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A BASIC STUDY ON AUTONOMOUS CHARACTERIZATION OF SQUARE ARRAY MACHINING CELLS FOR AGILE MANUFACTURING

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ABSTRACT

In this study, a manufacturing system locating machining cells in a square array is considered as an agile manufacturing system that can manufacture a variety of kinds of products with varying volumes. Each cell can process any work whose machining operations for each work are divided into some operation groups common to all works. An auction-based algorithm is proposed to select a cell to process a work after its processing of one operation group. Five types of bid are considered and their effects on the characterization of cells, i.e., concentration on the processing of specific work kinds and operation groups, are investigated.

1 INTRODUCTION

Agile manufacturing is one of the key issues for manufacturing industries in order to survive the severe competition in recent years (Kidd 1995). The manufacturing system needs to be able to respond to the rapidly changing market demands that require the effective and efficient manufacturing of a variety of products with varying volume. Flexible manufacturing systems (FMS) have been developed to cope with such requirements for rather small volume production of a variety of products (e.g., Raouf and Ben-Daya 1995), while flexible transfer lines (FTL) are for rather large volume production of a limited variety of products. A high volume FMS (HV-FMS) is proposed by authors to cope with the requirements of flexibility for the variety of products and the production volumes (Fujii et al. 1998a). These systems, however, have fixed layouts of processing stations with pre-specified role of processing.

A numerically controlled machining cell (MC) with tool magazine can process a wide range of machining operations when appropriate tooling and programs are provided and works are properly oriented and fixed on pallets. Since most of the products processed by FMS, FTL or HV-FMS are similar kinds with different sizes and different topologies for processing, e.g., differences in number, size and/or position of holes, the processing operations of products can be divided into some groups mostly based on the processability on one cell without changing the orientation of the work on a pallet. HV-FMS having a serial-parallel layout of machining cells is proposed taking this nature into consideration (Fujii, et al. 1998a, 1998b, 2000). Parallel MCs in HV-FMS have the same tools and machining programs for processing of a prespecified operation group and can process the operations of any work. By characterizing each of parallel MCs to the processing of a specific kind of works by some means, i.e., limiting the kind of works to process, number of tools on each MC can be reduced. HV-FMS can effectively cope with relatively large variation in product mix but may require to adjust the number of MCs in a group by relocating MCs or by adopting complicated routing rules of works among MCs belonging to different groups when large variation in product mix is encountered.

In this study, we consider a square array layout of MCs instead of a serial-parallel layout to resolve the drawbacks of HV-FMS to cope with the large variation of product mix described in the above. We assume that MCs can process any operation group of any work to be put into the system. Each work needs to visit a pallet change station to change its orientation after finishing a processing at one MC. An auction-based algorithm is proposed as a simple and autonomous rule in this study to select an MC for the next processing. For the effective utilization of such system, it will be necessary to characterize each MC to process a specific operation group and/or specific kinds of work so that a smooth work flow is formed in the system and total number of tools is reduced. In this paper, various types of bid used in the auction are investigated from the view point of the possibility to the characterization of MCs.

First we describe the system configuration and the types of bid for the auction-based algorithm proposed in this study. The basic property of the algorithm and its effectiveness on the system performance are then investigated. The possibility for the characterization of MCs is further investigated for various bid sets.

2 SYSTEM CONFIGURATION

In this section, we describe the hardware configuration of the system considered in this study and the auction-based algorithm as a control scheme of the flow of works.

2.1 Hardware Configuration

To realize an efficient manufacturing system for the agile manufacturing, it is essential to improve the flexibility of the system without losing productivity. We confine ourselves in this study to consider a system to manufacture similar kinds of products with differences in their sizes and shapes. The processing operations of each work are assumed to be divided into some operation groups (OP) based on the possibility to process it without changing the orientation on a pallet. This means that a work after completing the processing of one OP at an MC must visit a pallet change station (PCS) to change its orientation for succeeding processing. We assume all works are divided into common OPs where the operations in one OP may differ from work to work.

We consider a manufacturing system with a number of MCs located in a square array as shown in Figure 1. A material warehouse located to the left of the system stores works palletized in proper orientation for first OP. PCSs are located in the sequence of OPs at the position as shown in the figure. Their location is also an important factor affecting the system performance but is left for further study. A product warehouse located to the right of the system stores the completed works. One MC consists of one loading buffer, one unloading buffer and one machining station. Each buffer can hold one pallet at a time. The machining station can process any OP of any work if appropriate tools and programs for processing are furnished and if the work supplied is properly oriented and fixed on a pallet. Automated guided vehicles (AGV) transfer pallets among warehouses, MCs and PCSs.

The flows of works in the system are as follows:

(1) Assume one palletized work is ready for processing at the material warehouse or at a PCS.
(2) One MC is selected from available MCs by an algorithm given below. An available MC means that the loading buffer or both of the loading buffer and machining station is empty and is furnished with necessary tools and programs to process the candidate work.
(3) The pallet is transferred to the selected MC by an AGV.
(4) The work whose processing is completed is transferred to an appropriate PCS to change the orientation on a pallet for the processing of the next OP.
(5) If the completed processing is the last OP, the work is transferred to the product warehouse.

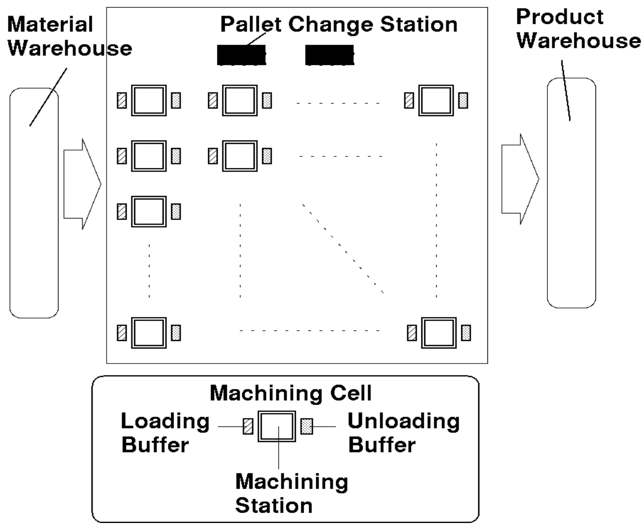


Figure 1: System Configuration of Square Array MCs

2.2 Selection Algorithm of MC

To select an MC to process a work, some selection rules are necessary. To assure the flexibility of the system, it will be preferable to adopt an algorithm as simple as possible. In this study, it is assumed that the MC selection is only made from available MCs and that it will wait until at least one MC becomes available if no MCs is available.

We propose to implement an algorithm based on the auction method (Fujiiet al. 2000) for the MC selection. Let us denote a work by Work (i, j), where i and j represent the kind of work, Kind-i, and the OP, OP-j, respectively, and a PCS handling a pallet for the processing OP-j by PCS-j. The algorithm is schematically shown in Figure 2 and outlined as follows, where the types of bid will be described later:

[Auction-based Algorithm]

(1) Work (i, j) becomes ready for processing at PCS-j or at the material warehouse and is named a candidate work. The coordinator announces the request for processing of the candidate work to all MCs in the system. The information announced contains the kind of work and the OP for processing, the present location, i.e., the position of PCS or the material warehouse and the type of bid to be answered.

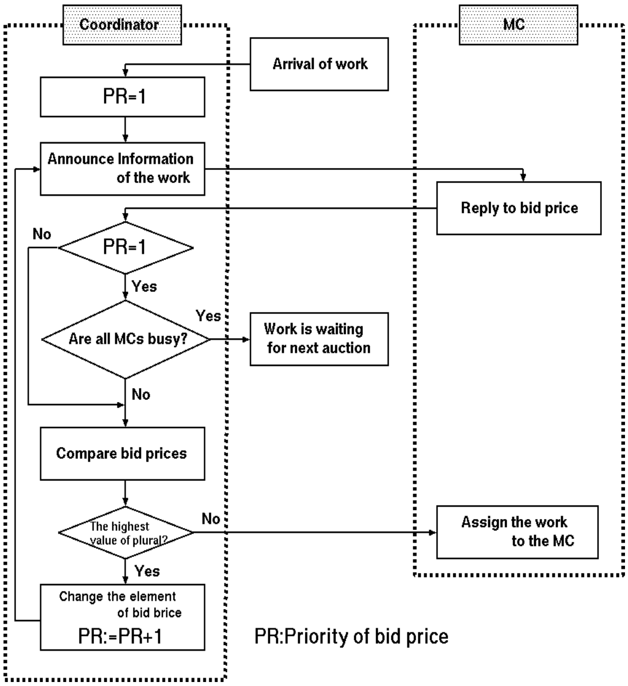


Figure 2: Auction-Based Algorithm

(2) Each MC determines the bid price and replies the bid price to the coordinator.

(3) The coordinator examines the replied bid prices and selects one MC if only one MC replied the price with the highest priority. The selected MC is informed the decision and the procedure to transfer the work to the MC is initiated. Otherwise, the type of bid requested for the reply is changed by a predetermined order of bid types and is announced to the MCs.

(4) If more than one MC reply the same bid price and the conflict in selecting MCs is not resolved after repeating the procedures 2 and 3 until all prepared bid types are exhausted, one MC is selected randomly.

We define five types of bid listed below. The order of bid types to be requested for the reply by the coordinator is the main interest of this study. The bid price is given in the parenthesis according to the condition matched in the bid type. Each MC keeps the record of Work (i, j) processed and calculates a ratio of the number of a specific Work (i, j) processed to the total number of works, named specialization ratio of (i, j), or S-ratio (i, j). The work (i*, j*) with the largest S-ratio is named a specialized work or S-Work (i*,j*). The OP and the kind of work of S-Work are referred to S-OP and S-Kind, but they can be similarly defined focusing on the ratio of specific OP and Kind at an MC, respectively.

Type 1: Availability of MC.

- The loading buffer and the machining station are empty. (2)
- The loading buffer is empty <<(1)>>
- Not available. <<(0)>>

Type 2: Matching between the candidate work (i, j) and S-Work (i*,j*) at the moment.

- Both of the kind of work and OP match; i.e., i=i* and j=j*. (3)
- OP matches; i.e., j=j*. (2)
- Kind of work matches; i.e., i=i*. (1)
- Do not match at all. (0)

Type 3: Distance from the present position (PCS or the material warehouse) to MC.

- Shorter distance corresponds to higher price. (x)

Type 4: Direction from the present position to MC.

- Toward the product warehouse. (2)
- Neutral. (1)
- Toward the material warehouse. (0)

Type 5: Matching between the candidate work (i, j) and the work (m, n) processed just before at the MC.

- Both of the kind and OP match; i.e., i=m and j=n. (3)
- OP matches; i.e., j=n. (2)
- Kind of work matches; i.e., i=m. (1)
- Do not match at all. (0)

3 SIMULATION MODEL AND EXPERIMENTAL CONDITIONS

In this study, we investigate the effect of bid types on the characterization of MCs and the possibility to form a work flow in the system by the simulation study. In this section, we describe the experimental conditions of the system.

3.1 Machining Cells

As described in 2.1, a machining cell consists of loading and unloading buffers with the capacity of one pallet and a machining station. In this study, we assume that each MC holds all tools and programs necessary to process all kinds of works and all OPs so that any candidate work can be processed without the setup time at any MC. This assumption is to be removed in the further study, however.

The system consists of thirty eight MCs in total as estimated later and is located in a square array as in Figures 1 and 3. They are assumed to be failure free.

We define two indices to measure the performance of auction algorithm on the characterization of MCs; that is, the utilization of MC and the specialization ratio of MC. The utilization of MC is the ratio between the total processing time of an MC and the total time span required to complete the processing of the predetermined number of works. The utilization of the system is defined as an average of all MC utilizations.

Each MC can process any OP of any kind of work. If an MC processes only one OP of one kind of work, say Work (i, j), then S-ratio (i, j)=1.0 and the MC is specialized for the processing of OP-j of Kind-i and requires to be furnished only with the tools and programs for the specific operations. This suggests that S-ratios of each MC at the end of the simulation reflect the degree of specialization to a certain OP and/or a kind of work and thus they are adopted as indices showing the degree of specialization. The largest S-ratio, S-Work, S-OP and S-Kind at each MC defined before are the special interest in this study. The specialization ratio of the system or the mean S-ratio is an average of the largest S-ratios at each MC.

3.2 Transportation System and Pallet Change Station

Automated guided vehicles are used to transfer the pallets in the system. Each AGV can carry one pallet at a time and considers no conflict on the route. They are also failure free. In this study, we assume a sufficiently large number of AGVs and any pallet ready for the transportation can be served immediately.

Each pallet change station can handle a work from a specific OP to the succeeding OP. PCSs from left to right in Figure 1 handle the pallet changes from OP1 to OP2, from OP2 to OP3 and so on so forth respectively. Each PCS has four pallet changers and takes 180 seconds for the changing operation. The number of pallets required in the system is assumed infinite in this study, although appropriate number needs to be investigated in the further study.

3.3 Processing Times of Works

We consider three kinds of works in this study. The machining operations of each kind of work are divided into five common operation groups, OP1 to OP5. Each OP for all kinds of works is constituted of similar operations requiring similar tools with different processing times as shown in Table 1. The product mix is assumed to be 45%, 20% and 35% for Work 1, 2 and 3, respectively. The material warehouse randomly dispatches works into the system according to the product mix. Setting the cycle time to 48 seconds, monthly working time to 480 hours and total production of 30,000 pieces in a month, thirty eight MCs are required in the system as given in 3.1. The utilization of the MCs are set to 85% anticipating the failure during the operation although no failure was assumed in this study.

Table 1: Processing Times for OPs of All Works

	OP1	OP2	OP3	OP4	OP5
WORK1	343.86	328.56	514.98	240.00	480.00
WORK2	276.06	301.20	351.00	193.80	360.00
WORK3	434.46	212.22	364.02	240.00	480.00

4 BASIC STUDY ON AUCTION-BASED ALGORITHM

In this section, we investigate the basic effect of the auction-based algorithm on the overall performance of a system with square array MCs.

4.1 MC Selection Algorithms

The purpose of this study is to investigate the behavior of specialization of MCs to a specific work and/or OP when the auction-based algorithm is employed as a simple selection rule of MCs and then to seek the possibility to specialize or characterize MCs for the processing of a specific work and/or OP. In other words, the proposed algorithm can be concluded to be effective if the following characteristics are observed in the experimental results.

- MC shows a high specialization ratio for a specific kind of work and OP.
- MC shows a high specialization ratio for a specific OP of any kind of works.
- MCs processing a specific OP form a group and locate from left to right in Figure 1 forming a flow of works.

The types of bid listed in 2.2 are expected to be effective to obtain such results. To investigate the effect of the auction algorithm, two algorithms below are applied to select an MC for processing the succeeding OP of a work.

[Algorithm 1] Use Type 1 bid only.

This is equivalent to select a first available MC. If some MCs are available, the one with the longest idle time is selected.

[Algorithm 2] Use all types of bid in the listed order in 2.2.

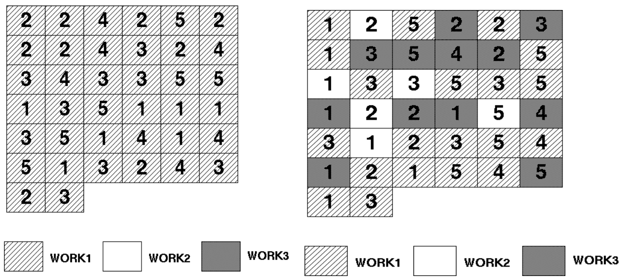
This is to apply all types of bid one by one when more than one MCs reply a same bid price.

4.2 Experimental Results

The experimental results applying the algorithms are summarized in Table 2. The simulation period is set to one month, manufacturing 30,000 pieces in total. The layout of thirty eight MCs was set in near square array as shown in Figure 3 in this study.

Table 2: Effect of Algorithms on System Performances

	Algorithm 1	Algorithm 2
Total processing time (hours)	497.87	399.84
Utilization of system	0.77	0.96
S-ratio of System	0.096	0.549



(a) Algorithm 1 (b) Algorithm 2

Figure 3: S-Work (i*, j*) at Each MC

Algorithm 2 reduced the total processing time about 20% and increased the average utilization of MCs from 0.77 to 0.96. Considering that the simulation time is measured from the time when the first work carried into the system to the time when the last work carried out to the product warehouse, we can conclude that the system is fully utilized by Algorithm 2 and can provide a sufficiently large margin for the larger production volume. These significant improvements observed in the system performance indicate the effectiveness of the auction-based algorithm for the MC selection.

The mean specialization ratio of the system by Algorithm 2 is 0.549, while that by Algorithm 1 is 0.096. This suggests that MCs may be specialized to process a certain work and OP by applying some types of bid instead of all types in Algorithm 2.

Figure 3 shows the work kind and OP of S-Work at each MC. Algorithm 1 selects a first available MC regardless to its position and specialization characteristics, and the work kinds of S-Work at all MCs were Work 1 reflecting the production volume. The numbers in Figure 3(a) represent the OP numbers of S-Work, which are equivalent to S-OP of Kind-1, while S-OP for other kinds were quite different from work to work.

On the other hand, the kinds of work of S-Works vary from MC to MC as shown in Figure 3(b) for Algorithm 2, while S-OP of each kind of work were the same at each MC. This suggests that each MC tends to process a certain OP of any work kinds since Type 2 bid selects an MC whose OP and/or kind of S-Work at the moment matches to those of the candidate work if possible. It is also noted that MCs for each kind of work in S-Work are 20, 6 and 12, which reflect the product mix.

5 EFFECT OF TYPE OF BIDS ON THE CHARACTERIZATION OF MCS

The effectiveness to introduce the auction-based algorithm for the MC selection is shown in the preceding section. In this section, we consider to apply a selected set of bid types instead of the full set in different order and investigate the effect of bid types on the characterization of MCs.

5.1 Selected Sets of Bid Types

Five types of bid were considered and applied in the previous section in the listed order. The first type of bid is to find out the availability of MCs and is reasonable to be requested for the reply at first. However, the bid types to be requested and their requesting order of the remaining types will affect the selection of MCs. In this section two types of bid are chosen from the remaining four types forming a triplet bid set together with the first type. Twelve sets are formed listing all possible combinations and permutations as given below and are tested. The simulation period for the experiments in this section is set to 10,000 pieces. In each test, 50,000 processing requests are sent to MCs.

{1,2,*} : {1,2,3},{1,2,4},{1,2,5}
{1,3,*} : {1,3,2},{1,3,4},{1,3,5}
{1,4,*} : {1,4,2},{1,4,3},{1,4,5}
{1,5,*} : {1,5,2},{1,5,3},{1,5,4}

5.2 Experimental Results

The S-OP and S-Kind of S-Work at each MC and its S-ratio for each test are summarized in various ways and compared. Typical summaries are in the forms of Figure 3 and of Tables 3 and 4.

5.2.1 Mean S-Ratio

The mean S-ratio is an indicator of overall specialization of MCs to specific work kinds and OPs, i.e., S-Works. High S-ratios are obtained by {1,2,*}; 0.57 by {1,2,3}, 0.51 by {1,2,4} and 0.62 by {1,2,5} which is the highest among the tested cases. The S-Work and other related results by {1,2,5} are summarized in Table 3. The degree of specialization by {1,2,5} at each MC is high but neither the distribution pattern of S-Kind nor that of S-OPs on MCs does not show any clear characteristics leading to the grouping of MCs to a specific work kind or to the work flow.

Table 3: S-OP, S-Kind and S-ratio of S-Work for {1,2,5}

[4][3] (0.49)	[4][1] (0.60)	[1][1] (0.66)	[2][1] (0.64)	[5][2] (0.46)	[3][3] (0.60)
[2][3] (0.58)	[3][1] (0.69)	[3][1] (0.72)	[5][3] (0.63)	[2][1] (0.66)	[2][1] (0.66)
[5][3] (0.66)	[3][3] (0.57)	[3][3] (0.59)	[3][2] (0.64)	[3][1] (0.73)	[5][1] (0.57)
[1][3] (0.62)	[1][3] (0.65)	[5][1] (0.61)	[1][1] (0.63)	[5][1] (0.61)	[2][2] (0.60)
[1][1] (0.63)	[1][2] (0.57)	[3][1] (0.67)	[2][3] (0.57)	[5][1] (0.57)	[2][3] (0.60)
[5][1] (0.58)	[1][1] (0.65)	[3][3] (0.58)	[4][1] (0.62)	[2][1] (0.65)	[1][3] (0.65)
[4][3] (0.49)	[3][1] (0.68)	[S-OP] [S-Kind] (The largest S-ratio)			

(Mean S-ratio: 0.62)

Table 4: S-OP, S-Kind and S-ratio of S-Work for {1,4,5}

[1][1] (0.27)	[1][1] (0.25)	[2][1] (0.35)	[3][1] (0.26)	[4][1] (0.20)	[5][1] (0.22)
[1][1] (0.21)	[1][1] (0.22)	[2][1] (0.34)	[3][1] (0.26)	[4][1] (0.18)	[5][1] (0.22)
[1][1] (0.26)	[1][1] (0.25)	[2][1] (0.34)	[3][1] (0.28)	[4][1] (0.18)	[5][1] (0.22)
[1][1] (0.27)	[1][1] (0.25)	[2][1] (0.31)	[3][1] (0.29)	[4][1] (0.20)	[5][1] (0.23)
[1][1] (0.23)	[1][1] (0.22)	[2][1] (0.34)	[3][1] (0.29)	[4][1] (0.19)	[5][1] (0.21)
[1][1] (0.27)	[1][1] (0.27)	[2][1] (0.33)	[3][1] (0.29)	[4][1] (0.19)	[5][1] (0.23)
[1][1] (0.25)	[1][1] (0.23)	[OP] [Kind] (S-ratio)			

(Mean S-ratio: 0.25)

Considering that the mean S-ratios by {1,*,2} are also relatively high, 0.28 by {1,3,2}, 0.43 by {1,4,2} and 0.31 by {1,5,2}, Bid type 2 which focuses on S-Work at each MC functions effectively to the specialization for a specific work although it does not form any specific characteristics on the patterns of S-Kinds and S-OPs by itself. Bid type 5 also focuses on the work kinds and OPs processed just before, but is not so effective as Bid type 2 in obtaining high mean S-ratios.

5.2.2 S-OP Pattern for Each Work Kind

In order to study the possibility to form a work flow by the algorithm, S-OP for each work kind at each MC is obtained and typical patterns for Kind-1 are shown in Figure 4. S-Work and related results for {1,4,5} are summarized in Table 4. The S-OP patterns for a bid set are slightly different from a kind to a kind, while those for all bid sets in {1,2,*}, {1,4,5} and {1,5,2} are the same for each bid set. It is noted that S-OP patterns for {1,2,5} and {1,4,5} are the same for all work kinds and are given in Tables 3 and 4, respectively. By these observations, it is concluded that each bid set yields similar S-OP patterns for all work kinds.

1	2	2	3	3	5
1	2	2	2	3	3
1	4	2	4	3	4
3	1	3	2	1	5
1	3	2	5	3	5
1	5	5	4	2	4
1	1				

(a) {1,2,3}

2	2	2	4	5	5
1	2	2	3	4	5
1	2	2	3	4	5
1	2	3	3	4	5
1	2	3	3	4	5
1	1	2	3	4	5
1	1				

(b) {1,3,4}

1	5	2	3	4	5
1	5	2	3	4	3
1	4	2	3	4	3
1	1	2	2	4	5
1	5	3	3	5	5
1	4	2	3	4	5
5	1				

(c) {1,4,2}

2	2	3	4	4	4
2	2	2	3	5	4
1	2	3	3	5	5
1	2	3	3	5	5
1	1	2	3	5	5
1	1	1	3	3	5
1	1				

(d) {1,5,3}

Figure 4: S-OP Patterns of Kind 1

Figures 4(a) and 4(c) and Figures 4(b) and 4(d) show differences in the MC locations with S-OPs 4 and 5. Patterns in Figures 4(b) and 4(d) show that a work flow from left to right is formed. These patterns are obtained by the bid sets with Bid type 3 which tends to select an MC close to PCS.

On the other hand, MCs with OP 4 and OP 5 in Figures 4(a) and 4(c) are located in the leftward columns close to the material warehouse, while a work flow from left to right can be observed on other MCs. The bid sets for these patterns include Bid type 2. Since Bid type 2 tends to select an MC with large S-ratio, it is possible that MCs far from the exit, i.e., the product warehouse, are repeatedly selected to process OP 4 and OP 5 in the early stage of production, resulting in a large S-ratio at such MCs. Especially, if no available MC for OP 5 exists in the rightmost two columns toward the exit, Bid type 4 selects MCs at any location. The pattern for {1,4,2} in Figure 4(c) reflects the above situation.

5.2.3 S-OP Pattern for {1,4,5}

Table 4 shows that S-Kinds of S-Work at all MCs obtained by the bid set {1,4,5} are Kind 1, and S-OPs form a perfect work flow from left to right. S-OP patterns are the same for all work kinds. Although Bid type 4 selects any MC located far from the exit if no MC are available close to the exit, it is considered that Bid type 5 pulls works for OP 5 to

MCs in the rightmost column once an MC in that column completes the processing of a work for OP 5.

S-ratios at each MC are recalculated with respect to OP numbers and the largest S-ratios and S-OPs are given in Table 5. The S-OP pattern remains the same as in Table 4. The largest S-ratios at MCs are ranging from 0.42 to 0.76 and are relatively high although the range depends on OP. The mean S-ratio of the system is 0.57 and those for each OP are 0.55 for OP 1, 0.75 for OP 2, 0.61 for OP 3, 0.45 for OP 4 and 0.50 for OP 5.

Table 5: S-ratio with respect to OP Numbers

1 (0.58)	1 (0.58)	2 (0.76)	3 (0.59)	4 (0.44)	5 (0.50)
1 (0.51)	1 (0.52)	2 (0.76)	3 (0.62)	4 (0.42)	5 (0.49)
1 (0.55)	1 (0.56)	2 (0.75)	3 (0.64)	4 (0.44)	5 (0.46)
1 (0.59)	1 (0.53)	2 (0.73)	3 (0.65)	4 (0.47)	5 (0.50)
1 (0.56)	1 (0.48)	2 (0.76)	3 (0.57)	4 (0.44)	5 (0.53)
1 (0.51)	1 (0.61)	2 (0.75)	3 (0.61)	4 (0.46)	5 (0.49)
1 (0.54)	1 (0.52)	OP (S-ratio)			

(Mean S-ratio: 0.57)

Since 10,000 pieces of works are manufactured in the simulation period, 50,000 requests for processing are announced in total. Among them 4,559 requests were terminated selecting an MC by the first bid, 11,066 by the second and 19,695 by the third. Remaining 14,680 were determined randomly. These results indicate that the third bid selecting an MC whose last processing work coincides to the candidate work has a dominant influence on determining S-OP pattern.

6 CONCLUSIONS

A manufacturing system with machining centers located in a square array is considered for an agile manufacturing in this study. All products are assumed to be processed by a sequence of common operation groups requiring the pallet changing operation after processing of each OP. Assuming that all MCs can process any OP of any kind of work properly fixed on a pallet, an auction-based algorithm with five types of bid is proposed to select an MC to process a work prepared at a pallet change station. The possibilities to form a smooth flow of works on MCs and/or to divide MCs into groups specialized to process a specific kind of works are investigated by simulation. Following results are obtained

The auction-based algorithm with five bid types is effective to improve the system utilization and to let MCs process a specific work kind and OP to certain extent.

A smooth work flow can be formed by properly selected and ordered bid sets, but the grouping of MCs with respect to a specific work kind is difficult to realize by simply applying the bid set.

Each bid type shows its characteristics in forming a work flow or in specializing to process a specific work, but the proper combination and the requesting order of bid types have dominant effect on the characterization of MCs.

In addition to more detailed study on the characterization of MCs, it is necessary to investigate how to find the proper numbers of pallets and AGVs and to investigate the effect of the location of PCSs. It is also an important and further study to seek an effective method enabling both to divide a square array MCs into groups for specific work kinds and to form a work flow within the group.

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