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Finite Capacity Material Requirement Planning System for a Multi-stage Automotive-Part Assembly Factory

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ABSTRACT: This paper aimed to develop a practical finite capacity material requirement planning (FCMRP) system based on the needs of an automotive-part manufacturing company in Thailand. The approach includes a linear programming model to determine the optimal start time of each operation to minimize the weighted average of total earliness, total tardiness, and average flow-time considering the finite capacity of all work centers and precedence of operations. Important factors of the proposed FCMRP system were objective function weights and dispatching rules. Effects of these factors on the performance measures were statistically analyzed based on a real situation of an auto-part factory. Statistical results showed that the dispatching rules and objective function weights had significant effects on the performance measures of the proposed FCMRP system. The proposed FCMRP system offered a good trade-off between conflicting performance measures and resulted in the best weighted average performance measure when compared with conventional forward and forward-backward finite capacity scheduling systems.

Abbreviation: ERP, Enterprise Resources Planning; WIP, work-in-process.

KEYWORDS: Material Requirement Planning, Finite Capacity, Scheduling Direction, Linear Programming.

INTRODUCTION

Manufacturing Resources planning (MRP II) is a well-known methodology for production planning and control in discrete part manufacturing and assembly. There is a main reason that makes the MRP II system unsuccessful. Most MRP II packages determine a production schedule under an assumption that work centers have infinite capacity[1]. This may result in a capacity infeasible schedule.

Nagendra and Das (2001) stated that some MRP II or ERP packages use a simple logic of finite capacity scheduling (FCS) in order to remedy the capacity problem on work centers[2]. This concept tries to move planned requirements forward or backward or both within a specified planning horizon. The moving is only based on available capacity and there is no consideration of holding and backorder costs that may result from the movement. The planners prefer FCS since it can answer what-if capacity questions. However, FCS systems cannot replace the MRP II. The logics of FCS systems are proprietary and only few of them are claimed to attempt schedule optimization.

Another approach for solving the capacity problem is a shop floor control (SFC) system. Examples include forward scheduling[1], backward scheduling[3], and a combination of forward and backward scheduling[4]. Taal and Wortmann (1997) and Bakke and Hellberg (1993) concluded that the SFC system is unable to solve the capacity problems, which are created at the material requirement planning (MRP) calculation stage[5,6]. 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, but it can handle only small problems and is difficult to understand by the users. Research works adopting the optimization approach are as follows. Billington and Thomas (1983, 1986) formulated a production planning model as a mixed integer linear programming[7,8]. The objective was to minimize the sum of inventory carrying, setup, overtime, and utilization costs, subject to capacity constraints of work centers. Adenso-Diaz and Laguna (1996) proposed an optimization model to support a production planner in solving capacity problems[9]. However, in order to keep the model small and simple, the effects of lot sizing and work in process are not considered. Tardiff and Spearman (1997) developed a technique called capacitated material requirements planning (MRP-C)[10]. MRP-C used fundamental relations between WIP and cycle time (Little's law) to optimize performances of the production system. Sum and Hill (1993) presented a method that not only adjusted lot sizes to minimize set-up time but also determines the release and due times of production orders while checking the capacity constraints[11]. They split or combine the production orders to minimize set-up and inventory costs. Wuttipornpun et al. (2005) developed a goal programming approach for FCMRP system that was applicable for assembly shop[12].

The second one is a non-optimization approach. This approach can handle large problems and is easy to understand by the user, but does not try to optimize related factors such as costs, tardiness, earliness, and flow-time. The non-optimization research works are as follows. Hastings et al (1982) applied a forward loading technique to schedule the orders on work centers[13]. This technique guaranteed feasible release date for production orders, but it may generate some tardy orders. Pandey et al (2000) developed a FCMRP algorithm, which was executed in two stages[14]. First, capacity-based production schedules were generated from the input data. Second, the algorithm determined an appropriate material requirement plan to satisfy the schedules obtained from the first stage. Wuttipornpun and Yenradee (2004) developed a FCMRP system for assembly operations that was capable of automatically allocating some jobs from one machine to another and adjusting timing of the jobs by considering a finite available time of all machines[15].

Conventional FCMRP systems being used in industries are a combination of MRP and finite capacity scheduling systems, which are the non-optimization approaches. 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 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 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.

This paper proposes a new FCMRP system, which integrates the optimization and non-optimization approaches and can be used in real industries. The proposed FCMRP system can handle large problems of real industry and tries to minimize the tardiness, earliness, and flow-time simultaneously. The schedule obtained from the proposed FCMRP system guarantees the optimal start and due times of production orders. The proposed FCMRP system is designed to handle industries with the following characteristics:

1. There are multiple products.
2. Some products may have a multi-level Bill of Material (BOM) with subassembly and assembly operations. Other products may require only fabrication without an assembly operation.
3. Some parts must be produced by just one work center but others can be produced by one of two alternative work centers (the first and second priority work centers).
4. Some work centers are bottleneck work centers and others are non-bottleneck work centers.
5. The structure of a production shop is a flow shop with assembly operations.
6. An overlapping of production batches to reduce production lead-time of sequential processes is allowed if it is required.

To prove that the proposed FCMRP can be applied in a real situation, experiments are performed on a selected manufacturing company in Thailand. The company produces steering wheels and gearshift knobs

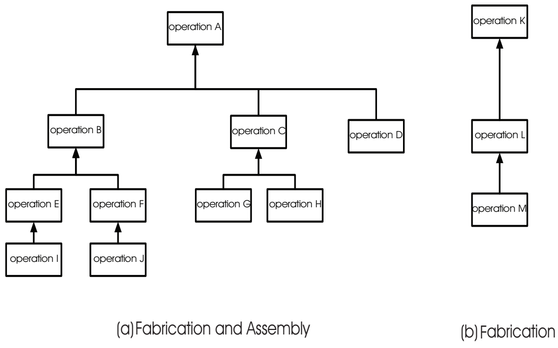

Fig 1. Structure of manufacturing process

for the automobile industry. The company operates a multi-stage assembly system and has 25 items of finished goods with 3 to 10 levels of BOMs, and 20 work centers. Some products can be produced by more than one work center. The first and second priority work centers are specified by the planner. All work centers are operated 8 hours a day. The company is especially concerned about customer service (tardiness) and costs related to inventories (earliness and flow-time).

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. The experiment to analyze the effect of important factors of the proposed FCMRP system and to compare the effectiveness between the proposed FCMRP system and the conventional FCMRP systems is described in Section 4. The experimental results are analyzed and discussed in Section 5. Finally, the results are concluded in Section 6.

The Proposed FCMRP System

The manufacturing process under consideration produces many products. Some products may require both sequential operations and convergent operations that are common for assembly shop as shown in Figure 1 a. Others may require only sequential operations that are common for fabrication shop as shown in Fig 1 b. Note that each operation must be performed on a work center and the flow of material through the work centers is unidirectional, which is a characteristic of the flow shop (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 the 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 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 for requirement and planned order are specified (bucketless MRP). A 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 BOM 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) work centers. An objective of this step is to check capacity problem on the first priority work centers. Third, the schedule will be 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 problem on the first priority work centers. After the second and third steps are completed, all operations are assigned to work centers considering finite capacity.

Fourth, the sequence of orders in all work centers is determined by applying simple dispatching rules. An objective of applying the dispatching rules is to generate different sequences of orders that may affect the performance measures. Finally, the start and due times of all operations are calculated using a linear programming (LP) model. An objective of this step is to minimize the sum of total tardiness, total earliness, and average flow-time obtained from the system.

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

Parameters

j index of customer order starting from 1 to N
i index of work center starting from 1 to W
$p_{i,j}$ 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

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

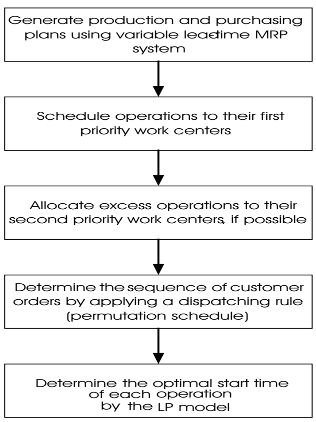

Fig 2. Block diagram of the proposed FCMRP system

Generation of production and purchasing plans using variable lead-time MRP system

The production and purchasing plans are initially generated by the MRP system called Thai SME Production and Inventory Control system (TSPICs). TSPICs has been developed by Sirindhorn International Institute of Technology and implemented in some factories in Thailand.[16] It is different from the conventional MRP system in that it assumes variable lead-times. The total lead-time ($p_{i,j}$) in TSPICs is a function of lot size, unit processing time, and setup time. The release time of operations is calculated from the due date minus the total lead-time considering a detailed work calendar of the factory. Thus, the release time of operations from TSPICs is more realistic than that of the conventional MRP system. Note that the proposed FCMRP system uses the lot-for-lot lot sizing rule since it is the simplest and results in the lowest inventory level.

Scheduling operations to the first priority work centers

Some operations of each order (j) may be produced by more than one work center (i). 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. This step requires that all operations of each order are scheduled on their first priority work centers. Fig 3 shows an example of load profiles of work centers 1 and 2. The X-axis shows the day and the Y-axis shows the time of day.

Allocation of the excess operations to the second priority work centers

The operation of order (j) that exceeds the capacity of the first priority work center (i) is called an "excess operation". This step tries to reduce capacity problems in 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. After applying this step, some operations of each order may be produced by their first priority work centers, whereas others may be produced by their second priority work centers. From Fig 3(a), the excess operation B on work

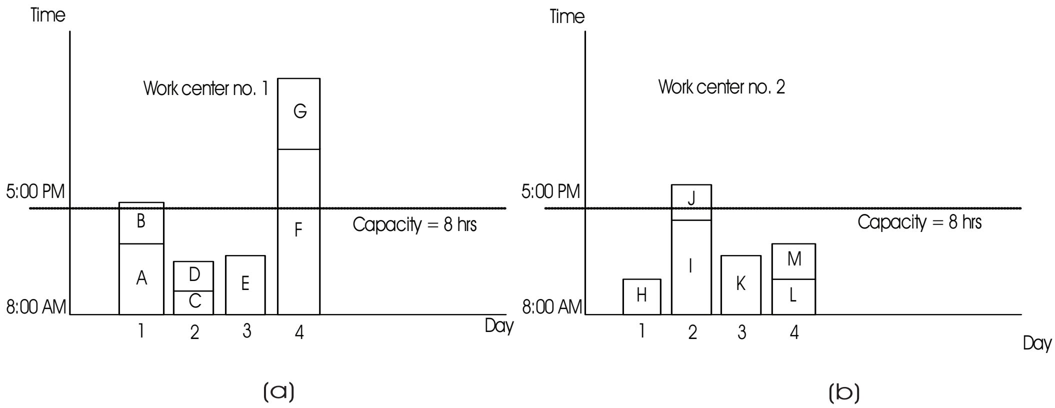

Fig 3. Load profile on the first priority work centers

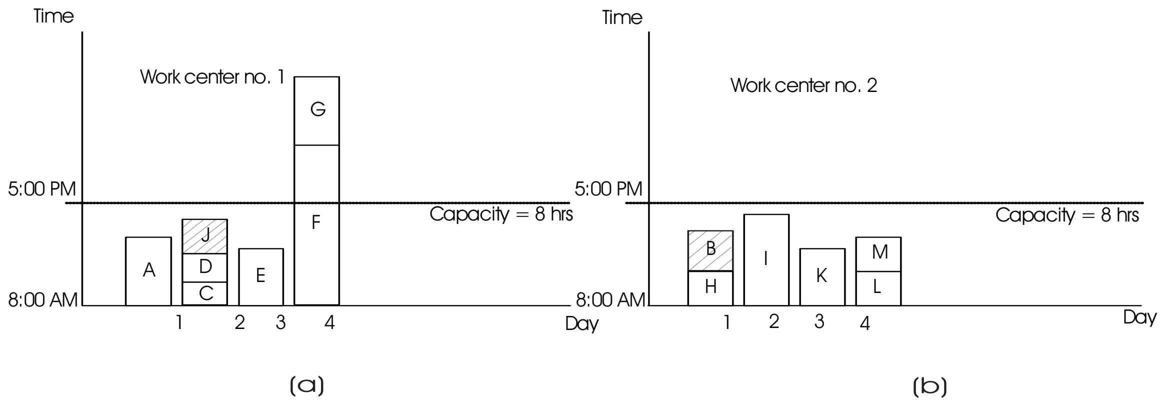

Fig 4. Load profile on work centers after allocating excess operations to the second priority work centers

center 1 in day 1 can be moved to work center 2 (see Fig 4(b)). Similarly, from Figure 3(b), the excess operation J on work center 2 in day 2 can be moved to work center 1 (see Fig 4(a)). However, the excess operation G 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 G.

Determination of the sequence of customer orders by applying dispatching rules

From the last step, all operations are assigned to the work centers considering finite capacity. However, the sequence of each operation on the work center is unknown. This step tries to determine the sequence of orders (j) based on the priority of customer orders by applying some dispatching rules. The objectives of this step are to generate different sequences and to study how dispatching rules affect the performance measures. There are three dispatching rules as follows:

1. Earliest due date (EDD) rule.

This rule tries to produce the order which has the earliest due date first and produce the order with relatively late due date later.

2. Shortest total processing time on the longest path (SPT).

This rule tries to produce the order with the shortest total processing time on the longest path first, and produce the order with relatively long total processing time on the longest path later.

3. Minimum slack time (MST).

This rule tries to produce the order with the minimum slack time first, and produce the order with relatively long slack time later. The slack time is defined in equation 1.

$$\text{Slack time} = \text{due date} - \text{current date} - \text{total processing time along the longest path} \quad (1)$$

Figure 5 shows an example for illustrating the dispatching rules. Order A requires work centers 1, 2, 3, 4, and 5, while order B requires work centers 1, 3, 5, and 6. Due dates of orders A and B are 28 and 31, respectively. When the EDD rule is applied, the production sequence is to produce order A and then B. The total processing time on the longest path of order A is 22 days (sum of processing times of work centers 1, 3, and 5) while that of order B is 19 days (sum of processing times of work centers 1, 3, and 5). Therefore, if the SPT rule is applied, the production sequence is to produce order B and then A. Suppose the current date is 1. The slack time of order A is 5 (28-1-22) while that of order B is 11 (31-1-19). According to the MST rule, the production sequence is to produce order A and then B.

To reduce the complication of the scheduling algorithm, the sequence of all operations on each work center is assumed the same as the sequence of orders. For instance, after applying MST rule, a sequence of orders is A and then B. Therefore, the operation of order A must be performed before the operation of order B on any required work center. This is a concept of permutation schedule, which is well known in flow shop scheduling.

Determining the optimal start time of each operation by the linear programming model

The objectives of all previous steps are to assign operations to work centers in a manner that reduces the capacity problem on work centers and to determine the sequence of all operations (j) on each work center. However, the start and due times of each operation obtained from the first step have not been optimized. This section explains the concept of the linear programming (LP) model to determine the optimal start time and due times of each operation.

Objective

The objective of the model is to minimize the weighted average of total tardiness, total earliness, and

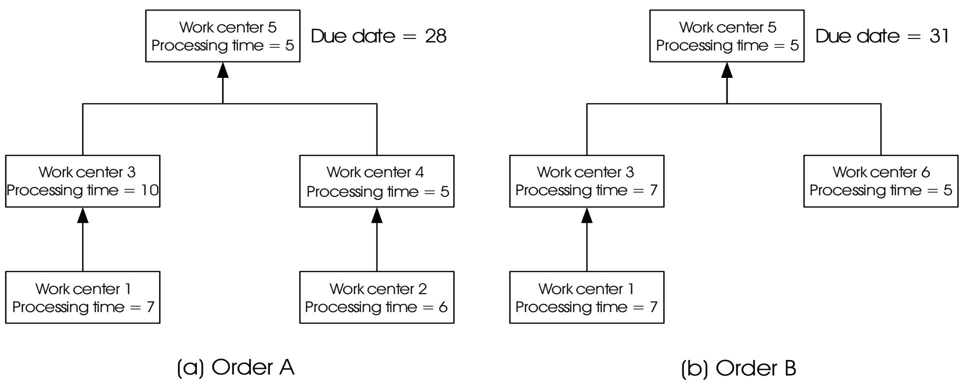

Fig 5. An example for illustrating the dispatching rules

average flow-time as shown in equation 2.

$$\text{Minimize } C_t \times \sum_{j=1}^{N} t_j + C_e \times \sum_{j=1}^{N} e_j + C_f \times \left(\frac{1}{N} \sum_{j=1}^{N} f_j\right) \quad (2)$$

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 dispatching rule in step 4.

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. Equation 3 ensures that the next order on the same work center cannot be started unless the earlier one has finished and the sequence of orders must follow the one determined by the dispatching rules.

$$x_{i,j+1} \geq x_{i,j} + p_{i,j} \quad j = 1, 2, \ldots, N\text{-}1;\ i = 1, 2, \ldots, W \quad (3)$$

2. The precedence relationship between work centers must be maintained.

Each product may have different production routes and requires 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, sequential and convergent relationships (see Fig 6). Complicated precedence relationships can be constructed from the basic sequential and convergent relationships.

For sequential relationship:

$$x_{1,j} \geq x_{2,j} + p_{2,j} \quad j = 1, 2, \ldots, N \quad (4)$$

$$x_{2,j} \geq x_{3,j} + p_{3,j} \quad j = 1, 2, \ldots, N \quad (5)$$

For convergent relationship:

$$x_{1,j} \geq x_{2,j} + p_{2,j} \quad j = 1, 2, \ldots, N \quad (6)$$

$$x_{1,j} \geq x_{3,j} + p_{3,j} \quad j = 1, 2, \ldots, N \quad (7)$$

Note that the equations 4 to 7 can be modified in order to allow the overlapping of production batches. For example, if the 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 equations 4' to 7'

For sequential relationship:

$$x_{1,j} \geq x_{2,j} + 0.1\, p_{2,j} \quad j = 1, 2, \ldots, N \quad (4')$$

$$x_{2,j} \geq x_{3,j} + 0.1\, p_{3,j} \quad j = 1, 2, \ldots, N \quad (5')$$

For convergent relationship:

$$x_{1,j} \geq x_{2,j} + 0.1\, p_{2,j} \quad j = 1, 2, \ldots, N \quad (6')$$

$$x_{1,j} \geq x_{3,j} + 0.1\, p_{3,j} \quad j = 1, 2, \ldots, N \quad (7')$$

3. Calculation of the completion time, tardiness, earliness, and flow-time

Based on the data in Figure 6, the completion time of finished products, tardiness, earliness, and flow-time of each order can be formulated as follows:

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

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

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

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

$$d_j - c_j = e_j - t_j \quad j = 1, 2, \ldots, N.$$

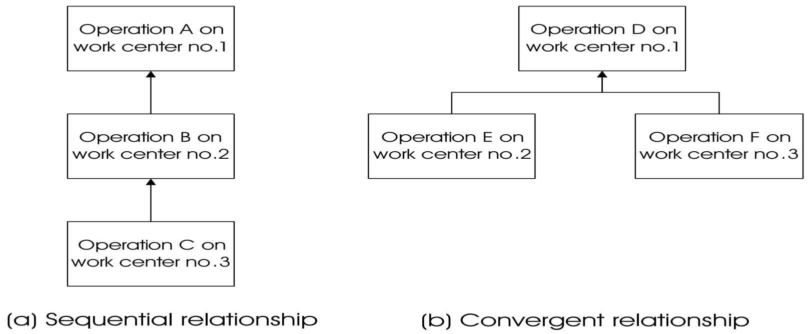

Fig 6. Precedence relationship between work centers

For sequential structures:

$$f_j = c_j - x_{3,j} \qquad j = 1, 2, \ldots, N \tag{11}$$

For convergent structures:

$$f_j = \max\,(c_j - x_{3,j}\,,\, c_j - x_{2,j})\;\; j = 1, 2, \ldots, N \tag{12}$$

Equation 12 may be specified as

$$f_j \geq c_j - x_{3,j} \qquad j = 1, 2, \ldots, N$$

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

4. Non-negativity condition

All parameters and decision variables are non-negative.

It is quite 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 non-working hours of the day are not existent). The flow-time, earliness, and tardiness measures are all relative to this new definition of time.

Conventional FCMRP Systems

This section explains the concept of conventional FCMRP systems. Two systems, namely, Forward (F) and Forward-Backward (FB) scheduling systems are considered. The algorithm of the F scheduling system is presented in Fig 7. The first four blocks of the algorithm are the same as those of the proposed FCMRP system. The remaining blocks of the algorithm try to schedule the operations based on the priority of customer orders (obtained from the dispatching rules). The operations of order with index 1 will be produced first and the operations of order with larger index will be produced later. These operations will be scheduled as soon as possible to the available time on the work centers considering precedence relationship of the operations. By this method, some orders may be completed before their due dates. This results in increasing inventory holding cost. The FB scheduling system tries to alleviate this drawback by delaying the early-completed orders as much as possible without making the orders completed late. The algorithm of the FB scheduling system is presented in Fig 8.

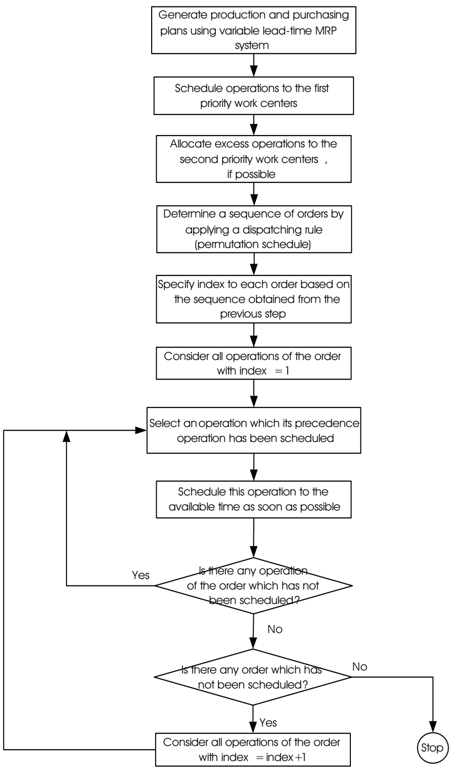

Fig 7. Algorithm of F system

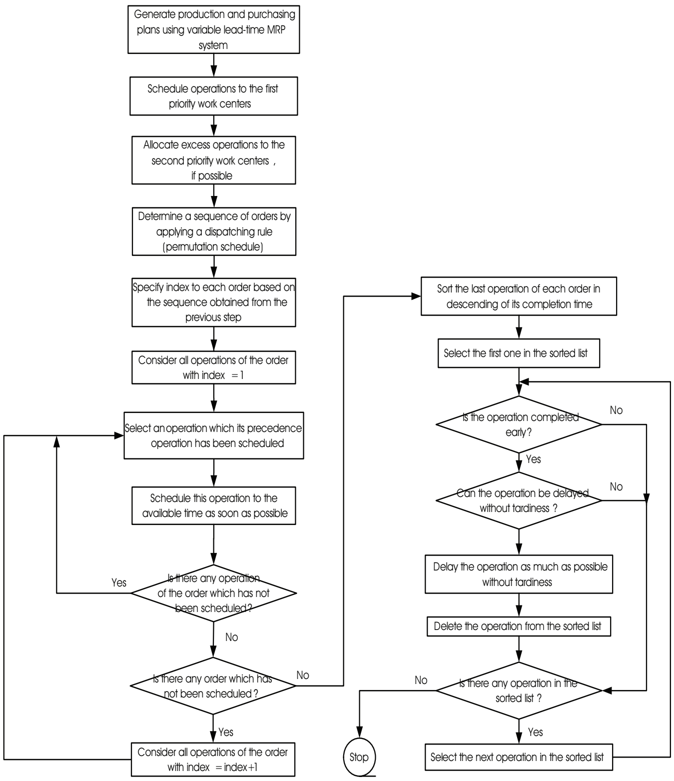

Fig 8. Algorithm of FB system

Design of Experiments

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 (FCMRP, F, and FB) and dispatching rules on 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, dependent variables, and the experimental case are explained as follows.

Independent Variables

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:

1. Set $C_t = C_e = C_f = 0.33$ denoted by FCMRP 1.
2. Set $C_t = 0.90$, $C_e = 0.05$, $C_f = 0.05$, denoted by FCMRP 2.
3. Set $C_t = 0.05$, $C_e = 0.90$, $C_f = 0.05$, denoted by FCMRP 3.
4. Set $C_t = 0.05$, $C_e = 0.05$, $C_f = 0.90$, denoted by FCMRP 4.

Note that the dispatching rule in this experiment is EDD.

Experiment to analyze the effect of different FCMRP systems (FCMRP, F, and FB) and dispatching rules

In this experiment, the weights are set based on the opinion of the planner of this company. The planner feels that the total earliness and total tardiness are equally important, and they are three times as important as the average flow-time. Thus, the weights of total tardiness (C_t), total earliness (C_e), and average flow-time (C_f) are 0.42, 0.42, and 0.14, respectively. The objective of this experiment is to analyze the effect of different FCMRP systems (FCMRP, F, and FB) and dispatching rules on the performance measures. There are two independent variables as follows:

1. FCMRP systems

There are three FCMRP systems, namely, FCMRP, F, and FB systems.

2. Dispatching rules

There are three dispatching rules, namely, EDD, SPT, and MST.

Dependent Variable

The dependent variable is performance measures of the schedule generated by the FCMRP systems. There are five performance measures, namely, number of early orders, total earliness (in days), number of tardy orders, total tardiness (in days), and average flow time of all products (in days). 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.

Experimental Case

The experiment was 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 shop with sequential and convergent precedence relationships and has 25 items of finished goods.
2. Each finished good has its product structure.
3. BOM has 3 to 10 levels depending on the products.
4. There are 20 work centers. Some are bottlenecks and some are non-bottlenecks.
5. Each product structure consists of at least three operations.
6. Each operation needs a work center.
7. Some operations can be produced on more than one work center (alternatively).
8. The first and second priority work centers are specified by the planner.
9. All work centers are operated 8 hours a day and overtime is not allowed.
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 techniques by MRP users[17].
12. The customer demand is assumed to follow 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 was conducted in 30 replications using 30 sets of randomly generated demands. The number of replication of 30 was sufficient to obtain accurate mean values of performance measures since the 95% confidence interval of the population mean of each performance measure was within ± 2% of the mean value. A one-way ANOVA was used to statistically analyze the first experiment, while a two-way ANOVA was used for the second experiment.

Table 1. Effects of weights in objective function on performance measures

Factors	weights			Total tardiness (days)	No. of tardy orders	Total earliness (days)	No. of early orders	Average flow-time (days)
	C_t	C_e	C_f					
FCMRP 1	0.33	0.33	0.33	103.12(2)	73.65(3)	48.66(2)	35.77(2)	17.21(2)
FCMRP 2	0.90	0.05	0.05	91.91(1)	65.18(1)	82.18(4)	58.70(4)	20.22(3)
FCMRP 3	0.05	0.90	0.05	113.32(4)	80.37(4)	40.05(1)	28.61(1)	22.46(4)
FCMRP 4	0.05	0.05	0.90	100.65(3)	71.89(2)	52.15(3)	37.52(3)	16.02(1)

Dispatching rule = EDD
Total number of customer orders = 252 orders

Results and Discussion

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

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

The average value of the performance measures and the ranking of the performance measures obtained from the Duncan's multiple mean comparison method are shown in Table 1. 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.

From Table 1, the weights had a significant effect on all performance measures, namely, number of early orders, total earliness, number of tardy orders, total tardiness, and average flow-time. The total tardiness was the lowest when FCMRP 2 is applied, this occurs since the weight of tardiness (C_t) is set to 0.90, which is greater than the weights of total earliness (C_e) and average flow-time (C_f). If the planners want to minimize the earliness and average flow-time, FCMRP 3 and FCMRP 4 should be applied, respectively. In contrast, if they want to compromise all performance measures, all weights should be set equally (FCMRP 1).

Table 2. P-values from analysis of variance

Factors	Total tardiness (days)	No. of tardy orders	Total earliness (days)	No. of early orders	Average flow-time (days)
FCMRP systems (FCMRP)	0.000*	0.000*	0.000*	0.000*	0.000*
Dispatchingrules (D)	0.000*	0.000*	0.000*	0.000*	0.000*
FCMRP x D	0.915	0.999	0.299	0.982	0.008*

* the effect is significant at significant level of 0.05

Table 3. Average values and ranking of performance measures

Factors	Total tardiness (days)	Number of tardy orders	Total earliness (days)	Number of early orders	Average flow-time (days)	Overall performance index
FCMRP systems (FCMRP)						
FCMRP	101.20(2)	45.74(2)	46.12(1)	32.18(1)	17.50(1)	65.64(1)
F	89.53(1)	40.46(1)	85.19(3)	60.60(3)	19.43(2)	77.66(3)
FB	89.53(1)	40.46(1)	59.07(2)	42.01(2)	25.53(3)	67.33(2)
Dispatching rules (D)						
EDD	92.35(1)	41.74(1)	63.47(2)	45.14(2)	20.97(2)	69.78(1)
SPT	94.53(3)	42.71(2)	62.30(1)	44.32(1)	19.82(1)	70.04(2)
MST	93.39(2)	42.21(2)	64.62(3)	45.96(2)	21.97(3)	70.86(3)
Combinations						
FCMRP*EDD	100.14(4)	45.26(3)	46.09(2)	32.78(2)	17.78(2)	65.21(1)
FCMRP*SPT	102.26(6)	46.21(4)	45.02(1)	32.02(1)	16.62(1)	65.49(2)
FCMRP*MST	101.23(5)	45.74(3)	47.27(3)	33.62(2)	19.01(4)	66.36(3)
F*EDD	88.46(1)	39.96(1)	85.21(7)	60.61(6)	19.56(4)	77.22(7)
F*SPT	90.66(3)	40.96(2)	84.02(6)	59.76(5)	18.50(3)	77.51(8)
F*MST	89.47(2)	40.44(2)	86.35(8)	61.42(7)	20.22(5)	78.24(9)
FB*EDD	88.46(1)	39.96(1)	59.10(4)	42.03(4)	25.56(7)	66.89(4)
FB*SPT	90.66(3)	40.96(2)	58.87(4)	41.16(3)	24.34(6)	67.56(5)
FB*MST	89.47(2)	40.44(2)	60.24(5)	42.85(4)	26.69(8)	67.97(6)

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 2. Different FCMRP systems and dispatching rules had significant effects on all performance measures. The interaction effect between the FCMRP systems and dispatching rules was only significant to average flow-time but insignificant to other performance measures. The average values and ranking of performance measures are shown in Table 3.

Based on Table 3, the earliness and average flow-time obtained from the proposed FCMRP system were better than those of F and FB systems, while the tardiness obtained from the F and FB scheduling systems was better. Comparing between F and FB systems, the FB system significantly outperformed the F system for total earliness and number of early orders. The F system was better than the FB system on average flow-time. Both systems were not significantly different in terms of total tardiness and number of tardy orders. This indicated that the algorithm of the FB system, which tried to delay too early-completed orders, was effective for reducing the earliness without affecting the tardiness. However, the algorithm of the FB system increases the average flow-time from that of the F system.

Note that the computation time of the F or FB system was about 40 minutes whereas the proposed FCMRP needed about 90 minutes for each replication. Thus, the computation time of the proposed FCMRP was higher than that of the F and FB systems. However, the computation time of 90 minutes was still acceptable and practical for industrial applications.

Comparing the dispatching rules presented in Table 3, the EDD rule turned out to be the best for total tardiness and number of tardy orders (it had rank 1 for these performance measures). The SPT rule was the best for total earliness, number of early orders, and average flow-time. The MST rule was the worst for most performance measures. Thus, the EDD rule is more appropriate than the SPT rule when the planner feels that the tardiness is more important than the earliness, and vice versa. Although the scheduling algorithm and environment in this experiment were much more complicated than those of the basic single-work center scheduling theory, the results were complying. Based on the single-work center scheduling theory, the SPT rule minimizes the average flow-time and the EDD rule minimizes the maximum tardiness. Moore (1968) developed an algorithm based on EDD, which minimized the number of tardy orders[18].

An overall performance index can be determined using a weighted average of some performance measures calculated based on the opinion of the planner (see Section 4.2). The weights of total earliness (C_e), total tardiness (C_t), and average flow-time (C_f) are 0.42, 0.42, and 0.14, respectively. The overall performance indices are presented in Table 3. It indicated that the proposed FCMRP system resulted in the best overall performance index when compared with the F and FB systems. It also indicated that the EDD rule resulted in the best overall performance index when compared with the SPT and MST rules. Furthermore, when the combination of FCMRP method and dispatching rule was considered at the same time, the best combination was to combine the proposed FCMRP method and the EDD rule since this combination can offer the best overall performance index (rank 1).

The reason why the proposed FCMRP system had the best overall performance index is that it tries to determine the start and finish times of all operations to get the best compromised solution among the tardiness, earliness, and flow-time using the optimization method. The F system tries to start and finish all operations as soon as possible. Thus, the tardiness is the best but the earliness and flow time are the worst. The FB system is similar to F system, except that it tries to delay some operations to reduce the earliness. Both F and FB systems have no optimization mechanism to trade-off between conflicting performance measures. Note that the difference between FCMRP systems will be reduced when there is little or no slack time on work centers. So, when the order/capacity ratio is high, the difference between FCMRP systems may not be clearly seen.

Focusing on the interaction effects, although Table 2 indicated that the interaction between the FCMRP systems and dispatching rules was significant on the average flow-time, the interaction effect was not clearly seen on the graph in Fig 9.

Conclusions

A new FCMRP system, which has optimization ability and is applicable for real industrial problems, was

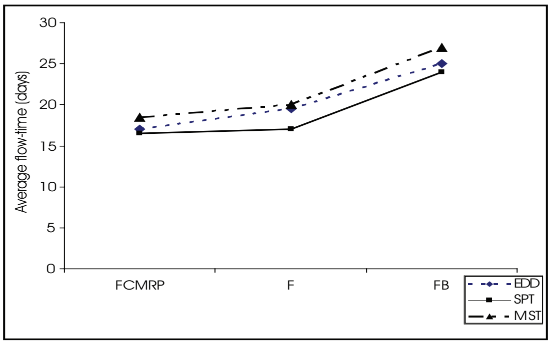

Fig 9. Interaction between FCMRP systems and dispatching rules on average flowtime

developed. It used a linear programming model to determine the optimal start time of each operation to minimize the weighted average of total earliness, total tardiness, 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 proposed FCMRP system and the EDD rule could offer the best overall performance index since it has an ability to trade-off between conflicting performance measures.

The performances of the proposed FCMRP system could be 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 an 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 those of the earliness and flow-time. In this way, the resulting schedule will have relatively low tardiness.

Three dispatching rules, namely, SPT, EDD, and MST, were considered in the proposed FCMRP system. The EDD rule resulted in low tardiness. The SPT rule resulted in low earliness and flow-time. The MST rule was the worst for most performance measures. Thus, the MST rule should not be used in the proposed FCMRP system.

The proposed 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. The dispatching rules under consideration are only simple ones. More complicated and effective dispatching rules can be developed. Thus, further research is needed to analyze and develop the FCMRP system to improve these limitations.

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