

A Finite Capacity Material Requirement Planning System for a Multi-Stage Assembly Factory: Goal Programming Approach

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Abstract. This paper aims to develop a practical finite capacity MRP (FCMRP) system based on the needs of an automotive parts manufacturing company in Thailand. The approach includes a linear 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 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 are penalty weights and dispatching rules. Effects of these factors on the performance measures are statistically analyzed based on a real situation of an auto-part factory. Statistical results show that the dispatching rules and penalty weights have significant effects on the performance measures. The proposed FCMRP system offers a good trade-off between conflicting performance measures and results in the best weighted average performance measures when compared to conventional forward and forward-backward finite capacity scheduling systems.

Keywords: Material Requirement Planning, Finite Capacity, Scheduling Direction, Goal Programming.

1. 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 (see McCarthy and Barber, 1990). 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. This concept tries to move planned requirements forward or backward or both within a speci-

fied 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. Their logics 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 (McCarthy and Barber, 1990), backward scheduling (White and Hastings, 1983), and a combination of forward and backward scheduling (Hastings and Yeh, 1990). Taal and Wortmann (1997) and Bakke and Hellberg (1993) concluded that the SFC system is unable to solve the capacity problems, which are cre-

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ated at the material requirement planning (MRP) calculation stage. 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 according to 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. 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 (1996) proposed an optimization model to support a production planner in solving capacity problems. 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). MRP-C uses 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 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. Meredith and Mantel (2000) stated that scheduling by optimization approaches are only the feasible methods of attacking the non-linear and complex problems that tend to occur in the real world of project management. They also suggest that the optimization technique must be applied to the real industries.

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. This technique guarantees feasible release dates for production orders but it may generate some tardy orders. Pandey et al (2000) developed a FCMRP algorithm, which is executed in two stages. First, capacity-based production schedules are generated from the input data. Second, the algorithm determines an appropriate material requirement plan to satisfy the schedules obtained from the first stage. Wutipornpun and Yenradee (2004) 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.

Conventional FCMRP systems used in industries are a combination of MRP and finite capacity scheduling systems, which are 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 dates 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.

However, a limitation of the FCMRP system is that the lot-sizing rule is lot-for-lot

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 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 on 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.

2. 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 Figure 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 fini-

shed 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 will be 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 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) 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 goal programming model. An objective of this step is to minimize the sum of penalty points incurred by exceeding the goals of per-

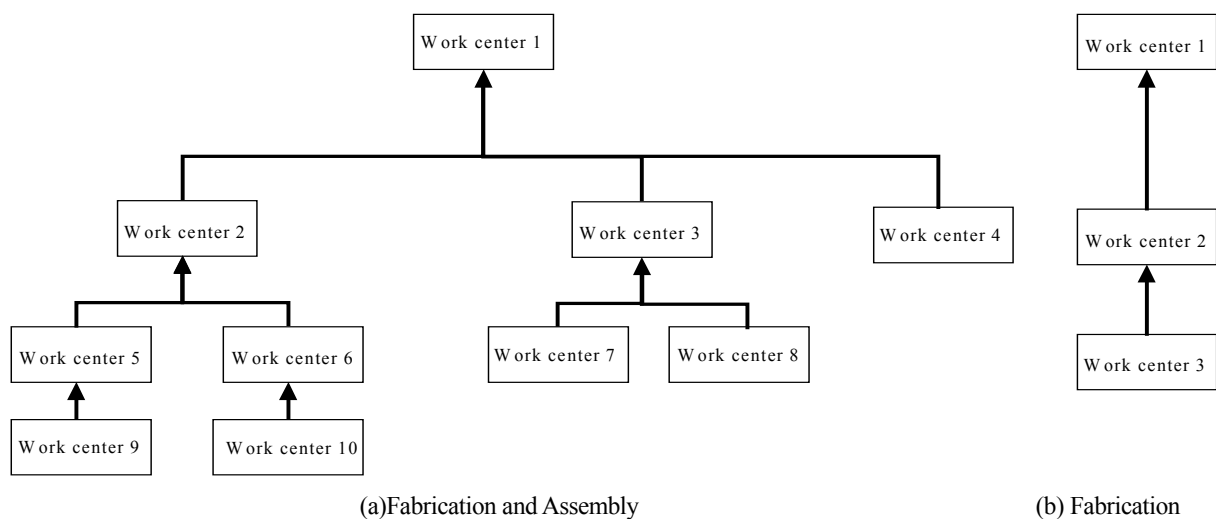


Figure 1. Structure of manufacturing process

formance measures (tardiness, earliness, and flow-time).
 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_{ij}	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	penalty weight of exceeding the goal of total tardiness
C_e	penalty weight of exceeding the goal of total earliness
C_f	penalty weight of exceeding the goal of average flow-time
X	goal of total tardiness
Y	goal of total earliness
Z	goal of average flow-time
T^+, T^-	deviation of the total tardiness from the goal X
E^+, E^-	deviation of the total earliness from the goal Y
AF^+, AF^-	deviation of the average flow-time from the goal Z

Decision variables

x_{ij}	start time of order j on work center i
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A block diagram of the proposed FCMRP system is shown in Figure 2. The algorithm is described step-by-step and illustrated by an example as follows.

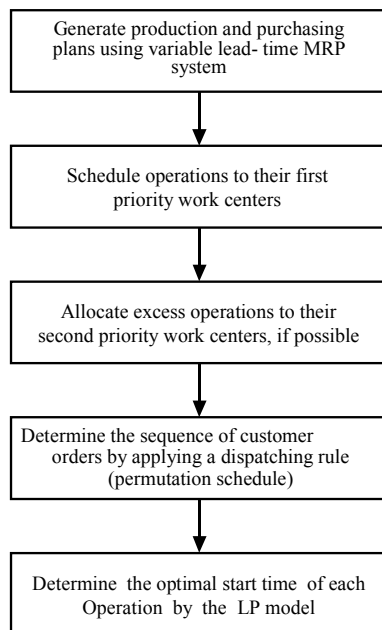


Figure 2. Block diagram of the proposed FCMRP system

2.1 Generate Production and Purchasing Plans using Variable Lead-time MRP System

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 (see Wuttipornpun 2005). It is different from the conventional MRP system in that it assumes variable lead-times. The total lead-time (p_{ij}) 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.

2.2 Schedule 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. Figure 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.

2.3 Allocate 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 on their first priority work centers whereas others may be produced on their second priority work centers. From Figure 3(a), the excess operation B on work center 1 in day 1 can be moved to work center 2 (see Figure 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 Figure 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.

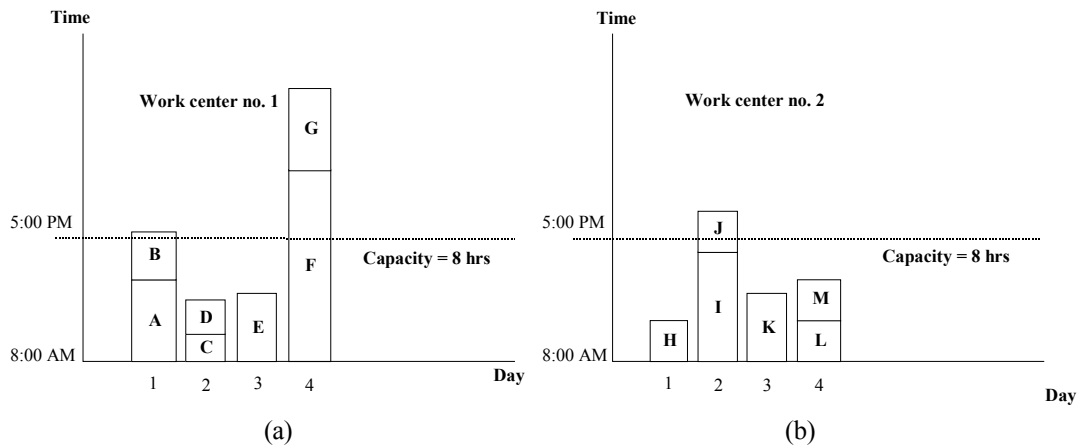


Figure 3. Load profile on the first priority work centers

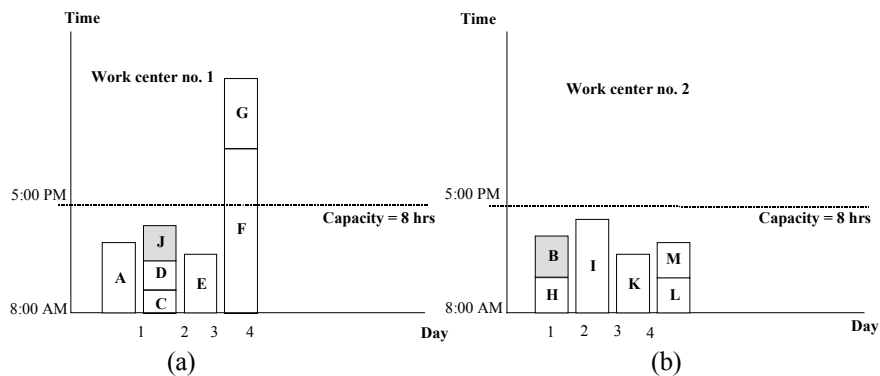


Figure 4. Load profile on work centers after allocating excess operations to the second priority work centers

2.4 Determine 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 tried 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:

2.4.1 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.

2.4.2 Shortest Total Processing Time on the Longest Path (SPT)

This rule tries to produce the order, which has 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.

2.4.3 Minimum Slack Time (MST)

This rule tries to produce the order, which has the minimum slack time first and produce the order with relatively long slack time later. The slack time is defined in Formula 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 12 (31-1-19).

According to the MST rule, the production sequence is to produce order A and then B.

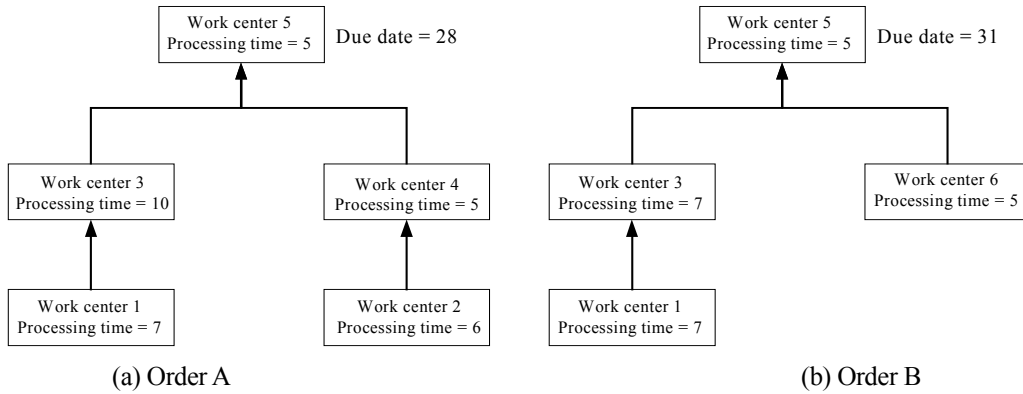


Figure 5. An example for illustrating the dispatching rules

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.

2.5 Determining the Optimal Start Time of each

Operation by a Linear Goal 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 presents a linear goal programming approach to determine the optimal start time (x_{ij}) and due time of each operation. The three performance measures considered as objectives (goals) are total tardiness (t_j), total earliness (e_j), and average flow-time (f_j). Other common performance criteria could also be of interest to the decision maker, including the number of early orders and tardy orders. They are not included as they do not alter the essential model characteristics. It is, however, possible and fairly easy to incorporate them as two additional goals. The model presented is a so-called weighted goal program (WGP) in that it considers all goals simultaneously as they are embodied in a composite objective function. From a modeling point of view there are several alternatives, see e.g. Romero (1991), Tamiz et al (1998). In lexicographic goal programming (LPG), for example, goals are classified into different levels of priority and highest priority goals are satisfied first and only then are lower priority goals considered. The selection of the best modeling alternative should be based on the practical problem under consideration; the decision maker's preferences

are the most important. LPG may be preferred over WGP, for example, in the case that the company considers trying to meet due dates of customer demand immeasurably more important than inventory levels, in which case total earliness and average flow-time would be goals in a lower class of priority than total tardiness. In addition, the decision maker may wish to include the number of tardy orders as an additional goal in the highest priority class.

Objective

The objective of the model is to minimize the sum of penalty points incurred by exceeding the goals of total tardiness, total earliness, and average flow-time as shown in formula 2.

$$\text{Minimize } C_t \cdot T^+ + C_e \cdot E^+ + C_f \cdot AF^+ \quad (2)$$

The penalty weights C_t , C_e , and C_f can be adjusted to obtain desirable performance measures. For example, if C_t is relatively high but C_e and C_f are relatively low, the total tardiness tends to be low but total earliness and average flow-time tend to be high.

Constraints

1. The sequence of operations 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 $j = 2$. This sequence is applied to all operations on each work center as well. Constraint 3 ensures that on any work center, the first order in the sequence must start no later than the second order in the sequence, and so on.

$$x_{ij} \leq x_{i,j+1} \quad j = 1, 2, \dots, N-1; \quad i = 1, 2, \dots, W \quad (3)$$

2. The work center cannot simultaneously produce more than one order.

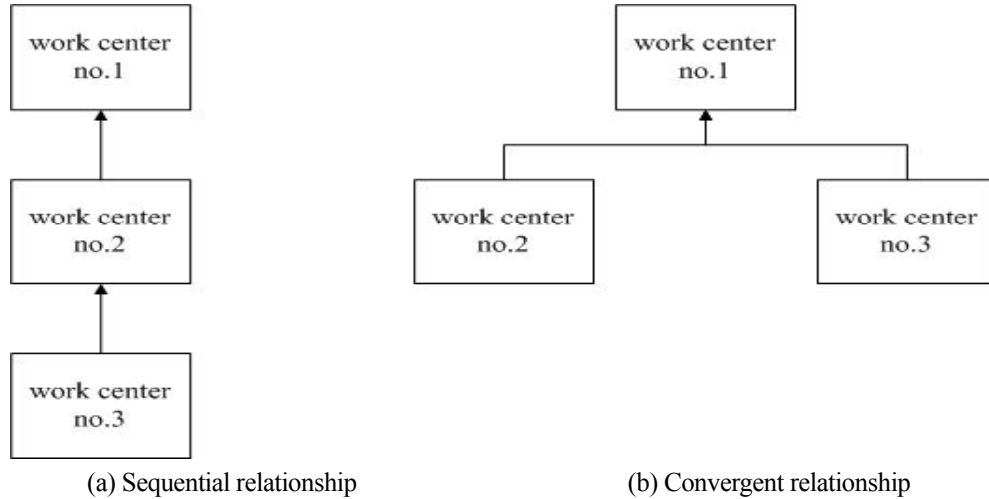


Figure 6. Precedence relationship between work centers

Constraint 4 ensures that the next order on the same work center cannot be started unless the earlier one has finished.

$$x_{ij+1} \geq x_{ij} + p_{ij} \quad j = 1, 2, \dots, N-1; \quad i = 1, 2, \dots, W \quad (4)$$

Note that constraints (4) in fact make constraints (3) redundant.

3. 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 Figure 6). Complicated precedence relationships can be constructed from the basic sequential and convergent relationships.

For sequential relationship:

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

$$x_{2j} \geq x_{3j} + p_{3j} \quad j = 1, 2, \dots, N \quad (6)$$

For convergent relationship:

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

$$x_{1j} \geq x_{3j} + p_{3j} \quad j = 1, 2, \dots, N \quad (8)$$

Note that the constraints 5 to 8 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 Formulas 5' to 8' For sequential relationship:

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

$$x_{2j} \geq x_{3j} + 0.1 p_{3j} \quad j = 1, 2, \dots, N \quad (6')$$

For convergent relationship:

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

$$x_{1j} \geq x_{3j} + 0.1 p_{3j} \quad j = 1, 2, \dots, N \quad (8')$$

4. 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:

$$c_j = x_{1j} + p_{1j} \quad j = 1, 2, \dots, N \quad (9)$$

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

$$e_j = \max(d_j - c_j, 0) \quad j = 1, 2, \dots, N \quad (11)$$

Of course, constraints (10) and (11) may be better written as one constraint:

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

For sequential structures:

$$f_j = c_j - x_{3j} \quad j = 1, 2, \dots, N \quad (12)$$

For convergent structures:

$$f_j = \max(c_j - x_{3j}, c_j - x_{2j}) \quad j = 1, 2, \dots, N \quad (13)$$

The constraint 13 may be specified as

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

$$f_j \geq c_j - x_{2j} \quad j = 1, 2, \dots, N$$

5. The deviation of the total tardiness from its goal is defined by constraint 14.

$$\sum_{j=1}^N t_j + T^- - T^+ = X \quad (14)$$

6. The deviation of the total tardiness from its goal is defined by constraint 15.

$$\sum_{j=1}^N e_j + E^- - E^+ = Y \quad (15)$$

7. The deviation of the average flow-time from its goal is defined by constraint 16.

$$(1/N) \sum_{j=1}^N f_j + AF^- - AF^+ = Z \quad (16)$$

8. 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.

Note that the goals X , Y , and Z must be set based on the sequence of orders obtained from dispatching rules before solving the goal programming model. In this paper, the best possible values of the total tardiness, total earliness, and average flow-time are set as the goals X , Y , and Z , respectively. A new objective function 17 and constraints 3 to 13 are used to determine the best possible values of the total tardiness, total earliness, and average flow-time.

Minimize

$$C_t \cdot \sum_{j=1}^N t_j + C_e \cdot \sum_{j=1}^N e_j + C_f \cdot \left(\frac{1}{N} \sum_{j=1}^N f_j \right) \quad (17)$$

The best possible values of the total tardiness, total earliness, and average flow-time are determined by setting $(C_t, C_e, C_f) = (1, 0, 0)$, $(0, 1, 0)$, and $(0, 0, 1)$, respectively. In this way, the goal of total tardiness (X) is equal to the minimum total tardiness obtained by minimizing the total tardiness without considering the total earliness and average flow-time, subjected to all constraints. As a result, the deviation T^+ is positive but the deviation T^- is always zero. The effects on the goals Y and Z are similar to that of the Goal X . The goal program obtained in this way has an underlying “optimizing philosophy” similar to distance metric optimization and therefore the solutions obtained will be Pareto optimal (see Tamiz et al, 1998). Alternatively, the decision maker may wish to set a value for X , Y , or

Z lower than the highest possible achievable value which then reflects a “satisficing philosophy”. In that case, it is best to check if the obtained solution is dominated and if so, to restore Pareto optimality (as in Tamiz and Jones, 1996). Finally, when including the number of early jobs and the number of late jobs as objectives, it is recommended to use a normalization technique in order to reduce any unintentional bias towards the objectives with a different magnitude (see Tamiz et al, 1998).

3. CONVENTIONAL FCMRP SYSTEM

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 Figure 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 the order with index 1 will be produced first and the operations of the order with larger index will be produced later.

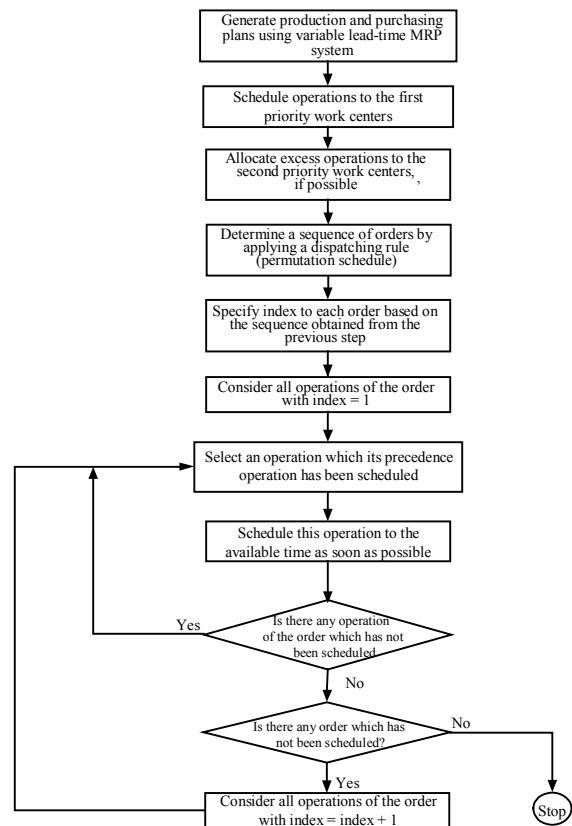


Figure 7. Algorithm of F system

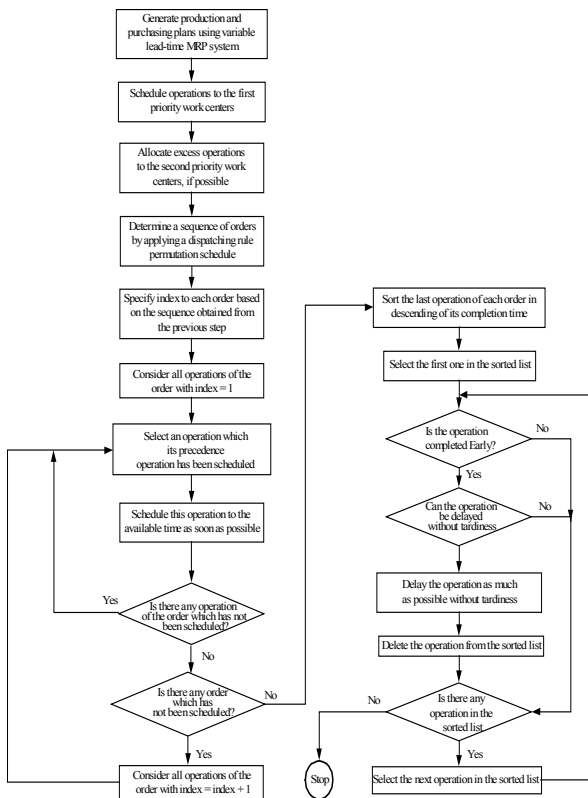


Figure 8. Algorithm of FB system

These operations will be scheduled as soon as possible to the available time on the work centers considering precedence relationships of 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 Figure 8.

4. DESIGN OF EXPERIMENTS

There are two experiments in this paper. The first experiment is to analyze the effect of the penalty 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 penalty 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

4.1 Experiment to Analyze the Effect of Penalty Weights in the Proposed FCMRP System

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

1. Set $C_t = 0.80$, $C_e = 0.1$, $C_f = 0.1$ denoted by FCMRP 1.
2. Set $C_t = 0.1$, $C_e = 0.80$, $C_f = 0.1$ denoted by FCMRP 2.
3. Set $C_t = 0.1$, $C_e = 0.1$, $C_f = 0.80$ denoted by FCMRP 3.
4. Set $C_t = 0.33$, $C_e = 0.33$, $C_f = 0.33$ denoted by FCMRP 4.

Note that the dispatching rule in this experiment is EDD.

4.2 Experiment to Analyze the Effect of Different FCMRP Systems (FCMRP, F, and FB) and Dispatching Rules

In this experiment, the penalty weights are set based on the opinion of the planner of this company. The planner feels that one day of total earliness is as important as one day of average flow-time while one day of total tardiness is five times as important as one day of total earliness. Thus, the penalty 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 (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: EDD, SPT, and MST.

Dependent variable

The dependent variable is the set of performance measures of the schedule generated by the FCMRP systems. There are five performance measures: 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 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 shop with sequential and convergent precedence relationships and has 25 items of finished goods.
2. Bill of materials (BOM) has 3 to 10 levels depending on the products.
3. There are 20 work centers and two of them, work centers 13 and 15, are bottlenecks.
4. Some operations can be produced on more than one work center.
5. The first and second priority work centers are specified by the planner.
6. All work centers are operated 8 hours a day and overtime is not allowed.
7. Overlapping of production batches is not allowed.
8. 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, 1989).
9. The customer demand is assumed to follow a uniform distribution, where the maximum and minimum demands are $\pm 15\%$ of the mean demand.
10. 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. The replication number of 30 is sufficient to obtain accurate mean values of performance measures since the 95% confidence interval of the population mean of each performance measure is within $\pm 2\%$ of the mean value. A one-way ANOVA is used to statistically analyze the first experiment while two-way ANOVA is used for the second experiment.

5. RESULTS AND DISCUSSIONS

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

FCMRP systems and dispatching rules.

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

Based on the method explained at the end of Section 2, the goals of the total tardiness (X), total earliness (Y), and average flow-time (Z) are set at 154.47, 15.06, and 12.52 days, respectively (based on EDD rule). The goals of these performance measures will be changed according to the selected dispatching rule explained in Section 2. 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 a better performance than the higher rank. The performance measures with the same rank are not significantly different.

Table 1 clearly shows that the penalty weights have a significant effect on all performance measures, the number of early orders, total earliness, the number of tardy orders, total tardiness, and average flow-time. The total tardiness is the lowest when FCMRP 1 is applied. This occurs since the penalty weight of exceeding the goal of total tardiness (C_t) is set to 0.80, which is greater than those of total earliness (C_e) and average flow-time (C_f). If the planners want to minimize the earliness and average flow-time, FCMRP 2 and FCMRP 3 should be applied, respectively. In contrast, if they want to compromise all performance measures, all penalty weights should be set equally (FCMRP 4).

5.2 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. It reveals that different FCMRP systems and dispatching rules have significant effect on all performance measures. The interaction effect between the FCMRP systems and dispatching rules is only significant on total earliness and number of early orders but insignificant on other performance measures. The average values and ranking of performance measures are shown in Table 3.

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

Factors	penalty 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	0.8	0.1	0.1	159.15(1)	119.58(1)	29.77(3)	24.52(3)	15.63(3)
FCMRP 2	0.1	0.8	0.1	169.64(5)	130.56(4)	22.33(1)	16.33(1)	15.11(3)
FCMRP 3	0.1	0.1	0.8	166.43(4)	126.72(3)	24.92(2)	18.84(2)	13.78(1)
FCMRP 4	0.33	0.33	0.33	164.33(3)	125.37(2)	25.06(2)	19.33(2)	14.48(2)

Dispatching rule = EDD

Total number of customer orders = 252 orders

Table 2. Analysis of variance results

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*
Dispatching rules (D)	0.000*	0.000*	0.000*	0.000*	0.000*
FCMRP x D	0.658	0.487	0.000*	0.000*	0.554

* 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	162.89(2)	120.97(2)	30.87(1)	25.13(1)	15.56(1)	209.32(1)
F	156.36(1)	115.06(1)	43.79(3)	39.08(3)	16.22(2)	216.37(3)
FB	156.36(1)	115.06(1)	38.80(2)	33.04(2)	16.49(2)	211.77(2)
Dispatching rules (D)						
EDD	156.69(1)	116.23(1)	36.37(2)	32.04(2)	16.60(2)	209.66(1)
SPT	159.94(3)	117.81(2)	35.74(1)	30.66(1)	16.04(1)	211.73(2)
MST	159.09(2)	116.96(1)	41.35(3)	32.54(2)	16.62(2)	217.07(3)

Based on Table 3, the earliness and average flow-time obtained from the proposed FCMRP system are better than those of F and FB systems while the tardiness obtained from the F and FB scheduling systems is better. The FB system significantly outperforms F system for total earliness and number of early orders, but both systems are not significantly different in terms of total tardiness, number of tardy orders, and average flow-time. This indicates that the algorithm of FB system, which tries to delay too early-completed orders, is effective for reducing the earliness without significantly deteriorating other performance measures.

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). The weights of total earliness (C_e), total tardiness (C_t), and average flow-time (C_f) are 0.14, 0.72, and 0.14, respectively. The overall performance indices are presented in Table 3. It indicates that the proposed FCMRP system results in the best overall performance index when compared to the F and FB systems. The FCMRP system can offer the best overall performance index since it has an ability to trade-off between conflicting performance measures.

However, when the trade-off is not required, such as to minimize only the tardiness ($C_t = 1$), the FCMRP system results in total tardiness, the total earliness, and average flow-time of 156.35, 43.77, and 16.22 days, respectively. These performance measures are the same as those of F system since the proposed FCMRP tries to minimize only the tardiness which is similar to the

algorithm of F system that tries to start and finish all operations as soon as possible.

Comparing the dispatching rules presented in Table 3, the EDD rule turns out to be the best for total tardiness and number of tardy orders (it has rank 1 for these performance measures). The SPT rule is the best for total earliness, number of early orders, and average flow-time. The MST rule is the best for only the number of tardy orders. 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 are much more complicated than those of the basic single-machine scheduling theory, the results are complying. Based on the single-machine 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 minimizes the number of tardy orders.

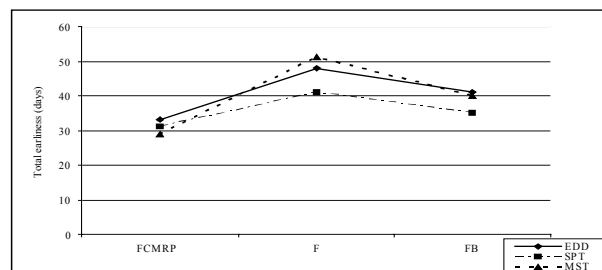


Figure 9. Interaction between FCMRP systems and dispatching rules on total earliness

The interaction effect between the FCMRP systems and dispatching rules is significant only on total earliness and number of early orders. The graphs showing the interaction effect are presented in Figures 9 and 10. They show that the effect of dispatching rules on total earliness and number of early orders of F system is greater than that of FB and the proposed FCMRP system.

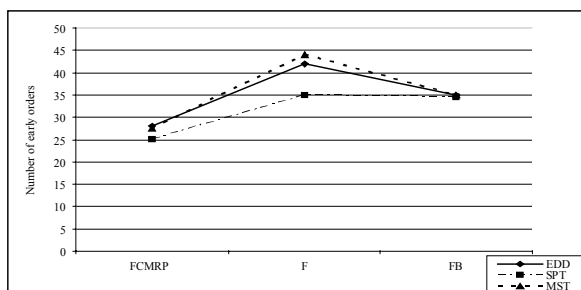


Figure 10. Interaction between FCMRP systems and dispatching rules on number of early

6. CONCLUSION

A new FCMRP system, which has optimization ability and is applicable for real industrial problems, was developed. It uses a linear 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 earliness, total tardiness, and average flow-time considering finite capacity of all work centers and precedence of operations. Based on the experimental results, The FCMRP system can 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 can be controlled by selecting appropriate dispatching rules and penalty weights. The effects of the dispatching rules and penalty weights on the performance measures are statistically analyzed based on the real data of an auto-part factory.

The penalty 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 weight of tardiness 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, are considered in the proposed FCMRP system. The EDD rule results in low tardiness. The SPT rule results in low earliness and flow-time. The MST rule offers the worst overall performance.

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 machines must be operated during an identical number of hours per 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 rules. 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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