Intelligent Job Shop Scheduling Based on MAS and Integrated Routing Wasp Algorithm and Scheduling Wasp Algorithm

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***Abstract*—Dynamic scheduling algorithms are gaining more and more special attention for their satisfying robustness when confronted with unexpected events as well as their considerably high performance in scheduling. An organization structure for intelligent job shop scheduling based on MAS (Multiple Agents System) is put forward to achieve effective and efficient production. A hybrid multi-layer agent structure is put forward to facilitate constructing various agents. Consequently, all resources in a manufacturing system are reorganized into an agile manufacturing network of agents of autonomous and cooperative characteristics. Regarding wasps as a specific kind of agents, wasp colony algorithms are used to solve job shop dynamic scheduling problem. Based on the principle of the wasp colony algorithm, two different algorithms, namely the routing wasp algorithm and the scheduling wasp algorithm, are combined to solve the job shop dynamic scheduling problem. The algorithms are modified to better adapt to job shop dynamic scheduling environment. The algorithms are developed based on Eclipse 3.2 and J2SE 6.0. Simulation experiments are accomplished and experimental data are analyzed. The results show that the principle of the algorithms is simple, their computational quantity is small, and they can be applied to multi-batch dynamic scheduling with unpredictable entry time due to their favorable potential.**

***Index Terms*—job shop scheduling, dynamic scheduling, MAS, wasp colony algorithm, Eclipse, J2SE**

I. INTRODUCTION

In a modern manufacturing system, each part of the system needs to make decision independently. Production scheduling and control [1][2] is regard as a pivotal technology to realize agile production where various constraints need to be satisfied by choosing and configuring different resources, and different production scheduling and control strategies and methods.

Confronted with the complexity of manufacturing environment, manufacturing system, and manufacturing process, how to abase this complexity is an important problem to realize production scheduling and control effectively. Production scheduling and decision-making are a multiple objective optimization problem where local decision-making and optimization lie at each phase of production scheduling and control. So, in the paper, workshop scheduling and control is regard as distributed problem solving based on MAS (Multiple Agents System) [3][4].

Most job shop scheduling problems are NP-hard. There is not a set of systematic theories and methods. The future research tendency of job shop scheduling is integrated, dynamic and intelligent theories and methods [5].

The researches on application of wasp colony algorithms to job shop scheduling are investigated in Carnegie Mellon University and Nanjing University of Aeronautics and Astronautics (NUAA) [6][7]. Vincent Cicirello and Stephen Smith put forward scheduling swap algorithm and routing wasp algorithm. The algorithms need to be investigated further to apply to practical scheduling problems.

Based on the basic principle of wasp colony algorithms, routing wasp algorithm and scheduling wasp algorithm are integrated to solve job shop dynamic scheduling in the paper. The algorithms are revised to adapt to different job shop scheduling environments. The algorithms are developed based on Eclipse 3.2 and J2SE 6.0. Simulation experiments are accomplished and the experimental data are analyzed.

II. THE REQUIREMENTS OF DYNAMIC JOB SHOP SCHEDULING

The future market competition environment is unpredictable, so a manufacturing system should have the ability to adapt to the change of the environment, and job shop scheduling should also be flexible, self-adaptive, open, and intelligent. The distributed control mode has more superiorities than the centralized control mode. According to the distributed control mode, the requirements of dynamic job shop scheduling are follows.

- Open distributed architecture. The manufacturing resources at each level of the manufacturing system are distributed geographically and logically. The open distributed architecture facilitates the dynamic integration of the required manufacturing resources, the communication and share of data and information on computer networks, and the mutual consultation and cooperation..
- Flexibility and agility: The self-organization ability of the whole manufacturing system combined with its autonomous manufacturing resource organization can satisfy the demand of small and medium batch production. The manufacturing resources can be associated optimally by reconstructing the resources. Various logical or functional units of different granularity can be established. So the utilization ratio of the manufacturing resources as well as the productivity of the manufacturing system can be improved. As a result, the production tasks can be finished on time according to production planning.
- Similarity of hierarchical structures. The manufacturing system possesses a hierarchical architecture. Similar structure can be found at different levels of the architecture. The manufacturing units at different levels are connected through computer networks. The manufacturing resources or subsystems at lower levels can be used as a whole body by the corresponding resources or subsystems at the upper levels.
- Multiplicity of the manufacturing resources. Under the tendency of the globalization of the manufacturing market, enterprises need not have all functions to produce some product. They can obtain capabilities through the cooperation with partners. So, various manufacturing resources of different structures, components, and capabilities are employed that store data, knowledge, and information in their specific formats. In order to realize the cooperation among the manufacturing resources, they should be connected through computer networks in some logical way.
- Adaptability to the dynamic manufacturing environment and the ability to deal with emergency. In order to quickly respond to the change of the manufacturing environment, the manufacturing system should have powerful adaptability and ability, such as fault tolerance, expendability, and recombination. The dynamic organization of the manufacturing system provides a way to realize the dynamic job shop scheduling. Thus, the manufacturing system can deal with incidents in time.
- Importance of local decision-making. In the dynamically changing manufacturing environment, as the information, such as production task, process planning, workshop and machine state, and so on, is difficult to estimate, a long-time production plan cannot be made effectively. So, local reasoning and decision made at different decision nodes in the manufacturing system become very important. Aiming at the whole objective, almost every functional node should make local decision by itself independently. Because various events are resolved independently at each decision-making node, the dynamic adaptability of the production scheduling and control is improved.

III. Intelligent Job Shop Scheduling Based on MAS

Because production tasks and state of a job shop are dynamic and transient, long-term production plan or scheduling and comprehensive analysis of manufacturing system and manufacturing process is unworkable by and large. Moreover, dynamic changes and unpredictable mutual action exist among various resources of a manufacturing system. In the course of production, local decision needs to be made independently at each workplace. Thus, local decision-making is especially important in a dynamic manufacturing environment. In order to effectively solve the problem, agile manufacturing oriented job shop scheduling based on MAS is put forward. Accordingly, a complex manufacturing system is divided into many small manageable agents that communicate and cooperate with each other. And, the problem of multiple objective optimization of production scheduling and control is converted into the problem of cooperative problem solving among agents.

All kinds of manufacturing resources are reorganized as multifarious agents with different resources and capability. They play different roles in different production tasks and at different time. Under given manufacturing constraints, through agent self-organization and cooperation, flexible mechanism of management and organization is used to dynamically form manufacturing system needed. Consequently, all manufacturing resources can be brought into full and balanced play to realize the common production aim, and respond to the demands of market and users quickly.

A. The Characteristics of Intelligent Job Shop Scheduling Based on MAS

Due to distributed problem solving method adopted, the requirements, such as flexibility, agility, reliability, robustness and expansibility of modern manufacturing system are satisfied with dynamic job shop scheduling based on MAS. Its characteristics are as follows.

- Various agents are reorganized into a loosely coupled, autonomous, and cooperative manufacturing system.

- All sorts of manufacturing agents are able to make local decision independently, have the ability to reconfigure, improve and adapt to the changes of manufacturing environment, and respond actively to the demands of market.
- Various agents cooperate concurrently in the MAS system. As a result, it possesses high efficiency of production scheduling and control.
- On the basis of unified information infrastructure, various agents are connected with each other to communicate and exchange information and data.
- Various agents solve the whole production scheduling problem through exchanging and disposing manufacturing information. The relation among the agents changes dynamically and continuously.
- It is convenient to expand the manufacturing system reconfiguration.
- Competition and cooperation coexist under the same production aim.
- Distributed problem solving is used to realize production scheduling and control. As a result, it is not sensitive to the scale of problem solving.
- Various sudden occurrences can be settled effectively and reliably.

B. The Architecture of Intelligent Job Shop Scheduling Based on MAS

According to the function analysis of a workshop, production scheduling and control put forward in the paper are divided into four levels, namely production schedule level, task decomposition and distribution level, production scheduling and control level, and resource management level. Its characteristics are as follows.

- Taking task decomposition and assignment level as the crux of the matter, the mechanism of cooperative decision-making and collaboration is constituted.
- Intelligent approaches are used to complete cooperative problem solving of distributed decomposition of production tasks.
- The effective integration of task distribution and production scheduling is realized by combining capability matching with dynamic task scheduling.
- The granularity of agents and construction of MAS are dynamically determined according to production requirements.
- Dynamic task reconfiguration can be carried out to be seasoned with the internal and external changes of the manufacturing system.

C. Intelligent Encapsulation of Manufacturing Resource Agents

According to the automation level and working mode of each functional entity to finish its task in a manufacturing environment, the manufacturing resource agents are divided into three categories.

- The automatic equipment agent. It can run automatically in the production process, for example, the top grade NC equipment, etc.
- The semi-automatic equipment agent. It works in an interactive mode, for example, the regular NC equipment, etc.
- The manual equipment agent. It is operated manually in the production process.

The functions of all manufacturing resources are definite. According to their current status, the performance and history data, decisions can be made by the man who is responsible for the resource agent based on a Decision Support System (DSS). In the manufacturing system, all resource agents constitute an integral whole to realize their functions. The resource agent is composed of a function module, a management module and a communication module. According to the different automatic level of the manufacturing equipment, the information exchange mode and the information coupling extent among the function module, manage module and communication module are different.

D. The General Multi-Layer Mixed Construction of the Agents

All the agents are a fully autonomous integrated system. They can make decisions and control their behavior independently. They can plan and control their behavior based on their perception of their environment and the information acquired by interacting with the outside. So, they can realize the defined goal by cooperating with the other agents. The general multilayer mixed construction of the agents is shown in Fig. 1.

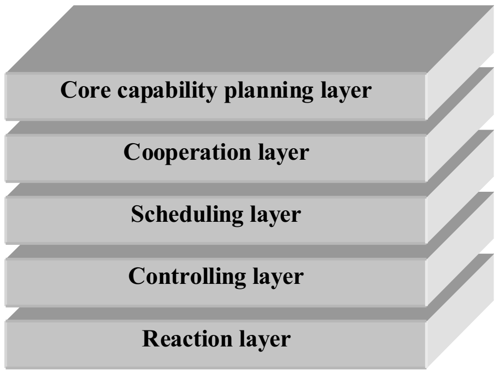

Figure 1. The general multilayer mixed construction of the agents.

- The core capability planning layer. As an autonomous entity that can make decisions independently, the layer takes charge of the planning and developing of the agent core capability and its core competitive power. Because the construction, capability and granularity of different agent are variant, so each agent should determine its developing orientation, starting plan and it's behavior rules according to the outside changes and itself status, and achieve the planed object by controlling its behavior and inner status.
- The cooperation layer. This layer responds to calling for tender and making bidding. It can evaluate an indent and decide whether it is worth

to bid and the tender offer. After the indent is accepted, it will be transformed into the inner productive task of the agent and will be sent to the scheduling layer. Based on corresponding communication protocol and language, the agent can complete its job by interacting with other agents.

- The scheduling layer. This layer decomposes the received task, makes and updates the scheduling task bill dynamically. It can coordinate the manufacturing task queue and make optimal arrangement for the manufacturing tasks. It can assign the productive sub-tasks according to the capability, status, performance and history data of the manufacturing resources defined within the agent, make the concrete working operation for each manufacturing resource and process productive tasks in batches. At same time, it can also assign and coordinate the equipment resources, make equipment occupation plan, generate equipment preparation task and send it to productive preparation departments. When a new productive task or an unforeseeable event occurs, such as equipment malfunction and emergent productive tasks, some productive tasks need to be re-decomposed, and a new task bill should also be made. If the problem cannot be resolved by the scheduling layer, it would be reported to the cooperation layer.
- The controlling Layer. The static characters of an agent, such as the machine model and specification, are fixed during its working process. But its dynamic characters are variant during its working process, for example, the machine is in idle state or not. The controlling Layer monitors the execution of the productive task according to the productive task bill from the scheduling layer, and reports the real productive state as well as its dynamic characters of manufacturing resources to the scheduling layer.
- The reaction Layer. This layer carries out the operation chain. It transmits the executable operation command to equipments. It also monitors the dynamic status of its manufacturing environment, and responds in real time according to the environment changes. It can reconstruct its inner manufacturing resources according to practical requirements. After it accepts the feedback information from the equipments and worker, it dynamically generates the status report that can be referenced by the other layers. The message exchange between the agents and outside environment is also carried out at this layer.

E. Construction of the Manufacturing Resource Agents

Because their requirements and functions are different in reality, the structural style and the components of each agent are different. In order to construct various agents conveniently, the mixture hierarchical agent structure is used to construct agents that can not only rapidly deal with incidents in the manufacturing system, but also recognize and predict the environmental change automatically. Based on agent construction rules, the main agent types in the manufacturing system MAS model include:

- Task Agent: The Task Agent manages all tasks and monitors their completion. The Task Agent takes charge of task bidding of the manufacturing system. It accepts or issues manufacturing tasks, receives information feedback, records task requirements and corresponding bonus or penalty methods. The Task Agent classifies and decomposes productive tasks and evaluates the feasibility of the required manufacturing resource agents. If it is feasible, Task Agent assigns the task to the Resource Agent. Otherwise, the task bidding is needed.
- Scheduling Agent: The Scheduling Agent takes charge of productive task scheduling and control by monitoring task implementation and controlling Resource Agents' activities. If events occur, such as indent change, emergent productive task and resource Agent delaying, it reschedules the productive tasks and timetable, or looks for substituted Resource Agents, or finishes the task with the cooperation of other Agents. If an agent cannot solve its issue and finish its productive task, the task would be returned to the Task Agent.
- Resource Management Agent: The Resource Management Agent takes charge of all Resource Agents and the manufacturing resources in the manufacturing system. It can provide decision-making support for the Task Agent and Scheduling Agent by recording Resource Agent data, such as attributes, function, capability, and so on. It takes charge of the configuration, maintenance, upgrade, reconstruction and its quantity and granularity of Resource Agents.
- Resource Agent: The Resource Agent is the final executant to complete the productive task in reality. It integrates all kinds of manufacturing resources such as robots, NC machines, machining centers and measurement devices, etc. Each Resource Agent has its own special structure and function. The function of the Resource Agent can be described with its function model, and its dynamic behavior attributes can be described with the dynamical behavioral model. So the Resource Agent can fully reflect the total function and state of the corresponding manufacturing resources. According to its current state and manufacturing system state, the Resource Agent determines its working sequence, the expected operating interval, idle time interval, etc.
- Communication Management Agent: The Communication Management Agent takes charge of all the communication transactions within or out of the manufacturing system, such as data report generation and network information identification, etc.

One agent can not only be composed with the other agents, but also can be a common component of several different agents.

IV. Wasp Colony Algorithms

Regarding wasps as a specific kind of agents, wasp colony algorithms are used to solve job shop dynamic scheduling problem.

A. *Routing Wasp Algorithm*

Each machine tool has a processing queue in a job shop. The unit of the processing queue length *L* is time. A routing wasp is assigned to each machine tool and responsible for scheduling workpieces for the machine tool [6] [7].

A threshold value decides whether the routing wasp can schedule a workpiece. $\theta_{w,j}$ is the threshold of routing wasp *w* for working operation *j*. Each workpiece waiting for processing has a stimulus value Sk that is equal to the time waiting for processing. Thereinto, *k* is the code name of the workpiece. Scheduling probability of routing wasp *w* for workpiece *k* is computed using equation (1).

$$P\left(\theta_{w,j},S_k\right)=\frac{S_k^2}{S_k^2+\theta_{w,j}^2} \quad (1)$$

In reference [6], $\theta_{w,j}$ is defined as below.

$$\theta_{w,j}=\delta_{w,j}+kT_w^p+kmT_w^s \quad (2)$$

Thereinto, $\delta_{w,j}$ is the initial threshold value, T_w^p is the processing time of a working operation, T_w^s is the setup time of a working operation, *k* is a constant to control the weights for processing time and setup time, *m* is 0 if working operation *j* is the last one in the waiting queue of a machine tool, otherwise, *m* is 1.

In reference [6], Sk is defined as below.

$$S_k=S_k^0+zt_w \quad (3)$$

Thereinto, S_k^0 is the initial stimulus value, t_w is the workpiece waiting time, and *z* is a constant that adjusts the weight of the workpiece waiting time.

In job shop scheduling, if the scheduling probabilities of several machine tools are equal, some researchers chooses a routing wasp randomly while reference [6] chooses the machine tool with the shortest queue. However, some researchers choose a routing wasp by competition.

B. *Scheduling Wasp Algorithm*

There is a scheduling wasp for each workpiece in the queue of a machine tool [8]. The force value of scheduling wasp *w* is defined as below.

$$F_w=T_w^p+T_w^s+i_w \quad (4)$$

Its success probability is defined as below.

$$P_w\left(F_w,F_p\right)=\frac{F_p^2}{F_w^2+F_p^2} \quad (5)$$

In the paper, the scheduling strategy and scheduling wasp competition are modified. When a working operation of a machine tool is completed, its processing queue is searched. If the type of a working operation in the queue is the same as that of the just completed working operation, it will be the next working operation to process. Otherwise, scheduling wasps compete to generate the winner in terms of equation (5).

V. Algorithm Realization

A. *Developing Tools*

In the paper, Eclipse 3.2 and J2SE 6.0 are used to develop the algorithms, which are supplier-independent open platforms. Eclipse provides a framework to develop software that makes it easer for users to create, integrate and employ its software tools.

B. *Procedure*

In the paper, the routing wasp algorithm and scheduling wasp algorithm are integrated to solve the job shop scheduling problem. A routing wasp is assigned to each machine tool to take charge of its scheduling. A scheduling wasp is assigned to each working operation in the processing queue. When a machine tool is going to process a new workpiece, a scheduling wasp gains its processing opportunity through competition.

The algorithm procedure is as follows.

(1) The machine tools in the job shop check the status of their processing queues. If a machine tool is idle and its processing queue is not empty, it begins to process a new working operation that is determined through scheduling wasp competition. Besides, the parameters of the machine tools are updated.

(2) The Machine tools judges whether it is needed to introduce new workpieces. If so, traverse the waiting queues of workpieces. For the workpieces that can be processed in the queues, their scheduling probabilities are computed in terms of equation (1), (2) and (3).

(3) According to the ranking sequence of the probabilities, the workpieces are assigned to the machine tools until their processing queues are full or there is no workpiece left. When the probabilities are equal, they compete in terms of equation (2) and (3).

(4) The machine tools check the status of their processing queues to determine whether a workpiece is completed. If so, the workpiece is removed from the queue. Then, return (1).

(5) When an event occurs, the related data are updated in the next cycle.

When the event occurs, the disposal procedure is as follows.

(1) When a new batch of workpieces arrives, the workpieces are added to the waiting queue of workpieces.

(2) When an emergent batch of workpieces arrives, the workpieces are added to the waiting queue of workpieces. Original workpieces are removed from the processing queues and waiting queues of machine tools. Then, the emergent workpieces are added to the waiting queues.

After the emergent workpieces are completed, the original workpieces are added to the waiting queues again.

(3) If a machine tool breaks down, the workpieces in the processing queue of the machine tool are added to the waiting queue. The workpiece being processed nullifies. The machine tool is removed from the job shop.

C. Simulation

The simulation of job shop scheduling is achieved by adopting succinct scheduling method and intuitionistic graphic interface. Once the scheduling button is clicked on the interface, the scheduling operation of one cycle is executed. Combined with scheduling Gantt charts, the whole scheduling procedure using the wasp colony algorithms can be shown clearly.

VI. Test of the Algorithms

A. Example

The example used here is from reference [5]. In a job shop, there are four kinds of workpieces and each kind needs three working operations. M1, M2, M3, M4, M5, and M6 are machine tools. The relations between workpieces and machine tools are shown in Table 1.

In the test, the time of working operation transition and workpiece transportation is not taken into account. So, L_i=0, L_f=6, m=0, δ_z=0, k=1, S_{z0} =0, and z=1.

B. Results

For one batch of workpieces, the processing time is 19. If the workpieces are divided into three batches and their time interval is 10, the time needed is 41. The scheduling Gantt chart is shown in Fig. 2.

In reference [6], the time needed for one batch is 19 and the time needed for three batches of workpieces is 39. Those are in accordance with the results of above simulation approximately.

VII. Analyses

A. Routing Wasp Algorithm

Compared with other machine tools, the performance of M6 is so poor that it cannot gain any workpiece to process in the whole scheduling procedure. If there are a lot of workpieces to process, it maybe benefit that a machine tool of poor performance gains some workpieces. Hence, t_u is added to equation (3) to represent the idle time of a machine tool. Equation (3) is modified as below.

$$S_k = S_k^0 + zt_w + yt_u \tag{6}$$

Thereinto, y is a constant that is used to control the weight of tu in equation (6).

In the following simulation, M6 gains some processing opportunities. But the whole scheduling effect is not improved. As shown in Fig. 3.

TABLE I. The Relations Between Workpieces and Machine Tools

Workpiece	Working operation	M1	M2	M3	M4	M5	M6
1	1-1	2	3	4	/	/	/
	1-2	/	3	/	2	4	/
	1-3	1	4	5	/	/	/
2	2-1	3	/	5	/	2	/
	2-2	4	3	/	/	7	/
	2-3	/	/	4	/	7	11
3	3-1	5	6	/	/	/	/
	3-2	/	/	4	3	5	/
	3-3	/	/	13	/	9	12
4	4-1	9	/	7	9	/	/
	4-2	/	6	/	4	/	5
	4-3	1	/	3	/	/	3

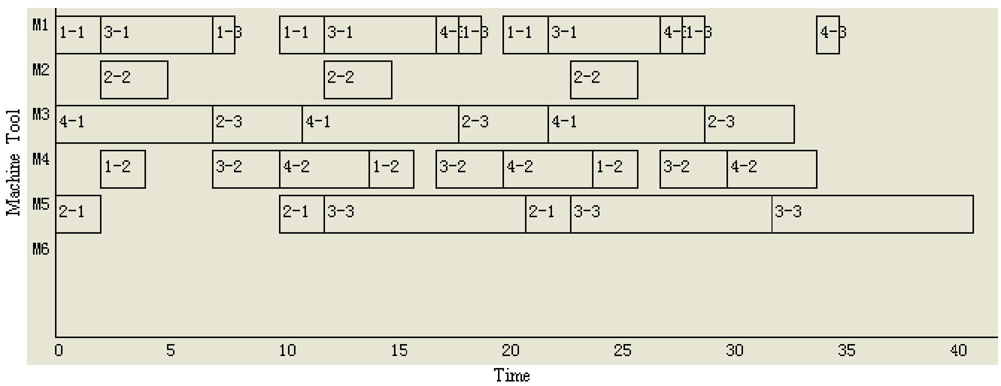

Figure 2. Scheduling Gantt chart for three batches of workpieces.

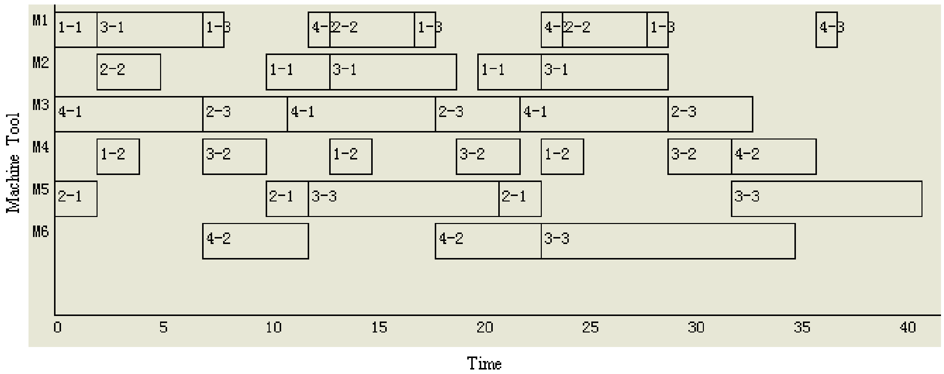

Figure 3. Gantt chart for scheduling three batches.

When multiple batches of workpieces arrive simultaneously, the simulation results are shown in Table 2.

The experimental data show that the processing queue of the machine tool with better performance is full when there are a lot of workpieces to process. As a result, the machine tool of poor performance has little influence on processing efficiency in the long term whether equation (3) or (6) is used. When the workpieces arrive batch by batch or there are not many processing tasks, the machine tool of poor performance usually is idle. Though it does not affect the whole scheduling result, from the point of view of reducing wear of machine tools with better performance, it is recommended to use equation (6) instead of equation (3).

Whereafter, more experiments are carried out and the experimental data are shown in Table 3.

As can be seen that the scheduling results are improved to some extent if the idle time of machine tools and the queuing time of workpieces are not considered.

TABLE II. EXPERIMENTAL DATA

Batch	Using equation (3)			Using equation (6)		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Scheduling of 1 batch	19	19	19	19	19	19
Simultaneous scheduling of 2 batches	29	29	29	30	28	30
Simultaneous scheduling of 3 batches	39	39	39	39	39	39
Simultaneous scheduling of 4 batches	54	50	50	53	53	53
Simultaneous scheduling of 5 batches	68	65	65	63	63	63
Simultaneous scheduling of 6 batches	71	71	71	73	73	73

B. *Scheduling Wasp Algorithm*

For the above example, the simulation results, whether using scheduling wasp or not, are shown in Table 4.

Because the queue length is short (L_f=6), the number of workpieces in a queue is small, there is usually one or two workpieces or the type of working operations are identical by and large. As a result, whether using scheduling wasp or not has little influence on the scheduling results.

TABLE III. EXPERIMENTAL DATA

Batch	$S_k = 1$			$S_k = 1 + t_u$		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Scheduling of 1 batch	19	19	19	19	19	19
Divided scheduling of 3 batches	41	41	41	41	41	41
Simultaneous scheduling of 2 batches	29	29	29	30	30	30
Simultaneous scheduling of 3 batches	39	39	39	39	39	39
Simultaneous scheduling of 4 batches	49	49	49	53	53	53
Simultaneous scheduling of 5 batches	63	63	63	63	63	63
Simultaneous scheduling of 6 batches	69	66	69	72	72	72

TABLE IV. EXPERIMENTAL DATA

Batch	Using scheduling wasp			Not using scheduling wasp		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Scheduling of 1 batch	19	19	19	19	19	19
Divided scheduling of 3 batches	41	41	41	41	41	41
Simultaneous scheduling of 2 batches	30	30	30	30	30	30
Simultaneous scheduling of 3 batches	39	39	39	39	39	39
Simultaneous scheduling of 4 batches	53	53	53	53	53	53
Simultaneous scheduling of 5 batches	63	63	63	63	63	63
Simultaneous scheduling of 6 batches	73	73	73	72	72	72

If the queue length is longer (L_f=15) and the scheduling wasp algorithm is employed at the same time, the experimental results are shown in Table 5. The influence is obvious.

The scheduling results of scheduling wasp algorithm are different in different job shops. It is suitable for multi-objective scheduling problems that need to consider average delay time, delivery cut-off time, etc [8].

C. Comparison with Other Algorithms

In reference [5], the shortest time for one batch scheduling is 18. When new batches arrive, the new batches cannot be processed batch by batch before anterior batch is finished. Hence, the time for three batches is 54.

TABLE V. EXPERIMENTAL DATA

Batch	Using scheduling wasp (L_f=6)			Using scheduling wasp (L_f=15)		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Scheduling of 1 batch	19	19	19	19	19	19
Divided scheduling of 3 batches	41	41	41	41	41	41
Simultaneous scheduling of 2 batches	30	30	30	29	29	29
Simultaneous scheduling of 3 batches	39	39	39	39	44	44
Simultaneous scheduling of 4 batches	53	53	53	49	49	49
Simultaneous scheduling of 5 batches	63	63	63	58	58	60
Simultaneous scheduling of 6 batches	73	73	73	74	74	74

For static scheduling of one batch of workpieces, the scheduling results of wasp colony algorithms are not better than those of other algorithms. But when confronted with uncertainties, such as temporarily added processing tasks, the scheduling results of wasp colony algorithms are better than those of static scheduling algorithms for divided scheduling batch by batch.

VIII. CONCLUSIONS

In the paper, job shop scheduling and control is regard as distributed problem solving based on MAS. An organization structure for intelligent job shop scheduling based on MAS is put forward to achieve effective and efficient production. A hybrid multi-layer agent structure is put forward to facilitate constructing various agents. Consequently, all resources in a manufacturing system are reorganized into an agile manufacturing network of agents of autonomous and cooperative characteristics.

Regarding wasps as a specific kind of agents, wasp colony algorithms are used to solve job shop dynamic scheduling problem. The wasp colony algorithm is a newly presented dynamic scheduling algorithm, which bases on natural insect society behavior models. Based on the principle of the wasp colony algorithm, two different algorithms, namely the routing wasp algorithm and the scheduling wasp algorithm, are combined to solve the job shop dynamic scheduling problem. The algorithms are modified to better adapt to job shop dynamic scheduling environment. The simulation results show that the principle of the algorithms is simple, their computational quantity is small, and the algorithms can be applied to multi-batch dynamic scheduling with unpredictable entry time due to their favorable potential. If the idle time of machine tools and queuing time of workpieces are not considered, the scheduling results are improved to some extent. The scheduling results of scheduling wasp algorithm are different in different job shops. It is suitable for multi-objective scheduling problems that need to consider average delay time, delivery cut-off time, etc. When confronted with uncertainties, such as temporarily added processing tasks, the scheduling results of wasp colony algorithms are better than those of static scheduling algorithms for divided scheduling batch by batch.

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