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Priority Scheduling for a Flexible Job Shop with a Reconfigurable Manufacturing Cell

Hyoung-Ho Doh, Jae-Min Yu, Yong-Ju Kwon, Dong-Ho Lee*
Department of Industrial Engineering, Hanyang University, Seoul, Korea

Min-Suk Suh
Graduate School of Technology and Innovation Management, Hanyang University, Seoul, Korea

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ABSTRACT

This paper considers a scheduling problem in a flexible job shop with a reconfigurable manufacturing cell. The flexible job shop has both operation and routing flexibilities, which can be represented in the form of a multiple process plan, i.e. each part can be processed through alternative operations, each of which can be processed on alternative machines. The scheduling problem has three decision variables: (a) selecting operation/machine pairs for each part; (b) sequencing of parts to be fed into the reconfigurable manufacturing cell; and (c) sequencing of the parts assigned to each machine. Due to the reconfigurable manufacturing cell's ability of adjusting the capacity, functionality and flexibility to the desired levels, the priority scheduling approach is proposed in which the three decisions are made at the same time by combining operation/machine selection rules, input sequencing rules and part sequencing rules. To show the performances of various rule combinations, simulation experiments were done on various instances generated randomly using the experiences of the manufacturing experts, and the results are reported for the objectives of minimizing makespan, mean flow time and mean tardiness, respectively.

Keywords: Flexible Job Shop, Reconfigurable Manufacturing Cell, Multiple Process Plan, Priority Rules

* Corresponding Author, E-mail: leman@hanyang.ac.kr

1. INTRODUCTION

During the last decades, manufacturing firms have given considerable attention to the issues associated with developing and implementing advanced manufacturing technologies. Among them, reconfigurable manufacturing is one of the attractive alternatives for conventional systems due to its inherent system reconfigurability. Reconfigurable manufacturing, also called modular or changeable manufacturing, is the one designed at the outset to facilitate rapid changes in its hardware and software components by adjusting its production capacity and functionality in response to sudden market changes or intrinsic system changes. In other words, a reconfigurable manufacturing system can be developed using basic hardware and software components that can be reconfigured quickly and also has flexibility not only for product variety, but also for system changes. Therefore, it has the potential to offer a cheaper solution compared to dedicated or flexible manufacturing systems because it can maximize the system utilization. See Koren *et al*. (1999), Mehrabi *et al*. (2000, 2002) and Bi *et al*. (2008) for more details on the concept of reconfigurable manufacturing.

In this study, we consider a flexible job shop equipped with a reconfigurable manufacturing cell (RMC). According to the recent advancements in reconfigurable manufacturing technology, such flexible job shops are expected to be found in the near future. In particular, if the conventional system is a high-variety with lowvolume job shop type, the implementation of RMC is highly recommended since it is capable of adjusting capacity, functionality and flexibility to the desired levels. See Suresh and Sarkis (1989), Chakravarty and Shtub (1990), Liang and Dutta (1992), Lee and Kim (1996), and Lim and Kim (1998) for the phased implementation models of flexible manufacturing systems, which are similar to the RMC considered in this study.

Among the design and operational problems in the flexible job shop especially equipped with an RMC, this study considers a scheduling problem. In the theoretical aspect, the scheduling problem considered in this study can be regarded as an extension of job shop scheduling that determines the sequence of operations to be processed on each machine. Job shop scheduling has been studied by many researchers due to its theoretical difficulties and many practical applications. Although various solution algorithms have been developed on the classical job shop scheduling problem, there is a recent research trend to deal with more generalized problems by including practical considerations that can be found across the broad range of application areas. One of them is the flexible job shop scheduling problem with alternative operations and/or machines. Unlike the classical version in which each operation of a job can be processsed on a specific machine, the flexible job shop scheduling problem has operation and/or routing flexibilities, i.e. each job can be processed through alternative operations, each of which can be processed on alternative machines. In fact, in the case that an RMC is introduced to a conventional job shop for the purpose of increasing system capacity and flexibility, the resulting system becomes a type of flexible job shop, and hence the scheduling problem becomes a type of the flexible job shop scheduling problem since each operation of a job can be processed on alternative machines either at the RMC or the conventional job shop.

The previous studies on the flexible job shop scheduling problem can be classified according to the types of process plan: single process plan with only alternative machines and multiple process plan with both alternative operations and machines. The graphical method to represent a multiple process plan will be explained in the next section. Most of the previous studies consider the single process plan cases. For examples, see Scrich *et al*. (2004), Xia and Wu (2005), Gao *et al*. (2006, 2008), Loukil *et al*. (2007) and Vilcot and Billaut (2008). As an extension, some previous studies consider the problem with the multiple process plan. See Kim *et al*. (2003), Baykasoglu *et al*. (2004), Ozguven *et al*. (2010) and Doh *et al*. (2013) for more information.

Although the scheduling problem considered in our study is similar to the flexible job shop scheduling problem with multiple process plans, there is a significant difference in that the RMC is a part of the entire system. Therefore, the operational characteristics of RMC must be considered explicitly (The detailed description of the RMC will be given in the next section). First, the number of pallets equipped with fixtures is limited and hence the parts cannot be fed into the RMC if a pallet is not available. Second, input sequencing must be considered since parts are fed into the RMC through the loading/unloading station. Finally, the material flow within the RMC must be considered.

In summary, the scheduling problem considered in this study has three main decisions. They are: (a) selecting operation/machine pairs for processing parts; (b) sequencing of the parts to be fed into the RMC; (c) sequencing of the parts assigned to each machine. To the best of the authors' knowledge, there are no previous studies on this type of flexible job shop scheduling problem. Note that the problem considered in this study is an extension of that of Doh *et al*. (2013) in that the input sequencing and scheduling problems at RMC is additional considered. See Lee and Kim (1999), Kim *et al*. (2001), He and Smith (2007) and Yu *et al*. (2013) for more details on input sequencing in flexible manufacturing systems. In fact, the RMC is a flexible manufacturing system in itself for a given system configuration, and hence input sequencing of RMCs is similar to that of flexible manufacturing systems.

Due to the RMC's ability of adjusting capacity, functionality and flexibility to the desired levels, we propose the practical priority scheduling approach in which the three decisions are done at the same time using a combination of operation/machine selection rules, input sequencing rules and part sequencing rules. In fact, this study was motivated from a research project that develops an RMC and its results must be commercialized. Therefore, the priority scheduling approach is more appropriate than others because it yields reasonable quality solutions within very short computation times. To show the performances of the rule combinations, simulation experiments were performed using the data provided by the manufacturing experts and the results are reported for the objectives of minimizing makespan, mean flow time and mean tardiness, respectively.

This paper is organized as follows. In the next section, the system and problem are described in more details. The three types of priority rules are explained in Section 3, and the simulation results are reported in Section 4. Finally, Section 5 concludes the paper with summary and future research topics.

2. PROBLEM DESCRIPTION

In this section, the flexible job shop considered in our study is explained, with an emphasis on the RMC. Then, after explaining the multiple process plan, the problem considered in our study is described in more details.

As explained earlier, the flexible job shop consists of an RMC and a conventional job shop. Here, the job shop is a conventional legacy system that consists of dedicated and flexible machines, such as numerical control (NC) machines, cleaning machines, quality test machines, etc. The NC machines within the job shop, which have less functions than those of RMC, may need workers to process the jobs and change the tools. Also, the automated RMC can be utilized as an alternative processor to the conventional job shop. Therefore, the hybrid system can be viewed as a parallel system in which the operations required to produce a part are done on either the RMC or the job shop. However, the two systems are different in operations and processing times even for the same part type.

The RMC, which is developed in our project, consists of identical NC machines, a loading/unloading (L/U) station, and a central buffer. Due to its reconfigurability, the RMC can quickly add/remove system components such as machines, L/U stations, etc. Each NC machine has an automatic tool changer and a tool magazine of a limited capacity. A part can be fed into the RMC through the L/U station after it is clamped onto a pallet with a required fixture type. Note that common pallets are used in the RMC, i.e. any fixture types can be mounted on a pallet. Also, a fixture type can be used for a specific set of part types. One or more tools are required to perform an operation on a part type, and each tool requires one or more slots in the tool magazine. The central buffer which is an automatic storage and retrieval system is used to store in-process parts within the RMC. Since the RMC has a limited central buffer, an upper limit is imposed on the number of parts circulating in the system. Figure 1 shows the RMC configuration considered in this study.

After released into the RMC, a part with a required fixture type on a pallet goes into the central buffer and waits for processing. Each part stored in the central buffer is sent to the machines for operations. After the required operations are finished, the part leaves the system through the L/U station and then it is removed from the pallet together with the fixture.

It is assumed that part types and their production quantities during the upcoming planning horizon are given in advance, and each part requires a predetermined set of operations. Also, it is assumed that a loading plan is given that specifies the assignments of operations and their cutting tools on the machines. See Kim *et al*. (2012) for more details on the loading problem. Also, it is assumed that fixture allocation is done in advance, i.e. the given set of common pallets is divided into mutually exclusive subsets, within which the pallets are equipped with a pre-determined fixture type. Finally, we assume that the number of fixtures is enough to clamp parts on pallets.

As stated earlier, this study considers multiple process plans since an operation of a part type can be done by the machines in the flexible job shop. To represent the multiple process plan, we use the network model of Ho and Moodie (1996), which consists of three types of nodes: source, intermediate and sink. The source and the sink are dummy nodes that represent the start and the end of processing a part. An intermediate node represents alternative machines and operations, together with the corresponding processing times. Also, an arc connecting two nodes represents the precedence relation between the two operations. In particular, if a part meets an OR relation, it must select one of the corresponding alternative operation/machine pairs. In summary, a part is completed through a path (set of intermediate nodes) from the source to the sink node. Figure 2, adopted from Doh *et al*. (2013), shows an example of the network model for a multiple process plan with 1 OR relation and 5 intermediate nodes. In this figure, there are two paths, i.e. s-1-3-t and s-2-4-5-t. For example, operation 1 can be processed by machine 1 or machine 2 whose processing times are 40 and 36, respectively.

Now, the problem can be briefly explained as follows. For a given set of parts, each of which is processed according to the corresponding multiple process plan, the problem is to determine the process route (op-

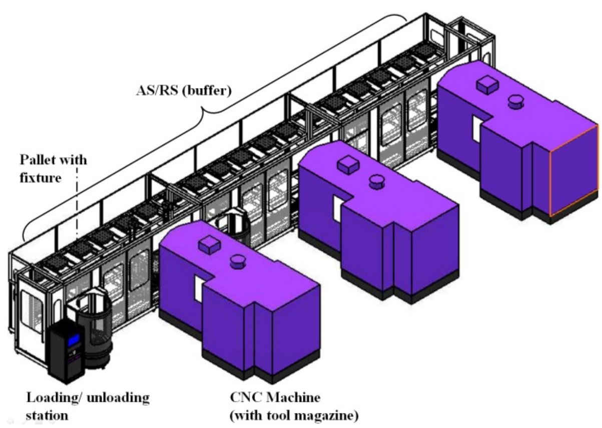

Figure 1. Configuration of RMC.

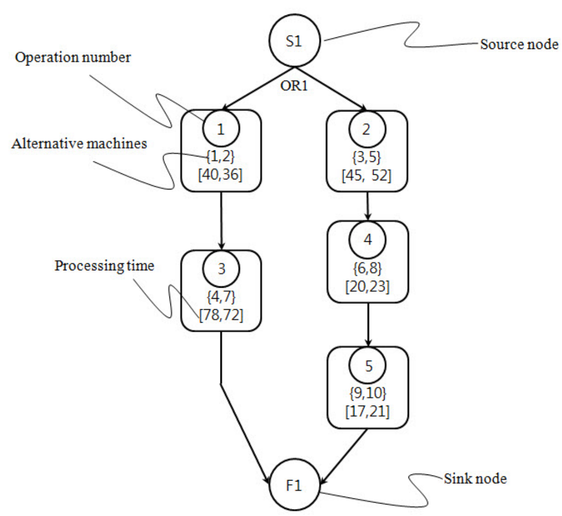

Figure 2. Network representation of a multiple process plan: example.

eration and machine pairs) of each part, the sequence of parts to be fed into the RMC, and the sequence of the parts assigned to each machine. The performance measures are minimizing makespan, mean flow time and mean tardiness, each of which can be represented as follows.

- Makespan: $f(C_i) = \max_{i\in I}\{C_i\}$, where C_i denotes the completion time of job i.
- Mean flow time: $f(C_i) = \Sigma_{i\in I}C_i/n$, where n denotes the number of parts.
- Mean tardiness: $f(C_i) = \Sigma_{i\in I}T_i/n$, where $T_i = \max\{0, C_i - d_i\}$ (tardiness of job i) and d_i denotes the due-date of job i.

As explained earlier, the scheduling problem considered here is different from the ordinary flexible job shop scheduling problem in that the characteristics of RMC are explicitly considered, i.e. releasing of parts through the L/U station, the constraint on number of pallets and fixtures, the constraint on number of parts circulating in the system, and so on.

In this study, we consider a static and deterministic version of the problem. In other words, all jobs are ready for processing at time zero, i.e. zero ready times, and the job descriptors such as process plans, processing times and due dates, are predetermined. Also, other assumptions made for the problem are: (a) each machine can process only one operation at a time; (b) pre-emption is not allowed, i.e. once a part is processed by a machine, it will stay with the machine until the operation is completed; (c) setup times are sequence-independent and hence they can be included in processing times; and (d) transportation times among the machines are negligible and hence can be included in the corresponding processing times if necessary.

3. SOLUTION APPROACH

As mentioned earlier, this study proposes the priority scheduling approach in which the schedule is determined by employing a combination of three types of priority rules. Although the performance of the priority scheduling approach is generally not guaranteed, it is more applicable to practical situations since it is easy for system managers and operators to understand and implement, and it requires very short computation times. Also, the RMC has the ability to adjust the capacity, functionality and flexibility to the desired levels and hence the time required to make a schedule must be short.

Since the scheduling problem considered in this study has three decisions, three types of priority rules are needed, i.e. selecting operation/machine pairs of each part (operation/machine selection rule), sequencing of parts to be fed into the RMC (input sequencing rule) and sequencing of the parts assigned to the machines (part sequencing rule). Here, the operation/machine selection rule is used for selecting an operation/machine pair if two or more alternatives are available. In fact, the operation/machine selection is done by selecting a machine because the machine is associated with the next operation. Also, the input sequencing rule is to select a part to be released into the RMC among those waiting in front of the L/U station. As explained earlier, a part can be fed into the RMC only if there is an available pallet equipped with a required fixture. Finally, the part sequencing rule is used for selecting a part among those waiting in a queue when the machine becomes available.

In this study, we test 32 priority rule combinations, i.e. 1 operation/machine selection rule, 4 input sequencing rules and 8 part sequencing rules. These rules are selected because they are known to be better than others for flexible job shop and RMC scheduling. See Doh *et al*. (2013) for the performances of various combinations of operation/machine selection and part sequencing rules for general flexible job shops with multiple process plans and Yu *et al*. (2013) for the performances of various combinations of input sequencing and scheduling rules for RMCs with a limited number of fixtures.

Before describing priority rules, the notations are summarized below.

t time at which a priority rule is used, i.e. when there is an available pallet to be released into the RMC, the current operation of a part is completed or a machine becomes idle
J_i set of operations of part i
N_t set of parts waiting to be released into the RMC at time t
N_{kt} set of parts waiting in the queue of machine k either in the RMC or job shop at time t
t_{ijk} processing time of operation j of part i on machine k
o_{ij} remaining operations of operation j of part i, i.e. number of successor operations including itself
w_{ij} remaining work of operation j of part i, i.e. sum of processing times of successor operations including itself
d_i due-date of part i

Now, the three types of priority rules are explained below.

- *Operation/machine selection rule*

SP select an operation (and its machine) with the shortest processing time of the imminent operation, i.e. select a machine k^* such that

$$k^* = \arg\min_{k\in K'}\{t_{ij(i)k}\},$$

where K' is the set of machines on which the corresponding operation can be processed and $j(i)$ is the index for the imminent operation of part i.

- *Input sequencing rules*

SPPT select a part with the shortest part processing time, i.e. the sum of processing times of the operations for the part (In case that the current part is in process, the shortest remaining processing time is used). If no OR relation exists in the network of multiple process plan, select a part i^* such that

$$i^* = \arg\min_{i \in N_t} \{\sum_{j \in J_i} t_{ijk}\}.$$

Otherwise, select a part with the smallest average part processing time (over alternative process routes).

LPPT select a part with the longest part processing time (The others are the same as those of the SPPT).

SRF/TF select a part with the smallest ratio of released fixtures (the number of fixtures released into the system from loading/unloading area) over the total number of fixtures required for the part

LRF/TF select a part with the largest ratio of released fixtures over the total number of fixtures required for the part

• *Part sequencing rules*

FIFO select a part that arrived the earliest at the queue of the machine.

SPT select a part with the shortest operation processing time

MWKR select a part with the largest remaining work. If no OR relation exists after the current operation, select a job i^* such that

$$i^* = \arg\max_{i \in N_{kt}} \{w_{ij(i)}\}.$$

Otherwise, select a part with the largest average remaining work.

LWKR select a part with the least remaining work. If no OR relation exists after the current operation, select a part i^* such that

$$i^* = \arg\min_{i \in N_{kt}} \{w_{ij(i)}\}.$$

Otherwise, select a part with the smallest average remaining work.

EDD select a part with the earliest due-date.

MDD select a part with the minimum modified due date, i.e. select a part i^* such that

$$i^* = \arg\min_{i \in N_{kt}} \{\max(d_i, t + w_{ij(i)})\}.$$

CR select a part with the minimum critical ratio value. If no OR relation exists after the current operation, select a job i^* such that

$$i^* = \arg\min_{i \in N_{kt}} \{(d_i - t) / w_{ij(i)}\}.$$

Otherwise, select a part with the minimum average critical ratio value.

COVERT select a part with the maximum COVERT value, i.e. ratio of expected delay penalty to the processing time. If no OR relation exists after the current operation, select a part i^* such that

$$i^* = \arg\max_{i \in N_{kt}} \left[\left\{ 1 - \frac{(d_i - w_{ij(i)} - t)}{a \cdot b \cdot w_{ij(i)}} \right\} / t_{i(j)k} \right]$$

where $x+$ denotes max(0, x). Otherwise, select a part with the maximum average COVERT value.

ATC select a part with the maximum apparent tardiness cost. If no OR relation exists after the current operation, select part i^* such that

$$i^* = \arg\max_{i \in N_{kt}} \left[\frac{\exp\left(-\left\{ d_i - b \cdot (w_{ij(i)} - t_{ij(i)k}) - t_{ij(i)k} - t \right\}^+ / a \cdot \bar{t} \right)}{t_{ij(i)k}} \right]$$

where $\bar{t}$ is the average processing time for the operations of waiting parts.

In COVERT and ATC, a and b are the parameters used to estimate the completion time of a job while considering the waiting time of operations in queues and machine utilization. See Rachamadugu and Morton (1981) for more details.

4. SIMULATION RESULTS

To compare the performances of the rule combinations, simulation experiments were done on the various test instances and the results are reported in this section. The simulation model were coded in C++ and the test were done on a personal computer with an Intel Core 2 Quad 3.00 GHz clock speed.

As stated earlier, the performance measures considered in this study are makespan, mean flow time, and mean tardiness. For the test, we generated the instances randomly using the experiences of the project partners. More specifically, we generated 10 instances for each of four levels of the total number of machines (20, 40, 60 and 80), three levels of the number of machines in the RMC (3, 4 and 5) and two levels of the number of part types (10 and 30) and two levels of fixture types (3 and 5), resulting in 480 instances in total. Also, the multiple process plan for each part type was generated randomly in order to consider various process routings. The detailed data were generated as follows. The number of operations for each part and the number of operations/ machine pairs were generated from DU(10, 20) and DU

(1, 3), where $DU(a, b)$ denotes the discrete uniform distribution with a range $[a, b]$. Also, the processing time of each operation was generated from $DU(20, 100)$. The capacity of the central buffer in the RMC was set to 36 according to the real RMC configuration developed in our research project. Finally, the due-dates were generated from $(\Sigma_j\Sigma_k t_{ijk}/M_{ij})\cdot u$, where M_{ij} is the number of alternative machines for operation j of part i and u is a due-date tightness parameter generated from $DU(13, 16)/10$.

For evaluation of the results, we use the relative performance ratio because we could not obtain the optimal solutions. Here, the relative performance ratio for a test instance is defined as

$$100 \cdot (C_r - C_{best})/C_{best},$$

where C_r is the objective value obtained using rule combinations r for the instance and C_{best} is the best objective function value among those obtained from the 32 rule combinations.

Test results are summarized in Table 1(a)-Table 1(c) that show the average relative performance ratios for makespan, mean flow time and mean tardiness, respectively. As in other studies on the priority rule based scheduling approach, no one rule dominates the others for each of the three performance measures, which implies that the performances of priority rules cannot be generalized for all possible instances. Therefore, their performances are compared statistically for the test instances.

Table 1(a) shows the test results for the makespan measure. As can be seen in the table, ATC and SPT are slightly better than the others for part selection in overall average, which is similar to the test results of Doh *et al*. (2013) for general flexible job shops with multiple process plans. For input sequencing, LPPT and LRF/TF give better performances than the others in overall average, which is different from the test results of Yu *et al*. (2013) that report no significant differences among the input sequencing rules for RMCs. However, it can be seen from the table that the best rule combinations are LPPT-FIFO, LPPT-SPPT and LPPT-MWKR. In fact, we performed the Duncan's multiple range test and the result showed that the three rule combinations outperform the others statistically. Table 1(b) shows the test results for the mean flow time measure. For the flow time measure, EDD and SRF/TF were better than the others for part selection and input sequencing, respectively. This is much different from the results of Doh *et al*. (2013) and Yu *et al*. (2013). However, it can be seen from the table that the best rule combinations were SPPT-EDD, SPPT-MDD, SPPT-CR and SPPT-COVERT according to the Duncan's multiple range test. Finally, Table 1(c) shows the results for the mean tardiness measure. As in the mean flow time case, EDD and SRF/TF are better than the others for part selection and input sequencing, but SPPT-EDD, SPPT-MDD, SPPT-CR and SPPT-COVERT give the best performances. This is because the due-dates were generated in such a way that they are proportional to the total processing times. Note that if the SPT sequence is identical to the EDD sequence, it is optimal for the basic single machine scheduling problem.

5. CONCLUDING REMARKS

This study considered a scheduling problem in a flexible job shop equipped with a conventional job shop and a reconfigurable manufacturing cell. In the flexible job shop, a part can be produced according to a multiple process plan, i.e. each part can be processed through alternative operations, each of which can be processed by alternative machines. The main decisions are: (a) selecting operation/machine pairs for each part; (b) sequencing of parts to be fed into the reconfigurable manufacturing cell; and (c) sequencing of the parts assigned to each machine. Due to the problem complexity and practical considerations, we suggested the priority scheduling approach in which the three decisions are

Table 1. Test results
(a) Makespan

Part selection rules	Input sequencing rules				
	SPPT	LPPT	SRF/TF	LRF/TF	Average
FIFO	7.7*	**4.4**	6.8	9.3	7.0
SPT	7.2	**4.3**	6.8	9.1	**6.9**
MWKR	7.1	**4.3**	10.2	8.7	7.6
LWKR	7.1	9.4	9.7	8.6	8.7
EDD	9.6	8.9	9.5	8.6	9.1
MDD	9.1	8.9	9.5	6.0	8.4
CR	9.1	8.9	9.8	5.5	8.3
COVERT	9.1	7.6	9.4	5.3	7.8
ATC	5.1	7.0	9.3	5.3	**6.7**
Average	7.9	**7.1**	9.0	7.4	

* average relative performance ratio out of 10 instances and all instance levels.

(b) Mean flow time

Part selection rules	Input sequencing rules				
	SPPT	LPPT	SRF/TF	LRF/TF	Average
FIFO	23.4	39.1	23.1	7.8	23.4
SPT	23.1	39.4	23.2	5.4	22.8
MWKR	23.5	39.5	9.8	5.2	19.5
LWKR	23.3	7.1	9.4	5.5	11.3
EDD	**4.7**	6.7	9.9	5.5	**6.7**
MDD	**4.5**	7.2	9.9	24.8	11.6
CR	**4.9**	7.2	7.6	24.5	11.1
COVERT	**4.9**	23.2	7.4	24.8	15.1
ATC	39.4	22.9	7.8	24.9	23.7
Average	16.8	21.4	**12.0**	14.3	

(c) Mean tardiness

Part selection rules	Input sequencing rules				
	SPPT	LPPT	SRF/TF	LRF/TF	Average
FIFO	48.3	75.8	40.3	18.3	45.7
SPT	47.7	76.1	40.4	13.0	44.3
MWKR	48.2	76.3	12.4	12.5	37.3
LWKR	47.2	15.5	11.6	13.0	21.8
EDD	**8.0**	14.8	12.2	12.9	**12.0**
MDD	**7.5**	15.5	12.2	46.6	20.4
CR	**8.1**	15.4	18.4	46.0	22.0
COVERT	**8.0**	40.6	17.8	46.5	28.2
ATC	76.4	40.4	18.4	46.5	45.4
Average	33.3	41.2	**20.4**	28.4	

made simultaneously using a rule combination. Simulation experiments were performed using the data provided by the experts, and the best rule combinations were identified for each of three performance measures: makespan, mean flow time and mean tardiness.

As a beginning study on operations scheduling in a new type of flexible job shop with a reconfigurable manufacturing cell, this research can be extended in several directions. First, it is needed to consider the dynamic version of the problem, i.e. non-zero ready times. For this extension, the real-time scheduling approach may be an appropriate methodology. Second, in the theoretical aspect, the optimal algorithm is worth to be developed. For this purpose, it is needed to derive the optimal solution properties of the new flexible job shop scheduling problem.

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