Enabling Technology of Multiagent Manufacturing System: A Novel Mode of Self-organizing IoT Manufacturing

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Abstract: As the manufacturing mode focuses more on network and community, the orders and production processes are becoming highly dynamic and unpredictable. The traditional manufacturing system cannot handle those exceptional events such as rush orders and machine breakdowns. Nevertheless, the multiagent manufacturing system (MAMS) becomes a critical pattern to deal with these disturbances in a real-time way. However, due to the lack of universality, MAMS is difficult to be applied to industrial sites. A new multiagent architecture and the relay cooperation model based on a positive process relation matrix are proposed to address this paper's issue. An optimized contract net protocol (CNP)-based negotiation mechanism is developed to improve the efficiency of collaboration in the proposed architecture. Finally, a case study of self-organizing internet of things (IoT) manufacturing system is used to test the feasibility and effectiveness of the method. It is shown that the proposed self-organizing IoT manufacturing mode outperforms the traditional manufacturing system in terms of makespan and critical machine workload balancing under disturbances through comparison.

Key words: multiagent manufacturing system (MAMS); contract net protocol (CNP); internet of things (IoT); disturbance; self-organizing

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0 Introduction

The concept of MAMS has a long history since it was put forward, but there are few reports about its practical application in the industry. On the one hand, personalized customization, unpredictable orders and the changeable process are becoming more and more apparent. It is urgent to realize self-organizing production through multiagent manufacturing system (MAMS). On the other hand, the research of MAMS is still mainly at the simulation level. It is one of the most concerning issues in MAMS to encapsulate these physical entities (machine tools, robots, etc.) in the shopfloor into agents with mutual communication and decision-making functions. Another research hotpot is how the task agent exists in the manufacturing system and how to develop the related programs. However, there is little research on the enabling technology of MAMS currently[1].

In this context, combined with current needs of internet of things (IoT) manufacturing, this paper puts forward a relay cooperation model based on a positive process relation matrix. The task information is encapsulated in an information matrix, which is called baton. The baton is used to describe the process of tasks in equipment by transferring between agents. The fundamental problems, such as unclear expression of agent and disconnection between agent and machine control, are solved, which provides a reference for the MAMS application in a shopfloor.

The remainder of this paper is organized as fol-

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lows. Section 1 provides an overview of the concepts related to the enabling technology of MAMS in self-organizing IoT manufacturing. Section 2 introduces an agent mapping relation in the self-organizing IoT manufacturing system and a relay collaboration model of the production process is proposed based on the discussion of a task agent rationality. Section 3 optimizes the traditional contract net protocol (CNP) according to the role definition and communication load balance. Section 4 discusses the specific ways to deal with disturbances through collaboration. Section 5 summarizes the related experimental work and analyzes experimental results.

1 Literature Review

As mentioned above, in this section, we briefly review the studies relevant to the negotiation-based MAMS problem in an IoT-enabled flexible job shop. The purpose of shop-floor scheduling is to assign all tasks to corresponding machines to reduce interference to other distribution resources as much as possible. The research of MAMS is classified into three categories: Multiagent scheduling, negotiation mechanism in multiagent system (MAS) and enabling technology of MAS.

1.1 Multiagent-based scheduling

The multiagent-based shop-floor scheduling is the fusion of distributed artificial intelligence (DAI) and the dynamic scheduling method. The MAS is composed of a series of loosely coupled, autonomous self-learning agents. Regarding multiagent modeling, scholars have conducted related research on different aspects. Cheng et al.[2] proposed a packaging method to make the CNC entity networked and intelligent based on multiagent technologies. Park et al.[3] developed an autonomous manufacturing system based on swarm cognitive agents for rigid structure disturbances. Rodrigues et al.[4] proposed an agent-based method for manufacturing system service reconfiguration and achieved reconfiguration utilizing agent-dynamic identification. Tehrani et al.[5] put forward the agent-based manufacturing dynamic system architecture for process planning. They combined the heuristic search algorithm with the negotiation protocol to deal with the dynamic disturbance. Liu et al.[6] proposed a bidirectional data flow framework between the equipment and the software system.

1.2 Negotiation mechanism in MAS

Multiagents collaborate through a specific negotiation mechanism to realize task assigning in MAS. Therefore, an efficient negotiation mechanism is the premise of real-time dynamic scheduling. Wang et al.[7] studied the real-time scheduling of an agent-based IoT manufacturing flexible job-shop through a negotiation mechanism based on bargaining games, which achieved the optimal assignment of tasks. Guo et al.[8] improved the CNP in three ways: Reducing negotiation communication, improving the multiagent coordination ability, and improving the task qualification evaluation strategy. Zhu et al.[9] used reinforcement learning to perform the task allocation process and improved the CNP to realize communication load balancing. Aiming to solve the local scheduling problem in a dynamic manufacturing environment, Reaidy et al.[10] created a new negotiation model of competition and cooperation. An inter-agent negotiation protocol is proposed based on the cooperative request session principle and competition game theory as well. Yeung.[11] studied the bidding negotiation plan in the multiagent system and solved the message congestion problem by reducing the idle time in negotiation. Yeung[12] put forward an improved CNP to reduce message congestion through the audience restriction strategy.

1.3 Enabling technology of MAS

The multiagent system solves optimally assign problems through the interactive negotiation between intelligent individuals in a swarm collaborative way. In view of the enabling technology of MAS, many scholars have carried out in-depth research on machine learning, Q-learning, swarm intelligence, etc. Jiang et al.[13] reviewed the literature on swarm intelligence and divided it into human systems, social systems, and artificial intelligence systems. Choi et al.[14] proposed a global optimization method for distributed learning and collaborative control of the MAS for intelligence acquisition at the swarm collaborative level. Dai et al.[15] proved the possibility of efficient cooperation among multiagents by embedding the Q-learning algorithm in the particle swarm optimization process. Lee[16] proposed a conflict resolution strategy to solve the environmental conflict between user activities and physical devices in MAS.

Besides, the MAS-based shop-floor dynamic scheduling is more suitable for the current production environment of IoT manufacturing when considering the above research directions[17]. On the one hand, MAMS-based IoT manufacturing combines radio frequency identification (RFID), other sensing, transmission units, etc., to traditional manufacturing shop floors and provides primary conditions for MAS communication. On the other hand, the real-time available capability information and real-time status of various distributed manufacturing resources provided by IoT manufacturing help respond effectively to exceptional events and unforeseen dynamic situations.

2 Multiagent Models

The standard method to realize the interconnection between manufacturing equipment and other units based on heterarchical and complex manufacturing control systems is constructing a software-defined model for the physical ontology. The individual manufacturing equipment can interact with the corresponding software model in real-time and achieve interconnectivity with other units. Therefore, the distributed artificial intelligence-based MAS is the foundation of realizing self-organizing IoT manufacturing[18]. According to the agent's role in the proposed MAMS, agents are divided into functional agents and service agents. In the MAMS framework, the functional agent (e.g., the machine agent) is responsible for the manufacturing execution stage, and the service agents (e.g., coordination agent, real-time monitoring agent, and baton

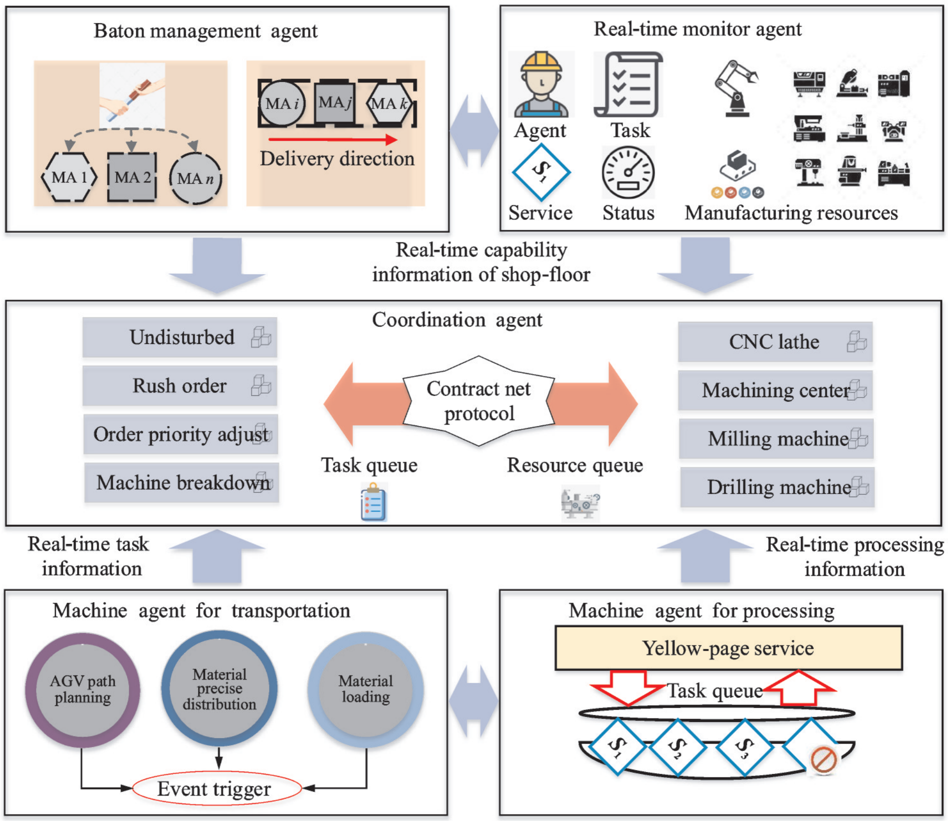


Fig.1 Architecture of MAMS

management agent) provide global optimization for functional agents[19]. Based on the multiagent models mentioned above, the architecture of MAMS is shown in Fig. 1. The machine agent (MA) decides whether to initiate negotiation requests according to the entity status and invites coordination agent (CA) to select appropriate MAs. The baton management agent (BMA) replaces the traditional IoT tracking methods (e. g., RFID) with virtual label, while real-time monitoring agent (RMA) provides real-time information support for scheduling.

2. 1 Machine agent

On traditional manufacturing shop floors, processing entities cannot be interconnected due to the heterarchical control system[7]. In order to realize the interconnection of whole entities on the shop floor, it is necessary to combine IoT manufacturing technology with MAs. As mentioned above, the MA is software-defined manufacturing equipment with essential functions such as perception, interaction, analysis, and execution. It can perceive its status, interact with other MAs on the shop floor, and process tasks timely based on real-time status. The MA consists of three layers, and the specific composition is as follows: Adaptation layer, interaction layer, and decision-making layer.

Fig. 2 shows a machine agent model. The MA is used for packaging all physical entities in the shopfloor, including processing entity, logistics entity, testing entity, etc. The MA mainly consists of two functions. First of all, the distributed heterogeneous physical entities are interconnected through a unified software package. Secondly, the real-time information of physical entities is sent to the suitable information management platform RMA through MA to provide information support for real-time scheduling and exception handling. The MA is mainly used for communication between the manufacturing units and the task pool. Owing to the numerous functions of MA, a single thread cannot meet all the requirements, and the multi-thread model is used in this agent. These threads are responsible for manufacturing unit control, real-time status monitoring, interaction among agents, and decision-making.

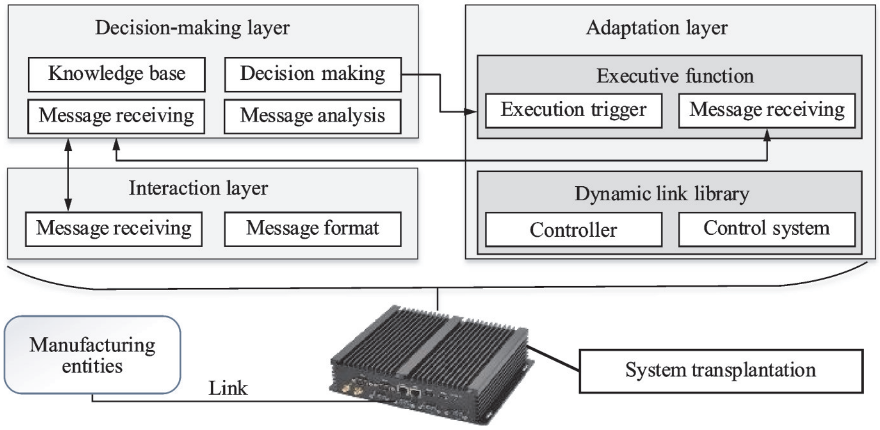


Fig.2 Machine agent model

(1) Adaptation layer

The adaptation layer is mainly used to solve incompatibility problems between different manufacturing entities under heterarchical control systems and communication formats. The adaptation layer design includes primary control, real-time station monitoring, and connection between manufacturing equipment modules, such as file transmission.

(2) Interaction layer

The interaction layer is responsible for the interconnection among agents. In the MAMS-based self-organizing IoT manufacturing, production is completed via the cooperation between different agents, which is realized in the interaction layer. The exchange of information between various MAs is mainly concerned with stable and disturbance conditions according to the characteristics of the process in the IoT manufacturing system.

(3) Decision-making layer

The decision-making layer is responsible for adjusting the processing parameters and selecting tasks by analyzing the real-time status, which is the core of MA. Real-time information mainly comes from two sources. The first is the status information of MA, which is obtained through the monitoring module in the adaptation layer. The second is the shopfloor information.

2. 2 Coordination agent

The CA works mainly in the interactive process of scanning the viable processing entity of the next production process in MA. Its logic module completes the calculation and screening of the feasible bidding set. The steps of the bidding negotiation mechanism are described in Fig.3. The CA is invocated and instantiated by MA in the form of microservice. As the core of real-time scheduling in the shopfloor, the working mechanism of CA will be detailed in Section 5.

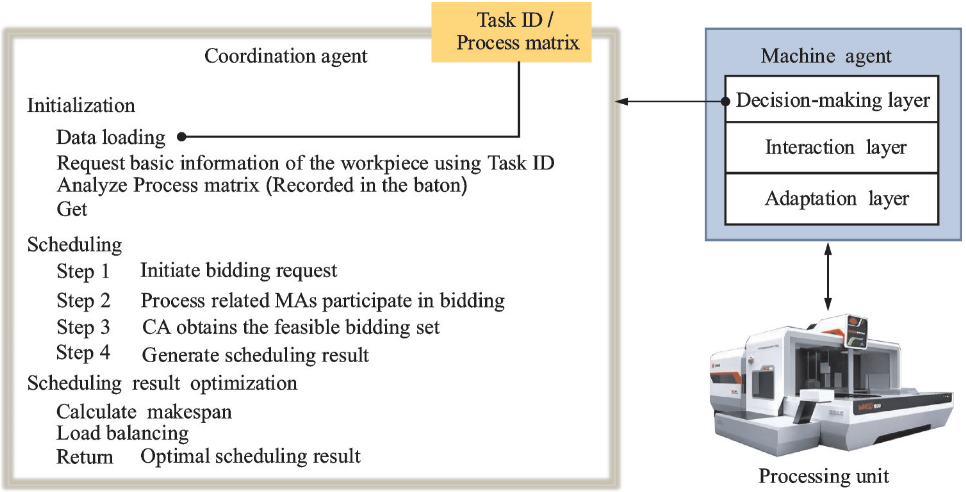


Fig.3 Solution procedure of CA

To reduce the calculation and communication load, it is necessary to separate CA from MA, and CA will become an individual service agent. Doing so may result in a distributed scheduling optimization based on the manufacturing entities' real-time status compared with the traditional dynamic scheduling system.

2. 3 Real-time monitor agent

It is difficult to complete complex tasks independently based on local information and insufficient knowledge of a single agent in the MAMS. It also means that each MA needs to collaborate with other agents to achieve a solution. Therefore, the interaction between agents in the MAMS is the key to allocating manufacturing tasks or exceptional events.

Distributed agents could be an option through negotiation to effectively deal with disturbances in the MAMS-based self-organizing manufacturing system. However, the negotiation result is often locally optimal because of the low utilization of global information for each agent. According to this issue, a solution is to add a RMA. The RMA displays information from the corresponding manufacturing entities, including real-time capability information and real-time task information.

The RMA model is shown in Fig.4. In actual production process, the inevitable short-sightedness of a single MA easily leads to unreasonable decisions. Therefore, to ensure the rationality of the scheduling results, the holistic production task information should be taken into consideration through RMA. The RMA provides real-time working in process (WIP) information and entity status for the scheduling. The existence of RMA ensures that the whole system is working towards global optimiza-

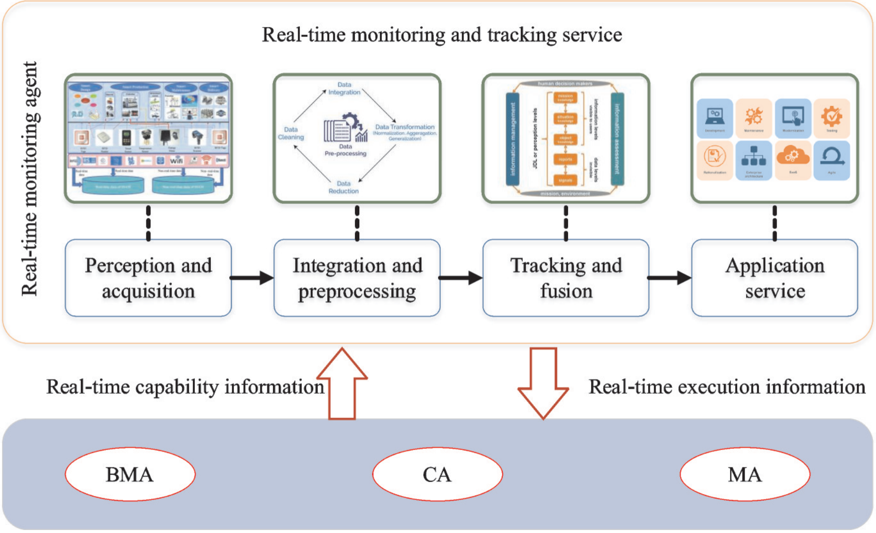


Fig.4 Real-time monitoring agent model

tion and each MA only needs to communicate with the RMA to obtain the global information.

2.4 Baton management agent

Scholars assumed that intelligent terminals such as machine agents or task agents existed on the shop floor before further study in many related studies on MAMS. The rationality of these assumptions was rarely considered. However, each manufacturing resource must encapsulate an individual agent to participate in task allocation negotiation. As the number of manufacturing entities and tasks increases, the computational complexity and communication load of the existing task agent are high.

The core element of IoT is interconnection, and all the manufacturing process information tracking and display rely on RFID. In this paper, the entity label and process information are recorded on the proposed process relationship matrix called baton. Through the baton transmission between MAs, the traditional RFID information reading and writing are replaced, and then the relay cooperation model based on a positive process relationship is established.

In order to express the dependency relationship between processes during processing, it is necessary to construct a positive process relationship matrix table based on process characteristics. The element values in the positive operation relation matrix table corresponding to the processing task are defined as

$$V_{ij}=\begin{cases}1 & O_j \text{ is the precedence operation of } O_i\\ 0 & \text{Else}\end{cases}$$

The operation relationship digraph and matrix table of task A are shown in Fig.5 and Table 1. Although the existence of a task agent has a negative effect on the system performance, it is also unreasonable that if there is no independent unit to man-

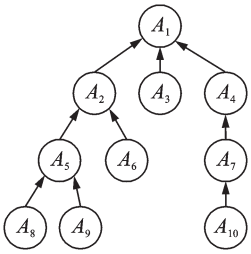


Fig.5 Relationship digraph corresponding to production process of task A

Table 1 Process relationship matrix table of task A

Task	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
A_1	0	1	1	1	0	0	0	0	0	0
A_2	0	0	0	0	1	1	0	0	0	0
A_3	0	0	0	0	0	0	0	0	0	0
A_4	0	0	0	0	0	0	1	0	0	0
A_5	0	0	0	0	0	0	0	1	1	0
A_6	0	0	0	0	0	0	0	0	0	0
A_7	0	0	0	0	0	0	0	0	0	1
A_8	0	0	0	0	0	0	0	0	0	0
A_9	0	0	0	0	0	0	0	0	0	0
A_{10}	0	0	0	0	0	0	0	0	0	0

age the tasks. Based on it, the relay collaboration control method is used to manage the tasks and production processes. The workpiece is regarded as a baton that changes its state between manufacturing resources in this method. The baton records the production process, consumed materials, processing details, etc., which exists in an n-dimensional matrix and is managed by the BMA. The specific workflow is as follows:

(1) The MAMS receives orders and the raw material warehouse performs the outbound delivery operation. At the same time, a new baton is generated by the BMA.

(2) The appropriate manufacturing unit is selected through negotiation with other MAs by CA according to the production process requirements.

(3) The suitable AGV is selected for the transportation of the workpiece, and the transportation AGV agent receives the baton at the same time.

(4) The AGV transports the workpiece to the manufacturing unit, and the baton is transferred to the corresponding MA. The manufacturing unit is then selected for the next process by the CA after the current production process is completed.

(5) The above steps are repeated until the processing is completed and the workpiece is transported to the finished product warehouse by the AGV. Simultaneously, the baton is accepted and stored by the finished product warehouse agent, and the processing is accomplished.

The task management solutions can be summarized in Fig.6.

As an independent service agent, the BMA manages all task information in a unified manner, such as the procedures, dimensions, manufacturing unit, etc. Besides, the existence of BMA gets rid of the constraints of physical identification (e.g., RFID, barcode, etc.) for the processed materials and achieves the online processing of the task management. As the core of IoT manufacturing information flow, the baton replaces the traditional information identification technology (e.g., RFID) with a matrix table, and contains two essential information parts as follows. The first is the process-related information, and the processing entity can be selected more flexibly through the process relation matrix. The second is task information, including task ID and makespan, processing log and additional management information, etc.

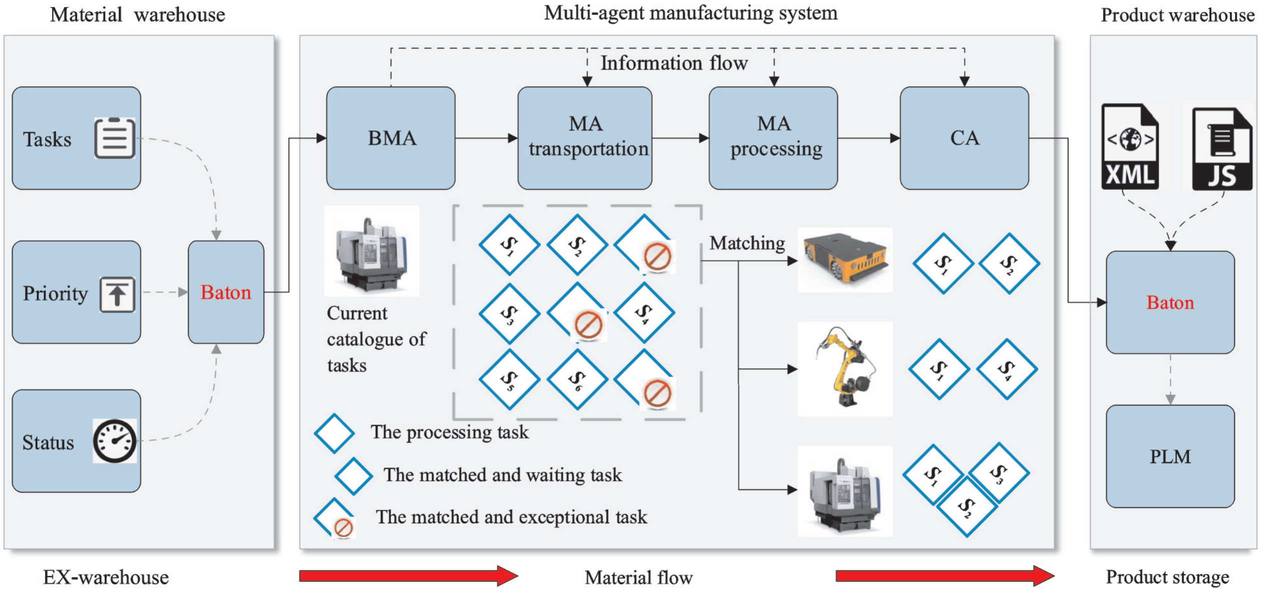


Fig.6 Task information manages of BMA

3 Efficient Negotiation Mechanism

It is challenging to deal with complex tasks independently owing to the insufficient capability of distributed MA in the MAMS. Therefore, it needs to cooperate with other MAs for optimal scheduling of MAMS. The cooperation between agents in the MAMS is the key to completing tasks or dealing with disturbances. The research on the negotiation mechanism between agents not only involves their application of domain knowledge but also is closely related to interdisciplinary subjects. Many scholars have studied the MAMS negotiation model and obtained many negotiation mechanisms[20]. There are two representative mechanisms: The blackboard model and the market mechanism.

The blackboard model belongs to centralized control architecture, and it is difficult to be implemented owing to the complex structure. By contrast, the market mechanism aims to achieve the distribution of resources and establish different calculation methods so that agents can coordinate activities by minimal communication load. The most widely used market mechanism in the MAMS is the CNP. It is similar to the market mechanism that the role of negotiation in the CNP is divided into participant agent and initiator agent. The MA will become an initiator in the MAMS using a broadcast to coordinate with other agents.

3.1 Contract net protocol

Considering the difficulty of the negotiation's industrial application as mentioned above mechanisms, the CNP is more suitable for the self-organizing negotiation of the MAMS. However, there are still many defects and shortcomings affecting the efficiency of the classic CNP.

The most obvious defect of classic CNP is that there is no restriction of bidding information release. The initiatory MA needs to broadcast the bidding information to all agents in the traditional CNP model, even though most of them cannot complete the production process. Each agent that receives the bidding information must reply regardless of whether it can bid or not. This negotiation method increases the communication load on the system and consumes the computing resources of the MAMS.

The other shortcoming of the classic CNP is the limitation of global performance. After determining the corresponding relationship between the task and the MA in the classic CNP, the task is arranged into the queue of manufacturing unit. The tasks are executed in the order of the queue[21]. The classic CNP does not consider the connection between the current and past tasks because it is essentially a single-step optimization, so the task with the highest priority is always arranged at the end of the queue.

3.2 Improved contract net protocol

According to the issues of excessive communication load and lack of sequence optimization among tasks in the processing queue of manufacturing entities, this paper proposes the yellow-page service and event-based task queue, strengthening the connection between tasks, and improving the ability of the CNP beyond single-step optimal scheduling. The improved CNP-based negotiation mechanism is shown in Fig.7.

3.2.1 Providing yellow-page service for MA

The capabilities of the manufacturing entity are mapped to the MA by the yellow-page service, which allows the MA to publish one or more functions to the public platform. If so, other agents that embed relevant functions can easily find and contact the corresponding agent. Any agent can register and search services through the yellow-page service. It is possible to initiate bidding for agents with relevant processing capability in a targeted manner using the yellow-page service. Thus, compared with traditional CNP, the yellow-page service can avoid wasting network resources caused by sending bids to all agents during the negotiation.

3.2.2 Setting bidding time expires for load balancing

The MA can initiate bidding to relevant agents through the yellow-page service, which will greatly improve negotiation efficiency. Through setting the bidding time expires, the real-time status can be assessed during the negotiation and the idle waiting time can be reduced obviously. Besides this, bidding time expires are set in the bidding process, which can further reduce the communication load on the system.

3.2.3 Update mechanism of event-based task queue

Any changes of the task queue such as rush orders, task priority modification, task cancellation, etc., are described as exceptional events, and different exceptions will trigger various processing strategies. For example, if a new task can be inserted directly into the arranged task queue according to its priority, or if anyone wants to cancel the task, the workpiece may be in the logistics queue or buffer of the manufacturing unit at the same time because the current state of the task is unsure. In order to reduce the impact of these exceptional events on the continuity of the whole production process, the processing information of the WIP must be considered at the time of rescheduling. Those exceptional events must be published to the MAMS, and every manufacturing unit on the shop floor can modify its task queue according to the disturbances.

4 Enabling Technology of MAMS

The MAMS comprises several independent and decentralized agents collaborating by an effective negotiation mechanism to achieve real-time dynamic scheduling finally. These agents are commonly distributed and isolated logically, and their behavior is highly autonomous[22]. Usually, people are concerned with how to organize the existing agents through a particular negotiation mechanism and allocate tasks in the MAMS. The realization of MAMS is based on the distributed agent self-learning mechanisms and interactive negotiation. Therefore, multi-agent collaboration is derived from a single agent that has interactive and decision-making functions.

4.1 Relay cooperation model based on process relation matrix

The main functions of MA are to monitor the production processing parameters of the task and respond to disturbances timely. A single agent's decision-making is mainly reflected in the real-time status analysis and responds to the corresponding negotiation. It also analyzes relevant information during the execution of processing tasks and makes optimal decisions based on the analysis results.

As the primary data source for the real-time scheduling system, the RMA mainly consists of two expects. The first is collected from the adaptation layer of MA, which is the real-time status of the manufacturing resource. The second is the information exchanged between MA and CA. These two types of information are transmitted to the decision-making layer of MA, which are described as follows.

Firstly, the information is classified into capability information of manufacturing resources, production processing information of tasks, and real-time scheduling information of MAMS.

Secondly, the decision-making layer of MA analyzes the real-time status and sequences the tasks according to the above-mentioned information.

Finally, the analysis results are packaged according to the format defined in the interaction layer and fed back to the MA to control the manufacturing entity or the sequence of tasks.

The realization of decision-making means that the MA can make decisions based on its available manufacturing capability and then assigns tasks through negotiation to other entities. Furthermore, the capacity utilization of the MAMS is increased, and the machine workload is more balanced than the traditional dynamic scheduling system. The self-learning and evolution mechanism of the MA can improve the process continuity with the help of some rules.

(1) Problem formulation module: Taking Petri net as a reference, this paper innovatively proposes a relay cooperation model based on a positive process relation matrix table, which is composed of the process model and organization model. Based on the notations listed in Table 2, a mathematical formulation for the problem is built, which is described as follows.

Main objective function is

$$f=\min\left(\sum_{i=1}^{n}\left\{\max\left(C_i-D_i,0\right)\right\}\right) \tag{1}$$

Secondary objective function is

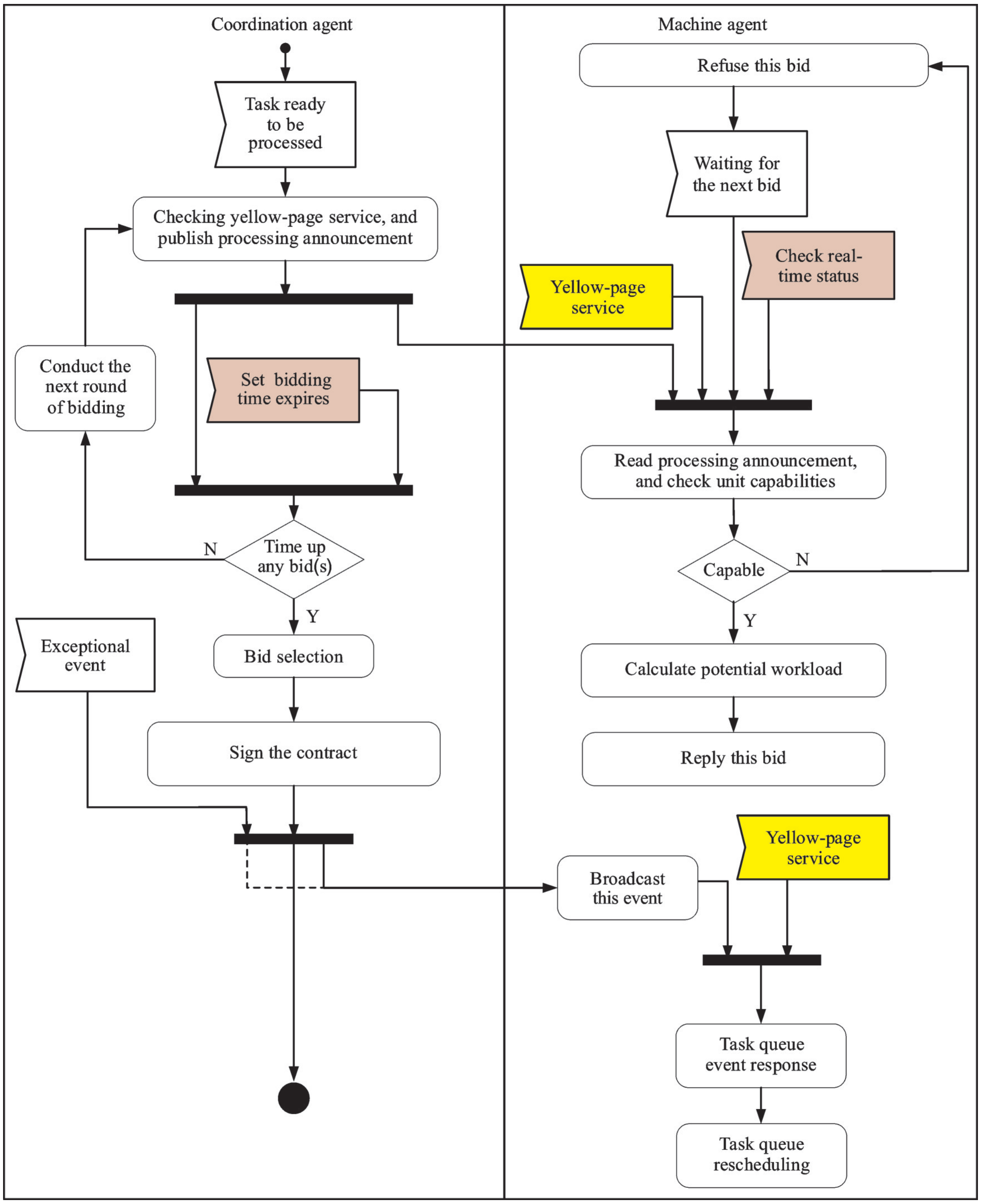


Fig.7 The improved negotiation process

$$T = \min\left(\max_{1\leqslant i\leqslant n} C_i\right) \tag{2}$$

$$C_i = S_i + t_{ik} \quad 1\leqslant i\leqslant n, 1\leqslant k\leqslant m \tag{3}$$

Subject to

$$\text{s.t.} \min\left\{S_i\right\} \,\&\, \min\left\{F_k\right\} \tag{4}$$

$$S_i \geqslant S_j + t_{jk}, Y_{ik} = 1, Y_{jk} = 1 \tag{5}$$

$$S_i \geqslant \max(C_l),\ X_{li} = 1 \tag{6}$$

where f represents the minimum makespan or completion time of the task. The product completion time value is as small as possible, which is the comprehensive scheduling optimization objective. Eq.(2) indicates that each operation can start the processing as soon as possible under the constraints of Eqs.(3, 4). The static idle period time on the equipment should be shortened. Eq.(5) indicates that the same entity's operation can only be processed serially, and Eq.(6) indicates that each process can only be started after the previous process is finished.

(2) Contract net protocol-based solving module: When the bidding mechanism is established to

Table 2 Notations

Notation	Description
n	The total number of tasks
m	The total number of machines
O_i	The ith operation of each process, $1\leqslant i\leqslant n$
M_k	The kth machine of all available devices, $1\leqslant k\leqslant m$
F_k	The idle time period of machine M_k
S_i	The start processing time of operation O_i
C_i	The completion time of operation O_i
D_i	The makespan of operation O_i
t_{ik}	The processing time of operation O_i on machine M_k
X_{li}	The operation O_l is the preceding procedure of operation O_i
Y_{ik}	The operation O_i is processed on machine M_k
$L_{\min}$	The minimum processing load

select the appropriate processing entity due to the greed of MA's task selection. It will cause too many inferior solutions to be generated based on the current state, which will affect the processing efficiency. Aiming at the disadvantages of MA's greedy bidding and shortsightedness, a new initial solution generation strategy is developed. In this strategy, it is necessary to combine global information with entity load balancing during CA's decision-making. The appropriate scheduling result can be selected through

$$M_k = f_{\min} \tag{7}$$

$$L_{\min} = L_{\min} + t_{ik} \tag{8}$$

where M_k is assumed to be the current minimum load device and its load value $L_{\min}$ during scheduling is required. At the same time, assume that the processing time of operation O_i on equipment M_k is t_{ik}. The initial solution generated by the above steps is load-balanced once the following conditions are satisfied.

$$\left|L_a - L_b\right| < \max\left\{t_{ik}\right\} \tag{9}$$

After adding the ith task, the manufacturing system consisting of entities a and b is in load balancing. For any manufacturing entity b except $f_{\min}$, $L_{\min}-L_b\leqslant 0$. After the kth operation, the difference between the load of the task J added in $f_{\min}$ and any other entity b is

$$\left|L_{\min} + t_{ik} - L_b\right| \leqslant t_{ik} \leqslant \max\left\{t_{ik}\right\} \tag{10}$$

It can be seen from Eq.(10) that the load difference between entity $f_{\min}$ and other entities meets the load balance after adding a new task, and the load difference among other entities is not affected by the newly added task.

$$\begin{cases} S_i = \left\{U_i(s^1), U_i(s^2), \cdots, U_i(s^k)\right\} \\ U_i(s^k) = \sum\limits_{i=1}^{N_i}\sum\limits_{j=1}^{N_j} V_{ijk}\, T(O_{ij}, M_k) \end{cases} \tag{11}$$

where S_i represents the alternative bidding set considering the global device load balancing. $T(O_{ij}, M_k)$ the processing time of operation O_{ij} on entity M_k. In this paper, $U_*(s^k)$ is the maximized bidding value for the contract net protocol.

$$V_{ijk} = \begin{cases} 1 & O_{ij} \text{ is the processed on equipment } M_k \\ 0 & \text{Else} \end{cases}$$

Thus, a negotiation solution $U_*(s^k)$ can be computed by the relay cooperation mechanism based on a positive process relation matrix.

4.2 Cooperation process among agents of MAMS

The normal production process can be achieved through interactive methods, such as process information sharing and collaboration among agents, which participate in the tasks assign negotiation[23]. However, the agent's decision-making is not accurate enough for the narrow field of knowledge, and optimal scheduling results cannot be achieved easily.

The function and service agents in the MAMS work together to realize real-time scheduling under the condition of limited manufacturing resources. Besides, when an exceptional event occurs in the manufacturing site, the multiagent can accurately identify the disturbance type and process it by cooperation in real-time. The MAMS uses distributed control strategies to verify the negotiation results, thereby ensuring the self-organization scheduling results of MAMS are moving forward in a positive direction in the task assign production process. The working mechanism of multiagent collaboration is shown in Fig.8. At each time t, the problem-solving procedure is described as follows.

Step 1 When a new task arrives, the BMA generates the corresponding baton. The baton records the current task ID and process relationship information, which is used to realize the synchronous information tracking of material flow in the shopfloor.

Step 2 According to the process position of the current material, the corresponding MA calls CA for the next process.

Step 3 The CA queries the yellow page service to find the related MA for the process, and initiates the processing bidding. After receiving the bidding information, each MA decides whether to bid or not according to its status. Finally, the CA generates the initial scheduling sequence.

Step 4 By querying the global information of RMA, CA selects the most suitable MA to execute the current process according to the optimization objectives such as makespan and load balancing.

In the new model of self-organizing IoT manufacturing, both normal processing and exception belong to event-driven rescheduling. Real-time rescheduling can significantly reduce the impact on the unexecuted part of the initial scheduling results.

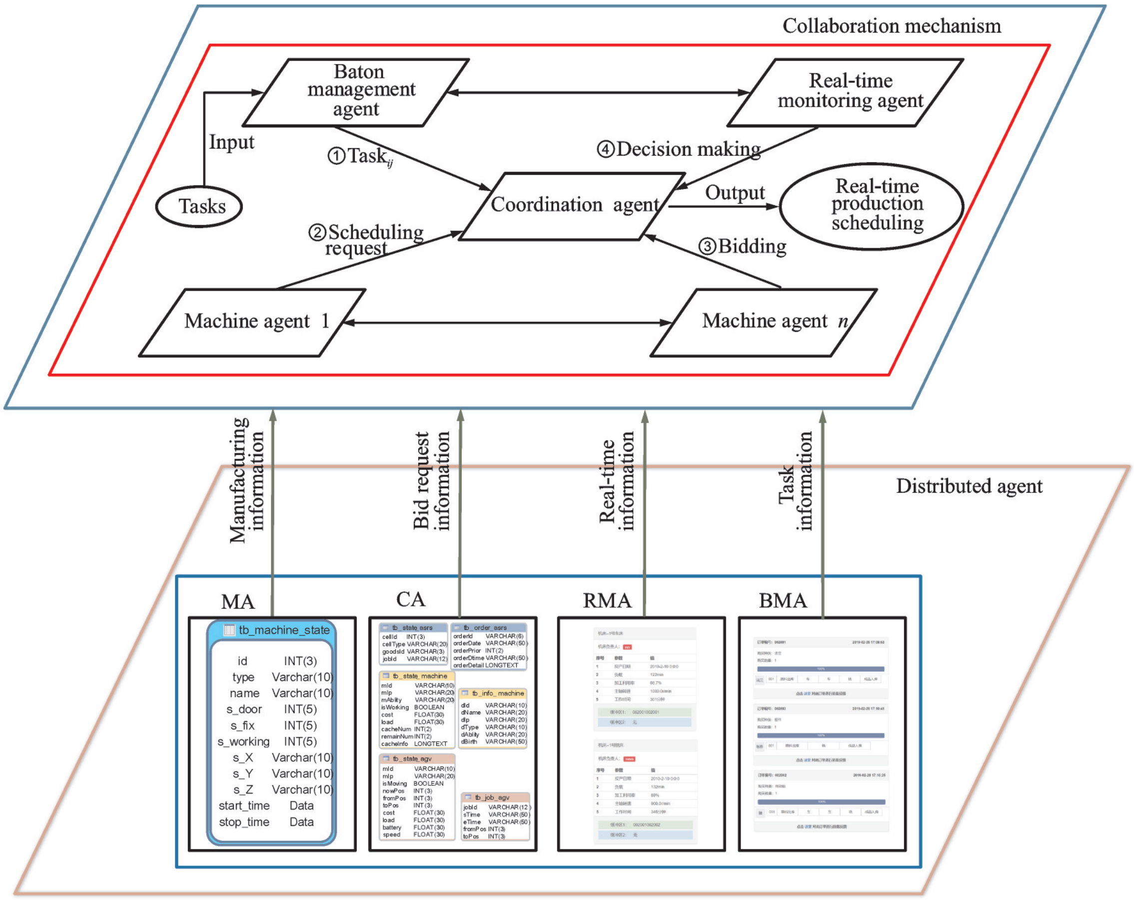


Fig.8 Working mechanism of multiagent collaboration in MAMS

5 Implementation of MAMS-Based Self-organizing IoT Manufacturing

Combined with the MAMS enabling technology, a self-organizing IoT manufacturing implementation architecture is established by the Java agent development framework (JADE) to verify the self-healing ability of the system under exceptional events.

5.1 Application scenarios

The layout of the shop floor experimental scenarios is shown in Fig. 9. The system mainly comprises the following manufacturing entities: An automated three-dimensional warehouse for storing raw materials, an automated three-dimensional warehouse for storing finished products, two magnetic guidance AGVs, three six-degree freedom manipulators, two CNC lathes, two CNC milling machines, and two CNC engraving machines. Every unit mentioned above has two task buffers.

In addition to showing that the MAMS-based system has theability of personalized customization, this paper compares the scheduling performance of the two systems. The information tracking of the production execution is managed by the BMA during the MAMS operation, which replaces physical tags such as RFID, barcode, etc. The detailed information about the orders is shown in Table 3.

Fig.9 Layout of application scenarios

Table 3 Instance of MAMS

Order ID	Task ID	Type ID	Process route	Time of each processing step /s	Delivery time /s
01	T_1	01	Milling→Turning→Engraving	12.3→15.6→13.3	70
	T_2	01	Milling→Turning→Engraving	12.3→15.6→13.3	
	T_3	02	Turning→Milling	20.0→5.3	
	T_4	04	Engraving→Milling	10.6→7.3	
02	T_5	02	Turning→Milling	20.0→5.3	75
	T_6	01	Milling→Turning→Engraving	12.3→15.6→13.3	
	T_7	03	Engraving→Milling	10.6→7.3	
	T_8	03	Engraving→Milling	10.6→7.3	
03	T_9	03	Engraving→Milling	10.6→7.3	80
	T_{10}	03	Engraving→Milling	10.6→7.3	
	T_{11}	01	Milling→Turning→Engraving	12.3→15.6→13.3	
	T_{12}	03	Engraving→Milling	10.6→7.3	
	T_{13}	02	Turning→Milling	20.0→5.3	

5.2 Self-healing of MAMS under disturbances

In the manufacturing environment, the occurrence of exceptional events has strong effect on process continuity. Thus, the rescheduling may greatly affect those operations that are not performed in the previous schedule and increase the instability of continuous operation for the whole system. Focusing on these issues, traditional centralized production scheduling performance is compared with self-organizing methods under disturbances (e.g., machine breakdown, the change of orders, etc.).

(1) Undisturbed situation

Since the general scheduling strategy belongs to the offline type, in the case of normal production without disturbance, the approximate optimal solution of the scheduling problem can be obtained by the genetic algorithm, and the results of the two experiments are similar. But the self-organizing production scheduling strategy has more advantages in real-time performance.

(2) Disturbance of rush order

The order dataset in the disturbance of rush order is consistent with the data in Table 1. The T_{10} of the order placed at time 50 s is set as the insertion order. At the same time, the task priority of T_{10} is the highest, and T_{10} will be executed first when the manufacturing resource is idle according to the real-time scheduling strategy.

(3) Disturbance of order priority adjustment

The order dataset in the disturbance of order priority adjustment is consistent with the data in Table 1, and the priority of T_{11} is adjusted to be the highest at time 150 s. Then the coordination agent broadcasts this priority adjustment exceptional event information. Afterward, the subsequent processing and logistics of T_{11} will be executed firstly according to the real-time scheduling strategy.

(4) Machine breakdown disturbance

According to the real-time scheduling strategy, when machine failure occurs, the failed unit can be deleted from the yellow-page service registry, and the disturbing task will be processed by the relevant manufacturing unit.

The comparison result of traditional centralized scheduling and the self-organizing scheduling under the exceptional events mentioned above is shown in Fig. 10 (a). It is clear that the relevant machine workload with the same processing capability is basically balanced by the real-time self-organizing scheduling. Moreover, without considering the rescheduling effect on the section of the previous scheduling that is not executed, the makespan is better than the traditional centralized scheduling method. Besides, the Gantt chart of the two scheduling methods in the case of the rush order disturbance is compared in Figs. 10 (b) and (c). It can be found that the MAMS-based scheduling response to the order changes is timely and has better performance in terms of makespan and load balancing.

5.3 Discussion

The proposed self-organizing IoT manufacturing mode is tested to certificate the optimal of real-time scheduling compared with the general manufacturing execution system (MES) scheduling strategy. The general strategy uses a genetic algorithm for scheduling and rescheduling the calculation.

According to the comparison of the makespan of the above situations, it is obvious that the lead time of the traditional scheduling strategy is slightly shorter than the self-organizing scheduling during the undisturbed situation. However, as any disturbance occurs, the traditional scheduling is slower owing to the fact that it needs to perform rescheduling calculations to deal with the disturbance. The proposed method is significantly better than the traditional scheduling strategy in terms of the makespan and the processing speed because of disturbances.

6 Conclusions

The traditional manufacturing system is difficult to deal with the demand of the dynamic and changeable task. Moreover, the rescheduling result of the traditional manufacturing system has great impact on the unexecuted operations in the original scheduling when an exceptional event occurs.

For most job shop scheduling problems, exceptional events are usually the trigger condition of rescheduling. The response mechanism of the rescheduling is basically the same whether the exceptional events occur alone or in batches. These exceptional events enter the message queue to be processed according to their priority and then are processed by the CA in turn.

This paper proposes a new self-organizing manufacturing mode based on IoT technology. Each manufacturing unit achieves the interconnection between entities through a negotiation mechanism among agents under the MAMS framework. Experiments show that the self-organizing IoT manufacturing mode has higher efficiency in dealing with disturbances.

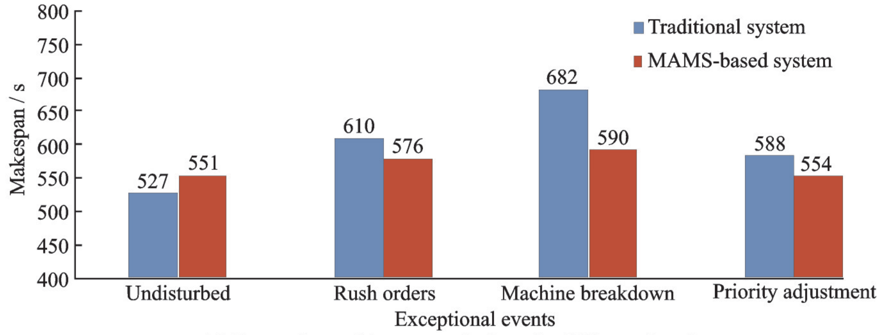
The main contributions of this paper are summarized as follows.

(1) The agent-based self-organizing manufacturing mode is achieved under the JADE framework through the multiagent modeling, and the real-time status of manufacturing entities are mapped into MAs that have functions such as perception, analysis, decision-making, communication, etc.

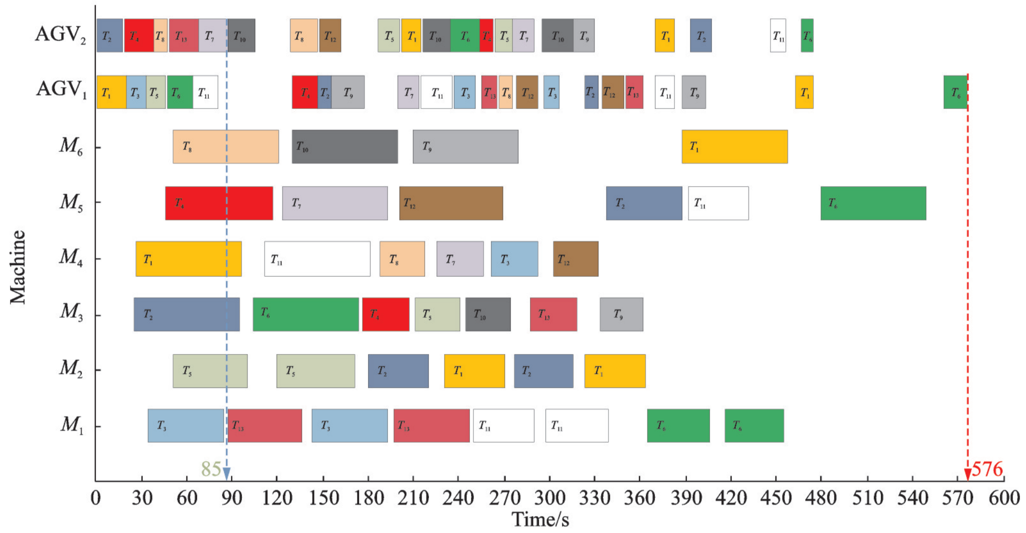
(2) The communication process is simplified and contrasted with the classic CNP. The negotiation efficiency is optimized through yellow pages service, set bidding time expires in the improved CNP.

(3) The MAMS-based implementation architecture of industrial site applications is realized by the interaction and collaboration mechanism of agents, which is shown in the self-healing treatment of disturbances.

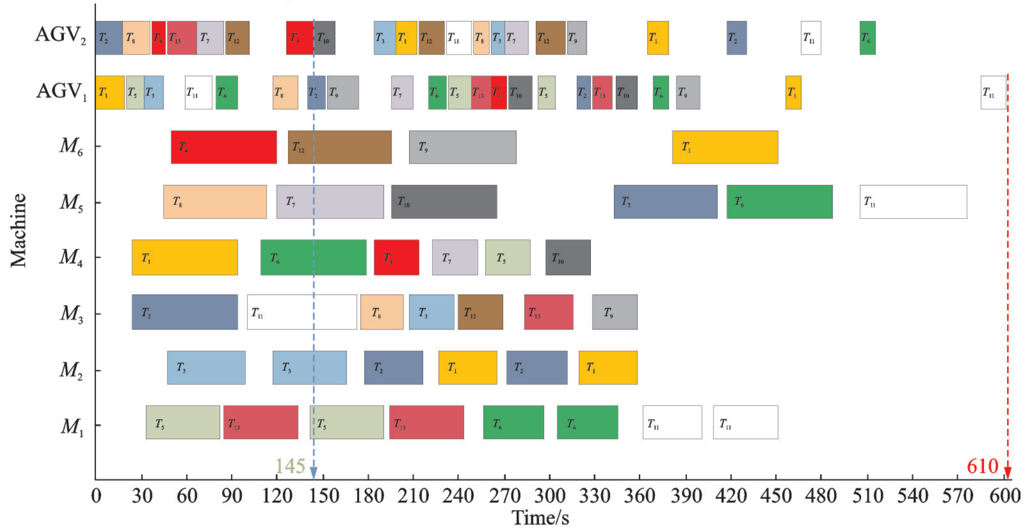
However, there also exists some limitations in the proposed structure that need to be enhanced in



(a) Comparison of the two methods under different disturbances



(b) Gantt chart of MAMS-based in the case of rush order disturbance



(c) Gantt chart of traditional methods in case of rush order disturbance

Fig.10 Gantt chart for disturbance of order insertion and experimental result

the future work. The complexity of the single-agent self-learning mechanism and swarm intelligence evolution model is needed for in-depth study in MAMS.

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Author contributions Mr. **WANG Liping** conducted the study and wrote the paper. Prof. **TANG Dunbing** completed the interview and assessment. Dr. **SUN Hongwei** and Mr. **ZHANG Zequn** designed the case study. Mr. **LIAO Liangchuang** and Mr. **ZHOU Tong** contributed to the conclusion and background. Mr. **NIE Qingwei** and Mr. **SONG Jiaye** improved the contract net protocol. All authors commented on the manuscript draft and approved the submission.

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自组织物联制造新模式:多智能体制造系统关键使能技术研究

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摘要:随着制造模式日益趋于网络化与社区化，订单及生产工艺充满着高度动态与不可预测性。在此背景下，传统的制造模式已然无法处理诸如紧急订单和机器故障等常见的突发异常事件。与此同时，多智能体制造系统凭借其对于异常事件处理的实时性从众多制造模式中脱颖而出，然而由于智能体封装通用性的缺乏使得多智能体制造系统很难应用于工业现场。基于此，本文提出了一种融合智能体封装、交互与决策的多智能体制造新模式。首先，建立了基于正向工序关系矩阵的多智能体接力协作模型；然后改进了传统的基于合同网协议(Contract net protocol, CNP)的协商机制，提高了智能体间的协商效率；最后，以自组织物联制造系统为例，验证了正常与扰动情形下该模式的可行性和有效性。实验结果表明，针对异常处理，本文提出的自组织物联制造模式在完工时间和关键机器负载平衡方面均优于传统集中式调度方式。

关键词:多智能体制造系统；合同网协议；物联网；扰动；自组织