Research on Flexible Flow-Shop Scheduling Problem with Lot Streaming in IOT-Based Manufacturing Environment

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Abstract: It is urgent to effectively improve the production efficiency in the running process of manufacturing systems through a new generation of information technology. According to the current growing trend of the internet of things (IOT) in the manufacturing industry, aiming at the capacitor manufacturing plant, a multi-level architecture oriented to IOT-based manufacturing environment is established for a flexible flow-shop scheduling system. Next, according to multi-source manufacturing information driven in the manufacturing execution process, a scheduling optimization model based on the lot-streaming strategy is proposed under the framework. An improved distribution estimation algorithm is developed to obtain the optimal solution of the problem by balancing local search and global search. Finally, experiments are carried out and the results verify the feasibility and effectiveness of the proposed approach.

Key words: IOT-based manufacturing; flexible flow-shop scheduling; intelligent algorithm; lot-streaming strategy

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0 Introduction

China is developing a new industrial revolution, which has resulted in a new type of smart manufacturing mode-internet of manufacturing things (IOMT)[1]. IOMT is mainly composed of the internet network, embedded systems, radio frequency identification (RFID), sensors and other electronic information technologies and can realize dynamic perception, comprehensive connectivity, intelligent processing and adaptive optimal control of manufacturing and information resources through the whole production process, thus to impel manufacturing industry to be more intelligent[2]. Under the background of rapid integration of manufacturing and new information technology, IOMT provides important technical support for the optimized operation of workshop scheduling to improve production performance in the manufacturing system.

As one of the most representative manufacturing modes, flexible flow shop has been successfully applied in the semiconductor industry, the steel industry, the capacitor industry and so on. Production scheduling is one of the most important contents. Flexible flow-shop scheduling problem (FFSP) has been proved to be strongly NP-hard. Furthermore, it is hard to track the flow of production process. Fortunately, through deploying various sensing technologies, multi-source information of the flexible flow-shop under IOMT could be collected and processed on line. For example, RFID technology can be utilized to collect real-time production records by tracking RFID tags of jobs and machines. At the same time, an intelligent optimization algorithm is also employed to generate effective production scheduling solutions under IOMT.

For FFSP, most research focuses on traditional scheduling problem from two aspects: Mathemat-

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ical models and optimization algorithms[3-7]. On one hand, due to the complexity of the practical problem, most mathematical models have been proposed based on idealized issues rather than practical application. On the other hand, since FFSP belongs to the NP-hard problem, new intelligent algorithms should be considered to improve the solution quality. Therefore, the actual scheduling problem of the capacitor production is investigated in the paper. To solve the optimal solution of the scheduling problem, an improved distribution estimation algorithm is designed.

In addition, it is significant for the manufacturing system to collect real-time manufacturing data to support production scheduling. With the development of the new generation of information technology, there has been increasing research on production scheduling based on RFID technology in recent years. A RFID-based traceability approach, which is based on a novel information visibility-based scheduling rule, was proposed to improve production scheduling[8]. Then, a RFID-based intelligent decision support system architecture was established to investigate production monitoring and scheduling in a distributed labor-intensive manufacturing environment[9]. For a ubiquitous shop-floor environment, Zhang et al. presented a multi-agent based real-time production scheduling model and method by deploying wireless devices like RFID[10]. A RFID event-driven mechanism was adopted to address a two-level advanced production planning and scheduling model to improve the quality and reliability of plans and schedules[11]. Few studies on the FFSP under the IOMT environment have been reported. For hybrid flow-shop production, a ubiquitous manufacturing environment was created by using RFID technologies to describe the multi-period hierarchical scheduling mechanism[12]. A manufacturing Petri Net-based scheduling model for IOT-enabled hybrid flow shop manufacturing was introduced to achieve optimal schedules[13]. Wu et al. focused on the hybrid flow shop scheduling problem in the ubiquitous manufacturing environment and established scheduling optimization models and algorithm by deploying RFID[14].

Although the majority of the research on production scheduling to date has not considered the new smart manufacturing mode completely, the efforts mentioned above provide a starting point for exploring a timely and accurate schedule solution under the IOT-based manufacturing environment. In addition, the lot-streaming strategy in flow-shop scheduling problems has attracted much attention[15-17]. Therefore, aiming at the capacitor manufacturing plant, a multi-level architecture oriented to IOT-based manufacturing environment is established to present the flexible lot-streaming flow shop scheduling model and optimization algorithm.

1 Framework of FFSP Under IOMT

Fig.1 shows a multi-level framework for the flexible flow-shop in the context of IOMT, which is divided into three layers: Sensor network topology, manufacturing context-aware middleware, and intelligent scheduling layer. As for the intelligent scheduling layer, it is the core part of the framework, which will be described in detail in the next section.

For the sensor network topology, it is equipped with a large number of sensing devices, such as RFID devices (including RFID tags and RFID readers), programmable logic controller (PLC) devices, and wireless networks. These devices provide a channel of real-time information interaction and communication among manufacturing sources such as machines, workers, and raw materials in the workshop.

For the manufacturing context-aware middleware, it includes an information communication module, information collection module, information pre-processing module, and information storage module. The layer can effectively combine the information awareness of the underlying workshop and upper application development. On the one hand, it can provide application of unified information interface up to application services; on the other hand, it can access different types of sensors to shield the differences of various heterogeneous manufacturing information effectively. Thus, it can provide unified and normative semantic interpretation and scenarios information to the upper scheduling system.

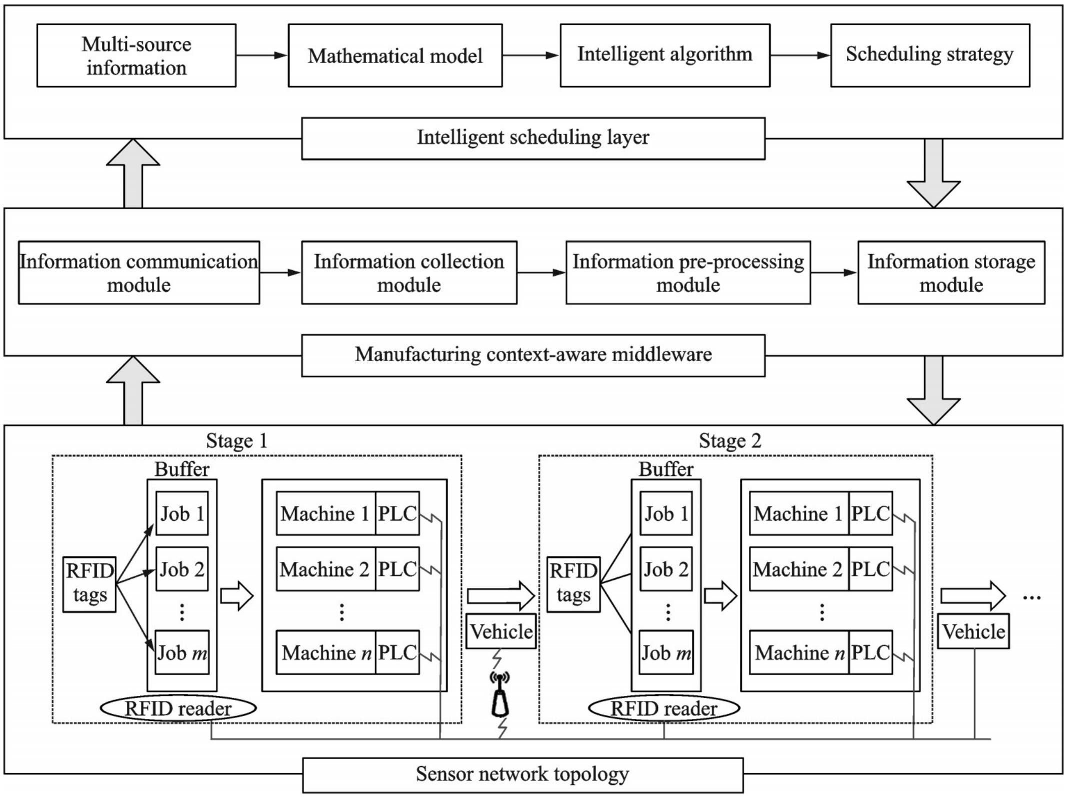

Fig.1 Multi-level framework of FFSP under IOMT

2 Mathematical Model of FFSP Under IOMT

2.1 Problem description

Due to the identical process routes for various production orders, production scheduling of the capacitor can be considered as a flexible flow-shop scheduling. The FFSP under IOMT can be described as follows. The number of available parallel machines, the number of production orders and product specifications in the workshop are obtained by IOMT on line. The workshop manager receives the production information and assigns all jobs to given machines accordingly. There exists a multi-stage production process that is composed of two or more production stages in series. It has at least one machine in each production stage, and at least one stage has more than one machine. All tasks have to go through all the production stages in the same order. In each production stage, there is a buffer for storing the jobs from the upstream stage. The buffer capacity between machines is unlimited. In addition, due to the manufacturing characteristic of the capacitor, there exists changing time of adjusting machine at some production stage, and the changing time can be recorded by PLC devices. To improve the production efficiency of the FFSP, a lot-streaming strategy based on the equivalent batch principle is considered in the paper.

The assumptions regarding the FFSP under IOMT are as follows.

(1) Each task can be processed by only one machine at each production stage;

(2) Each machine can process at most one task at a time;

(3) All machines are available at time $t=0$;

(4) There are no precedence relationships between tasks of different orders, but there are precedence relationships between different tasks of the same batch of orders;

(5) Preemption is not allowed for processing each task;

(6) Each order can be divided into multiple work orders, and all work orders are independent of each other;

(7) The transportation time between different buffers is ignored;

The notations used in the paper are listed in Table 1.

Table 1 Notations for FFSP under IOMT

Notation	Description	Notation	Description
i, i_1, i_2	Index of orders	C_i	Completion time of order i
j	Index of production stage	$C_{\max}$	Completion time of the last order
h	Index of machine	S_{ijh}	Starting time of task O_{ij} on machine h
k	Index of work orders	C_{ijh}	Completion time of task O_{ij} on machine h
l	Index of position	T_{ijh}	Processing time of task O_{ij} on machine h
I	Set of orders	DL_i	Completion time of the last work order for order i
J	Set of production stages	ST_{ikj}	Starting time of work order J_{ik} at stage j
M	Set of machines	CT_{ikj}	Completion time of work order J_{ik} at stage j
n	Number of all orders	TT_{ikj}	Processing time of work order J_{ik} at stage j
m_j	Number of parallel machines at stage j	S_{lh}	Starting time of work order for the lth position on machine h
TN_i	Number of order i	C_{lh}	Completion time of work order for the lth position on machine h
sp_i	Number of work order generated by order i	Y_{ijh}	Assignment binary variable that is set to 1 if task O_{ij} is to be processed on machine h, and 0 otherwise
SN	Number of the single batch	$X_{i_1 i_2 j}$	Sequencing binary variable that is set to 1 if order i_1 is be processed prior to order i_2 at stage j, and 0 otherwise
SN_{end}	Number of the last work order	$G_{i(i-1)2}$	Adjusting binary variable that is set to 1 if the size of two successive orders $(i,i-1)$ is different on the same machine of the second stage, and 0 otherwise
O_{ij}	Task of order i at stage j	GT	Changing time of adjusting machine
J_{ik}	The kth work order of order i	L	A big positive number

2.2 Mathematical model

To investigate the performance indicators of FFSP under IOMT, the scheduling optimization model with the objective of minimizing the makespan is proposed in the paper. Two scheduling strategies are studied to analyze the production performance. One is the schedule without considering the lot-streaming strategy and the other is the schedule with considering the lot-streaming strategy. The optimization model and constraints are described as follows.

$$f=\min(C_{\max}) \tag{1}$$

s.t.

$$C_{\max}\geqslant C_i \quad i\in I \tag{2}$$

$$\sum_{h=1}^{m_j} Y_{ijh}=1 \quad i\in I, j\in J \tag{3}$$

$$C_{ijh}=\begin{cases} S_{ijh}+T_{ijh} & i\in I; j\in J; h\in M \quad G_{i(i-1)2}=0 \\ S_{ijh}+T_{ijh}+GT & i\in I; j\in J; h\in M \quad G_{i(i-1)2}\neq 0 \end{cases} \tag{4}$$

$$X_{i_1 i_2 j}+X_{i_2 i_1 j}\leqslant 1 \quad i_1, i_2\in I \text{ and } i_1\neq i_2; j\in J \tag{5}$$

$$S_{i_1 jh}-C_{i_2 jh}+L(3-X_{i_2 i_1 j}-Y_{i_1 jh}-Y_{i_2 jh})\geqslant 0$$
$$i_1, i_2\in I \text{ and } i_1\neq i_2; j\in J; h\in M \tag{6}$$

$$C_{ijh}-S_{i(j+1)h}\leqslant 0 \quad i\in I; j=1,2,\cdots,S-1; h\in M \tag{7}$$

$$C_{(i-1)j2}+GT\leqslant S_{ij2} \quad i\in I \text{ and } i\neq 1; j\in J \tag{8}$$

$$sp_i\geqslant 1 \quad i\in I \tag{9}$$

$$TN_i=SN\cdot sp_i+SN_{\text{end}} \quad i\in I \tag{10}$$

$$C_{\max}\geqslant DL_i \quad i\in I \tag{11}$$

$$ST_{ik(j+1)}\geqslant CT_{ikj} \quad i\in I; k=1,2,\cdots,sp_i; j\in J \tag{12}$$

$$S_{(l+1)h}\geqslant C_{lh} \quad h\in M \tag{13}$$

Objective (1) is to minimize the makespan which is the completion time of the last order in FFSP. Constraint (2) defines that the makespan is not less than the completion time of any order in the schedule. Constraint (3) means that the same batch of orders at each stage can select only one machine. Constraint (4) gives the completion time of an order at any stage. Constraints (5) and (6) point out that one machine can process at most one batch of orders at a time. In other words, the next batch of orders can be processed after the current batch of orders has been finished on each machine. Constraint (7) gives the precedence constraints between the tasks of each batch, i.e., one task of the batch cannot be processed at the next production stage until it has been finished at the current stage. Constraint (8) indicates that machines should have the adjusting time due to the bottlenecks at the second stage. Constraint (9) ensures that the number of work orders generated by each order must be greater than or equal to 1. Constraint (10) means that the quantity of corresponding products cannot change after the order is divided into several batches. Constraint (11) indicates that the completion time of the last work order of any order cannot exceed the makespan. Constraint (12) gives that each process of the same batch still follows the specific process route after the order is divided into work orders. Constraint (13) ensures that any machine can process the next work order of the batch only after it has finished the current work order.

Hence, the scheduling model without considering the lot-streaming strategy can be described by objective (1) and constraints (2)—(9); the scheduling model with considering the lot-streaming strategy can be described by objective (1) and constraints (2)—(13).

3 Optimization Method of FFSP Under IOMT

It is important to note that the multi-source manufacturing information collected by sensing devices under IOMT is essential for the optimization algorithm. In the intelligent scheduling layer, the algorithm needs the real-time manufacturing information collected by sensing devices to clarify the current machine state and job state at the period, thus can ensure to yield an effective scheduling solution.

Due to the strongly NP-hard nature of FFSP, an improved distribution estimation algorithm is developed for solving the problem. Estimation of distribution algorithm is a global searching technique that is based on probabilistic model, which has been successfully applied at production scheduling. It can quickly approach to the optimization solution, but has a fatal shortcoming of limited local exploitation ability. Thus, the improved distribution estimation algorithm is designed for FFSP under IOMT. Fig.2 shows steps of the proposed algorithm.

Step 1 According to sensing devices like RFID and PLC, collect multi-source manufacturing information at the sampling period.

Step 2 Based on the encoding rule of manufacturing information, randomly generate chromosomes uniformly distributed in the search space to form the initial population.

Step 3 Evaluate the fitness value of each chromosome in the population according to the objective function, and keep optimal individuals.

Step 4 According to fitness value, select individuals with good fitness value to form an excellent group based on the elite strategy.

Step 5 Estimate the probability distribution model of the excellent population.

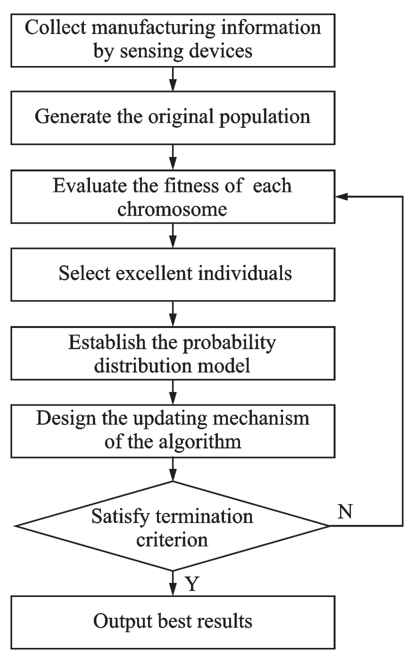

Fig.2 Flow chart of the proposed algorithm

Step 6 Update the probability distribution model by conducting the sampling to generate some new individuals.

Step 7 If the termination condition is satisfied, the algorithm ends, and the best individual in the group is the optimization result; otherwise, go to step 3 and continue the execution.

To efficiently improve the algorithm performance, a decision-making function $\alpha(t)$ is introduced to balance the global exploration and local exploitation of the proposed algorithm, which is expressed as

$$\alpha(t)=\exp(-t/\text{Maxgen}) \tag{14}$$

where t represents the iteration number and Maxgen the maximal number of iteration.

4 Case Study

To verify the feasibility and efficiency of the proposed model, a case study is tested. The experiments are carried out on a personal computer with Intel Pentium (R) with 4 GB memory and 2.60 GHz processor.

Consider one of capacitor production lines in which there are two cutting machines, three nailing machines, two leaching equipment, two casing machines, and two aging sorting devices. Each equipment is equipped with a RFID reader and PLC controller to record the relative manufacturing information. In addition, the wireless network is deployed in the manufacturing workshop and the manager can collect multi-source manufacturing information on line. For example, the detailed data regarding production orders on June 20, 2019 is sensed by RFID, which is shown in Table 2. Also, the processing time of each order at different production stages is collected in Table 3. All original information is processed and stored in the manufacturing context-aware middleware layer, and then the related value-added information is input into the scheduling layer to obtain the real-time scheduling results.

We analyze three different scenarios for FFSP under IOMT. Scenario 1: The scheduling strategy with lot streaming is considered for FFSP under IOMT. The experimental result is shown in Fig.3. According to the scheduling Gantt chart, the makespan is 36.9 h for the production line. Scenario 2: The scheduling strategy without lot streaming is considered for FFSP under IOMT. The experimental result is shown in Fig.4. According to the scheduling Gantt chart, the makespan is 38.8 h for the production line. Scenario 3: The scheduling solution on the day is obtained based on the artificial cal-

Table 2 Information on production orders

Order	Product ID	Order quantity	Due date
1	KM1J220ME110A00CV0	10.00	19/06/24
2	KM1J100MC110A00CV0	13.00	19/06/24
3	GM1C221ME110B25CV0	20.00	19/06/24
4	GM1H4R7MC110Z35CV0	8.00	19/06/25
5	GM1E100MC110Z35CV0	10.00	19/07/05
6	KM1H220MC110B25CE0	10.00	19/06/25
7	KM1H470ME110B25CE0	7.00	19/06/23
8	RL1H2R2MC110Z40CV0	5.00	19/06/25
9	RL1E101ME110A00CV0	7.00	19/06/24
10	RL1C220MC110Z40CV0	15.00	19/06/26

Table 3 Processing time of production orders at each stage h

Number	Stage 1		Stage 2			Stage 3		Stage 4		Stage 5	
	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	M_9	M_{10}	M_{11}
1	3.0	3.9	12.0	12.0	10	4.2	5.5	7.5	6.3	2.5	3.0
2	2.1	2.8	8.4	8.4	7.5	4.2	5.5	7.5	6.3	2.8	3.5
3	2.5	3.3	10.0	10.0	8.5	6.2	8.0	11.2	9.3	4.0	4.5
4	0.8	1.1	3.2	3.2	2.8	2.5	3.3	4.5	3.8	2.0	2.5
5	1.0	1.3	4.0	4.0	3.5	5.6	7.3	10.0	8.0	2.5	3.0
6	1.6	2.1	6.4	6.4	5.5	3.0	3.9	5.4	5.5	2.5	3.0
7	1.1	1.4	4.4	4.4	3.8	2.1	2.7	3.8	4.0	2.0	2.5
8	0.6	0.8	2.6	2.6	2.0	0.8	1.1	1.5	1.6	1.5	2.0
9	0.9	1.2	4.1	4.1	3.2	1.2	1.6	2.2	2.4	2.0	2.5
10	1.9	2.5	8.0	8.0	6.5	3.4	4.4	6.0	6.5	3.0	3.5

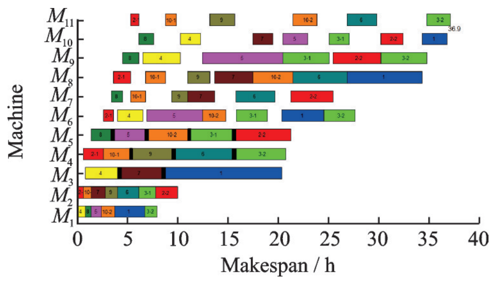

Fig.3 Scheduling Gantt chart with lot streaming

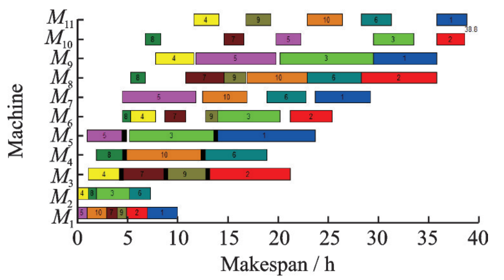

Fig.4 Scheduling Gantt chart without lot streaming

culation by the manager. The makespan is about 42 h for the production line.

It can be observed that the decision-maker can timely obtain real-time manufacturing information for production scheduling. For FFSP under IOMT, the makespan of the schedule with lot-streaming strategy decreases to 36.9 h from 38.8 h by comparing with the single batch strategy, which increases the production efficiency by 4.9%. Furthermore, compared with manual experience, the production efficiency is improved by 12%. Therefore, according to the experimental results of three scenarios, it can be seen that both scheduling results of scenarios 1 and 2 are obviously superior to that of scenario 3. In other words, the proposed approach is feasible and effective. Furthermore, the proposed lot-streaming strategy in the mathematical model could improve the production performance of FFSP under IOMT.

5 Discussion and Conclusions

We have investigated the capacitor manufacturing plant, which results in a flexible flow-shop scheduling problem. A multi-level architecture oriented to IOT-based manufacturing environment is established for FFSP, thus the real-time manufacturing information can be obtained timely for production scheduling. A scheduling optimization model with the objective of minimizing the maximum completion time is proposed for FFSP under IOMT. Due to the manufacturing characteristic of the capacitor, a lot-streaming strategy is designed in the mathematical model. To solve the optimal solution of the problem, an improved distribution estimation algorithm is employed by balancing local search and global search. Finally, the experimental results show that the method can effectively optimize scheduling tasks in the plant. Thus the feasibility and effectiveness of the proposed approach for FFSP under IOMT are verified.

Although the real-time relative data of production scheduling can be obtained for FFSP under IMOT, more evaluation of the proposed model by specifying the given parameters in factory applications needs to be performed. Second, uncertainty events such as machine breakdown, the number of new jobs, and the cancellations of existing jobs should be considered for FFSP under IMOT in the future.

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Author contributions Dr. **DAI Min** designed the study, provided the core idea and wrote the manuscript. Mr. **WANG Lixing** complied the algorithm programming of the model. Dr. **GU Wenbin** conducted the analysis of the manuscript. Mr. **ZHANG Yuwei** complied the model and collected the experimental data. Mr. **DORJOY M M H** modified the manuscript. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: WANG Jing)

面向制造物联环境下带有批量流的柔性流水车间调度问题研究

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摘要：如何通过新一代信息技术进一步提升制造企业的生产效率是需要迫切解决的问题。结合当前物联网技术在制造业的发展趋势，以电容器制造车间为研究对象，首先搭建面向制造物联环境下的柔性流水车间调度系统多层次体系架构；在此架构下，建立多源制造信息驱动制造执行过程的基于批量流策略的调度优化模型；其次，设计了一种改进的分布估计算法，通过平衡局部搜索和全局搜索，实现对问题的优化求解；最后，通过实验验证了所提方法的可行性和有效性。

关键词：物联制造；柔性流水车间调度；智能算法；批量流策略