Abstract: This paper aims to develop a new algorithm of bucketless finite capacity material requirement planning (FCMRP) system for multi-stage assembly flow shop. The developed FCMRP system is a combination between sequencing heuristic and optimization technique. The sequencing heuristic attempts to allocate operations to proper work centers and also determine the sequence of the operations on each work. The optimization technique is applied in order to determine the optimal start time of the sequenced operations. The result shows that the proposed FCMRP system outperforms the previous FCMRP for all performance measures except for number of early orders and total earliness. The combination of FCMRP-P system and MST rule outperforms other combinations in term of overall performance index. 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.

Keywords: Material requirement planning / Finite capacity / Permutation scheduling / Non-permutation scheduling / Linear programming / Application in industry.

1. INTRODUCTION

Manufacturing resource planning (MRP) is widely used in many business areas mostly in many manufacturing sectors. It now becomes enterprise resource planning (ERP) since many features are developed and integrated in order to cover all functions of business process. 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. A 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 [1-4]. A capacity requirement planning (CRP) and a finite capacity scheduling (FCS) concepts are then introduced in order to remedy the capacity problem after the MRP stage to obtain a feasible production plan [1, 5, 6]. Although the CRP and FCS 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 [7]. Thus, a finite capacity material requirement (FCMRP) system then has been developed to attack the problem at the MRP level. There are many researches related to the FCMRP system. They are discussed as follows. Pandey et al. [8] 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 planner. Wuttipornpun and Yenradee [9] developed an FCMRP system for a flow shop with assembly operations that is capable of allocating operations from one machine to another and also adjusting timing of the operations by considering the finite available time of all machines. The proposed FCMRP system can greatly reduce the overtime but increase earliness and/or tardiness to a certain extent. The characteristics of the schedule generated by the proposed FCMRP system comply with those generated by the theory of constraint (TOC) concept in that the schedules of the bottleneck machines are free of idle time and overtime. However, the schedule of non-bottleneck machines may have idle or overtime in some periods to deliver parts to the bottleneck machines whenever they are required. Nagendra and Das [4] 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 et al. [10] developed an FCMRP system for multi-stage assembly flow shop.
algorithm for a multi-stage automotive-part assembly flow shop. In this system, the capacity problem is reduced by moving tardy operations from their first priority work centers to their second priority work centers. The weight of each performance measure is assigned in order to obtain a desired solution. A linear programming approach is applied in order to determine the optimal start time of each operation. The result shows that the assigned weights are significantly affected to all performance measures. The planner can change the weights in order to get the desired performance. However, the move method in the proposed FCMRP system is appropriate only for short lead-time operations. If the lead-time of each operation is longer, there is less chance to move from first priority to second priority. Therefore, the capacity problem may not be reduced.

This research aims to propose a new FCMRP system which is an extension of Wuttipornpun et al. [10]. A main difference is that the proposed FCMRP system has a different algorithm to generate the sequence of operations on work centers. The algorithm of the proposed FCMRP system has an ability to handle long lead-time operations which is a weak point of the research done in the past [10]. The proposed FCMRP system has four main steps. 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 start times of each operation based on 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.

This paper is organized as follows. The algorithm of the proposed FCMRP system and the FCMRP system developed by Wuttipornpun et al. [10] are described in sections 2 and 3. An experiment to analyze the effectiveness of the proposed FCMRP system and an experimental case are explained in section 4 and 5. The experimental results are analyzed and discussed in section 6. Finally, the conclusion is made in section 7.

2. THE PROPOSED FCMRP SYSTEM

The manufacturing process under consideration is a flow shop with assembly operations. Some products require only sequential operations (without assembly operations) as shown in figure 1(a), whereas others require both sequential and convergent operations (with assembly operations) as shown in figure 1(b). 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.

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

Step 1: Generate production and purchasing plans by using a variable lead-time MRP system.

Step 2: Apply dispatching rules to determine the sequence of orders and operations.

Step 3: Schedule operations to proper work centers (Permutation and Non-permutation methods).

Step 4: Determine an optimal start time by using linear programming (LP) model.

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 [9]. An example of the result obtained from TSPICs is illustrated in figure 3. It can be seen from figure 3 that 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, 3, and 5. Note that all work centers shown in figure 3 are the first priority work center of each operation and the first and second priority work centers of each operation are shown in table 1. The proposed FCMRP system uses the lot-for-lot lot sizing rule since it is the simplest and results in lowest inventory level [11].

Step 2: Apply 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 to study how the dispatching rules affect the performance measures. Data in figure 3 is used to illustrate how to apply the dispatching rules to the orders.

Based on figure 3, the due hours 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 hour first and produce the order with relatively late due hour later. Therefore, the production sequence is A, C, B, and D. Note that when the tie occurs while any rule is applied, the first come first serve rule is then applied to break the tie.

The total processing time of the longest path of order A is 20 hours (sum of processing time on w/c 1, 3, and 4), while that of orders B, C, and D are 18, 19, and 20 hours 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 hour from the current hour and total processing time. Suppose the current hour is 1, the slack time of order A is 12 hours (33 - 1 = 12) and the slack times of orders B, C, and D are 17, 15, and 16 hours respectively. Then the result of the MST rule is to produce orders A, C, D, and B.

Table 1. First and second priority work center information

<table>
<thead>
<tr>
<th>Order</th>
<th>Operation</th>
<th>First priority work center (w/c)</th>
<th>Second priority work center (w/c)</th>
<th>Due hour</th>
<th>Due date</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A1</td>
<td>w/c 1</td>
<td>w/c 2</td>
<td>33</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>w/c 2</td>
<td>-</td>
<td>23</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>w/c 3</td>
<td>w/c 4</td>
<td>23</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>A4</td>
<td>w/c 4</td>
<td>-</td>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>B1</td>
<td>w/c 1</td>
<td>w/c 2</td>
<td>36</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>w/c 2</td>
<td>-</td>
<td>26</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>w/c 3</td>
<td>w/c 4</td>
<td>26</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>B4</td>
<td>w/c 4</td>
<td>-</td>
<td>22</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>B5</td>
<td>w/c 5</td>
<td>w/c 6</td>
<td>23</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>C1</td>
<td>w/c 1</td>
<td>w/c 2</td>
<td>35</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>w/c 3</td>
<td>w/c 4</td>
<td>27</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>w/c 5</td>
<td>w/c 6</td>
<td>32</td>
<td>3</td>
</tr>
<tr>
<td>D</td>
<td>D1</td>
<td>w/c 1</td>
<td>w/c 2</td>
<td>37</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>D2</td>
<td>w/c 2</td>
<td>-</td>
<td>32</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>D3</td>
<td>w/c 3</td>
<td>w/c 4</td>
<td>32</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>D4</td>
<td>w/c 5</td>
<td>w/c 6</td>
<td>26</td>
<td>4</td>
</tr>
</tbody>
</table>

Step 3: Schedule operations to proper work centers.

This step tries to schedule operations to proper work centers. The proper work centers are selected by considering the first and second priority work centers simultaneously. The operation will be scheduled to the work center that generates lower tardiness. Note that when the tie occurs, the operation will be scheduled to the first priority work center instead. The operations of the first order obtained from step 2 are scheduled first. The operations of the second order obtained from step 2 are then scheduled next and so on. This procedure attempts to schedule each operation to the release hour obtained from step 1. If the release hour is not available, the operation will be scheduled to the nearest available hour (after the release hour) as forward scheduling technique. There are two scheduling methods, namely, a permutation and a non-permutation. When the permutation method is applied, the sequence of operations of all work centers must still follow the sequence obtained from step 2, whereas it can be relaxed for the non-permutation method.

To make it more comprehensive, data in figure 3 and table 1 are used to illustrate how this step works and the result is shown in figure 4. Suppose that the EDD rule and permutation method are 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 hour first and operations A3, A2, and A1 are then scheduled consecutively. It can be seen from figure 4 that operations A1, A2, A3, and A4 are scheduled to the first priority work centers (w/c 1, 2, 3, and 4) since their release hours are available. They are on-time operations since their completion times are exactly the same as their due hours obtained from step 1. Note that the completion times of on-time operations come from the due hours in figure 3 minus one, since the on-time operation must be finished at the end of the hour before its due hour. For example, the due hour of operation A4 shown in figure 3 is 16 but it is shown as 15 in figure 4.

The next operations to schedule are C3, C2, and C1 respectively since order C is the second one to produce. The operation C3 is scheduled to the first priority work center (w/c 5) since its release hour is available, whereas the operations C2 and C1 are scheduled to the second priority work centers (w/c 4 and 2) since the second priority work centers generate lower tardiness than the first priority work centers. The Operation B5 is scheduled to the second priority work center (w/c 6), whereas the operation B3 is scheduled to the first priority work center (w/c 3). Operations B4 and B2 are scheduled to their first priority work centers after their release hours since there is no alternative work center for them and their release hours are seized by operations C2 and C1 respectively. Note that operation B4 cannot be scheduled to produce between operation A4 and C2 and operation B2 also cannot be scheduled to produce between operation A2 and C1 since the sequence obtained from step 2 is broken. For operation B1, it is scheduled to the first priority work center (w/c 1) since because the tardiness on the first and second priority work centers are the same. By the same procedure, operations of order D are scheduled to the proper work center as shown in figure 4. After applying this procedure, all operations are scheduled to the proper work centers with the same sequence obtained from step 2 and the existing tardiness is about 23 hours.

When the non-permutation method is selected, the sequence obtained from step 2 can be broken and the result of this method is shown in figure 5. The total tardiness is about 13 hours.
Parameters

- **i**: index of work center starting from 1 to W
- **j**: index of customer order starting from 1 to N
- **$p_{ij}$**: 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 $j$
- **$C_t$**: weight of total tardiness
- **$C_e$**: weight of total earliness
- **$C_f$**: weight of average flow-time

Decision variable

- **$x_{ij}$**: 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).

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

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.

\[
x_{ij+1} \geq x_{ij} + p_{ij} \quad i = 1, 2, \ldots, W, j = 1, 2, \ldots, N-1 \tag{2}
\]

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 Figure 1). Based on Figure 1, complicated precedence relationships of operations can be constructed from the basic sequential and convergent relationships as follows.

For sequential relationship:

\[
x_{ij} \geq x_{ij+1} + p_{ij} \quad j = 1, 2, \ldots, N \tag{3}
\]

For convergent relationship:

\[
x_{ij} \geq x_{ij+1} + p_{ij} \quad j = 1, 2, \ldots, N \tag{4}
\]

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

For complete time:

\[
c_j = x_{ij} + p_{ij} \quad j = 1, 2, \ldots, N \tag{5}
\]

For tardiness:

\[
t_j = \max(c_j - d_j, 0) \quad j = 1, 2, \ldots, N \tag{6}
\]

For earliness:

\[
e_j = \max(d_j - c_j, 0) \quad j = 1, 2, \ldots, N \tag{7}
\]

For average flow-time of sequential structures:

\[
f_j = c_j - x_{ij} \quad j = 1, 2, \ldots, N \tag{8}
\]

For average flow-time of convergent structures:

\[
f_j = \max(c_j - x_{ij}, c_j - x_{i+1}) \quad j = 1, 2, \ldots, N \tag{9}
\]

4) Non-negativity condition

All parameters and decision variables are non-negative.

3. A PREVIOUS FCMRP SYSTEM

The algorithm of the previous FCMRP system can be shown in Figure 6. There are five step of this FCMRP system. A main difference between this system and the proposed FCMRP system is about the methodology in generating the sequence of operations before applying LP model. This system allocates the operations to proper work centers before applying the dispatching rules, whereas they are performed backward in the proposed FCMRP system (see figure 6).
4. 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 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.

4.1. Independent variable

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

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

1. FCMRP1 ($C_t = 0.90, C_e = 0.05, C_f = 0.05$)
2. FCMRP2 ($C_t = 0.05, C_e = 0.90, C_f = 0.05$)
3. FCMRP3 ($C_t = 0.05, C_e = 0.05, C_f = 0.90$)
4. FCMRP4 ($C_t = C_e = C_f = 0.33$)

Note that this experiment used EDD rule and permutation method.

b) 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:

1. FCMRP systems

There are three FCMRP systems. They all are shown as follows:

- FCMRP (FCMRP in 2006).
- FCMRP-P (FCMRP with permutation).
- FCMRP-NP (FCMRP with non-permutation).


4.2. Dependent variable

The dependent variables are 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.

5. 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 flow shop with sequential and convergent relationships and has 16 items of finished products and all have their product structures.
2) BOM has 5 to 6 levels depending on the products.
3) There are 21 w/c and each operation needs one.
4) Some operations can be produced on more than one work center (alternatively) called the first and second priority work center and they are specified by the planner.
5) All work centers are operated 8 hours a day and overtime and overlapping of batches are not allowed.
6) Lot-sizing technique used is lot-for-lot since it results in low inventory [11].
7) The customer’s demand is assumed to follow a uniform distribution, where the maximum and minimum demands are 10% of the mean demand.

The experiment is conducted in 30 replications of randomly generated demands and they all are sufficient for obtaining accurate mean values of performance measures since the 95% confidence interval of the population mean of each performance measure. A one-way ANOVA is used to statistically analyze the first experiment, while a factorial experiment is used for the second experiment.

6. RESULT AND DISCUSSION

The results and discussion are divided into two sections.

6.1. Analysis on the effects of weights in the proposed FCMRP system.

The average value and the ranking of the performance measures obtained from the Turkey’s multiple mean comparison method are shown in table 2. 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 2, the weights have a significant effect on all performance measures, namely, 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.

6.2. 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 3. The different FCMRP systems have significant effects on all performance measures, whereas the different dispatching rules have no significant effects on only the total tardiness and earliness. The interaction effect between the FCMRP systems and dispatching rules are significant to all performance measures. This means that the planner must carefully consider the interaction effects before selecting a proper combination in order to obtain the desire performance. The average values and ranking of the performance measures are shown in table 4.

Comparing between two proposed FCMRP systems, the FCMRP-P obtains better tardiness, and number of tardy orders than FCMRP-NP, whereas the FCMRP-NP obtains better earliness and number of early orders. There is no significant effect on average flow-time from the proposed FCMRP systems.

Table 4. Average values and ranking of performance measures

<table>
<thead>
<tr>
<th>Factors</th>
<th>FCMRP systems</th>
<th>Total tardiness (days)</th>
<th>No of tardy orders</th>
<th>Total earliness (days)</th>
<th>No of early orders</th>
<th>Average flow-time (days)</th>
<th>Overall performance index</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCMRP-P</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
</tr>
<tr>
<td>MST</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
</tr>
<tr>
<td>EDD</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
</tr>
<tr>
<td>FCMRP-NP*EDD</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
</tr>
<tr>
<td>MST</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
</tr>
<tr>
<td>EDD</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
<td>0.00%*</td>
</tr>
</tbody>
</table>

* The effect is significant at significant level of 0.05

Comparing the proposed FCMRP systems (FCMRP-P and FCMRP-NP) and the previous FCMRP system (FCMRP) presented in table 4, it can be seen that the proposed FCMRP systems outperform the previous FCMRP system except for the number of early orders and total earliness. The total tardiness and the number of tardy orders obtained from the previous FCMRP system are highest compared to those of the proposed FCMRP system. A reason for this is that the previous FCMRP algorithm is appropriate for only the short lead-time orders. When the order requires higher lead-time, the proposed FCMRP algorithm has a higher ability to reduce the tardiness problem on the first priority work center than that of the previous FCMRP system. Since the tardiness obtained from the previous FCMRP system is highest, the earliness obtained from this system is then lowest.

The result shown in figure 4 is used to illustrate this effect. By using the EDD rule, the operations A2, C1, B2, D2, and D1 are scheduled to produce on w/c 2 and the due dates of these operations shown in figure 4 are 23, 35, 26, 32, and 37 respectively. It is obviously seen that these operations are not arranged based on the EDD concept. Therefore, the planners should 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 3 that the FCMRP system and dispatching rule are interacting. The planner can see these effects and also choose the desired the performance measures obtained from each interaction shown in table 4.

An overall performance index can be determined using the weighted average of some performance measures based on the opinion of the planner (see Section 4.1b). 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 4. It indicates that the FCMRP-P system results in the best overall performance index when compared among the other FCMRP systems. It also indicates that the EDD and MST rules result in the same overall performance. Furthermore, when the
combination of the proposed FCMRP method and the dispatching rule is considered at the same time (interaction), the best combination is to combine the FCMRP-P system and the MST 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 not more than 10 minutes, which is acceptable and practical for real industrial applications.

7. CONCLUSION

A new FCMRP system, which is a combination of scheduling heuristics and optimization technique applicable for real industrial problems, is developed. It employs the proposed heuristics to generate the sequence of operations on each work center and applies 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-P system and the MST 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 factors namely, dispatching rules, permutation or non-permutation method, and objective function weights. The effects of these factors 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 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 proposed scheduling heuristic generates the sequence that does not comply with the philosophy of those rules. The proposed FCMRP system still has limitations. The lot-sizing policy under consideration is only lot-for-lot, the effect of different lot-sizing policies has not been studied, and the overlapping of lot size is not allowed. 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 ones. More complicated and effective dispatching rules can be developed. Thus, further research is needed to develop and analyze in order to improve the FCMRP system that addresses these limitations.

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8. REFERENCES