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DEVELOPMENT OF A SIMULATION-BASED PLANNING SYSTEM FOR A FLEXIBLE MANUFACTURING SYSTEM

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ABSTRACT

This paper discusses authors' continued study on development of a discrete-event simulation model and associated software for a real-life commercial module-type flexible manufacturing systems (FMS). After describing the organization of the developed system, simulation analysis of the FMS would be given. In contrast to our previous study where makespan was taken as the performance measure, this analysis focuses on machine utilization and sojourn time, and the effects of routing flexibility and of the numbers of operations and pallets are examined.

Our analysis shows that increased routing flexibility achieved by having several alternative machines, which was found to help reduce makespan, also leads to improved machine utilization and reduced sojourn time. As in the case of makespan, most of improvement would be achieved by having two alternative machines, and contributions expected from further increase are only marginal.

It is also shown that an increase in the number of operations reduces machine utilization. The relationship between the number of operations and machine utilization is roughly linear, and the slope depends on the degree of routing flexibility. The paper also describes possible uses of the simulation system which could lead us to a simulation-based planning system.

1 INTRODUCTION

Recently Flexible Manufacturing Systems (FMS) are regarded as an established technology and many FMSs have been installed and are used in a variety of industries. As compared with the level achieved by latest FMSs from the technical view point of machining, the level achieved in the management aspects of FMSs appears to be far behind. Even though there have been constant efforts toward better management of FMSs, more studies would be required for efficient planning and control of FMSs.

Potential benefits expected from an introduction of FMSs can be classified into two categories, namely,
Type 1: those benefits that can be achieved simply by introducing FMSs
Type 2: those benefits that cannot be achieved by a simple introduction of FMSs, and can only be achieved if careful planning, control and management are administered.
There exists no question that an introduction of FMSs gives a good deal of benefits of the first type. We refer to one of these merits later in our analysis. Still, as FMSs become more popular and FMSs reach a *mature* stage, it will be more and more important to pursue the second type of benefits, that is, those that can be achieved by careful planning, control and management. If one considers cost of an FMS, in order for an FMS to be economically viable, it will be necessary to extract the second type of benefits by executing proper management of the system. In other words, full potential of an FMS must be extracted, and to achieve this goal, careful analysis will be necessary.

The paper is organized as follows. After reviewing decision items regarding FMSs in the next section, Section 3 describes a developed simulation system and its potential. Sections 4 and 5 discuss simulation analysis and results, respectively. Possible uses of the simulation system for planning and operation of FMSs are mentioned in Section 6, which is followed by concluding remarks.

2 FLEXIBLE MANUFACTURING SYSTEMS AND THEIR DECISION ITEMS

An FMS forms a complex system which generally consists of machining centers, load/unload stations (denoted as L/UL), material handling equipment such as AGVs and stacker cranes, pallets, local and/or common pallet storage, tools, an FMS computer, among others.

The particular FMS for which a simulation system is developed is the Mazatrol FMS manufactured by Yamazaki Mazak, which is a module-type commercial FMS. Table 1 summarizes major components and their capacity of the Mazatrol FMS. Additional information of the FMS can be found in Morito et al.(1991).

Table 1: Major Components and Their Capacity of the Mazatrol FMS

equipment	maximum capacity
•machining centers	8
•L/ULs (include wash stations)	4
•stacker crane	1
•pallet stocker	120
•tool magazine	120

There exist many levels of management decisions for introducing, planning, and using FMSs. These decisions are listed in Figure 1. Many of long-range decision items are those which must be decided when one newly introduces an FMS or when one changes a configuration of existing FMSs. Short-range decision would correspond to those items that can be or must be changed daily, whereas medium-range decision items are those which are changed less frequently.

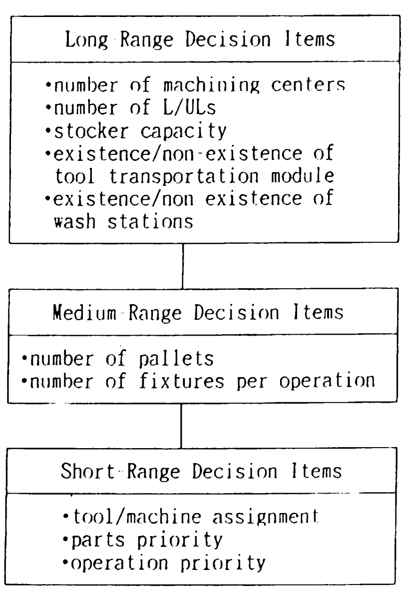

Figure 1: Decision Items Concerning FMSs

An FMS is a complex system and thus to extract its full potential, it will be necessary to perform careful analysis. There have been a huge number of quantitative studies to analyze FMSs. See, e.g., Jha(1991) and papers in *International Journal of Flexible Manufacturing Systems*. Techniques used for these analysis include discrete-event simulation, queueing network, mathematical programming, combinatorial optimization, and others. Among these techniques, discrete-event simulation is by far the most popular.

3 AN FMS SIMULATION SYSTEM

3.1 Organization of the Simulation System

A simulation system for the Mazatrol FMS has been developed. The system consists of three modules: data input module, simulation module, and output analysis and presentation module. Below we describe each module.

3.1.1 Data input module

This is a module to supply input data for simulation. Input data correspond to what an FMS user has to decide before operating a system and generally consist of the following:

1. system configuration (the numbers of machines, L/ULs, pallets, and workers; equipment specifications such as crane speed)
2. production requirements (parts and the associated operations, production quantities, processing time, parts priority, operation priority)
3. worker shift
4. initial condition of the system

An interface has been developed to transmit data from a real FMS to the simulator, and thus a system operator can transfer information regarding the "current status" of an FMS to the simulator and run a simulation to see what would happen on the system in the immediate future.

3.1.2 Simulation module

The core of the simulation system is the simulation model developed in SLAM II using its network modeling and discrete-event modeling (i.e., with user-written FORTRAN inserts) capabilities. Essentially, all control logics of the Mazatrol FMS are incorporated into the model, and thus the model is not a general one but a one specilized for the Mazatrol FMS.

The simulation program, as it stands now, is completely deterministic, even though it is a simple matter to include probabilistic factors. Simply, there has been no need to include stochastic variabilities directly into the simulation thus far.

3.1.3 Output analysis and presentation module

This module analyzes the simulation output and prepares the output in the form of graphs and charts, and also gives animated presentation of an FMS. Graphs include those which show the chronological development of parts production and also equipment utilization.

3.2 What to See from FMS Simulation

3.2.1 Understanding and predicting dynamic behavior of a complex system

When a system of interest is reasonably complex, it will be difficult to understand and predict its dynamic behavior. This is somewhat similar to reading openent's moves in a chess match. This applies even when the system is completely deterministic. Table 2 shows an outline of dispatching priorities of a stacker crane, which is an essential part of complicated control logics of the Mazatrol FMS. These dispatching priorities together with a set of parts/operations to be produced and also with an initial condition, determine the complete behavior of the system, provided that there exists no equipment failure and also that there exists no human intervention. Once a detailed simulator is developed, it is a simple matter to reproduce the dynamic behavior.

Table 2: Dispatching Priority of Stacker Crane

Dispatching Priority
1. Move a loaded pallet to machine
2. Move a pallet to L/UL for loading when a part is available for loading
3. Move a completed pallet to L/UL for unloading when parts to be loaded on the pallet are unavailable
4. Move a pallet to be washed to a wash station
5. Move a loaded pallet from L/UL to stocker
6. Move an empty pallet from L/UL to stocker
7. Move an unloaded pallet to stocker
8. Move a washed pallet to stocker

3.2.2 Exploring key factors that affect major performance measures

Under a particular hardware configuration as defined by the numbers of machines, L/ULs, etc., there still exist many factors affecting FMS performance. Figure 2 indicates important factors that affect FMS performance together with a list of major performance measures, considering medium- and short-range decisions. Even qualitative relationships between these factors and performance measures are often unknown, and not to mention quantitative relationships. With the assistance of simulation and some analysis, it would be possible to identify key relationships between factors and performance measures.

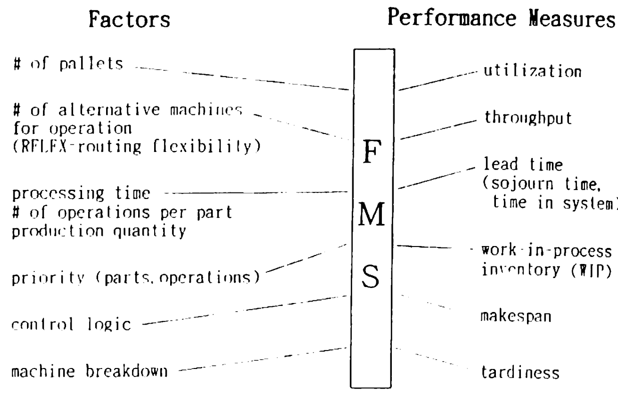

Figure 2: Factors Affecting Various Performance Measures of FMSs

The next two sections are concerned with the latter capabilities of simulation and present some analysis of the Mazatrol FMS, whereas Section 6 discusses possibilities to take advantage of the former capabilities.

4 SIMULATION ANALYSIS

4.1 Factors Whose Effects Are Studied

Among factors which affect FMS performance, we focus on the following three factors:

$RFLEX$ = the number of alternative machines that can process a particular operation

NOP = the number of operations per part

P = the number of pallets that can process a particular operation

Many different categories of flexibility has been identified regarding FMSs. When there exist alternative machines to process a particular operation, a part has a freedom to choose a machine. Sethi and Sethi (1990) called this freedom *routing flexibility*, which is measured here by $RFLEX$.

We also look at the number of operations per part. Here, an operation is defined as a collection of work that can be performed on a single machine without a pallet change. In other words, a part must return to L/UL between any two operations for unloading and then loading. As the number of operations per part increases, parts must go through several *stages* before they get completed. We analyze how the number of operations, NOP, affects system performance. The number of pallets for a particular operation is another important factor. The maximum number of parts going through a particular operation will be limited by the number of pallets, which is often a relatively small number.

4.2 Earlier Results

Morito et al.(1991) examined the effects of the routing flexibility *RFLEX* on makespan in relation to other factors such as the number of pallets P, the number of machines, and scheduling priorities. The main results are summarized below:

1. The average makespan decreases substantially as *RFLEX* is increased from 1 to 2. Increasing *RFLEX* from 2 to 3 reduces the average makespan marginally, but essentially no further reduction of makespan can be expected by increasing *RFLEX* above 3.
2. With regard to the effects of the number of pallets, the makespan initially decreases as the number of pallets is increased, and then after a certain point, the makespan starts to increase. It appears that the least makespan is attained when P is equal to *RFLEX* or *RFLEX* + 1. In any case, the effect of the number of pallets on the makespan is not as dramatic as that of *RFLEX*.
3. Scheduling priorities affect little with regard to the makespan.

4.3 Performance Measures

Makespan was the only performance measure considered in Morito et al.(1991). Despite the fact that makespan is an important measure, a real FMS would be rarely run to minimize makespan for given production requirements. There will not be, and should not be time when "no more parts exist that can be processed on a machine," as it means that the machine sits idle. Rather, jobs should be supplied before any machine runs out of parts to process. Therefore, one has to face a rolling schedule-type situation where machines keep working constantly. An important factor behind this would be an ability of recent FMSs to perform longer and longer unmanned automatic operation.

If one considers such production environment, it appears more meaningful to minimize machine idle time, or equivalently, to maximize machine utilization, rather than to minimize makespan. Even though simulation runs are performed in the same fashion as in our previous study, i.e., for a finite set of parts, this study mainly looks at machine utilization while each machine has something to work on.

In this study, simulation is run as follows:

1) Simulation starts from an empty-and-idle condition where a fixed quantity of raw material of each parts are available.

2) No machine breakdown is assumed.

3) Simulation ends when all parts finish production.

4.4 Classification of Periods

To analyze machine utilization, we first divide the entire makespan into several periods conceptually as shown in Figure 3(a) and defined below, where subscript i stands for machine i:

1. Initial Idle period ($0 \rightarrow t_{i1}$)
2. Operating period ($t_{i1} \rightarrow f_i$)
   (a) Initial Transient (IT) period ($t_{i1} \rightarrow t_{i2}$)
   (b) Steady State (SS) period ($t_{i2} \rightarrow t_{i3}$)
   (c) Closing Down (CD) period ($t_{i3} \rightarrow t_{i4} = f_i$)
3. Ending Idle period ($f_i \rightarrow MS$)

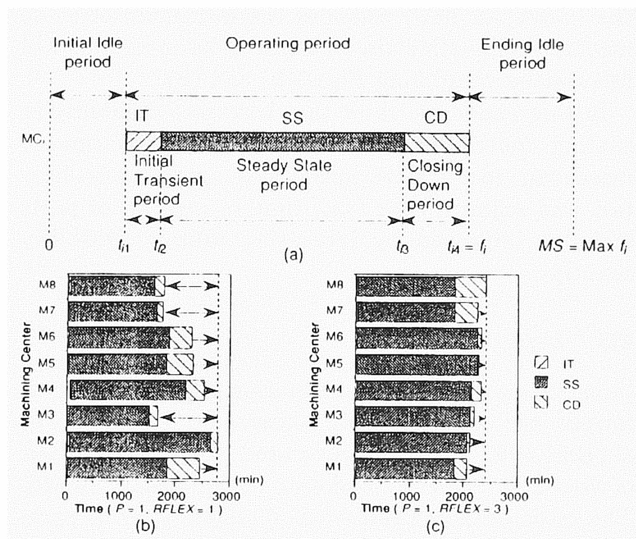

Figure 3: Classification of Periods within Makespan

Our simulation starts from the empty-and-idle state, and thus there initially exists a machine idle period. The "operating period" of a machine starts when the machine starts processing its first workpiece, and ends when the final processing is completed, i.e., at $t_{i4} = f_i$, which we call the machine completion time. The makespan MS is the maximum of f_i over all machines, and the period between f_i and MS is called the ending idle period. Note that the operating period as defined above consists of (a) actual processing (=machining) periods, and (b) machine idle periods.

The operating period is further divided into three subperiods, (a) the initial transient (IT) period, (b) the steady state (SS) period, (c) the closing down (CD) period. We define that the time when the input buffer of machine i is filled, denoted as t_{i2}, marks the end of the initial transient period. The closing down period, on the other hand, is defined to start when the expected number of pallets assigned to machine i falls down to 1 or less, as more and more parts complete their production. More precisely, the initiation of the closing down period, t_{i3}, is equal to the time when $\sum(1/RFLEX_j) \leq 1$, where $RFLEX_j$ is the value of $RFLEX$ for operation j, and the summation is taken over all possible operations j assigned to machine i. We call the subperiod between the initial transient and the closing down subperiods the *steady state* period.

The findings of Morito et al.(1991) described above can be interpreted as follows: An increase of $RFLEX$ has an effect of averaging out ending idle periods of machines, and thus reduces the average makespan MS. In other words, as the variability of the machine completion times over machines gets smaller, the makespan MS, which is the maximum of these machine completion times, tends to be smaller as will be clear by comparing Figs.3(b) and (c).

In this paper, we show that increased flexibility in routing contributes favorably to other performance measures, too. More specifically, machine utilization and sojourn time (i.e., time in system) of parts are also improved by increasing routing flexibility slightly.

4.5 Input Data

Input data with which simulation analysis are performed are identical with those used in Morito et al.(1991,1992) and were generated by a technical staff of Mazak as "typical" load data of the Mazatrol FMS. The basic data consists of 26 distinct types of parts with the total of 38 different operations. The number of operations for each part ranges from 1 to 3. The required quantity of each part is assumed to be 10, and raw materials of the first operation of each part are assumed to be available. Higher priority is given to those parts with more operations, and also to those operations with shorter processing time.

5 SIMULATION RESULTS AND OBSERVATIONS

5.1 Effects of $RFLEX$ and P on Machine Utilization

Figure 4 shows the distribution of machine idle time during operating periods. Effects of changing the number of pallets P for fixed $RFLEX$ is shown in Figure 4(a), and those of changing $RFLEX$ for fixed P in Figure 4(b). The former indicates that P does not affect the amount of idle time during steady state subperiods , but affects the occurrance of machine idle time during initial transient and closing down subperiods. The latter shows, on the other hand, that machine idle time during steady state subperiods would be affected by $RFLEX$.

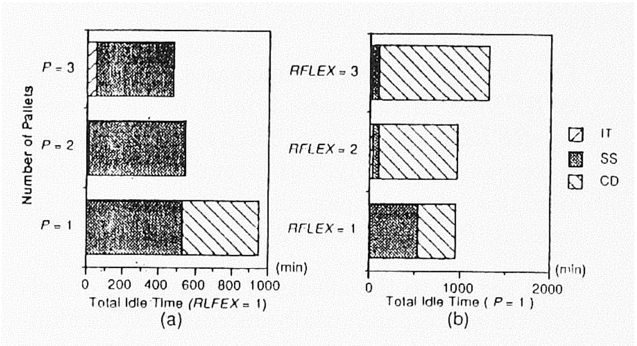

Figure 4: Distribution of Machine Idle Time

Figure 5 shows the effects of routing flexibility on machine utilization during steady state subperiods when P is 1. Interestingly, the effects of $RFLEX$ on machine utilization looks almost the same as those on makespan. Specifically, when $RFLEX$ is 1, machine utilization is penalized, but as $RFLEX$ is increased to 2, utilization improves substantially. Further increase in $RFLEX$ contributes only marginally to machine utilization. Though this is not of a practical interest, the graph seems to indicate that too much flexibility hurts utilization, as utilization appears to decrease slightly when $RFLEX$ approaches 8, i.e., the number of machines. Note that the similar phenomenon was observed for the makespan, too.

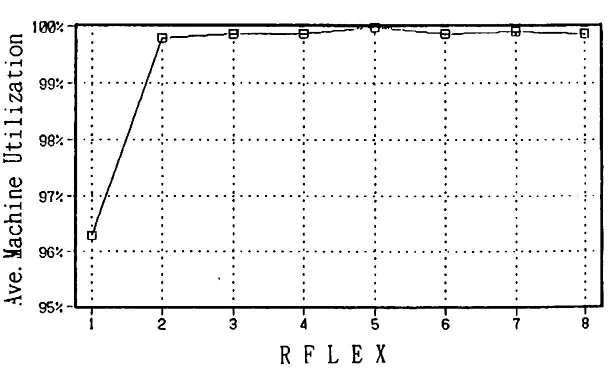

Figure 5: Effects of Routing Flexibility on Machine Utilization during Steady State Subperiod

5.2 Effects of $RFLEX$ on Sojourn Time

The relationship between sojourn time and $RFLEX$ is shown in Figure 6. Sojourn time is time parts spend in the system, and is measured as the time from the start of loading the part on a pallet for the first operation to the end of unloading the part from a pallet after the last operation.

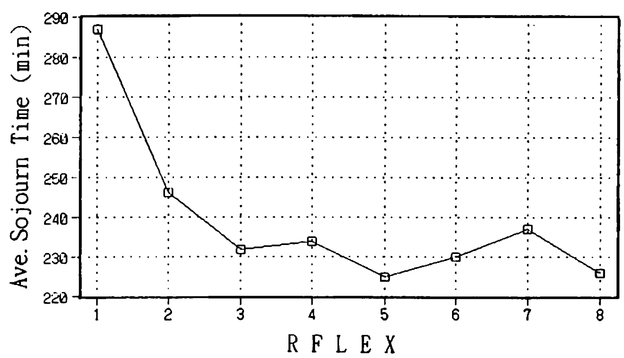

Figure 6: Effects of Routing Flexibility on Sojourn Time

The effects obtained here are again very much similar to those of *RFLEX* on makespan and also on machine utilization. The average sojourn time is reduced substantially as *RFLEX* is increased from 1 to 2, but no more substantial improvement of sojourn time can be expected by increasing RFLEX. Note that reduction of sojourn time leads naturally to the reduction of lead time.

5.3 Effects of the Number of Operations on Machine Utilization

Figure 7 shows the relationship between the (average) number of operations per part and machine utilization. The experiment was performed in such a way that a fixed set of 38 operations was allocated to varying number of part types ranging from 1 to 10. Therefore, all runs were performed under the assumption of equal workload.

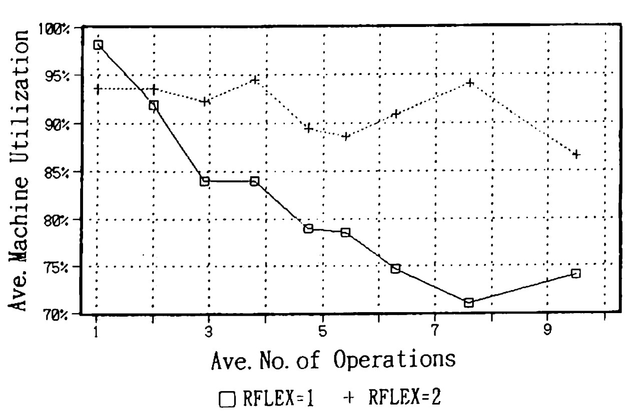

Figure 7: Effects of the Number of Operations on Machine Utilization

The results indicate that the more operations parts have, the lower the machine utilization would be. The graph shows the cases for *RFLEX* of 1 and 2, and the relationship is more or less linear for the fixed value of *RFLEX*. The slope, however, depends on the degree of routing flexibility and increased routing flexibility clearly reduces the penalty in machine utilization due to more operations.

Note that this graph shows one of merits achievable by a simple introduction of FMS, as a single operation on FMS is most likely to correspond to a (often large) number of operations in a traditional job shop. Therefore, twenty to thirty operations in a job shop may be done in just a few operations on an FMS. Since the graph indicates that the shop's utilization decreases as the number of operations increases, aggregation of many operations into a single operation with the introduction of FMSs helps improve machine utilization. Obviously, the results would be valid for FMSs, too. That is, smaller number of operations per part would be preferred to achieve higher machine utilization.

5.4 Summary of Findings

We now summarize findings of this and related earlier studies:

1) Under the assumption of no machine breakdown, the Mazatrol FMS is capable of achieving high utilization of 95% or higher (Morito et al. 1992).

2) Causes of machine idle time depend on system status. That is, machine idle time due to a certain type of causes tends to occur more frequently during a certain subperiod (Morito et al. 1992).

3) A slight increase in routing flexibility has an effect of automatic load balancing, thus acting as an *automatic load balancer*. Balanced load leads to a reduction in makespan (Morito et al. 1991).

4) A slight increase in routing flexibility also has an effect of increasing machine utilization during the steady-state subperiod.

5) Similarly, a slight increase in routing flexibility has an effect of reducing sojourn time of parts. No major improvement in sojourn time is expected when *RFLEX* is increased above 3.

6) The main cause of machine idle time during the steady-state subperiod is found to be the existence of the multi-operation parts.

7) The increased proportion of multi-operation parts as well as the increased number of operations per part lead to lower machine utilization.

With regard to the effectiveness of having alternative machines, we note that Nasr and Elsayed(1990) gave similar results for a much simpler standard job shop.

6 TOWARDS A SIMULATION-BASED PLANNING SYSTEM

6.1 Simulation as a Tool for Short-Term Look-Ahead

Using simulation as a tool for short-term look-ahead is based on the ability of simulation to represent dynamic behavior of FMSs. Some of the areas where simulation analysis look promising are listed below:

1. Forecasting completion time of a particular lot of a particular part type
2. Estimating workload accumulation for unmanned automatic operation
3. Predicting time needed to recover from a special system condition created by such events as equipment failure, switch from unmanned operation to manned operation, etc.

6.2 Simulation as an Ideal

As in "model city" or "model child", a word "model" contains a flavor of something to be imitated. Since any model is an abstraction of some reality, and since in the process of abstraction non-essential factors must be omitted, a resultant model tends to be a "beauty" extracted from a reality.

If one assumes that a reality should follow the simulated course of actions without any discrepancies, it is very likely to get disappointed. Since the simulated course of actions is the outcome of an *idealistic model*, one has to face some discrepancies. Rather than worrying about the discrepancies, it would be more important to analyze the causes of discrepancies and take appropriate actions or to reflect them in future planning. This implies needs for an evaluation system of FMSs that can be and should be combined with the simulation system. Effective planning only works when it is combined with proper evaluation of what has happened.

It is important to note that modeling is closely related to planning. Simulation-based thinking is nothing but model-based thinking, and is expected to let people recognize the importance as well as joy of planning.

7 CONCLUDING REMARKS

A simulation system for a real module-type commercial FMS was described together with an analysis of the FMS and its possible uses. The analysis has shown that a slight increase in routing flexibility contributes favorably not only to makespan but also to other aspects of the FMS such as machine utilization and sojourn time.

It should be mentioned that the results presented in this paper are the outcomes of the model specialized for the Mazatrol FMS based on a rather limited set of data. However, many of the results presented here seem to be not only data independent but also valid for many other job shop environment. Further research will be needed to confirm the generality of the results presented in this paper.

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