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An Energy-Efficient Scheduling Approach for Flexible Job Shop Problem in an Internet of Manufacturing Things Environment

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ABSTRACT This paper addresses the energy-efficient scheduling and real-time control of flexible job shop that requires rescheduling affected operations and updating the scheduling. For energy-efficient scheduling shop floor efficiently, we propose a metaheuristic algorithm called PN-ACO algorithm, which combines a timed transition Petri nets (TTPN) based representation tool and an ant colony optimization (ACO) heuristic search method. To address the real-time control problem in energy-efficient scheduling of the shop floor, we apply the Internet of Things (IoT) technology to product production to form an Internet of Manufacturing Things environment (IoMT). In the IoMT environment, there are usually many abnormal event disturbances, including machine breakdown and urgent order arrival. To quickly handle the disturbance problem of abnormal events, the distributed control system architecture is proposed, the core of which is the negotiation and cooperation between manufacturing resources based on the wireless communication network. The proposed approach is further illustrated by a case energy-efficient of scheduling for a flexible job shop through which the optimal scheduling and correct supervisory control instructions can be obtained easily and quickly. In sum, the proposed optimization algorithm obtains a good effect in engineering applications while the validity of optimization is proved.

INDEX TERMS Energy efficient, Internet of Things, flexible job shop scheduling, RFID, ant colony optimization, negotiation mechanism.

I. INTRODUCTION

With the increasingly fierce competition in manufacturing industry and the increasingly prominent energy problem, sustainable manufacturing has become an inevitable choice for the current manufacturing industry. A large number of statistical data show that in the process of machining, the cutting power of machine tool is less than 30% of its total operating power. Relevant research shows that in the process of manufacturing machining, due to standby, no-load and other conditions, the effective utilization rate of energy is only 14.8%. Therefore, e energy-efficient scheduling at the shop floor level is a more practical means to improve energy efficiency. In addition, shop floor energy-efficient scheduling does not need to increase the cost of shop floor operation, which is a more acceptable way for enterprises.

In the past, due to the lack of sufficient attention to the environmental impact of the shop floor, the study of energy-efficient shop floor scheduling is quite limited, mainly for single machine and flow shop. Flexible job shop is gradually accepted by enterprises because of its flexible production mode, in order to meet diverse customer needs and respond quickly to market changes.

Few researches focus on the Flexible job shop problem (FJSP) under a real-life environment in which dynamic or random event (i.e. machine breakdown, unexpected processing times, random arrival of the urgent orders and cancellation of the job orders) may occur [1], [2].

To detect abnormal disturbance rapidly and accurately and to respond to abnormal correctly is one of the precondition

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of ensuring the efficient shop floor operation. So the real-time detection and feedback control are becoming a topic of concern in shop floor [3].

Nowadays, it is not easy to acquire real-time and accurate information of manufacturing resources and interruptions because there is a very large amount of data being generated over time [4]. Obviously, this lead to the delay, distortion and a high probability of producing error as well as frequent rescheduling in the shop floor [5], [6].

Internet technology brings human's ability to perceive physical environment to a new height, and also changes the way in which human use information technology to manage physical environment. The deep integration of information system and physical environment gives birth to a series of new manufacturing modes: computer integrated manufacturing, flexible manufacturing and Internet of Manufacturing Things (IoMT). In order to shorten the product development cycle, reduce the cost of resource consumption and improve the energy utilization, it is necessary to integrate information and sensing technology, computer-aided technology and artificial intelligence methods in all aspects of product manufacturing and management.

The motivation of this research is to propose an approach of energy-efficient scheduling and real-time control in shop floor production, which combines the IoT technology, the dynamic scheduling optimization method and negotiation-based reactive control approach.

In our view, this paper mainly includes three aspects contributions:

1) The energy-efficient scheduling algorithm formulates an energy-efficient scheduling problem using a Petri nets model.

2) To obtain a more feasible search effect, we focus on presenting an ACO search algorithm and heuristic function.

3) Based on the deeply study on the application of the RFID and the distributed control manner to develop an RFID-enabled distributed control system that dynamically responds to disturbance of abnormal events in IoMT environment.

This paper is organized as follows. In Section 2, we describe the problem of IoT-enabled real-time scheduling and control in shop floor production; Section 3 explains the proposed negotiation-based reactive control approach; Section 4 illustrate procedure of scheduling and rescheduling algorithm FJSP-ACO; In Section 5, the detailed experimental results are presented, followed by some final remarks and future research suggestions in Section 6.

The remainder of this paper is organized as follows. Section 2 describes the related literature reviews. In Section 3, dynamic FJSP is described. Energy-efficient scheduling of FJSP are presented in Section 4. In Section 5, we explain the proposed negotiation-based reactive control approach. Experimental design, comparisons and discussions are presented in Section 6. We conclude this paper and give the future research directions in Section 7.

II. RELATED WORK

This section introduces the background of relevant research. We review the energy-efficient scheduling, shop floor scheduling methods and Internet of Manufacturing Things.

A. ENERGY-EFFICIENT SCHEDULING

Shop floor scheduling scheme has a significant impact on energy consumption of machining manufacturing system. In recent years, many scholars carry out research on energy consumption optimization of mechanical manufacturing system from the perspective of shop floor production scheduling. The processing sequence of each operation directly affects the idle waiting time between two adjacent operations, and then affects the idle energy consumption. By optimizing the processing sequence of each operation on the machines, the purpose of reducing energy consumption can be achieved.

Bruzzone *et al.* [7] optimize the production and scheduling of job-shop by establishing an energy-efficient scheduling model (energy-aware scheduling, EAS), and establish a mathematical model to effectively solve the optimization of the two objectives of energy consumption and equipment idle time. Aiming at job shop scheduling problem, Dong *et al.* [8] established a multi-objective optimal scheduling model with the objective of minimizing idle energy consumption and delayed delivery time of machine tools, and the processing sequence of each process on machine tools as decision variables. An improved genetic algorithm based optimal solution scheduling model was proposed. Mashaei and Lennartson [9] aimed at the flow shop scheduling problem, took energy consumption and completion time as decision variables. A mixed integer programming model is established with the objective of minimizing machine tool on/off time, machine tool selection of each process and processing sequence of each process as optimization variables, and an optimization solution method based on heuristic algorithm is proposed. Yildirim and Mouzon [10] aim at single machine scheduling problem in job shop, aim at minimizing energy consumption and completion time, take machine tool on/off time, machine tool processing sequence as optimization variables. A multi-objective optimal scheduling model is established, and an optimization solution method of multi-objective genetic algorithm is proposed. Salido *et al.* [11] established a multi-objective scheduling optimization model for job-shop scheduling problem, with the objective of minimizing energy consumption and completion time, and the processing speed of machine tools and the processing sequence of each process as decision variables. An optimization solution method based on improved genetic algorithm was proposed. Aiming at the flow shop scheduling problem, Ding *et al.* [12] set up a multi-objective optimal scheduling model with the objective of minimizing carbon emissions and completion time, including power consumption, and taking the processing speed of machine tools and the start processing time of each process as optimization variables, and put forward an optimization solution method based on improved NEH algorithm.

B. SHOP FLOOR SCHEDULING

There are many shop floor scheduling problems such as: single-machine scheduling problem, parallel machines scheduling problem, Job-shop scheduling problem (JSP), Flow-shop scheduling problem (FSP), Flexible job-shop scheduling problem (FJSP) and Open-shop scheduling problem (OSP), and others [13].

Flexible job shop scheduling problem (FJSP), is a generalization of the traditional job shop scheduling problem (JSP) in which there are no alternative machines [14] [15]. The JSP is demonstrated as a NP-hard problem, and so is the FJSP.

Initially, the research on scheduling algorithm for FJSP is based on the simulation model of shop floor production system, including branch and bound method, linear or nonlinear programming and other operational research methods [16]. Then researchers began to use heuristic algorithms such as rule-based algorithm, Lagrange relaxation algorithm and insertion algorithm to optimize the scheduling results. With the FJSP proved to be NP-hard, many scholars began to use artificial intelligent (AI) optimization method to solve scheduling problems. They tried to find some near-optimal solutions in the solution space at a faster convergence rate, including tabu search algorithm, simulated annealing algorithm, particle swarm optimization algorithm, neural network, genetic algorithm, ant colony optimization (ACO) algorithm and so on [17].

In recent years, with the development of distributed artificial intelligence, multi-agent technology has gradually been used by some scholars in the field of production scheduling. However, from the view of scheduling results, the multi-agent algorithm does not perform better than the AI algorithm. Compared with other AI algorithms, ACO algorithm can effectively reduce the computational space and thus shorten the convergence time [18], [19]. The effectiveness of ACO depends largely on heuristic function, but the heuristic function widely used now do not take into account the allocation principle of the shop floor, and the actual scheduling results are not satisfactory.

Scheduling approaches under uncertainty can be categorized as proactive scheduling approach and reactive scheduling approach as well as predictive-reactive approaches [20]. The proactive approach focuses on the development of a baseline schedule that is against anticipated schedule unexpected events disruptions that may occur during project execution [21]. The reactive approach focuses on revising or re-optimizing the schedule when an unexpected event occurs [22]. The use of a baseline schedule in combination with reactive approach is sometimes referred to as predictive-reactive scheduling, which concentrate on repairing the baseline schedule [23], [24].

C. INTERNET OF MANUFACTURING THINGS

The IoT technology enables various physical devices to realize the real-time shop floor scheduling. The implementation of the predictive-reactive approach is relying on sensing, processing, and sharing the data in the constructed IoMT environment [25], [26].

Furthermore, in IoMT environment, a shop floor control system plays an important role in coordinating manufacturing resources to accomplish complex production tasks, such as responding to events across shop floor systems, recovering from errors and executing rescheduling tasks. Since a single controller is incapable of executing all of these activities, equipment controllers are developed and hooked up into a shop floor control system in a hierarchical or distributed manner [27].Under hierarchical control, equipment controllers are hierarchically connected by a host computer in a centralized method, which often restricts the ability of self-adaptability and reconstruction required when shop floor production environment varies dynamically. Currently, a great deal of effort has been spent on distributed control manner, where no hierarchy exists and all the control decisions are made through negotiation [28].

Under distributed control, equipment controllers are combined into a loosely coupled system. On the basis of the local optimization of the equipment controller itself, the negotiation between equipment controllers or sub-systems is realized to achieve global optimization. This control manner can adapt to the changes and failures of various components, and respond to an interruption of abnormal events.

Holon or Agent based negotiation technology is widely accepted and developed in implementation of the distributed control, which goal is to propose a systematic methodology to develop and implement reconfiguration mechanism to deal with interruption of abnormal events in shop floor [29]–[31].

Although many attempts have been made in the IoT technology, especially in the integration of the Internet of Things and manufacturing, it is still in the stage of development and there are many problems to be solved. At present, most of researches focus on information acquisition and real-time monitoring using IoT technology, while the research of fusion scheduling strategy and control method is still needed to be further in-depth.

III. PROBLEM DESCRIPTIONS

The FJSP, also called the general job shop problem with parallel (or alternative) resources, can be formulated as follows. Let $J = \{1, 2, \ldots, n\}$ be a set of jobs which have to be executed on machines from the set $M = \{1, 2, \ldots, m\}$. Each job J_i consists of a given sequence of operations. Each operation O_{ij} (operation $j$of job i) can be processed on an adequate type of machines$M_{ij}(M_{ij} \subseteq M)$. We denote P_{ijk} to be processing time of O_{ij} on machine $M_k(M_k \in M_{ij})$. The problem consists in the jobs allocation to machines from the adequate type (i.e., routing sub-problem) and the schedule of jobs execution determination on each machine to minimize the energy consumption (i.e., sequencing sub-problem).

According to the actual production situation in the shop floor environment, the energy consumption in the shop floor can be divided into four parts: preparation energy consumption, processing energy consumption, no-load energy consumption and transportation energy consumption. FJSP does not consider the logistics link and the preparation link in the processing. Therefore, the energy consumption of FJSP consists of processing energy consumption and no-load energy consumption. The energy consumption curve of flexible job shop scheduling is shown in the Figure 1.

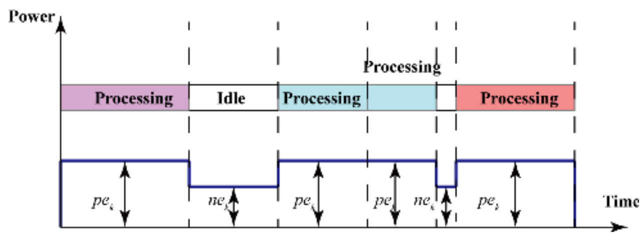

FIGURE 1. The energy consumption curve.

TABLE 1. Example OF FJSP.

	Process 1	Process 2
Job 1	1 or 2/3 or 2	2/2
Job 2	1/3	1 or 2/1 or 2

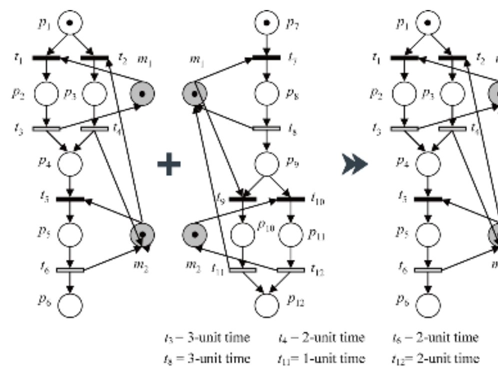

FIGURE 2. The S^3 PR model.

To further simplify the TTPN model, the TTPN derives a large number of sub nets or variant network models. Our proposed hybrid modelling method follows the concept of S^3PR, which represents the sub nets of TTPN [32]. The job shop system is shown in Table 1; for example, the S^3PR of this example is illustrated in Figure 2.

IV. SCHEDULING METHOD OF THE FJSP

An optimal schedule can be obtained by generating the reachability graph and enumerating all state as well as finding the optimal path from the initial marking to the goal marking. The path is a firing sequence of the transitions of the S^3PR model, which can be expended as the loop iteration procedure in Figure 3 [33]. But even for a simple Petri net, the reachability graph may be too large to generate in its entirety. Instead of generating the entire reachability graph, a heuristic search algorithm is employed.

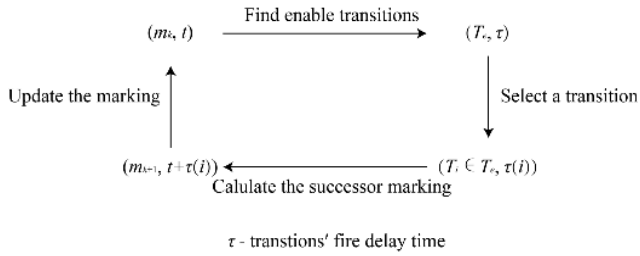

FIGURE 3. Expanding procedure of the reachability graph.

A. HEURISTIC FUNCTIONS

The scheduling algorithm presented in this paper is based on ACO heuristic search algorithm. In ACO algorithm a feasible solution is usually shown as a path in a graph [34]. In FJSP, the solutions of the problem are shown with a reachability graph of a S^3PR model where the nodes or markings correspond to the activities of the ants. Ants can work effectively to find good solutions by applying a stochastic local decision policy that makes use of effective local search and constructive pheromone updating rule [35].

During the search, ants are guided by two factors: pheromone trail τ and heuristic desirability η. τ_{ij} considered as the pheromone intensity associated with the movement from marking i to batch marking j, which is changed during the running of the ACO algorithm. η_{ij} is the heuristic desirability of moving marking$i$ to marking. At each step, an ant chooses a node from all unsearched feasible node by a probabilistic procedure.

$$P_{ij}^{l} = \begin{cases} \dfrac{\tau_{ij}^{\alpha}\eta_{ij}^{\beta}}{\sum_{i\in N_i}\tau_{ij}^{\alpha}\eta_{ij}^{\beta}}, & j \notin N_i^l \\ 0 & j \notin N_i^l \end{cases} \tag{1}$$

where N_i^l is the neighborhood at node (marking) i which is searched by ant l, and α,β respective weights of pheromone trail and heuristic desirability.

If the processing power and no-load power of the machine are known, the energy consumption of the machine is also a function of the time, so the energy consumption heuristic information factor η_{ij} can also be constructed with the idea of heuristic information factor of the processing time. Because this paper studies the FJSP, that is, the same operation on different machines has different unit operating energy consumption costs. In order to reduce the energy consumption, it is natural to arrange the operation on the machine which makes the processing energy consumption the lowest.

The function η_{ij} is the actual energy cost required from node (marking)M_i to reachable node (marking) M_j, and the heuristic desirability can be defined as:

$$\eta_{ij} = ne_k \cdot Et\,(t) + pe_k \cdot Dt\,(t) \tag{2}$$

where marking j can be reached through firing transition t, $Et(t)$ is the real response time that transition t is enable, $Dt(t)$ the time delay associated with the transition t, pe_k the processing power of machine k, ne_k the no-load power of machine k.

B. SOLUTION PROCEDURE

In order to avoid premature convergence of the search process, we adopt the strategy of setting the information concentration up and down. The information concentration on each path is limited to $[\tau_{\min}, \tau_{\max}]$. The values beyond this range are forcibly set to $\tau_{\min}$ or $\tau_{\max}$. When all ants complete the deconstruction process, the global pheromone trajectory is updated according to the following rules:

$$\tau_{ij}(t+1) = (1-\rho)\cdot\tau_{ij}(t) + \sum_{k=1}^{m}\Delta\tau_{ij}^{l}(t) \tag{3}$$

where ρ $(0 < \rho \le 1)$ is a volatile factor, $\tau_{ij}(t+1)$ represents the pheromone concentration of node j at the next step, $\Delta\tau_{ij}^{l}$ represents pheromone increment, and its calculation method is as follows:

$$\Delta\tau_{ij}^{l} = \begin{cases} \dfrac{Q}{L^{l}}, & f(i,j) \in \text{BPath} \\ 0, & f(i,j) \notin \text{BPath} \end{cases} \tag{4}$$

where BPath is the incumbent global best solution, Q is a constant, L is the time delay from current node (marking) i to node (marking) j.

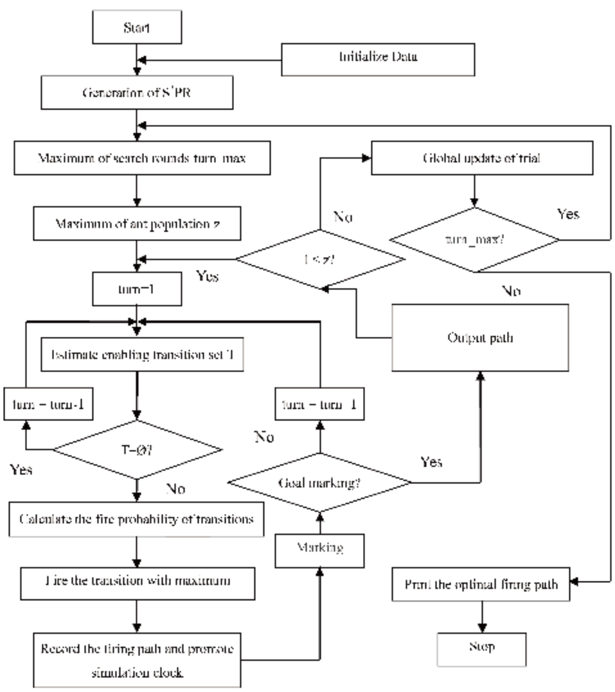

FIGURE 4. Procedure of PN-ACO algorithm.

The proposed metaheuristics algorithm based on Petri nets and ACO (PN-ACO) is described in Figure 4.

V. INTERNET OF THINGS -ENABLED REAL-TIME SHOP FLOOR MANAGEMENT PROBLEM

The combination of the IoT technology and scheduling method can provide feedback on the implementation of shop floor scheduling. At this time, the open-loop scheduling system will be transformed into a semi-closed-loop system. This section first describes the IoMT environment, and then describes the scheduling problem of the shop floor.

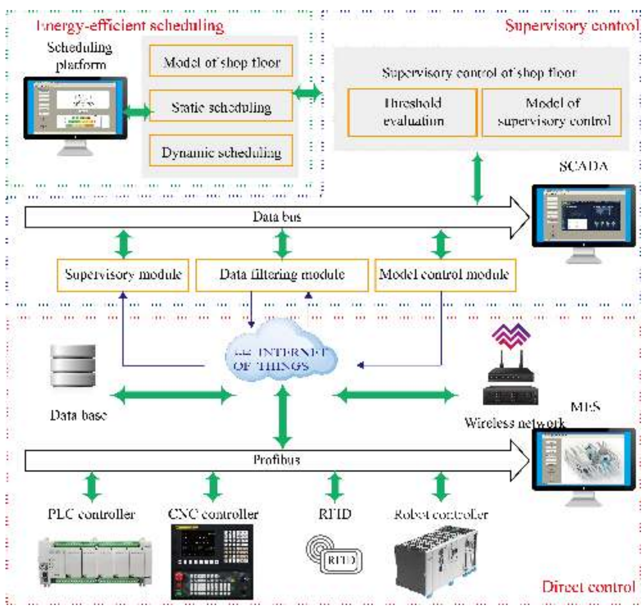

FIGURE 5. The framework of IoMT.

A. THE CONFIGURATION OF THE INTERNET OF MANUFACTURING THING ENVIRONMENT

The IoT enabled system is a system based on the integration of IoT and physical system. Taking manufacturing system as an example, it connects machine tools, robots, logistics transmission and auxiliary equipment to the computer processing units. Figure 5 shows the shop floor system under IoMT environment. In this system, the computer acts as the brain of the system and the machine acts as the body of the system. When the environment of the system changes, the computer network makes decisions and makes the machines cooperate with each other to complete the response to environmental changes. At this time, the system should include a feedback loop, and when some input parameters of the system change, the output also changes. In the IoT, there is a network of devices, and each device through its connected computer system has a unique ID. The real-time scheduling and control of the shop floor system is realized by the interaction between machine and machine without manual intervention in IoMT environment.

The perceptive and execution layer belongs to the bottom of the whole shop floor system. The commonly used hardware devices are all kinds of sensors and RFID devices. RFID is the key technology in IoMT environment. It establishes a unique identity for each job in the system mainly through electronic tags. It can also contain the production and processing information of each job. The manufacturing equipment acquires the specific information of jobs in real time through the RFID reader.

In network transport layer, communication is the basis of information exchange in IoMT environment, and also an important means to realize dynamic scheduling and execution. Wireless network communication is the mainstream communication mode of the IoT in the future.

The main function of application layer is to provide users of the system (including people, organizations or other systems) with the use of interfaces, in order to achieve the intelligent operation of the whole shop floor system. This paper focuses on the implementation and application of the interface of shop floor real-time scheduling and control.

B. RFID-ENABLED INFORMATION CAPTURING SYSTEM

In the IoMT environment, production equipment, warehousing equipment, communication equipment and logistics equipment are integrated with intelligent hardware and the Internet. Through the IoT and wireless network technology, equipment, warehousing and logistics data can be easily obtained, and the complete supervisory from raw materials to products can be realized [36].

In the IoMT environment, a large number of RFID and sensors are at the bottom of the IoT, collecting the required data for the manufacturing shop floor. The RFID system mainly includes electronic tags, read-write devices and application system. RFID and sensors are connected to servers through the Internet, and the collected data are exchanged between devices through wireless networks. The application layer supervises the interaction in real time. Once the interaction is abnormal, the scheduling and control system intervenes to adjust the scheduling data and update the RFID tag information of manufacturing equipment and jobs through wireless network.

In order to combine the material flow and information flow of the jobs, each job carries an RFID tag from the beginning of the blank and attaches the tag to the non-processing surface of the job. When the job enters the shop floor and reaches manufacturing equipment, the RFID read-write devices write the data information in the tag, so that the data in each operation of the production process can be read and written with it. Logistics and information flow are closely integrated, which is very suitable for real-time and dynamic scheduling and control of manufacturing systems.

According to the operation of the job, the label of the job is divided into several process blocks, and the data in each process block is divided into two categories: scheduling data and processing data. Figure 6 describes the storage structure and data type of the RFID tag.

The RFID middleware is the core of the RFID system, which plays the role of undertaking the reading and writing equipment at the bottom of the RFID system and the business

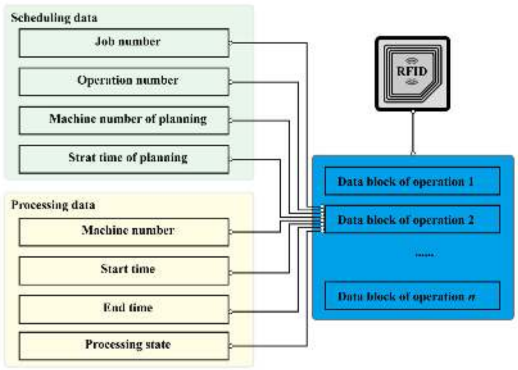

FIGURE 6. The storage structure and data type of the RFID tag.

application system of the enterprise. The original tag data information is captured by the reading and writing equipment, and then transferred to the RFID middleware for preprocessing, including data cleaning, filtering, filtering, summarizing and analyzing.

In the production scheduling stage, RFID technology can be used to achieve monitoring and management, including binding RFID tags on the worksheets such as production scheduling plan and production process technical documents, so as to achieve tracking and management of the implementation of production tasks.

In the stage of production implementation, the monitoring and management realized by using RFID technology includes embedding RFID tags into materials and equipment, tracking and managing production tasks with fixed-point RFID reading and writing equipment in conveyor belts and workbenches, monitoring whether the materials on production site is conforming to the specifications, monitoring whether the materials is arriving at the designated location in time, etc.

In order to ensure the smooth execution of the whole production scheduling plan, there are specific requirements for the processing sequence and processing time of the products in process, and the transit time between each operations. It is also necessary to monitor the occurrence of deviations from the production scheduling plan.

Abnormal event disturbance can cause deviation from production scheduling. Production scheduling has specific requirements for the execution of events and sequence. By monitoring the time stamp in the RFID tag, we can get whether the actual production process deviates from the initial scheduling plan.

C. NEGOTIATION-BASED DISTRIBUTED CONTROL APPROACH

In the IoMT environment, manufacturing shop floor is composed of a group of distributed and intelligent manufacturing equipment, and the manufacturing equipment are communicated via a wireless communication. Flexibility and responsiveness are the mainly characterized of distributed control approach. In distributed control approach, distributed equipment controllers have to continuously negotiate for solving the complex production scheduling and control problem. The communication between the manufacturing equipment is realized by means of message, which can be divided into point-to-point communication and broadcasting communication. Message mode is a way of message exchange directly between the two sides of communication. The sender needs to specify a specific address for the message, and the device that meets the specified address can read the message.

The negotiation strategy between manufacturing equipment is the key to shop floor scheduling control [37]. In addition to maintaining the normal operation of the shop floor, we also need to consider disturbance problems in special situations, such as machine or AGV breakdown, urgent order arrival, which requires us to develop a negotiation mechanism to coordinate the various manufacturing equipment to deal with these problems. These negotiation mechanisms are also expressed, understood and communicated on the basis of system communication in manufacturing shop floor.

In shop floor production, the advancement of manufacturing processing is based on the transshipment of transfer robot (or AGV). Therefore, the transfer robot (or AGV) can be transferred as the core of the system control, and the minimum manufacturing processing loop is set for each operation of jobs. Each minimum manufacturing processing loop is a negotiation process, which contains three steps:

1) The transfer robot reads the RFID tag information and transfers the job to the buffer of the machine selected in the scheduling scheme based on the scheduling information stored in the tag;

2) After the job reaches the buffer, arrange to process or wait and return to the buffer after processing.

3) According to the processing status information in the label of the job in the buffer, the transfer robot can complete the storage or transfer to the machine selected by the next operation.

Therefore, the manufacturing processing of based manufacturing shop floor is composed of several minimum manufacturing processing loops. Firstly, the transfer robot sends a broadcast inquiry message to the buffer device and the storage device to ask if there is a transfer task. After receiving the inquiry message, the buffer device and the storage device inquire about their status information. If there are jobs in the buffer that are processed and waiting for transportation, the transfer robot will respond to the task feedback. If there is no transshipment task, the transshipment robot will continue to ask for information after a period of time until there is a transshipment task. If multiple jobs need to be transported at the same time, priority should be given to the process with the earliest planned start time for transshipment. The Socket based communication mechanism is used to realize the information exchange among the devices in the manufacturing equipment. The communication protocol adopts TCP/IP with connection.

Manufacturing systems often encounter many disturbances, and this paper focus on the shop floor coordination strategy when machine breakdown and urgent order arrival. When the machine breakdown occurs, the unscheduled and affected operations need to be rescheduled to ensure the smooth operation of the shop floor. When an urgent order arrives, rescheduling of unscheduled operations and emergency urgent order operations is needed. The rescheduling scheme is transmitted to the RFID tags of all the jobs in the form of broadcasting. After updating the label scheduling information, the manufacturing processing can continue according to the rescheduling scheme. The dynamic coordination and negotiation mechanism control mechanism of manufacturing process is shown in Figure 7.

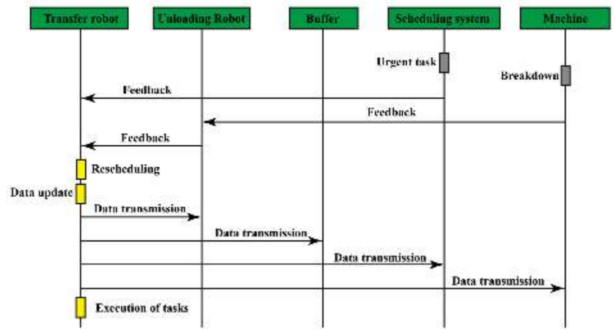

FIGURE 7. Dynamic coordination and negotiation control mechanism for manufacturing processing.

Frequent rescheduling will further affect the stability of shop floor production operation, so it is necessary to establish a buffer mechanism, and rescheduling needs to reach a certain threshold to stimulate. As far as energy efficiency scheduling is concerned, abnormal event disturbances will cause deviation from production scheduling plan. Total energy value problem needs to be considered. Deviation may lead to a sharp increase of total energy at a certain time. Therefore, rescheduling can be triggered when the total energy reaches a given threshold.

VI. EXPERIMENTS

A. EXPERIMENTAL

The experimental data are obtained from the actual production. As shown in Table 2, the flexible shop floor model uses 6 jobs and 8 machines, which requires 26 operations. Table 3 shows the energy consumption per unit of no-load during the processing of each machine. Figure 8 illustrates the Gantt charts of the best solution.

Assuming that process $J6.3$ deviates from the initial scheduling due to the disturbance of abnormal events at the time, if production is carried out according to the initial scheduling scheme, the total energy consumption will increase sharply at the time, as shown in Figure 9. If the threshold of total energy consumption is given, the

TABLE 2. Processing information.

JOB	OPERATIONS	ENERGY CONSUMPTION/ TIME DEALY							
		K1	K2	K3	K4	K5	K6	K7	K8
J1	O11		4.60/12			4.89/14		6.15/20	
	O12	5.83/18			6.31/19			3.95/11	
	O13			5.51/14	3.57/9		5.76/17		
	O14		4.13/11			3.42/9			4.47/12
	O15	4.81/15			3.42/8				6.29/18
J2	O21			4.43/12	5.92/19	4.83/14			
	O22	3.06/8			3.09/9			4.76/15	
	O23	4.95/16	3.19/7				3.69/9		
J3	O31				4.24/11	3.80/10			4.50/13
	O32			4.54/12	5.83/18			4.50/14	
	O33	3.08/9			4.5/15	2.93/7			
	O34		4.53/12				2.67/5		3.09/9
	O35	1.79/3			2.59/4		3.10/8		
J4	O41		6.05/19			3.01/7		4.44/13	
	O42			3.25/8		3.96/11			4.73/16
	O43		4.27/11		3.74/8			5.64/18	
	O44	2.26/6						4.44/14	3.58/9
J5	O51				7.43/22		4.39/12	4.89/17	
	O52		4.11/18			3.46/11			3.60/9
	O53	3.37/9		4.55/12					2.72/7
J6	O61		4.19/11				3.48/9	3.31/14	
	O62	3.11/8				3.06/6			3.79/9
	O63			4.07/11		5.95/17			5.98/18
	O64	1.92/5			5.54/15			2.79/7	
	O65		4.47/11				2.96/8		2.98/7
	O66	6.07/19			4.08/7		4.71/15		

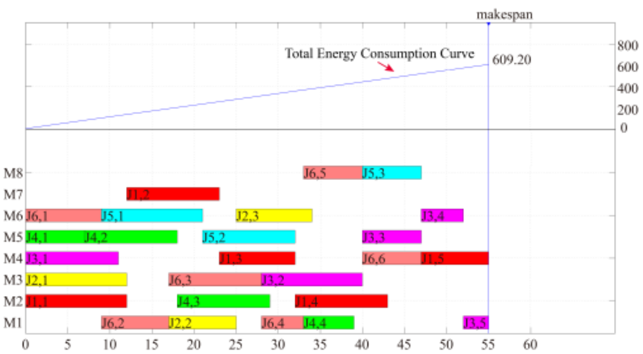

FIGURE 8. Initial scheduling scheme and total energy consumption curve.

rescheduling should be carried out at all times. The rescheduling scheme is shown in Figure 10.

B. RESULTS DISCUSSION

From the results of the above experiments, it can be concluded that PN-ACO it is an effective algorithm to solve energy-efficient FJSP and the negotiation and cooperation based

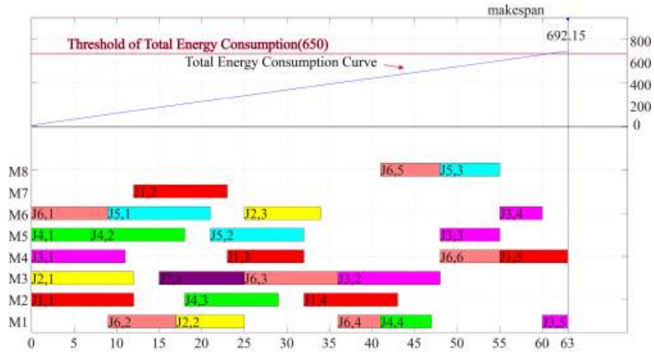

FIGURE 9. Scheduling scheme with on rescheduling and total energy consumption curve.

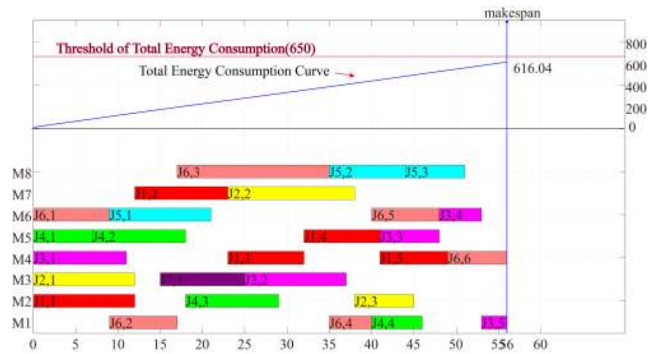

FIGURE 10. Scheduling scheme with rescheduling and total energy consumption curve.

TABLE 3. Machine energy consumption per unit time of no-load.

MACHINE	K1	K2	K3	K4	K5	K6	K7	K8
POWER	0.30	0.42	0.24	0.21	0.21	0.24	0.33	0.42

information interaction and process control method can be used to solve the dynamic scheduling problems according to the real-time status of the IoT enabled shop floor.

VII. CONCLUSION AND PROSPECTS

This work presents an approach for the modeling and scheduling of the energy-efficient FJSP. In our work, a new meta-heuristic algorithm, denoted as PN-ACO based metaheuristic algorithm, is developed for solving energy-efficient FJSP. This work proposes a negotiation and cooperation based information interaction and process control method, which combines the IoT and energy-efficient scheduling method. The proposed approach is further illustrated by a case energy-efficient of scheduling for a flexible job shop through which the optimal scheduling and correct supervisory control instructions can be obtained easily and quickly. In sum the proposed optimization algorithm obtains a good effect in engineering applications while the validity of optimization is proved.

In future research, we will focus on improving the efficiency and stability of the proposed scheduling and control approaches. In addition, it would be interesting to apply the proposed approaches to other types of manufacturing systems such as distributed manufacturing system and holon manufacturing system.

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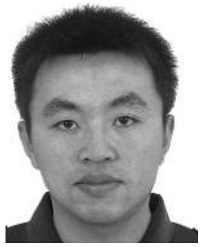

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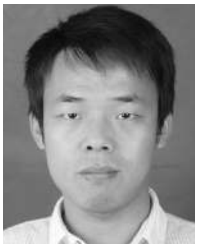

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