A study on Multi-objective Flexible Job-shop Dynamic Scheduling Based on Control Window

DAI Daqi1*, FU Weiping2, SHE Jianhua1
1Xi’an Siyuan University Xi’an Shanxi 710038 China;
2 Xi’an University of Technology Xi’an Shanxi 710048 China.
DAI Daqi e-mail: xxddq88@163.com; 99376319@qq.com

Abstract: It is of great practical significance to study the dynamic scheduling of production in flexible job-shop. In the flexible job-shop scheduling, process, cost, machine tool and processing environment constitute the constraint set of scheduling. In this paper, starting from the multi constraints of scheduling system, the multi-objective linear synthesis of cost, time, quality and resource utilization is carried out. The scheduling intelligent algorithm is improved by using the polychromatic sets contour matrix to improve the operational efficiency. On the basis of the multi-objective flexible job-shop scheduling model under this multi constraints condition, from the actual situation of production scheduling, this paper constructs a scheduling control window according to the dynamic influence domain formed by the dynamic factors in the scheduling process. Dynamic scheduling control is carried out through control window to realize flexible scheduling and intelligent production. The effectiveness and feasibility of the model are verified by dynamic scheduling analysis of a simulation example.

1. Introduction
Flexible Job-shop Scheduling Problem (FJSP) is a recognized NP hard problem [1], as the basic link of intelligent manufacturing system. Although FJSP is very complex, it has very important practical significance because of its compatibility with the actual production and processing. It has been a research hotspot for many years. In the face of complex intelligent manufacturing system, intelligent algorithm and multi-objective research are important aspects. In the research of intelligent algorithm of flexible job-shop scheduling, Huang Xuewen and others put forward a process route scheduling algorithm based on genetic algorithm [2]. Li Yang etc. proposed a simulated annealing algorithm for replacement shop [3]. Xie Ruiqiang and others gave a discrete wolf swarm algorithm for flow shop[4],etc. In the research of scheduling objectives and algorithms, there are the genetic weed algorithm based on minimizing time[5], the discrete pollen algorithm based on time cost[6], the multi-objective particle swarm optimization based on energy consumption and time[7], etc. These researches enrich the selection of scheduling algorithm, enhance the adaptability to scheduling reality, and improve the efficiency of complex scheduling operation. Modern intelligent manufacturing should respond to the dynamic changes such as rapid technological progress, changes in external environment such as market, changes in internal manufacturing resources and capabilities, and emergencies. Its scheduling system must realize flexible scheduling for dynamic changes. Some research have been done on multi-objective machine fault scheduling [8], resource load and fault dynamic relationship scheduling [9], dynamic relation scheduling of resource load and fault [9], dynamic selection by dynamic strategy pool [10], dynamic scheduling of system considering both efficiency and stability.
[11], integration of simulation and algorithm [12], etc. To a certain extent, all of these consider the dynamic environment of flexible scheduling system, which lays the foundation for dynamic flexible scheduling and accumulates the experience that can be used for reference. In the process of solving the problem of FJSP, dynamic factors and constraints constitute a complex scheduling constraint environment. For example, scholars have built a dual resource constrained scheduling model [13] to solve the production scheduling problem of aerospace structures and introduced data flow to build a network resource scheduling model [14] in combination with 5G new business requirements, which are good research ideas.

In FJSP, multi-objective dynamic scheduling under multi constraints is a more practical problem. It is an important research direction of FJSP to deal with the dynamic factors of production system scientifically to promote the reasonable and rapid response of scheduling system. This paper analyzes the multi-objective problem of dynamic scheduling environment of FJSP under multi-constraints, and the genetic algorithm in the model is improved by polychromatic sets, the principle of window control technology is used for reference [15], the threshold of scheduling control window is determined by the influence domain of dynamic drivers on flexible shop floor scheduling resources, and reconfiguration of production resources within window thresholds to cope with dynamic changes. In this way a Multi-objective Flexible Job-shop Dynamic Scheduling Model with multi constraints is constructed to achieve dynamic and effective scheduling.

2. Dynamic Scheduling Model of Multi-objective Flexible Job-shop under Multi-constraints

2.1 Constraints and Multi-objective Optimization

There are four kinds of job-shop machining system: process constraint, machining environment constraint, machining efficiency constraint and fuzzy constraint. For convenient representation, the constraint set is represented by the symbol R {ri}. The process constraints include the process sequence (r1), the process specification (r2), and the machine tool technical capability (r3), etc. The constraints of machining environment include workers, cutting tool conditions (r4), workshop transportation and logistics conditions (r5), etc. Benefit constraints mainly include process time requirement (r6), material limitation and cost requirement (r7), etc. Fuzzy constraints mainly refer to market supply conditions and customer requirements (r8), etc. These constraints constitute the condition space of flexible scheduling system. In addition to constraints, FJSP is controlled by multiple related objectives while completing production tasks. These objects are represented by the set O {oi}. The objective of scheduling system can be divided into four basic objects: cost objective (O1), time objective (O2), quality objective (O3), resource utilization objective (O4). Multi-objective comprehensive optimization is the systematic requirement of scheduling.

Flexible job-shop production scheduling plan shall not only suit the technical requirements of production, but also suit the management requirements of production organization. In a complex system composed of O-set and R-set, cost objectives and constraints are closely related and transformed. As for multi-objective optimization, the first problem is to straighten out the relationship between conditions and objectives. In the process of model building, using Decision Making Trial and Evaluation Laboratory (DEMATEL) technology to analyze the factor relationship is a common technical means [16]. The technology determines the weight of each factor and scientific assignment through production experts, technical designers and workers' masters, and straightens out the relationship between multiple factors through qualitative and quantitative processing. At present, there are many methods about multi-objective optimization, such as linear synthesis, additive synthesis, ideal solution point method, ε-constraint method, intelligent algorithm Pareto solution set optimization and so on. Among these methods, the more concise is the linear synthesis method. This multi-objective synthesis method is used in the simulation model verification in this paper. Of course, different multi-objective optimization methods can be used to obtain the objective function of the model. The general scheduling model of the common multi reduction beam multi-objective problem is described as follows:
\[
\min \text{ or } \max f(x) = [f_1(x), f_2(x), \ldots, f_n(x)] \\
\text{s.t. } g_i(x) \leq 0; i = 1, 2, \ldots, N. \\
Z_j(x) = 0; j = 1, 2, \ldots, m \\
x_j \in X, i = 1 \ldots n
\]  

(1.1) (1.2) (1.3) (1.4)

Where: \( X_i \) is the multi-dimensional decision vector. \( X \) is the construction of decision vector space. \( f(x) \) is the objective function, \( n \) is the number of optimization objectives, which is specifically determined by the combination of the collection \( O \{o_i\} \) in FJSP. \( g_i(x) \) is the i-th inequality constraint. \( Z_j(x) \) is the j-th equality constraint. \( N, m \) are inequality, equality constraint number respectively. In FJSP, \( g_i(x) \) and \( Z_j(x) \) are determined by the relationship between \( R \) sets and \( O \) sets.

2.2 Intelligent Algorithm Application

Intelligent algorithm is an effective method to solve the problem of multi-objective uncertainty. Genetic algorithm is more mature to solve the single objective problem, and particle swarm optimization algorithm has advantages to deal with the multi-objective Pareto solution set. Choosing the appropriate intelligent algorithm in FJSP is the key to the success of the scheduling model. It should be seen that the algorithm module in scheduling can be selected flexibly according to the complexity of scheduling system and the actual production situation such as workshop processing capacity. In this flexible dynamic scheduling model, based on the requirements of timeliness and simplicity, the multi-objective linear synthesis with \( \max F(x) = \sum_{i=1}^{n} \omega_i f_i(x) \) is taken as the objective function. The constraint spaces are constructed \( g_i(x) \) and \( Z_j(x) \) by \( O \) set. Genetic algorithm is selected for iterative optimization. Considering the complexity of multi constraint solution space of optimization problem, the constraint conditions are defined by using the contour matrix of polychromatic sets (PS) technology\(^{17}\). The decision vector space constructed by the contour matrix improves the evolution speed of the algorithm, and the operation efficiency of the dispatching system is improved. There are many mature researches and applications on the improved genetic algorithm\(^{18-19}\), which will not be covered here.

2.3 Control Window for Dynamic Scheduling

2.3.1 Control windows

In the actual job-shop production and processing process, market demand change, process technology change, plug-ins and various emergency treatment and other situations occur from time to time, so this requires dynamic scheduling based on the actual dynamic factor situation. In terms of dynamic scheduling, the essence of dynamic scheduling is task redistribution due to scheduling task changes caused by changes in job-shop resources (human resources, equipment, etc.) and external environment (market demand, product batch, etc.). The key point is readjustment of production resources. The scheduling conditions and information can be adjusted according to the requirements of the dynamic factors, without the change of the whole model. It is necessary to build a special control domain for scheduling model to realize dynamic and timely scheduling according to the driver factors and their changes. This control domain is defined as scheduling control window because of its time property. In the processing of control window, the key of dynamic scheduling control is to consider the window adjustment period between the new and old scheduling schemes. It should be seen that the control window is a dynamic control process in scheduling control. An example is given to illustrate the dynamic control process. Suppose the window control domain is \([t_{is}, t_{ie}]\), the upper bound \( T_{\text{max}} = \max \{ t_{ie} \} \), the lower bound \( T_{\text{min}} = \min \{ t_{is} \} \), where \( t_{is} \) is the completion time of the processing
operation when the dynamic event occurs, $t_w$ is the start time of the working procedure when the dynamic event occurs. For example, in Figure 1, an emergency occurs at $t = 20$, the influence range is between the left and right vertical lines with $t = 20$, that is, the process between $t = 17$–$22$ is the window to be controlled. This window is not bilateral symmetry on the generation time of dynamic events, but depends on the processing time of the disturbed process. The production system is objectively affected by dynamic events, and the scheduling model must give a response, which is the role of establishing the control window.

![Scheduling Gantt chart](image)

**Fig.1 Schematic case diagram for control window**

### 2.3.2 Dynamic Scheduling Time Decision

In the control window, the confirmation of rescheduling time caused by dynamic event is a process of system judgment and decision, and its flow is shown in Figure 2.

![Flow decision chart for rescheduling](image)

**Fig.2 Flow decision chart for rescheduling**

When the production system is disturbed by internal and external dynamic events, the system responds and gives decisions, and makes scheduling adjustment plans to meet the needs of flexible scheduling.

### 2.4 Dynamic FJSP Model with Multiple Constraints and Objectives

According to the above analysis, the flow chart of multi-objective FJSP dynamic scheduling solution model under multi constraint conditions is shown in Figure 3.
3. A multi-objective Flexible Job-shop dynamic Scheduling Case under Multi Constraints

3.1 Case
Two kinds of dynamic events are selected to analyze the multi-objective dynamic scheduling instance of FJSP. The initial state of the flexible workshop is \((5 \times 5 \times 8)\), as shown in Table 1, among them, M and G represent the machine and production processes respectively, and the three numbers in the table represent the machining time, cost and quality value respectively. Using PS improved genetic algorithm, the specific setting of the algorithm is that the population size is 10. The maximum genetic algebra is 300, and the mutation probability is 0.07. In this case, the multi-objective consists of three parts: cost objective, time objective and quality objective, the objective function adopts linear multi-objective synthesis, weight \(\omega_j = [0.3, 0.3, 0.4]\). According to the multi-objective flexible scheduling model under multi constraints, the scheduling results are shown in Figure 4.

Table 1 Basic information table about job-shop

| Equipments | M1# | M2# | M3# | M4# | M5# | M6# | M7# | M8# |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Unit1      |     |     |     |     |     |     |     |     |
| G1         | 10,15,8 |     |     |     |     |     |     |     |
| G2         |     | 11,9,4 |     |     |     |     |     |     |
| G3         |     | 18,16,8 |     |     |     |     |     |     |
| G4         |     |     | 16,9,5 |     |     |     |     |     |
| G5         |     |     |     | 15,11,6 |     |     |     |     |
| Unit2      |     |     |     |     |     |     |     |     |
| G1         |     |     |     |     |     |     |     | 11,8,3 |
| G2         |     | 15,9,4 |     |     |     |     |     | 19,4,2 |
| G3         |     | 15,16,6 |     |     |     |     |     | 13,18,8 |
| Unit3      |     |     |     |     |     |     |     |     |
| G1         |     | 18,16,9 | 19,17,10 |     |     |     |     | 15,13,6 |
| G2         |     | 8,9,6 |     |     |     |     |     | 15,8,3 |
| G3         |     | 15,9,4 |     |     |     |     |     | 10,8,6 |
| Unit4      |     |     |     |     |     |     |     |     |
| G1         |     | 8,6,3 |     |     |     |     |     | 15,18,9 |
| G2         |     |     | 18,19,9 | 12,18,9 |     |     |     |     |
| G3         |     |     | 9,18,10 |     |     |     |     | 15,10,5 |
| G4         |     | 10,16,9 |     |     |     |     |     | 15,8,6 |
| Unit5      |     |     |     |     |     |     |     |     |
| G1         |     | 13,9,6 |     |     |     |     | 16,17,8 |     |
| G2         |     |     | 9,8,4 |     |     |     | 8,5,3 |     |
| G3         |     | 9,8,4 |     |     |     |     | 10,8,5 |     |
| G4         |     | 14,8,4 |     |     |     |     |     |     |
| G5         |     | 18,15,8 |     |     |     |     |     | 16,20,9 |
3.2 Dynamic Scheduling Simulation

In this paper, two kinds of scheduling simulation examples are given.

1. Driver 1: batch change, caused by an emergency plug-in unit. When $t = 40$, an emergency plug-in unit needs to be processed, see Table 2 for the process sequence and processing of the workpiece.

| Equipment | M1# | M2# | M3# | M4# | M5#   | M6#   | M7# | M8# |
|-----------|-----|-----|-----|-----|-------|-------|-----|-----|
| Put-in unit1 |     |     |     |     |       |       |     |     |
| G1        | 8,10,5 |     |     |     |       |       |     |     |
| G2        |       | 12,9,4 |     |     |       |       |     |     |
| G3        | 9,16,8 |   |     |     | 14,9,5 |     |     |     |

It can be seen from table 2 that when $t = 40$, the Plug-in unit needs to be processed urgently. The names of the processes that may be affected are 4-3, 1-3, 2-2 and 5-4. Process 4-3 and 1-3 are not affected. Although operations 2-2 and 5-4 are partially affected, most of these processes have been processed according to the nature of plug-in event, which should be considered as unaffected. According to fig.2 and control principle, the rescheduling time is:

$$T = \max \{t_{4-3} = 41, t_{1-3} = 43, t_{2-2} = 45, t_{5-4} = 46\} = 46$$

,see Fig.5.
Fig. 5 Situation rescheduling diagram

Table 3 Job-shop tasks information table about plug-in unit

| Equipments | M1# | M2# | M3# | M4# | M5# | M6# | M7# | M8# |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Unit1      | G4  |     |     | 16,9,5 |     |     |     |     |
| Unit2      | G3  | 15,16,6 | 13,18,8 |     |     |     |     |     |
| Unit3      | G3  | 15,9,4 |     |     |     |     |     |     |
| Unit4      | G4  | 10,16,9 |     |     |     |     |     |     |
| Unit5      | G5  | 18,15,8 |     | 15,8,6 |     |     |     |     |
| Put-in     | G1  | 8,10,5 |     |       |     |     |     | 10,12,6 |
| unit1      | G2  |     |     | 12,9,4 |     |     |     | 12,12,5 |
|            | G3  | 9,16,8 |     |       |     |     |     | 14,9,5 |

T = 46 is the ideal time for task connection, but it can’t be achieved basically. It only represents the beginning of scheduling adjustment due to dynamic events. Next, schedule according to table 3, in the middle, prepare for 4 units of time, that is, start production of new tasks at t = 50. Adopt the same scheduling algorithm conditions as the original, and adopt process coding. The scheduling goal is still the comprehensive goal, that is

\[
\min F(x) = \sum_{i=1}^{n} \omega_i f_i(x), \quad \text{among them } \omega_i = [0.3, 0.3, 0.4].
\]

Of course, the whole problem has become a 5 × 6 × 8 problem. The chromosome length is 30. The mutation rate is 0.07. And the maximum number of iterations is 300. The operation result is shown in Fig. 6 and Fig. 7.
Fig. 6 shows that the optimal chromosome was obtained at about 40 generations of operation, and the Gantt chart shown in Fig. 7 was obtained by chromosome decoding. In Fig. 7, the decision-making time of the four reserved units is the objective and practical need of the system operation, the real real-time scheduling seamless production connection is unrealistic. Of course, with the continuous improvement of enterprise information system, decision-making time can be shortened.

2. Driver 2: equipment or personnel status changes, with a sick leave, resulting in a workshop equipment can’t work.

If the M3# machine tool is affected, the time occurs at t = 40. According to the principle analysis, the ideal time of rescheduling is t = 46. This is the same as driver 1. The current status of the job-shop is shown in Table 4.

Table 4 Job-shop information table for machine failure

| Equipments | M1#  | M2#  | M3#  | M4#  | M5#  | M6#  | M7#  | M8#  |
|------------|------|------|------|------|------|------|------|------|
| Unit1      | G4   |      |      |      |      |      |      |      |
| Unit2      | G3   | 15,16,6 |     | 13,18,8 |     |      |      |      |
| Unit3      | G3   | 15,9,4 |     |      |      | 15,11,6 |     |      |
| Unit4      | G4   | 10,16,9 |     |      |     |      |      | 10,8,6 |
| Unit5      | G5   |      |      |      | 18,15,8 |     |      | 16,20,9 |

Fig. 6 The genetic evolutionary diagram

Fig. 7 Scheduling Gantt diagram for plug-in unit
When $t = 46$, a $5 \times 5 \times 7$ multi-objective scheduling problem is formed. Take the same optimization method as driver 1, and also give 4 units of preparation time, i.e. start rescheduling at $t = 50$, under the same condition of scheduling algorithm, process is adopted. The scheduling goal is still the comprehensive goal, that is $\min F(x) = \sum_{i=1}^{n} \omega_i f_i(x)$, among them $\omega_i = [0.3, 0.3, 0.4]$. The chromosome length is 30, the mutation rate is 0.07, and the maximum number of iterations is 100. The operation result is that after being affected by the driver event, the system readjusts the subsequent process processing according to the control window judgment. The scheduling progress curve and Gantt chart are shown in Fig.8 and Fig.9.

Two of the dynamic factors are studied above. For the scheduling disturbance caused by other dynamic factors, it is similar to the $N \times M \times Q$ problem, and the processing method is similar. In the example, the target does not involve the resource utilization target $O_4$. When the data is provided, the $O_4$ addition can be directly synthesized into the comprehensive target, or the weight coefficient can be transformed to obtain a variety of scheduling results. The $O_4$ is used for target hierarchical optimization, which will not be discussed here.

![Fig.8 Evolution curve diagram for Rescheduling](image1)

![Fig.9 Rescheduling diagram for machine failure](image2)
4. Summary and Prospect
This paper proposes a flexible dynamic scheduling problem for multi-objective realization under multi constraint conditions, establishes a dynamic scheduling model based on control window, and analyzes it with simulation examples. With strong pertinence and application, this paper effectively solves the dynamic scheduling problem of some enterprises' flexible job-shops. Of course, when encountering various and sudden motivations, we need to fine tune according to the specific situation of the workshop. However, this does not affect the feasibility of the whole model.

It should be noted that there are still some further improvements in this model, such as classification, hierarchical level, constraint and target mutual transformation, etc. in multi-objective additive linear synthesis processing. There are also better methods to explore for weight coefficients. When the system is more complex, it can be considered to use Pareto solution set with random coefficient to obtain the target stratification and then make the decision, which needs further study.

References
[1] Demir Y, Isleyen SK. Evaluation of mathematical models for flexible job-shop scheduling problems [J]. Applied Mathematical Modelling, 2013, 37(3): 977–988.
[2] HUANG Xuwen, ZHANG Xiaotong, SUN Rong, LI Guanxiong. GA based scheduling algorithm for job-shop with processing flexibility [J]. Operations Research and Management Science, 2018, 27(6): 184–193.
[3] LI Yang, LI Xinyu, MOU Jianhui. Large-scale permutation flow-shop scheduling method based on improved simulated annealing algorithm [J]. Computer Integrated manufacturing Systems, 2020, 26(2): 366–375.
[4] XIE Ruiqiang, ZHANG Huizhen. Discrete wolf pack algorithm for permutation flow shop scheduling problem [J]. Control Engineering of China, 2020, 27(2): 288–296.
[5] HUANG Haisong, LIU Kai, CHU Guangyong. Self-adaptive multistage GA-IWO for solving flexible job shop Scheduling Problem [J]. Journal of Mechanical Engineering, 2019, 55(6): 223–232.
[6] LI Yang, LI Xinyu, MOU Jianhui. Discrete flower pollination algorithm for solving multi-objective flexible job shop scheduling problem [J]. Computer Integrated manufacturing Systems, 2018, 2(11): 2808–2818.
[7] LI Yang, LI Xinyu, MOU Jianhui. Multi-objective optimization algorithm for flexible job shop scheduling based on energy consumption [J]. Modern Electronics Technique, 2020, 43(7): 126–130.
[8] ZHU Chuanjun, QIU Wen, ZHANG Chaoyong etc. Multi-objective flexible job shop dynamic scheduling strategy aiming at scheduling stability and robustness[J]. China Mechanical Engineering, 2017, 28(2): 173–182.
[9] TAO Liyan, ZHAO Pengfei, CHEN Ranran. Research on multi-objective scheduling of parallel machining system resources based on dynamic machine failure rate [J]. Computer Integrated manufacturing Systems, 2020, 26(1): 66–73.
[10] ZHANG Guijun, WANG Wen, ZHOU Xiaogen, etc. Dynamic strategy-based differential evolution for flexible job shop scheduling optimization[J]. Computer Science, 2018, 45(10): 240–245.
[11] FATTAIHI P.FALLHI A. Dynamic scheduling in flexible Job Shop systems by considering simultaneously efficiency san stability[J].Journal of Manufacturing Science and Technology, 2010,2(2):114–123.
[12] GHOLAMI M, ZANDIEH M. Integrating simulation and genetic algorithm to schedule a dynamic flexible job shop [J]. Journal of Intelligent Manufacturing, 2009, 20(4):481–498.
[13] ZHOU Yaqin, YANG Changqi, LU Youlong, etc. Scheduling the Production of Aerospace Structural Parts with Dual Resource Constraints [J]. Journal of Mechanical Engineering, 2018,54(9):55–63.
[14] WANG Chen, TANG Hongbo, YOU Wei, etc. A Resource Scheduling Algorithm With
Low Latency For 5G Networks Based on Effective Hybrid Genetic Algorithm and Tabu Search [J]. Journal of Xi’an Jiaotong University, 2018, 52(4):117~124.

[15] HONG Wei TIAN Yantao DONG Zaili, etc. Extracting features from local environment for intelligent robot system [J]. Robot, 2003, 25(3):264~269.

[16] JIN Weijian, HU Hanhui, YOU Wei, etc. Extended application of fuzzy DEMATEL method [J]. Statistics and Decision, 2011, (23):170~171.

[17] GAO Xinqin, LI Zongbin. Workflow modeling method based on UML & polychromatic sets theory [J]. Computer Integrated manufacturing Systems, 2006, 12(7): 969~975.

[18] FU Weiping, LIU Dongmei, LAI Chunwei, etc. Polychromatic-sets-based improved genetic algorithm for solving multi-species FJSP [J]. Computer Integrated manufacturing Systems, 2011, 17(5): 1104~1010.

[19] LUAN Fei, WANG Wen, FU Weiping, etc. FJSP solving by improved GA based on PST hierarchy structure [J]. Computer Integrated manufacturing Systems, 2014, 20(10): 2494~2501.