Evaluation of Tool Allocation Strategies in Flexible Manufacturing System*

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The unprecedented challenges such as massive customizations and unstable demands require the manufacturing systems to be more flexible in responding marketplace changes and the system disturbances. In flexible manufacturing system, tool allocation strategy which involves tool planning in the system and scheduling of parts and tools can strongly affect the system efficiency. Considering the basic flows in FMS, a part-centric tool allocation strategy and a tool-centric tool allocation strategy are proposed. Generally, the part-centric allocation strategy involves few tool movements and the tool-centric allocation strategy involves few part movements. In this paper, the solution methods for the tool planning problem and the scheduling problem are proposed for both tool allocation strategies. Considering tool amount constraint, their performances are evaluated by simulations to compare their characteristics under different production conditions.

Key Words: Flexible Manufacturing System, Machine Loading, Tool Allocation, Scheduling and Auction

1. Introduction

Increasing global competition has made producers consider improving or changing their manufacturing operations to cope with diversified and quickly changing demands of customers. Flexible Manufacturing System (FMS) provides the potential operational benefits to respond marketplace changes quickly with the versatile machining centers. Management of tools and parts in FMS is very important for the successful implementation of FMS.

To ensure the efficient performance of FMS, the appropriate tool allocation strategy including a tool planning method and a scheduling method are critically important. The tool planning problem is the issue to provide the proper quantities of tools for the necessary tool types. The scheduling problem is the issue to process the parts in a right time and on a right machine with the provided tools.

In literal, there are two strategies, part-centric strategy and tool-centric strategy, to solve the above-mentioned problems.

The basic idea of part-centric strategy is that the initial loading plan, which is to decide the proper tool-operation allocation, is decided supposing the plan is kept fixed throughout the production process. This approach is employed by Stecke(1), and Shanker and Rajamarthandan(2). In their studies, the tools for the operations on a machining center can be allocated as many as the capacity that the tool magazine allows. Their loading objectives are to balance the workload among machining centers and to minimize the part movements among machining centers. Auction method to solve this problem is proposed by Fujii, et al.(3) Based on the auction method, we proposed a method to decrease part movements(4).

Comparing with part-centric strategy, the basic idea...
of tool-centric strategy is that there is no initial loading plan and the tools can be transferred among machining centers and a tool storage area. It is called Single Stage Multi-machine Systems (SSMS) in some studies (5) – (7). A distinct characteristic of SSMS involves no part routing between machines. This approach becomes available with the development of technical evolutions such as the automated tool delivery system and efficient shop floor systems. Li, Koo, Jun and Chen suggest their control methods of SSMS (5) – (9).

There are few studies on SSMS providing the solution method for the tool planning problem. Although Jun (8) proposed the method to solve the tool planning problem on a deterministic model, it is not proper for the dynamic job release situation.

Most studies on above-mentioned scheduling problems assume that there are no buffer constraints. However, buffer constraint is an import parameter and affects the system performance (10). Therefore, the buffer constraint is considered in this study.

The primary purpose of this paper is to compare the above-mentioned tool allocation strategies. The buffer constraint is also considered. A scheduling method for part-centric strategy and a method to solve the tool planning problem for tool-centric strategy are proposed in this paper. In section 2, the target FMS is introduced and tool allocation problem is explained. The detail of the two kinds of tool allocation strategies and the related solution methods are explained in sections 3 and 4. The characteristics of the strategies are shown in section 5 by simulation experiments and the conclusion is given in section 6.

2. FMS Model

In this paper, we consider a FMS that consists of several identical machines, each of which has a tool magazine of limited capacity and a local loading/unloading buffer of limited capacity (Fig. 1). Each machining center has a limited tool stock to save exchanged tools from other machining centers. A material handling system is used to transfer tools and parts. The parts stay at a Loading/Unloading (L/U) station until it can be transferred to a machining center. A tool center is used to stock the tools which are unnecessary to the machining center.

Fig. 1 FMS model

As far as necessary tools and programs are supplied to the machining center, it can perform a variety of operations without moving the parts until the cleaning or posture change of the part becomes unavoidable. We define that a job in this study is a set of ordered operations which can be continuously processed on one machining center when necessary tools and programs are available. An operation is processed by only one tool. Before the start of system, jobs to be processed are decided. Therefore, the tool used for each operation and the processing time of each operation are known in the planning stage. However, job release time is unknown in advance.

When a job is released, the center computer instructs to transfer the job to a machining center according to the tool allocation strategy employed. If the job can not be allocated due to the tool unavailability or the buffer constraint, the job stays at L/U station. After all operations of the job are completed, the job is transferred back to the L/U station. The objective of this study is to find a proper tool allocation method and scheduling method to improve the system throughput. The system throughput is evaluated by the makespan, which is the completion time of the last job in the system.

There are two problems which must be solved. One is how many tools for each tool type should be prepared under a constraint of total number of tools. Another is to find a proper scheduling method. In this paper, two allocation strategies for tools, part-centric strategy and tool-centric strategy, are considered.

When the part-centric strategy is employed, the well balanced loading plan can not keep its efficiency because of the loading unbalance caused by the random job arrival. Therefore, adjustment of tool-operation allocation is necessary when jobs concentrate on some machining centers while the other machining centers have few jobs. In this paper, an adjustment method is proposed to cope with such kind of problem.

When the tool-centric strategy is employed, the job can be allocated to any machining center because tools are shared by all machining centers. If a job is allocated to a machining center, it is processed after all tools for the job are installed in the tool magazine. The job will stay on the machining center until all the processing is completed. In actual manufacturing procedure, the prepared tools are limited. If the jobs are allocated to machining centers and the tool availability is not considered, the jobs without necessary tools can not be processed until the tools are transferred from other machining centers or the central tool storage area. If each machining center keeps some tools and there is no machining center can get enough tools to process the transferred parts, then deadlock occurs because machining center will not lend their tools to other machining center when the tools are necessary to the jobs waiting for process. And if each ma-
chining center keeps some tools, the tool magazine must be large enough to accommodate the tools from other machining center. Considering the tool exchange among machining centers can complex tool flow in the system, we propose a tool allocation strategy with tool center to simplify the tool flow. The basic idea is as follows:

- If a job can be allocated to a machining center, the machining center must own or be able to get the tools necessary from the tool center.
- If there are tools unnecessary to the jobs on the machining centers, the tools must be returned to the tool center.
- There is no tool exchange among machining centers.

3. Part-Centric Strategy

When the part-centric strategy is employed, all the tools are prepared in tool magazine of each machining center. Because of the limited magazine capacity on each machining center, proper tool-operation allocation planning is necessary to minimize job movements and to balance machine load. However, it is difficult to keep the load balance once FMS starts its operation because the jobs are released at random. The adjustment method integrated with real time scheduling is applied for better system performance. In this section the machine loading problem is introduced firstly. After that the scheduling method is explained.

3.1 Machine loading problem

The tool and operation allocation plan is decided based on an auction method. The auctioneer, the center computer in this study, is regarded as a coordinator. Machining centers are the bidders. Bid item is a job. The outline is as follows:

Step1. Center computer broadcasts jobs to machining centers.
Step2. Each machining center answers its load.
Step3. Center computer selects a machine with minimum load. In case of ties, a machining center is selected at random.
Step4. The machining center calculates its gain from the allocation of each job. The gain is defined as the range of continuous operations. The job with the longest range is preferable. The unassigned operations in the range and necessary tools are assigned to the machining center.
Step5. If there are unassigned operations, go to Step2. Otherwise stop.

In order to decrease the average movement of jobs, a repeated auction procedure is carried out. From the result of auction procedure, the tools with high frequency of tool usage are increased and the tools seldom used in each machining center are decreased. The solution with the fewest job movements is selected for the allocation problem.

If the capacity of a tool magazine is able to accommodate sufficient tools, a job can be allocated to a machining center to complete all operations. However, with a limited tool magazine capacity, some jobs must move among machining centers for their completion. It means a job is divided into several tasks (a set of operations which are processed continuously on the same machining center) with precedence constraints (Fig. 2).

3.2 Scheduling method of part-centric strategy

The allocation plan without consideration of job release situation is not efficient in case of dynamical job releases. The load, which is the remaining processing time of task in process and the processing time of tasks in buffer, must change with dynamical job releases. Therefore, the load unbalance among machining centers is easy to occur. A reallocation method of operations and tools is applied to overcome the inefficiency of original allocation plan by controlling the load of each machining center between LLB (Lower Load Bound) and ULB (Upper Load Bound). The unit of LLB and ULB is time. The reallocation method is outlined by following decision making points:

PT1: job release

If there are plural jobs, the following auction is carried out:

Step1. Center computer informs the jobs to machining centers and invites them to bid.
Step2. Machining centers answer their bidding prices.
Step3. Center computer selects a machining center which answers the preferable bidding price. The nearest free machining center is preferable to be selected and the machining center with lowest load is selected if there is no free machining center.
Step4. The selected machining center checks jobs by the order of a dispatching rule until there is an available job found according to the following job allocation method (a job can be allocated only when the allocated continuous operations have available tools):

The machining center chooses different policy to decide the available continuous operations according to its load.

Case1. If the load is under LLB and there is free space to accommodate borrowed tools in the tool stock, the machining center borrows tools from other machining centers to check the available operations by its own tools in tool

Fig. 2 An example of job allocation
magnetically and the tools which can be borrowed from other machining centers. The following tool exchange policy is employed:

- machining centers with load under LLB refuse to lend tools to other machining centers;
- machining centers with load between LLB and ULB refuse to lend tools for the processing of tasks in their buffers and scheduled tasks according to the original loading plan;
- machining centers with load over ULB refuse to lend tools for the task in process;
- machining centers can lend their own tools only.

Case2. If the load is between LLB and ULB, the machining center checks the available operations with its own tools in the tool magazine.

Case3. If the load is over ULB, there is no job to be allocated to the machining center.

If an available job is found, transfer the job to the selected machining center. If tool exchanges are necessary, transfer the tools. If all jobs can not be allocated, the selected machining center is deleted from candidate machining centers.

Step5. Delete the job from allocation candidate jobs. If there is no candidate job and no candidate machining center, Stop. Otherwise go to Step1.

If there is only one released job, the job will be allocated to the machining center according to the original loading plan. If the necessary tools are not in the machining center, its load is over ULB, or there is no free space in L/U job buffer, the job waits for another allocation chance to be allocated.

PT2: job arrival to machining center

If there is no job in processing, the job is loaded into the machining center immediately. Otherwise, the job waits in the L/U job buffer. If all necessary tools to the job are in the tool magazine, the job processing is started after the setup of job. Otherwise, the job processing is started after the tools are installed in the tool magazine.

PT3: job completion on machining center

If all operations of the job are completed, transfer the job to the L/U station. Otherwise, center computer sends the job information to the machining center which processes the next operation according to the original loading plan. If the job can be allocated to the machining center (same as Step4 in PT1), transfer the job. Otherwise, transfer the job back to the L/U station. If there were tools borrowed from other machining centers for processing the completed job, return the tools. Because a free space is generated, the center computer sends information of jobs in L/U station to the machining center. If a job can be allocated to the machining center (same as Step4 in PT1), transfer the job.

PT4: return of lent tools to machining center

The machining center checks the jobs in L/U station. If a job can be allocated to the machining center (same as Step4 in PT1), transfer the job.

PT5: arrival of borrowed tools at machining center

Tools are exchanged into the tool magazine. If a job is on the machining center, start to process the job after tool setup.

4. Tool-Centric Strategy

When the tool-centric strategy is employed, all tools are prepared in the tool center. The solution method for tool-preparation in tool center is based on the simulation results. Therefore, the decision-making procedure for tool and job allocation is introduced firstly.

4.1 Scheduling method of tool-centric strategy

Because the tools prepared in the tool center are limited, it is difficult to keep all tool types in the tool center with the dynamical tool allocation. A job can be allocated to a machining center only when all necessary tools are in the local tool magazine or can be borrowed from tool center. When all tools of a necessary tool type are allocated to the other machining centers, a tool conflict for the tool type occurs because the machining center requiring this tool type can not get the necessary tool from the other machining centers until it is returned to the tool center. The job with tool conflict can not be allocated because the whole processing of all operations must be done on the same machining center. Considering dynamical system condition changes, the decision making is carried out by following decision making points:

TT1: job release

If there is only one job, the following auction is carried out:

Step1. Center computer broadcasts the job to machining centers.

Step2. Each machining center answers its bid (the completion time of the job). Machining centers can process the job with the tools in their local tool magazine and borrowing tools from tool center if the necessary tools are not in. The machining centers without free space in their L/U buffer answer a sufficient large number.

Step3. Center computer selects a machining center answering the earliest completion time. In case of ties, a machining center is selected from the tied machining centers randomly.

Step4. If a job can be allocated to a machining center, transfer the job. If there are borrowed tools, prepare and transfer the tools.

When several jobs are released at the same time, their allocations are decided by following auction procedure:

Step1. Center computer broadcasts jobs to machining centers.

Step2. Each machining center answers its bid.
Step 3. Center computer selects a machining center by its bid (operation state, distance from L/U station, load). If several machining centers tie after the last bid item, select a machining center from the tied machining centers randomly.

Step 4. The selected machining center chooses an available job by the order according to a dispatching rule.

Step 5. If there is a job which can be allocated, start to transfer the job and necessary tools. Otherwise the machining center is deleted from the auction candidates.

Step 6. If there is no auction candidate, stop. Otherwise go to Step 1 with the remained candidates.

TT 2: job arrival to machining center
The similar procedure of PT 2 is carried out.

TT 3: job completion on machining center
The similar procedures (Step 4 and Step 5 in TT 1 for plural job releases) are carried out.

TT 4: return of lent tools to tool center
The similar procedures (Step 4 and Step 5 in TT 1 for plural job releases) are carried out.

TT 5: arrival of borrowed tools at machining center
The similar procedure of PT 5 is carried out.

4.2 Tool require problem
When the total amount of tools is constrained, an important problem is to decide the proper duplications of each tool type. If the newly released job can not be allocated although there is a free machining center, the tool conflicts which occur in the job are recorded. Besides the consideration of tool frequency, we also consider decreasing tool conflicts by the adjustment of tool duplications among tool types. The following Pair Swap to Decrease Tool Conflicts (PSDC) algorithm is used to decide the duplications for each tool type (suppose the total amount of tools is \( \sum (T) \)).

Step 1. Prepare one tool for each tool type.
Step 2. Sort tool types by the frequency of tool usage (tool frequency).
Step 3. Duplicate one tool from the tool types with the highest tool frequency until the amount of tools becomes \( \sum (T) \).
Step 4. If the amount of tools is \( \sum (T) \), the initial solution is decided. Otherwise go to Step 3.
Step 5. Run simulations for \( N \) times. Calculate the tool conflicts for each tool type and the total tool conflicts.
Step 6. Duplicate the tool type with the largest tool conflicts and delete the number of tools for the tool type with the least tool conflicts if it is not 1 (pair swap).
Step 7. If the paired tool types have been swapped for \( M \) times, the tool set with the least total tool conflicts is the solution of the problem and stop. Otherwise go to Step 5.

5. Simulation Experiments

The following simulations are carried out to investigate the above-mentioned tool allocation strategies and to verify their solution methods.

5.1 Simulation data

Table 1 shows the common simulation input data used for above-mentioned tool allocation strategies. Comparing with most studies on tool allocation strategies, our models are large in size enough to deal with practical

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td># of machining centers (MC)</td>
<td>4</td>
</tr>
<tr>
<td># of part types</td>
<td>100</td>
</tr>
<tr>
<td># of order for each part type (o)</td>
<td>Uniform (1, 9)</td>
</tr>
<tr>
<td># of operations for each part type</td>
<td>(10, 15, 20, 25, 30) × 5</td>
</tr>
<tr>
<td># of jobs</td>
<td>500</td>
</tr>
<tr>
<td># of tool types</td>
<td>120</td>
</tr>
<tr>
<td># of tool usage frequency in part types</td>
<td>Uniform (1, 8)</td>
</tr>
<tr>
<td>Low level frequency tool types</td>
<td>Uniform (9, 23)</td>
</tr>
<tr>
<td>Middle level frequency tool types</td>
<td>Uniform (23, 50)</td>
</tr>
<tr>
<td>Processing of each operation (p)</td>
<td>Uniform (1, 50)</td>
</tr>
<tr>
<td>(the summation is ( L ))</td>
<td></td>
</tr>
<tr>
<td>Inter-arrival time</td>
<td>( 4.2 )</td>
</tr>
<tr>
<td># of jobs released initially (select at random)</td>
<td></td>
</tr>
<tr>
<td>Lot production</td>
<td>Exponential ((L/(4×100)))</td>
</tr>
<tr>
<td>Random production</td>
<td>Exponential ((L/(4×500)))</td>
</tr>
<tr>
<td>Due date</td>
<td></td>
</tr>
<tr>
<td>Lot production</td>
<td>Arrival time + p × uniform (3, 7)</td>
</tr>
<tr>
<td>Random production</td>
<td>Arrival time + p × uniform (3, 7)</td>
</tr>
<tr>
<td>Job loading/unloading time</td>
<td>30</td>
</tr>
<tr>
<td>Tool exchange time</td>
<td>5</td>
</tr>
<tr>
<td>Transfer time for job</td>
<td></td>
</tr>
<tr>
<td>between machining centers</td>
<td>60</td>
</tr>
<tr>
<td>from L/U station to nearest MC</td>
<td>60</td>
</tr>
<tr>
<td>Transfer time for tool</td>
<td></td>
</tr>
<tr>
<td>between machining centers</td>
<td>60</td>
</tr>
<tr>
<td>from tool center to nearest MC</td>
<td>60</td>
</tr>
</tbody>
</table>
cases. The lot production (jobs with same part type are released at the same time) and random production (all jobs are released at random) are considered. In this paper, only the results with FIFO rule are shown because there is no great difference found from the simulations by comparing different traditional dispatching rules, such as SPT, LPT, EDD and FIFO.

5.2 Part-centric strategy

In this section, simulations are carried out to investigate the influence of buffer size, the efficiency of the scheduling method considering tool and operation reallocation.

Experiment 1: investigation of buffer size

Since the L/U job buffer is important to relieve the impact of job transfer lateness, the investigation of buffer constraint is carried out. The buffer size is changed from 1 to 10 and the tool magazine capacity is changed from 60 to 110. Figure 3 shows their makespans.

It is obvious that when tool magazine is small, larger buffer is necessary. In case of small tool magazine, job is easy to be divided into tasks which have short processing time. Therefore, the small buffer causes that jobs are easy to be transferred back to L/U station and the small buffer can not stock enough tasks to cover the transfer time. As a result, the idling time for waiting job is enlarged. On the contrary, there is almost no job movement if sufficiently large tool magazine is employed. The processing time of any job is longer than the job transfer time from L/U station to any machining center. Therefore, there is no great difference of makespans when the tool magazine capacity is 110 (MC (110) in Fig. 3). When job movements do not occur, 1 is enough to the job buffer capacity. Comparing with large magazine capacity, sufficient large buffer capacity is critically important to machining center with small magazine capacity.

Experiment 2: investigation of LLB and ULB

Since LLB and ULB are used to adjust the load among machining centers, simulations with different values of LLB and ULB are carried out in case that tool exchanges are allowed. The magazine capacity is set to 60 and the buffer capacity is set to 10. Firstly, ULB is set to 1000 and LLB is changed from 100 to 600. After that LLB is set to 400 and ULB is changed from 500 to 2000. With the same LLB and ULB, simulations are executed at 100 times with different job release data and the average makespan is obtained.

Figure 4 shows the average makespan of different LLB. It has been observed that the average makespan is shortest when LLB is set to 400. The reallocation can be carried out when system condition changes (PT1, PT3 and PT4 in section 3.2). However, reallocation does not occur when the machining center whose load is under LLB can not get the necessary tools. Because the job transfer time between the farthest machining center and the pallet station is 240, the farthest machining center is easy to be idle if LLB is smaller than 240 and the system performance is decreased. When the LLB is larger than 240, the time span between 240 and LLB is useful for machining center to try more reallocations to prevent idling. The machining centers keep busy whether jobs are transferred in advance or immediately if the summation of the remained processing time of task in process and the processing time of tasks waiting in their L/U buffer is longer than job transfer time. Therefore, too large LLB does no benefit to makespan.

Figure 5 shows the average makespan of different ULB. It has been observed that the average makespan is shortest when ULB is set to 1000. If ULB is too small, machining centers lend their tools frequently. However, the machining center can not process the tasks according to the original loading plan before the return of these tools.
Considering that most of the tasks are processed according to the original plan, machining centers are easy to be idle if their tools are not returned. Therefore, too small ULB cannot cover the transfer time of tools and that causes machine idling time. In order to balance the load among machining centers, too large ULB is not efficient.

Experiment 3: effect of operation reallocation

In order to verify the efficiency of the proposed reallocation method, simulations are carried out with different magazine capacities. Both lot production and random production are considered. Figure 6 shows makespan and Fig. 7 shows average lead-time of jobs. Method 1 is the scheduling method based on the original loading plan. Method 2 is the reallocation method without tool reallocation and Method 3 is the reallocation method with tool reallocation.

Each case with same tool magazine shows Method 2 and Method 3 reduce makespan and average lead-time of jobs, and Method 3 performs better. Specially, makepan and average lead-time of jobs are improved vastly in lot production when the magazine capacity is set to 110. It means the large tool magazine capacity can not assure the efficiency of original loading plan in the scheduling stage. Therefore, the adjustment of loading plan is necessary with the dynamical job releases.

In most cases, the makespan has no remarkable changes with different magazine capacities. However, the larger tool magazine capacity generates shorter lead-time. It is because that there are few job movements when sufficient tools are provided with the large tool magazine.

5.3 Tool-centric strategy

PSDC algorithm explained in section 4.2 is used to decide the proper tool duplications for each tool type. \( N \) is set to 10 and \( M \) is set to 100. The buffer capacity is set to 1 because there is no job movement.

Experiment 4: investigation of PSDC algorithm

Figure 8 shows the total tool conflicts in lot production with different total number of tools. Figure 9 shows the total tool conflicts in random production. Generally, there are fewer tool conflicts when the total number of tools is larger. Also it has been observed that the proposed PSDC algorithm can decrease the amount of tool conflicts as the run index of \( M \) increases. Therefore, PSDC algorithm is efficient to decide the proper number of tools for each tool type when the total amount of tools is decided.

In order to investigate the relation between tool conflict and system performance, the total tool amount is set to 360 and simulations are carried out by \( M \) tool settings obtained from each run in PSDC. Figures 10 and 11 show the simulation results in lot production and in random production, respectively. Although there is no big difference of makespans, according to the evaluation criterion such as the lead-time, tardiness and total number of tardy jobs, the system performance is improved by the run of PSDC algorithm.

Experiment 5: effect of tool amount

Simulations are carried out when tool amounts are 200, 240, 280, 320, 360, 400 and 440 in both random production and lot production. It has been observed that with the increase of tool amount, the system performance is improved (see Figs. 12 and 13). However, the improvement is converged and there is no great change when the tool amount becomes 320. Therefore, the constraint of tool amount in tool center should be set properly (320 is enough).
5.4 Comparison of tool allocation strategies

Considering same total tool amounts, the proposed tool allocation strategies, part-centric strategy and tool-centric strategy are compared by makespan, lead-time, tardiness and total tardy jobs by 10 simulations with different sets of job release data. Table 2 shows the ratio that tool-centric strategy performs better than part-centric strategy in random production. Table 3 show the ratio in lot production.

When the total amount is set to 200, part-centric strategy performs better than tool-centric strategy in most cases. However, the tool-centric performs better if the total amount of tools is set to a larger number. Therefore, part-centric is suitable when lower tool cost is the key issue while tool-centric strategy is a better tool allocation strategy when higher tool cost is bearable.

Most studies on SSMS emphasize that the tool cost is low because fewer tools are employed to obtain the same system throughput which are obtained by traditional part-centric tool allocation strategy with large number of tools. Our results show the same conclusion when the total amount of tools is large. On the other hand, our results also show that the tool-centric strategy is not proper when the tool cost is constrained to a lower level. When the tool-centric strategy is employed with few tools in the system, a free machining center can not process a job if it can not get the whole set of tools for the job. In this case, part movement is necessary to be considered to improve the system performance.

6. Conclusion

In this paper, two strategies for tool and operation allocation in FMS are presented. One is to allocate tools and operations to machining centers in the planning stage and to improve the system performance by reallocation in the operation stage. The other is to prepare tools in a tool center in the planning stage and to allocate tools and operations dynamically to machining centers. The control method and solution method for each tool allocation strategy are also proposed.

By simulations, our proposed scheduling method for part-centric strategy can improve the system performance.
The simulation results also show the importance of proper buffer capacity to system performance. For tool planning problem of tool-centric strategy, the efficiency of PSDC algorithm has been verified. Comparing different tool allocation strategies by various production conditions, it has been revealed that the tool amount constraint should be taken into consideration to select the proper tool allocation strategy.

As the enhancement of this work, part movement for tool-centric strategy and the solution methods for rush jobs and machine failure are necessary to be considered.

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