Scheduling for a Reconfigurable Manufacturing System with Multiple Process Plans and Limited Pallets/Fixtures

Jae-Min Yu, Hyoung-Ho Doh, Ji-Su Kim, Dong-Ho Lee and Sung-Ho Nam

Abstract—A reconfigurable manufacturing system (RMS) is an advanced system designed at the outset for rapid changes in its hardware and software components in order to quickly adjust its production capacity and functionally. Among various operational decisions, this study considers the scheduling problem that determines the input sequence and schedule at the same time for a given set of parts. In particular, we consider the practical constraints that the numbers of pallets/fixtures are limited and hence a part can be released into the system only when the fixture required for the part is available. To solve the integrated input sequencing and scheduling problems, we suggest a priority rule based approach in which the two sub-problems are solved using a combination of priority rules. To show the effectiveness of various rule combinations, a simulation experiment was done on the data for a real RMS, and the test results are reported.

Keywords—Reconfigurable manufacturing system, scheduling, priority rules, multiple process plans, pallets/fixtures

I. INTRODUCTION

CURRENT competitive markets, together with fast social and technological progresses, has made the manufacturing environment be highly uncertain. Under such a situation, it is necessary for manufacturing firms to adopt more advanced manufacturing technologies that are: (a) more responsive with shorter lead-time; (b) more product variety; (c) high quality; and (d) lower price. To cope with these requirements, various manufacturing paradigms have been emerged during the last decades.

Among others, reconfigurable manufacturing is the most recent paradigm to reduce the time to launch a new manufacturing system. A reconfigurable manufacturing system (RMS), alternatively called a modular or changeable manufacturing system, is defined as the one designed at the outset for rapid changes in its hardware and software components in order to quickly adjust its production capacity and functionality in response to sudden market changes or intrinsic system changes [1]. In other words, a new system can be developed using basic hardware and software components that can be reconfigured

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quickly, i.e., short ramp-up time, and it has flexibility not only in product variety, but also in system changes. Here, ramp-up implies that a production system must be fine-tuned before it can constantly produce products at the required quality and production volume. In fact, an RMS, as an intermediate paradigm between dedicated and flexible manufacturing systems, was designed to adjust production capacity, functionality, and flexibility exactly needed. Therefore, the RMS has the potential to offer a cheaper solution compared to dedicated and flexible manufacturing systems because it can increase life and utility of a manufacturing system. See [2]–[4] for more details on RMSs.

Various design and operation problems have been emerged for RMSs. According to Mehrabi *et al.* [2], they can be classified into system-level issues, component-level issues, and ramp-up time reduction issues. Among system level ones, in this study, we focus on the input sequencing and scheduling problems. The input sequencing is the problem of determining the sequence of the parts released into the system. On the other hand, the scheduling is to determine the schedule of the released parts, i.e., where (on which machine) and when (in what sequence) operations of the parts are to be processed. To the best of the authors' knowledge, there are no previous studies on scheduling in RMSs. However, since the RMS is actually a type of flexible manufacturing system (FMS) in itself for a given system configuration, the input sequencing and scheduling problems are similar to those of FMS and hence the literature review is done on the two problems in FMSs.

Most previous studies on input sequencing are done on flexible flow system and adopt the cyclic sequencing approach based on a minimal part set, i.e., set of the smallest integers representing the product-mix of part types [5]–[7]. Unlike these, some articles consider input sequencing in job-shop type FMSs. Escudero [8] develops an algorithm to balance workloads among the machine groups, and Lee and Kim [9] compare several part input sequencing methods in which sequences are determined based on a minimal part set. Also, Kim *et al.* [10] suggest two-stage heuristic algorithms that decompose the entire problem into input part grouping and sequencing problems. See Melnyk and Ragatz [11] for various order release mechanisms. There are a number of previous studies on FMS scheduling, most of which determines the schedule of the jobs released into the system. For example, Lee and Kim [9] suggest priority rule based heuristics and a meta-heuristic for the FMS makespan scheduling problem after decomposing the entire problem into machine selection and job scheduling. Recently, Speedhar Kumar *et al.* [12] suggest other meta-heuristics for the FMS scheduling problem that minimizes makespan. See

Low and Wu [13], Noorul Haq *et al.* [14] and Low *et al.* [15] for other studies on various FMS scheduling problems. Also, in the aspect of scheduling theory, the FMS scheduling problem can be regarded as the flexible job shop scheduling problem with alternative machines. See [16]-[18] for previous studies on the flexible job shop scheduling problems with alternative machines.We consider the input sequencing and scheduling problems at the same time for an RMS. In fact, this study was motivated from a research project that develops an RMS and hence some practical considerations must be incorporated in the two problems. More specifically, in input sequencing, we consider the practical constraint that the numbers of pallets and fixtures are limited and hence a part can be released into the system only when the pallet and fixture required for the part are available. Also, in scheduling for the parts released into the system, we consider alternative operations and machines at the same time due to the inherent flexibility of machines in the RMS. Here, alternative operations and machines are considered in the form of multiple process plans, i.e., each part can be processed on alternative operations, each of which can be processed on alternative machines. Note that the scheduling problem considered in this study is flexible job shop scheduling with multiple process plans. See [19]-[25] for previous studies on the problem.Due to the complexity of the problem considered in this study, we suggest a priority scheduling approach in which input sequencing and scheduling are done simultaneously by employing a combination of three types of priority rules, i.e., part input sequencing, operation/machine selection and job sequencing rules. Recall that the scheduling sub-problem is flexible job shop scheduling with multiple process plans and hence has two main decisions: (a) process route of each part, i.e., operation/machine selections; and (b) sequence of the parts assigned to machines, i.e., job sequencing. To show the effectiveness of various rule combinations, a simulation experiment was done on the data for a real RMS, and the test results are reported. Because we adopt the practical priority scheduling approach, multiple objectives can be considered in this study. They are minimizing makespan (for maximizing system throughput), minimizing mean flow time (for minimizing work-in-process), and minimizing mean tardiness (for meeting due-dates), respectively.

Although the priority rule based scheduling approach has a disadvantage that its performance is far from optimal, it is much more applicable to various practical situations because it is easy to implement, simple to be understood by system managers and operators, and also very short computation times. Recall that this study was motivated from a practical research project and hence the priority scheduling approach is more appropriate than others such as branch and bound, meta-heuristics, etc.

This paper is organized as follows. In the next section, the RMS and the problem are described in more detail with the required assumptions. The priority rules are explained in third section, and simulation results for the data on a real RMS are reported in the fourth section. The final section concludes the paper with a summary and discussion of future research.

II. SYSTEM AND PROBLEM DESCRIPTION

The RMS considered in this study is shown in Fig. 1. As can be seen in the figure, the RMS consists of several identical computer numerical control machines, each of them has an automatic tool changer and a tool magazine of a limited capacity. Due to the reconfigurability, the RMS has the capability that system components, such as machines, loading/unloading stations, etc., can be added or removed quickly.
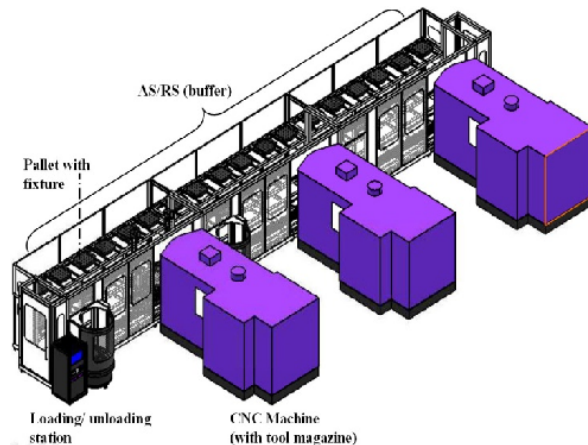

Fig. 1 Schematic description of the RMS

Each part can be released into the RMS through the loading/unloading station after it is mounted on a pallet and then fixed using a required fixture type. As stated earlier, the numbers of pallets and fixtures are limited and hence a part can be released into the system only when the pallet and fixture required for the part are available. After released into the system, the part goes into the central buffer, i.e., the automatic retrieval/storage system (AS/RS). It is assumed that the buffer capacity is limited. Each part stored in the central buffer is sent to the machines for processing its operations. To perform an operation on each machine, one or more tools are required, each of which requires one or more slots in the tool magazine. After the required operations of a part are performed, the part fixed with a fixture on a pallet exits the system through the loading/unloading station. Then, the part is removed from the pallet, together with the fixture.

Each part is associated with a multiple process plan that specifies alternative operations, their sequence, and alternative machines on which each operation is to be processed. To represent a multiple process plan, we use the network model of Ho and Moodie [26] that consists of three node types: source, intermediate and sink nodes. The source and the sink nodes are dummy ones that represent starting and ending of processing a part. The intermediate nodes represent alternative operations, together with alternative machines that can perform each of the operations, and their processing times. The processing time of an operation is the same over the machines since the machines are identical. Also, an arc connecting two nodes represents the precedence relation between the corresponding two operations. In particular, the OR relations represent alternative opera-

tion/machine pairs. More specifically, 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. Fig. 2 shows an example of the network model for a multiple process plan with 1 OR relation and 5 intermediate nodes, adopted from Doh *et al*. [25].
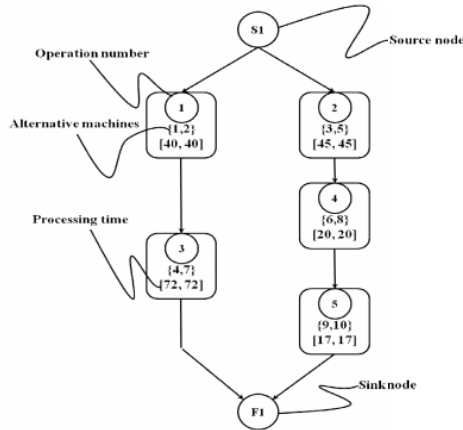

Fig. 2 Representing a multiple process plan

The input sequencing and scheduling problems considered in this study has three main decisions: (a) part input sequence; (b) process route of each part, i.e., operation/machine selections; and (c) sequence of the parts assigned to machines, i.e., part sequencing. Here, an operation/machine selection in the multiple process plan network model is done by selecting a machine because the machine is associated with the next operation.It is assumed that part types and their production quantities to be produced during the planning horizon are given in advance, and each part type requires a predetermined set of operations. Also, it is assumed that a loading plan is given that specifies assignments of operations and their cutting tools to the machines. See Kim *et al*. [27] for more details on the loading problem in FMSs. As stated earlier, the objectives considered are makespan, mean flow time, and mean tardiness, respectively.This study considers 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 processing times, due dates, etc., are deterministic and given in advance. 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 job is processed on a machine, it will stay on that machine until its completion; (c) setup times are sequence-independent and hence can be included in processing times; and (d) transportation times among machines are ignorable or can be included in processing times if necessary.

III. PRIORITY RULES

As mentioned earlier, we suggest the priority scheduling approach in which the RMC scheduling problem (part input sequencing and scheduling) is solved using a combination of priority rules. Recall that the problem considered in this study can be decomposed into three sub-problems: (a) part input

sequencing; (b) operation/machine selection; and (c) job sequencing. Here, input sequencing is the problem of determining a sequence to release parts into the system, operation/machine selection is the problem of determining operations as well as a machine for each operation among those associated with the operation, and job sequencing is the problem of determining the sequence of the parts assigned to each machine.

Since the problem consists of three sub-problems, three types of priority rules are needed, i.e., one for part input sequencing, another for operation/machine selection and the last for job sequencing. The part input sequencing rule is used to select a part to be released into the system. Note that a part can be released into the system when there is available pallet and fixture. Also, an operation/machine selection rule is used to select an operation/machine pair if two or more alternatives are available. In fact, operation/machine selection is done by selecting a machine because the machine is associated with the next operation. Finally, a job sequencing rule is used to select a job among those waiting in a queue for a machine when the machine becomes available.

In this study, we test 48 priority rule combinations, 6 part input sequencing rules, 1 operation/machine selection rules and 8 job sequencing rules. These rules were selected because they are known to be better than others in job shop and flexible job shop scheduling [25].

Before describing priority rules, the notations are summarized below.

t	time at which a priority rule is applied
N_{kt}	set of parts waiting in queue of machine k 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., the number of successor operations including itself
w_{ij}	remaining work of operation j of part i, i.e., the sum of processing times of successor operations including itself
d_i	due-date of part i

Input sequencing rules

SPPT	select a part with the shortest part processing time
LPPT	select a part with the longest part processing time
SRF/TF	select a part with the smallest ratio of released fixtures over the total number of fixtures
LRF/TF	select a part with the largest ratio of released fixtures over the total number of fixtures
EDD	select a part with the earliest due date
CR	select a part with the minimum CR value. If no OR relation exists in the first operation, select a part i^* that satisfies the following condition.

$$i^* = \arg\min_{i \in N_{kt}} \{d_i - t - w_{i1}\}$$

Otherwise, select a part with the minimum average CR value.

Operation/machine selection rule

SP	select a machine (and its operation) with the shortest processing time of the imminent operation, i.e., select a machine $k*$ that satisfies the following condition $$k* = \arg\min_{k \in K'}\{t_{ij(i)k}\},$$ where K' is the set of machines that the corresponding operation can be processed

Job sequencing rules

FIFO	select a part that arrived the earliest at the queue of the machine
SPPT	select a part with the shortest part processing time, i.e., the sum of processing times of the operations for the part. If no OR relation exists after the current operation in the network representation of multiple process plans, select a part $i*$ that satisfies the following condition $$i* = \arg\min_{i \in N_{kt}}\{\sum_{j \in J_i} t_{ijk}\}$$ where J_i is the set of operations of part i. Otherwise, select a part with the smallest average part processing time (over alternative process routes).
LWKR	select a part with the least work remaining. If no OR relation exists after the current operation, select a part $i*$ that satisfies the following condition. $$i* = \arg\min_{i \in N_{kt}}\{w_{ij(i)}\}$$ Otherwise, select a part with the smallest average remaining work.
EDD	select a part with the earliest due date.
CR	select a part with the minimum CR value. If no OR relation exists after the current operation, select a part $i*$ that satisfies the following condition. $$i* = \arg\min_{i \in N_{kt}}\{(d_i - t)/w_{ij(i)}\}$$ Otherwise, select a part with the minimum average CR value.
MDD	select a part with the minimum modified due date. If no OR relation exists after the current operation, select a part $i*$ that satisfies the following condition. $$i* = \arg\min_{i \in N_{kt}}\{\max(d_i, t + w_{ij(i)})\}$$
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 $i*$ that satisfies the following condition $$i* = \arg\max_{i \in N_{kt}}\left[\left\{1 - \frac{(d_i - w_{ij(i)} - t)}{a \cdot b \cdot w_{ij(i)}}\right\}/t_{i(j)k}\right]^+$$ where x^+ denotes $\max(0,x)$. Otherwise, select a job 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 $i*$ that satisfies the following condition $$i* = \arg\max_{i \in N_{kt}}\left[\frac{\exp\left(-\{d_i - b\cdot(w_{ij(i)} - t_{ij(i)k}) - t_{ij(i)k} - t\}^+/a\cdot\bar{t}\right)}{t_{ij(i)k}}\right]$$ where $\bar{t}$ is the average processing time for the operations of waiting jobs.

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.

IV. SIMULATION RESULTS

To compare the performances of the rule combinations, a simulation experiment was done on the various RMS configurations and the results are reported in this section. Since the RMS is being developed, we could not obtain the real data on part types. Instead, we generated various data based on the experiences of the project partners. More specifically, we generated 10 instances for each of 12 combinations of four levels of the number of machines (3, 4, 5 and 6) and three levels of the number of part types (30, 50 and 100). Also, multiple process plans for each part type was generated randomly in order to consider various process routing configurations. The detailed data were generated as follows. The number of operations for each part and the number of alternative operation/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 $DU(20, 100)$. Finally, the capacity of the central buffer is 36 and the number of pallets (with fixtures) was set to the number of part types. Here, 10% of the parts share fixtures and pallets. 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

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

where C_a is the objective value obtained using rule combination a for the instance and C_{best} is the best objective function value among those obtained from the 48 rule combinations.

Test results on the rule combinations are summarized in Tables I(a), (b), and (c) that show the average relative performance ratios. As can be seen in the table, no one rule dominates the others for the performance measures considered. For the makespan measure (given in Table I(a)), the LPPT rule for input sequencing and the ATC rule for job sequencing were slightly better than the others. Among the 48 rule combinations, SRF/TF-ATC, LRF/TF-ATC, SPPT-ATC, LPPT- FIFO, LPPT-ATC, EDD-ATC, CR-ATC were slightly better than the others. For the mean flow time measure (given in Table I(b)), the SPPT rule for input sequencing and the COVERT rule for job sequencing were slightly better than the others. Also, the better rule combinations were SPPT- COVERT, SPPT-MDD and SPPT-LWKR. Finally, for the mean tardiness measure

(given in Table I(c)), the best rule combination was SPPT-COVERT.

TABLE I
(A) TEST RESULTS: MAKESPAN

Job sequencing rules	Input sequencing rules						Average
	SRF/TF	LRF/TF	SPPT	LPPT	EDD	CR	
FIFO	0.05[*]	0.05	0.06	0.03	0.04	0.05	0.05[**]
SPPT	0.08	0.08	0.09	0.06	0.08	0.09	0.08
LWKR	0.10	0.10	0.11	0.09	0.11	0.11	0.10
EDD	0.06	0.06	0.07	0.05	0.06	0.07	0.06
CR	0.08	0.08	0.09	0.07	0.08	0.08	0.08
MDD	0.10	0.10	0.11	0.09	0.11	0.11	0.11
COVERT	0.07	0.07	0.07	0.06	0.07	0.07	0.07
ATC	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Average	0.07[***]	0.07	0.08	0.06	0.07	0.08	

[*] average relative performance ratio out of all instances
[**] average relative performance ratio of a job sequencing rule
[***] average relative performance ratio of a input sequencing rule

(B) TEST RESULTS: MEAN FLOW TIME

Job sequencing rules	Input sequencing rules						Average
	SRF/TF	LRF/TF	SPPT	LPPT	EDD	CR	
FIFO	0.25	0.25	0.13	0.42	0.26	0.20	0.25
SPPT	0.13	0.13	0.06	0.30	0.13	0.10	0.14
LWKR	0.08	0.09	0.02	0.20	0.09	0.06	0.09
EDD	0.22	0.22	0.14	0.32	0.21	0.18	0.22
CR	0.14	0.14	0.06	0.25	0.13	0.10	0.14
MDD	0.08	0.09	0.02	0.20	0.09	0.06	0.09
COVERT	0.08	0.08	0.01	0.19	0.08	0.05	0.08
ATC	0.18	0.18	0.10	0.29	0.18	0.15	0.18
Average	0.15	0.15	0.07	0.27	0.14	0.11	

See the footnotes of Table I(a).

(C) TEST RESULTS: MEAN TARDINESS

Job sequencing rules	Input sequencing rules						Average
	SRF/TF	LRF/TF	SPPT	LPPT	EDD	CR	
FIFO	0.28	0.28	0.15	0.46	0.28	0.23	0.28
SPPT	0.15	0.15	0.07	0.33	0.15	0.11	0.16
LWKR	0.09	0.10	0.02	0.22	0.09	0.07	0.10
EDD	0.25	0.25	0.15	0.36	0.23	0.21	0.24
CR	0.15	0.15	0.07	0.27	0.14	0.11	0.15
MDD	0.09	0.10	0.02	0.22	0.09	0.07	0.10
COVERT	0.08	0.09	0.01	0.21	0.08	0.06	0.09
ATC	0.20	0.20	0.12	0.33	0.20	0.17	0.20
Average	0.16	0.16	0.08	0.30	0.16	0.13	

See the footnotes of Table I(a).

Figure 3 shows the performances of the rule combinations in a graphical form.

Rule combination; a-b

a: operation/machine selection rule (A: SRF/TF, B: LRF/TF, C: SPPT, D: LPPT, E: EDD, F: CR)

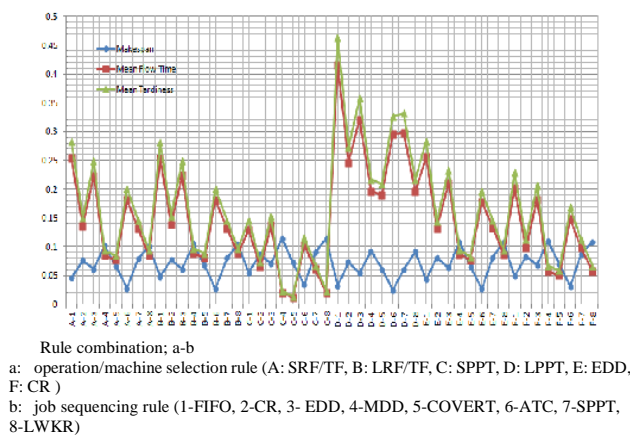b: job sequencing rule (1-FIFO, 2-CR, 3- EDD, 4-MDD, 5-COVERT, 6-ATC, 7-SPPT, 8-LWKR)

Fig. 3 Performances of rule combinations

V. CONCLUDING REMARKS

This study considered the scheduling problem in a reconfigurable manufacturing system, i.e., an advanced system designed at the outset for rapid changes in its hardware and software components. Each part is processed through a multiple process plan in which each part can be processed by alternative operations, each of which can be processed on alternative machines. The decision variables are: (a) input sequencing; (b) selecting operation/machine pairs (process routing); and (c) sequencing the jobs assigned to each machine (job sequencing). Since the problem is very complicated, we suggested a practical approach in which the three decisions are done using a rule combination for input sequencing, operation/machine selection, and job sequencing. We tested 48 rule combinations, i.e., 6 rules for input sequencing, 1 rule for operation/machine selection and 8 rules for job sequencing. The performances of the 48 rule combinations were compared with a simulation experiments on the data generated on a real RMC and the better rule combinations were reported for each performance measure.

This research can be extended in several directions. First, dynamic and stochastic versions of the problem, e.g., non-zero and stochastic ready times, stochastic processing times, machine breakdowns, etc., must be considered. For the extensions, the real-time scheduling approach may be an appropriate alternative. Second, it is needed to consider a hybrid system with reconfigurable manufacturing systems and legacy systems, e.g., set of numerical control machines together with human labor.

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