be used in real situations. The characteristics of the selected factory are described as follows:

1) There are multiple products and multiple work centers.
2) Some work centers are bottlenecks and the others are non-bottlenecks.
3) Some products have multiple levels of BOM with subassembly operations. Other products require only fabrication without assembly operations.
4) Some operations have only one work center to produce, whereas the others can be produced by two alternative work centers called the first and second priority work centers.
5) The structure of the production shop is a flow shop with assembly operations.

This paper is organized as follows. The algorithm of the proposed FCMRP system is described in section II. An experiment to analyze the effectiveness of the proposed FCMRP system and an experimental case are explained in section III and IV. The experimental results are analyzed and discussed in section V. Finally, the conclusion is made in section VI.

II. THE PROPOSED FCMRP SYSTEM

The manufacturing process under consideration is a flow shop with assembly operations. Some products require only sequential operation shops (without assembly operations) as shown in Fig 1(a), whereas the others require both sequential and convergent operation shops (with assembly operations) as shown in Fig. 1(b). A set of customer orders come to the factory without bucket (bucketless) and the information such as product name, due date, and quantity are specified by the customers. Note that some operations have two alternative work centers (w/c) called as the first priority and second priority work centers. They all are specified by the planner of the factory.



(a) Sequential operation (b) Convergent operation

Fig.1 Example of operation shops

The algorithm of the proposed FCMRP system is shown in Fig. 2. The algorithm is described step by step and illustrated by an example as follows.

Step1: Generate production and purchasing plans by using a variable lead-time MRP system.

The ERP software called Thai SME Production and Inventory Control system (TSPICs) is used to generate production and purchasing plans based on the variable lead-time MRP. TSPICs was developed by Sirindhorn International Institute of Technology (SIIT) and implemented in some factories in Thailand. It is different from the conventional MRP in that it assumes the variable lead-time concept. The total processing time in TSPICs is a function of lot size, unit processing time, and setup time (see Wuttipornpun and Yenradee [7]). The release time of operations is calculated from the due date minus the total lead-time considering the detail of work calendar of the factory. Thus, the release time of operations from TSPICs is more realistic than that of conventional MRP systems. Note that the proposed FCMRP system uses the lot-for-lot sizing rule since it is the simplest and results in lowest inventory level.

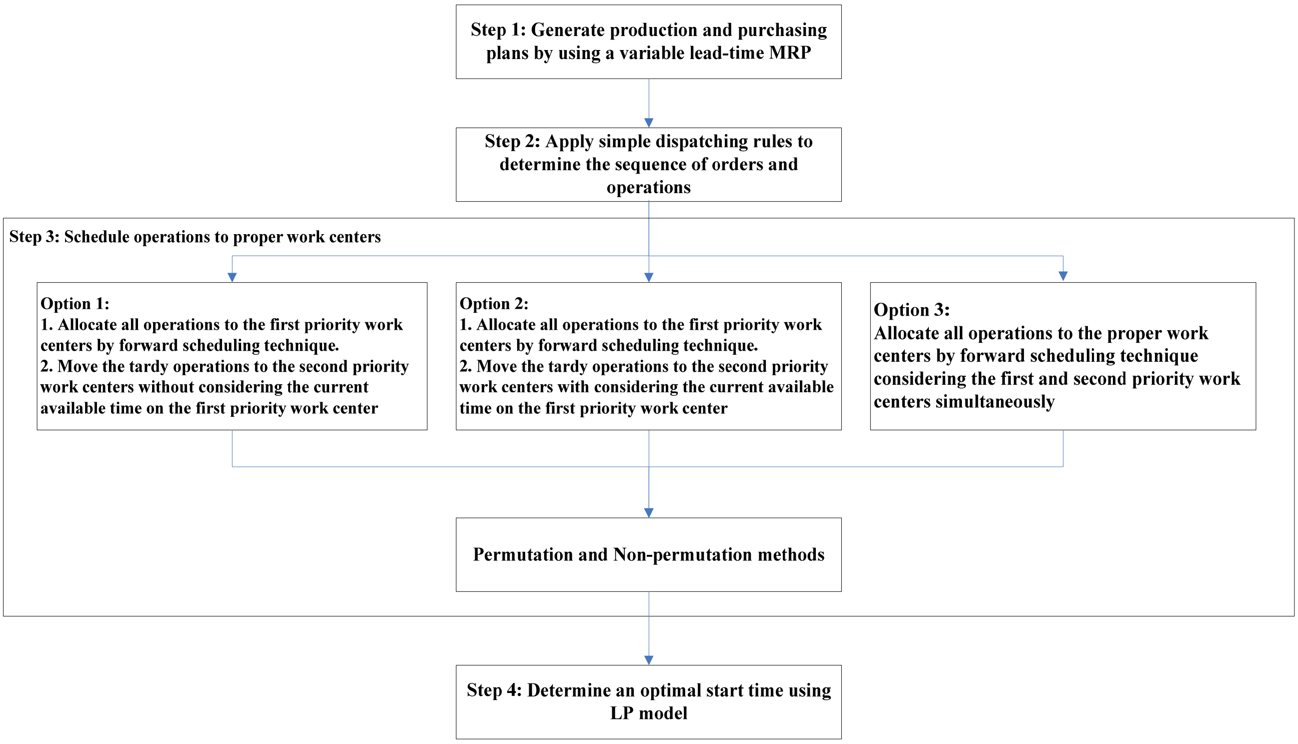


Fig. 2 An algorithm of the proposed FCMRP system

Step2: Apply simple dispatching rules to determine the sequence of orders and operations.

This step attempts to generate different sequences of orders by applying simple dispatching rules. Two well-known dispatching rules, namely, the earliest due date (EDD) and the minimum slack time (MST) are applied in order to study how the dispatching rules affect the performance measures. Fig. 3 illustrates how to apply the dispatching rules to the orders. Each order may require more than one work center. For instance, order A requires w/c 1, 2, 3, and 4, while order C requires w/c 1, 2, and 4. Note that all work centers shown in Fig. 3 are the first priority work center of each operation. The first and second priority work centers of each operation are shown in Table I.

Based on Fig. 3, the total processing time of the longest path of order A is 20 (sum of processing time on w/c 1, 2, and 4), while that of orders B, C, and D are 16, 19, and 16 respectively. When the MST rule is applied, the production sequence is to produce the order which has the minimum slack time first and produce the order with relatively long slack time later. The slack time can be calculated by subtracting the due date from the current date and total processing time. Suppose the current date is 1, the slack time of order A is 12 (33-1-20) and the slack times of orders B, C, and D are 19, 15, and 20 respectively. Then the result of the MST rule is to produce orders A, C, B, and D.

The due dates of order A, B, C, and D are 33, 36, 35, and 37 respectively. When the EDD rule is applied, the production sequence is to produce the order that has the earliest due date first and produce the order with relatively late due date later. Therefore, the production sequence is to produce A, C, B, and D. Note that when the tie break occurs while any rule is applied, the first come first serve rule is then applied to select the order to produce.

Step3: Schedule all operations to proper work centers.

This step attempts to schedule all operations to proper work centers. An objective of this step is to reduce tardiness on each work center. There are three options for this step and they are explained as follows:

TABLE I
FIRST AND SECOND PRIORITY WORK CENTER INFORMATION

Order	Operation	First priority work center (w/c)	Second priority work center (w/c)
A	A1	w/c 1	w/c 3
	A2	w/c 3	w/c 1
	A3	w/c 2	w/c 1
	A4	w/c 4	w/c 2
B	B1	w/c 1	w/c 2
	B2	w/c 2	w/c 1
	B3	w/c 3	w/c 4
	B4	w/c 4	w/c 3
	B5	w/c 2	w/c 1
C	C1	w/c 1	w/c 3
	C2	w/c 2	w/c 1
	C3	w/c 4	w/c 2
D	D1	w/c 3	w/c 4
	D2	w/c 1	w/c 3
	D3	w/c 2	w/c 1
	D4	w/c 4	w/c 3

Option 1: There are two procedures for this option. The first procedure is to schedule the operations to the first priority work centers by using the sequence obtained from step 2. The operations of the first order obtained from step 2 are scheduled first. The operations of the second order obtained from step 2

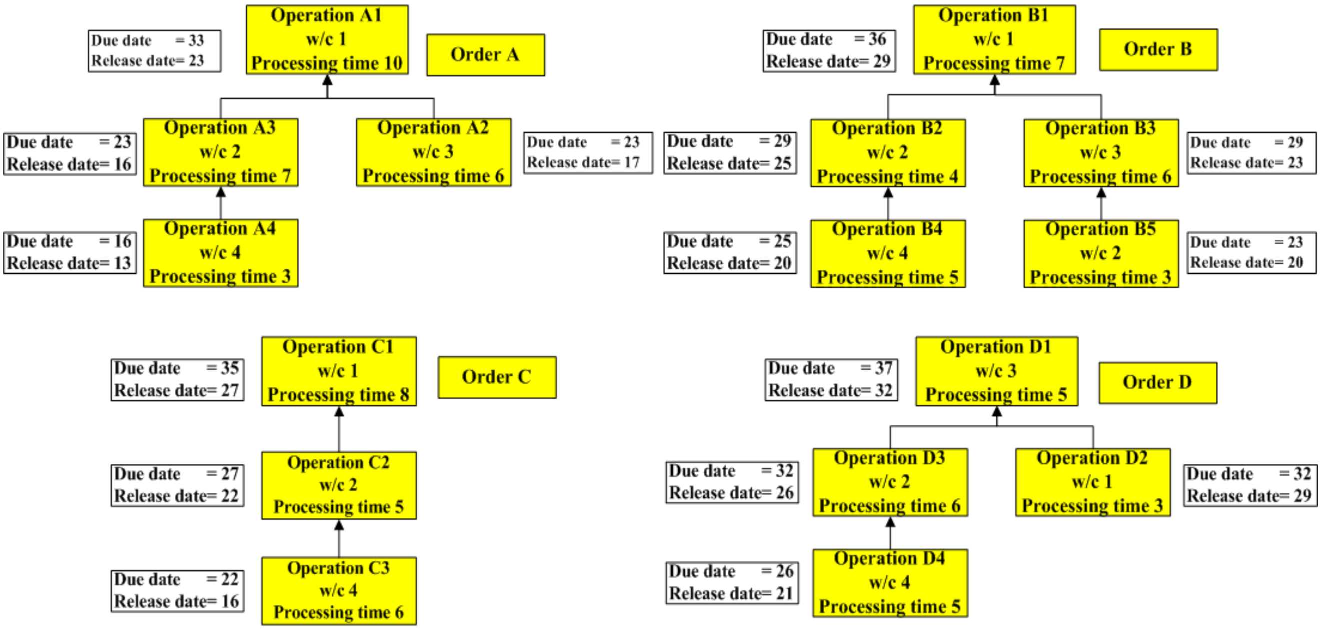


Fig. 3 An example for illustrating how the dispatching rule works

are then scheduled next and so on. This procedure attempts to schedule each operation to the release date obtained from step 1. If the release date is not available, the operation will be scheduled to the nearest available date (after the release date) as the forward scheduling technique. The second procedure of this option attempts to move tardy operations from the first priority work centers to the second priority work centers. There are two moving methods, namely, a permutation and a non-permutation. When the permutation method is applied, the sequence of operations of all work centers after moving must follow the sequence obtained from step 2, whereas it can be relaxed for the non-permutation method. Note that each tardy operation will be moved only if the four conditions below are satisfied.

Condition 1: Only the entire operation is allowed to move.

Condition 2: The tardy operation will be moved to the second priority work center only if the tardiness on the second priority work center is less than the tardiness on the first priority work center. Otherwise, the tardy operation will be left on the release time obtained from the first procedure.

Condition 3: The move must not produce any earliness.

Condition 4: The precedence of operations must not be in conflict.

To make it more comprehensive, data in Fig. 3 and Table I are used to illustrate how the first procedure works and the result is shown in Fig. 4. Suppose that the EDD rule is selected (obtained from step 2). The production sequence now is A, C, B, and D. The operations A4, A3, A2, and A1 are scheduled first since order A is the first order to produce. The operation A4 is scheduled to the release date first and operations A3, A2, and A1 are then scheduled consecutively. It can be seen from Fig. 4 that operations A1, A2, A3, and A4 are on-time operations since their completion times are exactly the same as their due dates obtained from step 1. Note that the completion times of these operations come from the due dates in Fig. 3 minus one, since the on-time operation must be finished at the end of the day before its due date. For example, the due date of operation A4 shown in Fig. 3 is 16 but it is shown as 15 in Fig. 4.

The next operations that must be scheduled are operations C3, C2, and C1 respectively since order C is the second one to produce. It is obviously seen that only operation C3 can be scheduled on the release date (16). The operations C2 and C1 are then scheduled to the nearest available time which is next to operations A3 and A1 respectively. The operations B5, B4, B2, and B1 are scheduled after the release dates since they are occupied by the operations of orders A and C, whereas operation B3 is scheduled after the release date although it is available since this operation must be produced after operation B5 in order to maintain the precedence constraint. The operations D4, D3, and D2 are scheduled after the release dates because of the same reason as operations B5, B4, B2, and B1, while the operation D1 is scheduled after the release date since it must be produced after operation D2. After applying this procedure, all operations are scheduled to the first priority work centers as shown in Fig.4

To illustrate how the second procedure works, the result shown in Fig. 4 will be used as an initiate sequence. It can be seen from Fig. 4 that there are some operations completed after the due dates specified from step 1. They are called tardy operations. For instance, C1 and C2 are tardy operations on w/c 1 and 2 respectively. This procedure moves the tardy operations from the first priority work centers to the second priority work centers. When the permutation method is selected, the result is shown in Fig. 5. Based on Fig.5, the operations C2, C1, B4, B2, B3, B1, and D3 cannot be moved to the second priority work centers since there is not enough time for each entire operation. The operation B5 cannot be

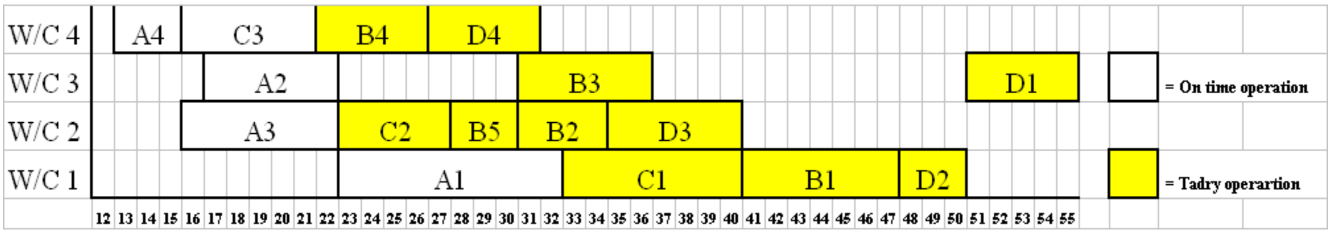


Fig. 4 An example of scheduling operations to the first priority work centers

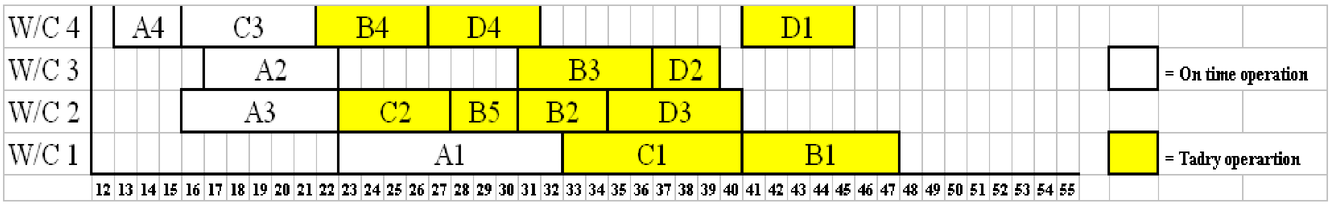


Fig. 5 The result of the permutation method of option 1

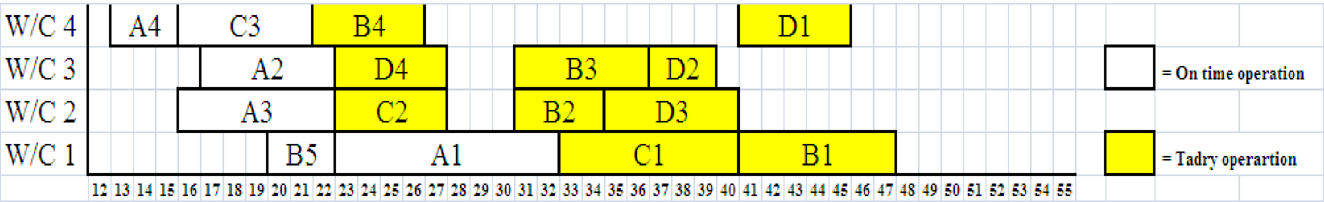


Fig. 6 The result of the non-permutation method of option 1

moved to produce before operation A1 (on w/c 1) and the operations A2 and B3 (on w/c 3) otherwise the sequence obtained from step 2 will be broken. Operations D2 and D1 are moved to w/c 3 and 4 respectively since there is enough time for each entire operation, the tardiness of each operation is reduced, no earliness generated, the precedence is correct, and the sequence obtained from step 2 is still maintained. It can be seen from Fig. 5 that after applying this procedure, the tardiness of moved operations is reduced and all operations on each work center are still in the same sequence as obtained from step 2 which follows the permutation method.

When the non-permutation method is selected, it is not necessary to maintain the sequence obtained from step 2. The result of the non-permutation method is shown in Fig. 6. The two main differences between Fig. 5 and 6 are at operations B5 and D4. Without maintaining the sequence obtained from step 2 as non-permutation method, operation B5 can be moved to produce before operation A1 and operation D4 can be moved to produce between operations A2 and B3. It is obviously seen that the non-permutation method generates a new sequence which obtains the lower tardiness. Note that operation B5 becomes an on-time operation since it is scheduled to start and finish precisely on its release and due date.

Option 2: There are two procedures for option 2 as well. The first procedure is similar to that of option 1 and the result is exactly the same as the result shown in Fig. 4. The second procedure is different from option 1 in that the moving conditions are different. When the second procedure of option 1 is applied, it attempts to move the tardy operation to the second priority work center without checking the available time on the first priority work center. If the tardy operation is not moved, it will be scheduled on the same release time obtained from the first procedure. When the second procedure of option 2 is applied, it attempts to move the tardy operation to the work center that generates lower tardiness. This means that the tardy operation can be moved backward on the first priority work center or it can be moved to the second priority work center depending on which way generates the lower tardiness. When a tie break occurs, the tardy operation will be scheduled to the first priority work center instead. The details of conditions of option 2 can be summarized as follows:

Condition 1, 3, and 4: They are the same as in option 1.

Condition 2: This condition can be separated into two ways. The first way is to check that if the tardiness of moving the tardy operation backward on the first priority work center is not more than the tardiness of moving the tardy operation to the second priority work center, the tardy operation will be moved backward on the first priority work center. Otherwise, the tardy operation will be moved to the second priority work center. The second way will be performed when there is no space for moving backward on the first priority work center. It is actually similar to the condition 2 explained in option 1. It clearly shows that the first way makes the condition 2 of option 2 different from the condition 2 of option 1.

The results of the permutation and non-permutation methods of the second procedure of option 2 are shown in Fig. 7 and 8 respectively. Based on Fig. 7, the result is very similar to the result in Fig. 5 except only operation D1. When the second procedure of option 2 is applied, the operation D1 is scheduled

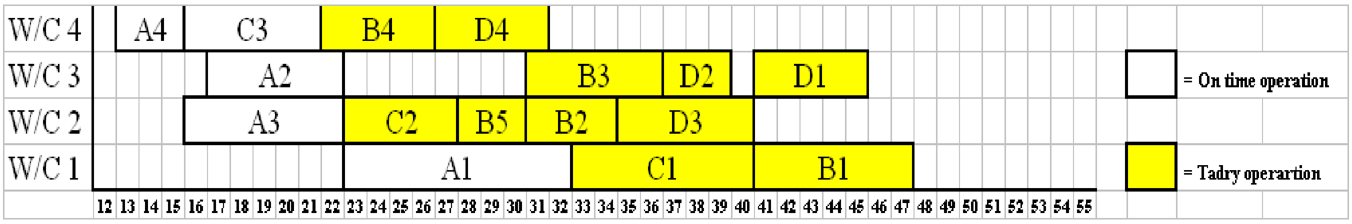


Fig.7 The result of the permutation method of option 2

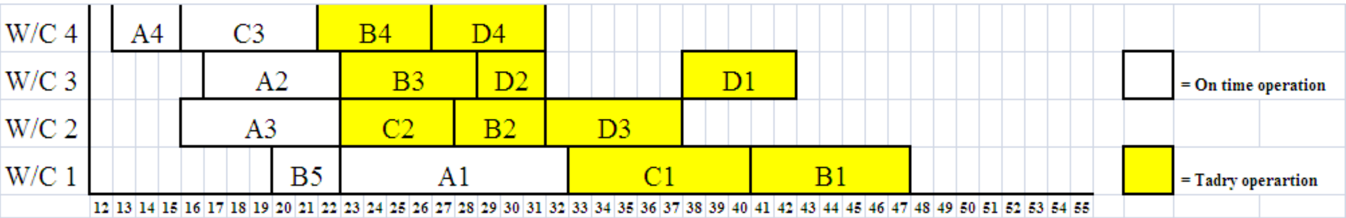


Fig.8 The result of the non-permutation method of option 2

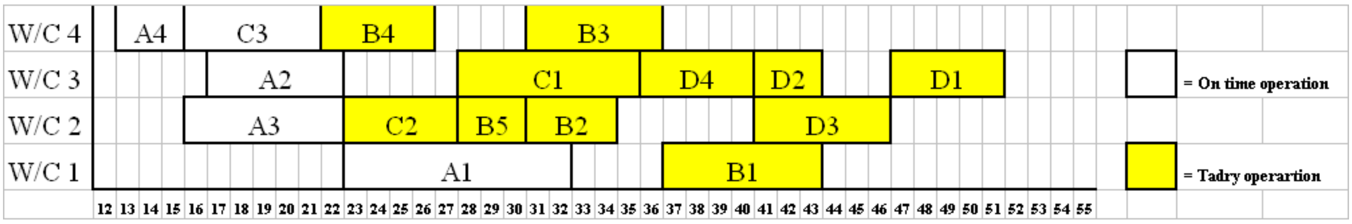


Fig.9 The result of the permutation method of option 3

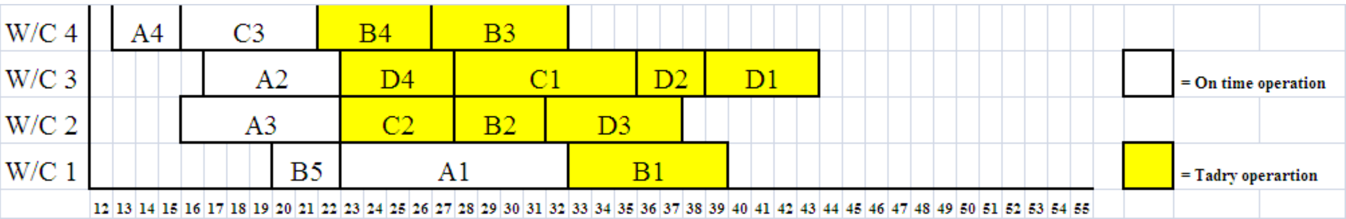


Fig.10 The result of the non-permutation of option 3

to produce on the first priority work center (w/c 3). On the other hand, it is scheduled to produce on the second priority work center (w/c 4) if the second procedure of option 1 is applied. This is because all conditions on the first priority work center are satisfied. Fig. 8 shows the result of the non-permutation method of option 2. It obviously shows that the tardiness is reduced dramatically when compared to the result in Fig. 6.

Option 3: While option 1 and option 2 have two procedures which are to schedule operations to the first priority work centers and then to move the tardy operations to the second priority work centers, the option 3 has only one procedure which is to schedule operations to proper work centers. The proper work centers are selected by considering the first and second priority work centers simultaneously. Since the option 1 and 2 must schedule all operations to the first priority work centers first, therefore, there are limited available times for moving the tardy operation to the second priority work center. The option 3 attempts to remedy this problem by scheduling the operation to the work center which generates less tardiness. In fact, only the second procedure of option 2 is required for option 3. Note that the permutation and non-permutation methods are also available for this option. The results of the permutation and non-permutation methods of option 3 are shown in Fig. 9 and 10 respectively.

Based on Fig. 9, when the permutation method is applied, operations A4, A3, A2, A1, C3, and C2 are scheduled to the first priority work centers as explained in option 1, whereas operation C1 is scheduled to the second priority work center since the tardiness of this operation is less than the tardiness on the first priority work center. In addition, no earliness is generated and the precedence constraint is satisfied. The rest of operations of orders B and D are also scheduled by the same method and the result is shown in Fig. 9. Fig. 10 shows the result of the non-permutation method of option 3. It can be seen from Fig. 10 that the non-permutation method generates tardiness less than the permutation method.

Based on the explanation in step 2 and 3, a set of different sequences are generated by combination between dispatching rules and scheduling options. They all are sent into a linear programming (LP) model in order to determine an optimal start time of each operation explained in the next step.

Step4: Determine an optimal start time by using linear programming (LP) model

The objectives of all previous steps are to allocate the operations to the first and second priority work centers and also determine the sequence of operations on each work center. However, the start times of each operation obtained from the previous steps have not been optimized. This step attempts to determine an optimal start time of each operation by using the LP model.

The parameters and variables used in the algorithm are defined as follows:

Parameters

i = index of work center starting from 1 to W
j = index of customer order starting from 1 to N
$p_{i,j}$ = processing time of order j on work center i
d_j = due date of order j
c_j = completion time of order j
f_j = flow-time of order j
e_j = earliness of order j
t_j = tardiness of order j
C_t = weight of total tardiness
C_e = weight of total earliness
C_f = weight of average flow-time

Decision variable

$x_{i,j}$ = start time of order j on work center i

Objective

The objective of the model is to minimize the weighted average of the total tardiness, total earliness, and average flow-time as shown in (1).

$$\text{Minimize} \quad C_e \sum_{j=1}^{n} e_j + C_f\left(\tfrac{1}{n}\sum_{j=1}^{n} f_j\right) + C_t \sum_{j=1}^{n} t_j \qquad (1)$$

The weights C_t, C_e, and C_f can be adjusted to obtain desirable performance measures. For example, the tardiness tends to be low if C_t is high.

Constraints

1) The sequence of orders on each work center must follow the one obtained by the options explained in step 3. Note that the orders are renumbered based on the sequence of orders in a way that the first order in the sequence has j = 1, and the second order has j = 2, and so on. Equation (2) ensures that the next order on the same work center cannot be started unless the earlier one has been finished.

$$x_{i,j+1} \ge x_{i,j}+p_{i,j} \qquad i = 1, 2, \ldots, W; \quad j = 1, 2, \ldots, N\text{-}1 \qquad (2)$$

2) The precedence relationship between work centers must be maintained. Each product may have different production routes and requires a different set of work centers. Based on the production route, there are some precedence relationships between work centers, which can be classified into two basic types, namely, the sequential and convergent relationships (see Fig.1). Based on Fig. 1, complicated precedence relationships of operations can be constructed from the basic sequential and convergent relationships as follows.

For sequential relationship:

$$x_{3,j} \ge x_{2,j} + p_{2,j} \qquad j = 1, 2, \ldots, N \qquad (3)$$
$$x_{2,j} \ge x_{1,j} + p_{1,j} \qquad j = 1, 2, \ldots, N \qquad (4)$$

For convergent relationship:

$$x_{4,j} \ge x_{3,j} + p_{3,j} \qquad j = 1, 2, \ldots, N \qquad (5)$$
$$x_{3,j} \ge x_{2,j} + p_{2,j} \qquad j = 1, 2, \ldots, N \qquad (6)$$
$$x_{3,j} \ge x_{1,j} + p_{1,j} \qquad j = 1, 2, \ldots, N \qquad (7)$$

Note that (3) to (7) can be modified in order to allow the overlapping of production batches. For example, if a downstream work center is allowed to start after 10% of work has been finished on the upstream work center, the constraints can be modified as shown in (3') to (7')

For sequential relationship:

$$x_{3,j} \ge x_{2,j} + 0.1p_{2,j} \qquad j = 1, 2, \ldots, N \qquad (3')$$
$$x_{2,j} \ge x_{1,j} + 0.1p_{1,j} \qquad j = 1, 2, \ldots, N \qquad (4')$$

For convergent relationship:

$$x_{4,j} \ge x_{3,j} + 0.1p_{3,j} \qquad j = 1, 2, \ldots, N \qquad (5')$$
$$x_{3,j} \ge x_{2,j} + 0.1p_{2,j} \qquad j = 1, 2, \ldots, N \qquad (6')$$
$$x_{3,j} \ge x_{1,j} + 0.1p_{1,j} \qquad j = 1, 2, \ldots, N \qquad (7')$$

3) Calculation of the completion time, tardiness, earliness, and flow-time. Based on the data in Fig. 1, the completion time of finished products, tardiness, earliness, and flow-time of each order can be formulated as follows:

For complete time:

$$c_j = x_{1,j} + p_{1,j} \qquad j = 1, 2, \ldots, N \qquad (8)$$

For tardiness:

$$t_j = \max(c_j - d_j, 0) \qquad j = 1, 2, \ldots, N \qquad (9)$$

For earliness:

$$e_j = \max(d_j - c_j, 0) \qquad j = 1, 2, \ldots, N \qquad (10)$$

Equations (9) and (10) may be better written as one constraint:

$$d_j - c_j = e_j - t_j \qquad j = 1, 2, \ldots, N \qquad (11)$$

For average flow- time of sequential structures:

$$f_j = c_j - x_{1,j} \qquad j = 1, 2, \ldots, N \qquad (12)$$

For average flow-time of convergent structures:

$$f_j = \max\,(c_j - x_{1,j}\,,\, c_j - x_{2,j}) \qquad j = 1, 2, \ldots, N \qquad (13)$$

Equation (13) may be specified as

$$f_j \ge c_j - x_{1,j} \qquad j = 1, 2, \ldots, N \qquad (14)$$
$$f_j \ge c_j - x_{2,j} \qquad j = 1, 2, \ldots, N \qquad (15)$$

4) Non-negativity condition

All parameters and decision variables are non-negative. It is very essential for the model, in particular, because of the precedence relationship constraints, that all work centers are operational and only operational during the same hours of a day, for example, x hours a day. This can be easily handled by defining a day as only consisting of x hours (as if the nonworking hours of the day are not existent). The flow-time, earliness, and tardiness are all also relative to this definition.

III. EXPERIMENTAL DESIGN

There are two experiments in this paper. The first experiment is to analyze the effect of the weights (C_t, C_e, and C_f) on the performance measures. The second experiment is to analyze the effect of different FCMRP systems and dispatching rules on the performance measures. Results of the analysis will indicate how the weights and dispatching rules are selected to obtain the desirable performance. Both experiments use the same experimental case and dependent variables but different independent variables. The independent variables and dependent variables are explained as follows.

A. Independent Variables

1) Experiment to analyze the effect of weights in the proposed FCMRP system.

The independent variable of this experiment is the weight settings in the proposed FCMRP system. There are four sets of weights as follows:

a) Set $C_t = C_e = C_f = 0.33$, denoted by FCMRP1.
b) Set C_t=0.90, C_e=0.05, C_f=0.05, denoted by FCMRP2.
c) Set C_t=0.05, C_e=0.90, C_f=0.05, denoted by FCMRP3.
d) Set C_t=0.05, C_e=0.05, C_f=0.90, denoted by FCMRP4.

Note that this experiment uses the EDD rule, option 1, and the permutation method.

2) Experiment to analyze the effect of different FCMRP systems and dispatching rules.

In this experiment, the weights are set based on the opinion of the planner of this company. The planner feels that one hour of total earliness and average flow-time are equally important, whereas one hour of total tardiness is five times as important as one hour of total earliness. Thus, the weights of total tardiness (C_t), total earliness (C_e), and average flow-time (C_f) are 0.72, 0.14, and 0.14, respectively. The objective of this experiment is to analyze the effect of different FCMRP systems and dispatching rules on the performance measures. There are two independent variables as follows:

a) FCMRP systems

There are six FCMRP systems obtained from combination of three options and two methods (permutation and non-permutation) as follows:

- Combination of option 1 and permutation denoted as FCMRP-P1.
- Combination of option 1 and non-permutation denoted as FCMRP-NP1.
- Combination of option 2 and permutation denoted as FCMRP-P2.
- Combination of option 2 and non-permutation denoted as FCMRP-NP2.
- Combination of option 3 and permutation denoted as FCMRP-P3.
- Combination of option 3 and non-permutation denoted as FCMRP-NP3.

b) Dispatching rules

There are two dispatching rules, namely, the EDD and MST. They all are explained in section II.

B. Dependent Variables

The dependent variables are performance measures of the schedule generated by the FCMRP systems. There are five performance measures, namely, the number of early orders, total earliness (in hours), the number of tardy orders, total tardiness (in hours), and average flow time of all products (in hours). Note that the total tardiness and earliness are calculated only from the operations for producing finished products. The flow time of a product is the elapsed time, from the earliest time among the start times of all parts, to the finish time of the finished product.

IV. EXPERIMENTAL CASE

The experiment is performed based on the 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 shop with sequential and convergent precedence relationships and has 16 items of finished products.
2) Each finished product has its product structure.
3) BOM has 5 to 6 levels depending on the products.
4) There are 21 work centers. Some are bottlenecks and the others are non-bottlenecks.
5) Each operation needs a work center.
6) Some operations can be produced on more than one work center (alternatively) called the first and second priority work center.
7) The first and second priority work centers are specified by the planner.
8) All work centers are operated 8 hours a day and overtime is not allowed.
9) The overlapping of production batches is not allowed.
10) 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 techniques by MRP users (Haddock and Hubicki [15]).
11) The customer's demand is assumed to follow a uniform distribution, where the maximum and minimum demands are 10% of the mean demand.
12) The actual demand of each product in a month is collected and used as the mean demand.

The experiment is conducted in two replications using two sets of randomly generated demands. Two replications are sufficient for obtaining accurate mean values of performance measures since the 95% confidence interval of the population mean of each performance measure is within ± 2% of the mean value. A one-way ANOVA is used to statistically analyze the first experiment, while a general factorial experiment is used for the second experiment.

V. RESULT AND DISCUSSION

The results and discussions are divided into two sections. The first section is the analysis on the effect of weights in the proposed FCMRP system. The second section is the analysis on the effects of the different FCMRP systems and dispatching rules.

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A. Analysis on the Effect of Weights in the Proposed FCMRP System.

The average value of the performance measures and the ranking of the performance measures obtained from the Turkey's multiple mean comparison method are shown in Table II. The rankings are presented in parentheses. The lower rank means better performance than the higher rank. The performance measures with the same rank are not significantly different.

From Table II, the weights have a significant effect on all performance measures, namely, the total tardiness, number of tardy orders, total earliness, number of early orders, and average flow-time. The total tardiness is the lowest when FCMRP1 is applied. This is because the weight of tardiness (C_t) is set to 0.9, which is greater than the weights of total earliness (C_e) and average flow-time (C_f). If the planner wants to minimize the earliness and average flow-time, the FCMRP2 and FCMRP3 should be applied, respectively. In contrast, if the planner wants to compromise all performance measures, all weights should be set equally as in FCMRP4.

B. Analysis on the Effects of Different FCMRP Systems and Dispatching Rules.

The ANOVA results of the experiment used to analyze the effects of the FCMRP systems and dispatching rules are shown in Table III. The different FCMRP systems have significant effects on all performance measures, whereas the different dispatching rules have no significant effects on only the number of tardy orders. The interaction effect between the FCMRP systems and dispatching rules are also significant to all performance measures. This means that the planner must carefully consider the interaction effects before selecting a proper setting in order to obtain the desire performance. The average values and ranking of the performance measures are shown in Table IV.

Based on Table IV, The FCMRP-NP3 system results in the best tardiness and number of tardy orders, whereas the FCMRP-P3 system results in the best earliness and number of early orders. Both FCMRP-P3 and FCMRP-NP3 systems result in the best average flow-time.

Comparing the dispatching rules presented in Table IV, the MST rule turns out to be the best for the total tardiness, number of tardy orders, number of early orders and average flow-time (it has rank 1 for these performance measures). The EDD rule is the best for total earliness. It can be seen that the result of each dispatching rule does not comply with the theory. A reason for this is that the dispatching rules applied in this research are appropriate for only pure single work center environment while the environment of this research is more complicated. The result shown in Fig. 9 is used to illustrate this effect. By using the EDD rule, the operations A2, C1, D4, D2, and D1 are scheduled to produce on w/c 3. It is obviously seen that these operations are not arranged based on the EDD concept since the due date shown in Fig. 3 are 23, 35, 26, 32, and 37 respectively. Therefore, the planners must not directly select the desire performance by using the theory's benefit from the EDD or MST rules. In fact, they must consider the details of the performance measures or the overall performance indices obtained from the proposed FCMRP system instead.

For the interaction effects, it is obviously seen from Table III that the FCMRP system and dispatching rule are interacting. Although, the interaction graphs is not illustrated, the planner can see these effects and also choose the desired the performance measures obtained from each interaction shown in Table IV.

An overall performance index can be determined using the weighted average of some performance measures based on the opinion of the planner (see Section III). The weights of total tardiness (C_t), total earliness (C_e), and average flow-time (C_f) are 0.72, 0.14, and 0.14, respectively. The overall performance indices are presented in Table IV. It indicates that the FCMRP NP3 system results in the best overall performance index when compared with the other FCMRP systems. It also indicates that the MST rule results in the best overall performance index when compared with the EDD rule. Furthermore, when the combination of the FCMRP method and the dispatching rule is considered at the same time, the best combination is to combine the FCMRP-NP 3 system and the EDD rule since this combination can offer the best overall performance index (rank 1). Note that the computation time of the FCMRP system including a generation of a set of scheduling reports is about 10 minutes, which is acceptable and practical for real industrial applications.

VI. CONCLUSIONS

A new FCMRP system, which is a combination of scheduling heuristic and optimization technique applicable for real industrial problems, is developed. It uses the proposed heuristics to generate the sequence of operations on each work center and uses the linear programming model to determine the optimal start time of each operation to minimize the weighted average of total tardiness, total earliness, and average flow-time, considering the finite capacity of all work centers and precedence of operations. Based on the experimental results, the combination of the FCMRP-NP3 system and the EDD rule offers the best overall performance index since it has an ability to trade-off between conflicting performance measures. The performance of the proposed FCMRP system is controlled by selecting appropriate dispatching rules and objective function weights. The effects of the dispatching rules and objective function weights on the performance measures are statistically analyzed based on the real data of the auto-part factory. The objective function weights should be set based on relative importance of each performance measure. For example, when the planner feels that the tardiness is the most important, followed by the earliness and flow-time, the tardiness weight should be the highest, followed by the weights of the earliness and flow-time. In this way, the resulting schedule has relatively low tardiness. Two dispatching rules, namely, the EDD and MST, are considered in the proposed FCMRP system. The effects of these rules may not comply with the theory since the environment in this research is more complicated. The proposed

TABLE II
EFFECTS OF WEIGHTS IN OBJECTIVE FUNCTION ON PERFORMANCE MEASURES

Factors	Weights			Total tardiness (hrs)	No. of tardy orders	Total earliness (hrs)	No. of early Orders	Average flow-time (hrs)
	Ct	Ce	Cf					
FCMRP1	0.9	0.05	0.05	215.53(1)	27(1)	30.54(3)	15(4)	29.37(2)
FCMRP2	0.05	0.9	0.05	246.06(2)	40(3)	0(1)	0(1)	29.78(2)
FCMRP3	0.05	0.05	0.9	277.25(3)	32(2)	14.01(2)	9(2)	23.57(1)
FCMRP4	0.33	0.33	0.33	217.24(1)	28(1)	28.82(3)	13(3)	29.05(2)

Experiments performed by: EDD, Option 1, and Permutation method
Total number of customer orders: 80 orders (520 operations)

TABLE III
P-VALUES FROM ANALYSIS OF VARIANCE

Factors	Total tardiness (hrs)	No. of tardy orders	Total earliness (hrs)	No .of early orders	Average flow-time (hrs)
FCMRP systems (FCMRP)	0.000*	0.000*	0.000*	0.000*	0.000*
Dispatching rules (D)	0.000*	0.073	0.000*	0.000*	0.000*
FCMRP x D	0.000*	0.000*	0.000*	0.000*	0.000*

* The effect is significant at significant level of 0.05

TABLE IV
AVERAGE VALUES AND RANKING OF PERFORMANCE MEASURES

Factors	Total tardiness (hrs)	No.of tardy orders	Total earliness (hrs)	No.of early orders	Average flow-time (hrs)	Overall performance index
FCMRP systems						
FCMRP-P1	162.96(2)	22.50(1)	49.62(4)	19.00(3)	29.21(4)	241.79(2)
FCMRP-NP1	201.56(4)	24.25(2)	197.64(5)	25.50(4)	34.67(5)	433.87(6)
FCMRP-P2	242.70(6)	24.50(2)	37.65(2)	15.50(2)	27.77(3)	308.12(5)
FCMRP-NP2	190.00(3)	29.25(3)	40.61(3)	16.00(2)	25.08(2)	255.69(3)
FCMRP-P3	214.01(5)	37.00(4)	24.88(1)	10.00(1)	21.87(1)	260.76(4)
FCMRP-NP3	57.11(1)	20.75(1)	35.90(2)	14.50(2)	21.80(1)	114.81(1)
Dispatching rules						
EDD	213.64(2)	26.00(1)	62.41(1)	17.67(2)	28.15(2)	304.2(2)
MST	142.47(1)	26.75(1)	66.35(2)	15.83(1)	25.31(1)	234.13(1)
Combinations						
FCMRP-P1*EDD	215.53(8)	26.50(4)	30.54(3)	15.00(3)	29.61(4)	275.68(6)
FCMRP-P1*MST	110.39(3)	18.50(2)	68.71(7)	23.00(6)	28.81(4)	207.91(4)
FCMRP-NP1*EDD	227.23(10)	22.50(3)	172.78(8)	24.00(6)	37.49(6)	437.5(11)
FCMRP-NP1*MST	175.90(6)	26.00(4)	222.49(9)	27.00(7)	31.85(5)	430.24(10)
FCMRP-P2*EDD	335.42(12)	24.50(3)	52.19(6)	20.00(5)	31.55(5)	419.16(9)
FCMRP-P2*MST	149.99(5)	24.50(3)	23.11(2)	11.00(2)	23.99(2)	197.09(3)
FCMRP-NP2*EDD	237.42(11)	33.00(5)	39.52(4)	14.00(3)	26.15(3)	303.09(8)
FCMRP-NP2*MST	142.58(4)	25.50(4)	41.71(4)	18.00(4)	24.02(2)	208.31(4)
FCMRP-P3*EDD	223.76(9)	34.50(5)	33.55(3)	12.00(2)	21.12(1)	278.43(7)
FCMRP-P3*MST	204.27(7)	39.50(6)	16.21(1)	8.00(1)	22.62(2)	243.1(5)
FCMRP-NP3*EDD	42.49(1)	15.00(1)	45.90(5)	21.00(5)	23.00(2)	111.39(1)
FCMRP-NP3*MST	71.74(2)	26.50(4)	25.91(2)	8.00(1)	20.60(1)	118.25(2)

Experiments performed by: $C_t = 0.72$, $C_e = 0.14$, $C_f = 0.14$
Total number of customer orders: 80 orders (520 operations)

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FCMRP system still has limitations. The lot-sizing policy under consideration is only lot-for-lot, and the effect of different lot-sizing policies has not been studied. All work centers must be operated during the same hours in a day. This limitation can be relaxed by introducing some binary variables to the model. However, the model with binary variables is more difficult to solve and take much time consuming. The dispatching rules under consideration are the only simple cases. More complicated and effective dispatching rules can be developed. Thus, further research is needed to develop and analyze an improved FCMRP system that addresses these limitations.

ACKNOWLEDGEMENTS

This research has been supported by two sources as follows:
1) Funding from Engineering Faculty of King Mongkut's University of Technology North Bangkok.
2) Thailand Research Fund (TRF), grant number MRG 5280191.

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