The Hybrid Production Optimization Model of Prefabricated Components from the Perspective of Multiple Orders

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Abstract. The production of prefabricated components in modular construction is an important part of the modular construction supply chain. Starting from the perspective of multi-order and considering the characteristics of prefabricated concrete components, a dual-objective optimization model is proposed for prefabricated component production scheduling under the constraints of prefabricated component molds and order delivery time windows in a parallel production mode of multiple production lines. The NSGA-II algorithm is used for optimization to improve the on-time delivery rate of orders and reduce the idle time of production lines.

Keywords: Production optimization of prefabricated components · multiple orders · parallel production with multiple lines · NSGA-II · multiple objectives

1 Introduction

The Ministry of Housing and Urban-Rural Development of China pointed out in the "Several Opinions on Accelerating the Development of New-Type Building Industrialization" that new-type building industrialization is driven by the new generation of information technology, with the main means of systematic integrated design and lean production and construction throughout the life cycle of the project, and the integration of the entire industry chain, value chain, and innovation chain of the project to achieve high efficiency, high quality, low consumption, and low emission of building industrialization. Prefabricated components have become an important means for the transformation and upgrading of China's construction industry [1]. The production of prefabricated concrete components for assembly buildings is characterized by high cost, long cycle, and complex processes [2, 3]. With the upgrading of the industry, the demand for prefabricated components will increase significantly, and the increase in the number of prefabricated component orders will break the original balance of the production system. In this situation, reasonable production plans and scientific scheduling decisions become complex [4].

Currently, there is little research on prefabricated component production scheduling from the perspective of multiple orders. Leu S [5] considered the influence of limited resources on the production cycle of prefabricated components and established a

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resource-constrained mixed production line scheduling system. Khalili A et al. [6] established a mixed integer linear programming (MILP) model with on-site construction factors as constraints and created the best production plan by designing a mold fitness matrix. Yang [7] studied the influence of mold, labor load, and curing pit capacity constraints on the parallel production system of prefabricated components in multiple production lines and established a prefabricated component multi-production line scheduling model. Xie Sicong et al. [8] used a genetic algorithm based on multi-layer coding to solve the optimization problem of production progress for multiple types and quantities of prefabricated components and proposed a two-stage optimization model to achieve efficient production management. Xiong Fuli [9] considered the joint optimization objectives of prefabricated component process constraints, inter-order and intra-order scheduling from the perspective of production orders and used the collaborative evolution mixed-discrete difference evolution algorithm to solve the optimization problem. Wang Heping [10] established a multi-objective optimization model for mixed production in a flow shop from the perspective of five aspects: waiting time for component processing, energy consumption, total production time, on-time production, and number of changes in component models, and used the NSGA-III algorithm to solve the high-dimensional model. Therefore, it is an urgent problem to solve how production manufacturers can coordinate production resources, develop reasonable production plans, and ensure that components are delivered on time and production is coherent from the perspective of multiple orders.

2 Problem Description

The production of precast concrete components generally includes two production modes: assembly line production and fixed mold production. The research object in this paper is the assembly line production mode. The production process of precast concrete components can usually be summarized as six processes: formwork (k1), reinforcement (k2), concrete pouring (k3), concrete curing (k4), demoulding (k5), and finished product repair (k6). Due to the differences in the components, the processing time for each component in each process is different. Precast components flow through these six processes in sequence, and finally complete production.

3 Hypotheses and Symbel Definitions

3.1 Hypotheses

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

- Hypothesis 1: All processes of a component can only be produced on a single production line, and once the production line is determined, it cannot be changed.
- Hypothesis 2: The supply of other resources required during the production process is sufficient, and only the quantity of precast concrete mold is considered.

- Hypothesis 3: Mixed production refers to the production of all component orders and different types of mold components on the same production line. The conversion cost and conversion time between different types of components on the production line are not considered.
- Hypothesis 4: All orders arrive simultaneously.
- Hypothesis 5: Each process on the production line can process one component at most at the same time.

3.2 Symbol Definitions

The symbol definitions are shown in the Table 1.

4 Model Construction

4.1 Model Construction Approach

There are L ($l = 1, 2, \ldots, L$) precast component assembly lines in the workshop of a precast concrete component production factory, with 6 workstations each (corresponding to the 6 processes for producing precast concrete components). The number of precast components produced on the 1th assembly line is n_l. . Assuming that the precast production factory needs to supply precast components for I ($i = 1, 2, \ldots, I$) projects, i.e., I orders, each order includes n_i ($j = 1, 2, \ldots, n_i$) different precast components. As the precast component producer faces production orders from multiple projects, the producer will negotiate with the buyer to agree on delivery time windows for each order. The time windows can provide a buffer effect to some extent for the precast component producer, thereby improving the delivery rate of orders and reducing the idle time of assembly lines. Let $\left[T_i^{min}, T_i^{max}\right]$ denote the delivery time window for the i-th production order, i.e., the producer must deliver all components in order i within the agreed time window. As project orders arrive at the same time but with different delivery time windows, it is necessary to develop a reasonable precast component production plan. Figure 1 is a schematic diagram of production plan.

4.2 Optimization Objectives

The minimum idle time of the production line is the main optimization objective. The curing of concrete is a parallel, non-interruptible process, and assuming that there are no capacity constraints in the concrete curing kiln, the curing process can start immediately after the previous task is completed. Therefore, Task 4 does not have any idle time, as shown in Eq. (1). From a multi-order perspective, the highest on-time delivery rate is the objective, which means minimizing the total storage and delay costs. Assuming that all orders arrive simultaneously but have different delivery time windows; and as all components within an order are delivered at the same time, the actual completion time of an order is the time when the last component in the order is completed, as shown in Eq. (2). Storage costs are incurred if the component's production completion time is earlier than the actual completion time of the order, and if the actual completion time is earlier than the agreed earliest delivery time, storage costs will also be incurred. Delay

Table 1. Symbol definitions and descriptions

Symbol	Description
$V_{i,j}$	The j_{th} precast component of the i_{th} order, where $i = 1, 2, 3, \ldots, I$; $j = 1, 2, \ldots, n_i$
n_i	The total number of components in the ith order $n_i = \sum_{j=1}^{J} V_{i,j},\ j \in i$
L	The l_{th} production line, $l = 1, 2, \ldots, L$
S	The s_{th} produced precast component on the lth production line, where $s = 1, 2, \ldots, n_l$
n_l	The total number of precast components produced on the l_{th} production line, where $\sum_{l=1}^{L} n_l = \sum_{i=1}^{I} \sum_{j=1}^{J} V_{i,j}$
K	The process on the production line, $k = 1, 2, \ldots, 6$
A	The priority value of precast component production, with smaller values indicating earlier production, $a < b$
Σ	The storage cost per unit time of a component
γ_i	The penalty cost per unit time of delay for a component in the i_{th} order
T_i^{min}	The earliest delivery time agreed upon for the i_{th} order
T_i^{rel}	The actual completion time of the i_{th} order
T_i^{max}	The latest delivery time agreed upon for the i_{th} order
$	The mold type of precast component
$Q^{\$}$	The quantity of mold $
H_W	The normal working time per day
H_A	The allowed overtime per day
H_N	The non-working time per day
$(V_{i,j})_{l,s}$	The production sequence of the j_{th} component in the i_{th} order on the lth production line is s
$M_{l,k}$	The kth production process on the lth production line
$S_{((V_{i,j})_{l,s},M_{l,k})}$	The start time of the j_{th} component in the i_{th} order on the lth production line, which enters the k_{th} process
$C_{((V_{i,j})_{l,s},M_{l,k})}$	The completion time of the j_{th} component in the ith order on the lth production line, which goes through the kth process
$P_{((V_{i,j})_{l,s,k})}$	The planned production time of the j_{th} component in the ith project in the kth process

costs will be incurred if the actual completion time is later than the agreed latest delivery time. The combined result of storage and delay costs is used to evaluate the on-time delivery rate of prefabricated component production from a multi-order perspective, as

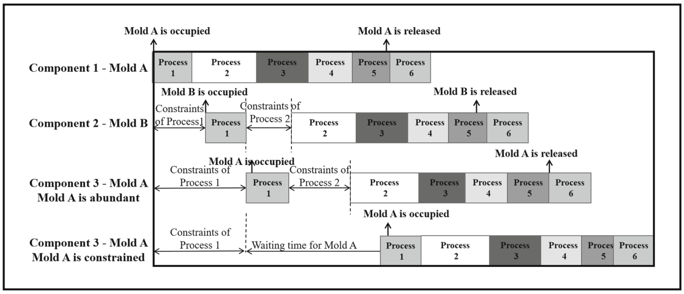

Fig. 1. Schematic diagram of production plan

shown in Eq. (3).

$$minf_1 = min\left\{\sum_{l=1}^{L}\sum_{k=1}^{6}\left\{C_{(V_{i,j})_{l,n_l},M_{l,k}} - S_{(V_{i,j})_{l,1},M_{l,k}} - \sum_{s=1}^{n_l} P_{(V_{i,j})_{l,s,k}}\right\}\right\} \quad k \neq 4 \tag{1}$$

$$T_i^{rel} = max_{j=1}^{n_i}\left(C_{(V_{i,j})_{l,s},M_{l,6}}\right) \quad \forall j \in i \tag{2}$$

$$\begin{aligned} minf_2 = & min\sum_{i=1}^{I}\sum_{j=1}^{n_i}\left\lceil\left(T_i^{rel} - C_{(V_{i,j})_{l,s},\mathrm{M}_{l,6}}\right)\times\sigma\right\rceil \\ & + \sum_{i=1}^{I} max(T_i^{min} - T_i^{rel}, 0)\times(n_i - 1)\times\sigma \\ & + \sum_{i=1}^{I} max(T_i^{rel} - T_i^{max}, 0)\times(n_i - 1)\times\gamma_i \end{aligned} \tag{3}$$

4.3 Constraints

The constraints are as follows: Eq. (4) represents the time limit for prefabricated components to enter each task. A component can only enter a task when its previous task and the previous component in this task have both been completed. Equations (5) and (6) represent the calculation method for the starting time of a component in different tasks. Equation (7) represents the calculation method for D. Equations (8), (9), and (10) represent the calculation process for the completion time of a component in different tasks. The calculation process for the completion time is different depending on the nature of the task. Equations (11) and (12) represent the actual processing time of a component in different tasks. Equation (13) represents that all components must go through six production tasks. Equation (14) represents the constraint on the mold used for producing components. The calculation process is based on Yang [7] with modifications. Since all components that need to be produced share the same mold resources, components with higher priority can occupy the mold first. When a mold is occupied, other components with the same mold type must wait until the mold is released. Equations (15) and (16) represent the constraints on the completion and starting time of a component.

$$S_{(V_{i,j})_{l,s},M_{1,k}} \geq \begin{cases} C_{(V_{i,j})_{l,s},M_{1,k-1}} & k = 4 \\ max\left(C_{(V_{i,j})_{l,s-1},M_{1,k}}, C_{(V_{i,j})_{l,s},M_{1,k-1}}\right) & k \neq 4 \end{cases} \tag{4}$$

$$S_{(V_{i,j})_{l,s},M_{l,k}} = \begin{cases} max(C_{(V_{i,j})_{l,s-1},M_{l,k}}, C_{(V_{i,j})_{l,s},M_{l,k-1}}) & \begin{array}{l} if\ 0 < max(C_{(V_{i,j})_{l,s-1},\mathrm{M}_{l,k}}, \\ C_{(V_{i,j})_{l,s},\mathrm{M}_{l,k-1}})\ mod\ 24 < 8 \end{array} \\ \left\lceil max(C_{(V_{i,j})_{l,s-1},\mathrm{M}_{l,k}}, C_{(V_{i,j})_{l,s},\mathrm{M}_{l,k-1}}) \div 24 \right\rceil \times 24\ else & \end{cases} \quad k \neq 3 \tag{5}$$

$$S_{(V_{i,j})_{l,s},M_{l,3}} = \begin{cases} C_{(V_{i,j})_{l,s},M_{l,2}} + 16 & if\ C_{(V_{i,j})_{l,s},M_{l,2}}\ mod\ 24 = 8 \\ C_{(V_{i,j})_{l,s},M_{l,2}} & if\ 12 - C_{(V_{i,j})_{l,s},M_{l,2}}\ mod\ 24 \leq P_{(V_{i,j})_{l,s,3}} \\ \left\lceil C_{(V_{i,j})_{l,s},M_{l,2}} \div 24 \right\rceil \times 24 & if\ 12 - C_{(V_{i,j})_{l,s},M_{l,2}}\ mod\ 24 > P_{(V_{i,j})_{l,s,3}} \end{cases} \quad k = 3 \tag{6}$$

$$D = int\left(\frac{T}{24}\right) \tag{7}$$

$$C_{(V_{i,j})_{l,s},\mathrm{M}_{l,3}} \geq \begin{cases} T & if\ T \leq 24D + H_W + H_A \\ 24(D+1) + P_{(V_{i,j})_{l,s,3}} & if\ T > 24D + H_W + H_A \end{cases} \quad k = 3 \tag{8}$$

$$C_{(V_{i,j})_{l,s},M_{l,4}} \geq \begin{cases} T^* & if\ T^* \leq 24D + H_W \\ 24(D+1) & if\ 24D + H_W \leq T^* \leq 24(D+1) + H_W \\ T^* & if\ T^* > 24(D+1) + H_W \end{cases} \quad k = 4 \tag{9}$$

$$C_{(V_{i,j})_{l,s},M_{l,k}} \geq \begin{cases} T & if\ T \leq 24D + H_W \\ T + H_N & if\ T > 24D + H_W \end{cases} \quad k = 1, 2, 5, 6 \tag{10}$$

$$T = max\left\{C_{(V_{i,j})_{l,s},M_{l,k-1}}, C_{(V_{i,j})_{l,s-1},M_{l,k}}\right\} + P_{(V_{i,j})_{l,s,k}} \quad k = 1, 2, 4, 5, 6 \tag{11}$$

$$T^* = C_{(V_{i,j})_{l,s},M_{l,3}} + P_{(V_{i,j})_{l,s,3}} \quad k = 3 \tag{12}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}(V_{i,j})_{l,s} = \sum_{l=1}^{L}\sum_{s=1}^{n_l}(V_{i,j})_{l,s} \tag{13}$$

$$S_{(V_{i,j})^{b,\$}_{l,s_1},M_{l,1}} \geq min\left\{max^{Q_\$}_{\forall l' \in N^+ | l' \leq L, \forall S_2 \in N^+ | S_2 < n_l, \forall a \in N^+ | a < b} C_{(V_{i,j})^{a,\$}_{l',s_2},M_{l',6}}\right\} \tag{14}$$

$$C_{(V_{i,j})_{l,s},M_{l,k}} \geq 0 \quad \forall s = 1, 2, ..., n_l, \forall k = 1, 2, ..., 6, \forall l = 1, 2, ..., L \tag{15}$$

$$S_{(V_{i,j})_{l,1},M_{l,1}} = 0 \quad \forall l = 1, 2, ..., L \tag{16}$$

5 Algorithm Description

The Non-dominated Sorting Genetic Algorithm (NSGA) was proposed by SRINIVAS and DEB in 1994. It uses a hierarchical selection method to highlight excellent individuals and maintains the stability of excellent subgroups through niching methods [11]. DEB et al. improved the NSGA algorithm and proposed the NSGA-II algorithm. In NSGA-II, a new non-dominated solution sorting method, elitist selection strategy, and crowding distance were used, and the computational complexity was reduced accordingly [12].

The multi-objective genetic algorithm NSGA-II with an elite strategy and non-dominated sorting process can be described as follows: for each individual in the swarm, it is compared with the remaining individuals based on the fitness function to determine whether it dominates or is dominated. If the current individual is not dominated by any other individual, it is marked as a non-dominated individual. This process is continued until all non-dominated individuals are found and labeled as the first non-dominated layer. Then, the labeled non-dominated individuals are ignored, and the process is repeated to find all remaining non-dominated layers until all individuals in the swarm are divided into several non-dominated layers. The specific process of NSGA-II is shown in Fig. 2.

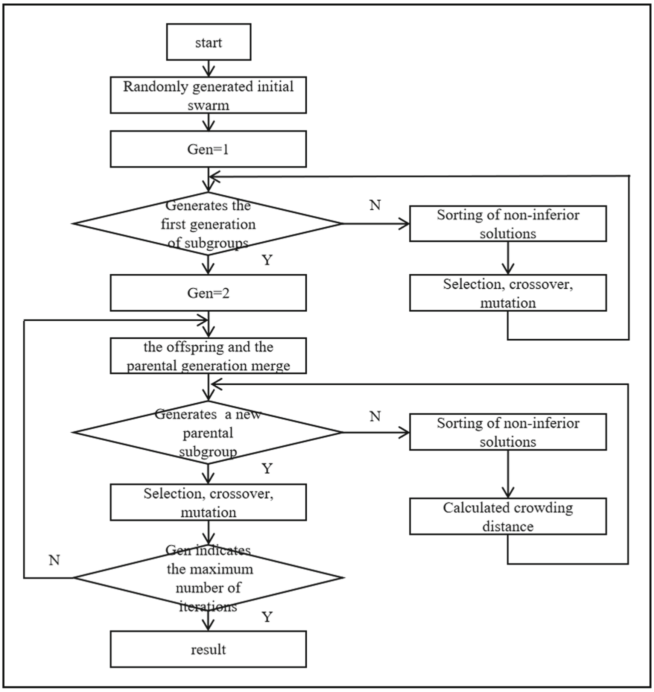

Fig. 2. Flowchart of NSGA-II

Table 2. Details of each order (a)

Order number	serial number of component	mold type	The processing time of each production task					
			task 1	*task 2*	*task 3*	*task 4*	*task 5*	*task 6*
1	1	A	1.5	2.0	3.0	8.0	0.5	0.5
	2	A	2.0	1.0	2.0	8.0	0.5	1.0
	3	B	3.0	1.5	2.0	8.0	0.5	1.0
	7	C	2.0	1.0	1.5	8.0	1.0	1.0
	11	C	0.5	1.0	2.0	8.0	0.5	0.5
2	4	B	1.5	0.5	0.5	8.0	0.5	2.0
	5	C	2.5	2.0	1.5	8.0	1.0	3.0
	6	A	2.0	1.0	0.5	8.0	1.0	2.0
	10	A	2.5	0.5	1.0	8.0	0.5	0.5
	12	A	1.0	1.0	2.0	8.0	1.0	0.5
3	8	A	1.5	0.5	1.0	8.0	0.5	0.5
	9	B	3.0	2.0	4.0	8.0	1.5	0.5
	13	A	1.0	1.5	0.5	8.0	0.5	1.0
	14	B	1.5	2.0	1.0	8.0	1.5	0.5

6 Case Study

6.1 Case Background

A prefabricated component manufacturer in Jiangbei New District of Nanjing City received three orders at the same time, namely A, B, and C, each corresponding to a separate project. Information about each order was obtained through research and interviews. The prefabricated component manufacturer currently has two production lines, and aims to develop a reasonable production plan to achieve optimal production idle time on the assembly line as well as on-time delivery of all orders. A, B, and C require 3, 2, and 2 molds, respectively. The normal working time of workers is 8 h, and the overtime is 4 h. The specific information of the three orders is shown in Table 2.

7 Results Analysis

The NSGA-II algorithm was implemented using Python3.9. After a literature review and experimental screening, the following parameters were selected: swarm size of 200; 500 iterations; crossover probability of 0.9; and mutation probability of 0.1. The program was run on a computer with a dual-core Intel Core i5 processor and 8GB of memory. Due to multi-objective optimization, multiple Pareto solutions exist for each run. To reduce the randomness of each run, the case was run 16 times, with an average computation time of 1669 s. The Pareto front solutions generated from the 16 runs were combined,

Table 3. Details of each order (b)

Order number	serial number of component	mold type	delivery time windows(h)		cost (yuan)	
			earliest delivery time	*latest delivery time*	*storage cost*	*delay cost*
1	1	A	48	52	45	90
	2	A				
	3	B				
	7	C				
	11	C				
2	4	B	48	56		180
	5	C				
	6	A				
	10	A				
	12	A				
3	8	A	24	32		150
	9	B				
	13	A				
	14	B				

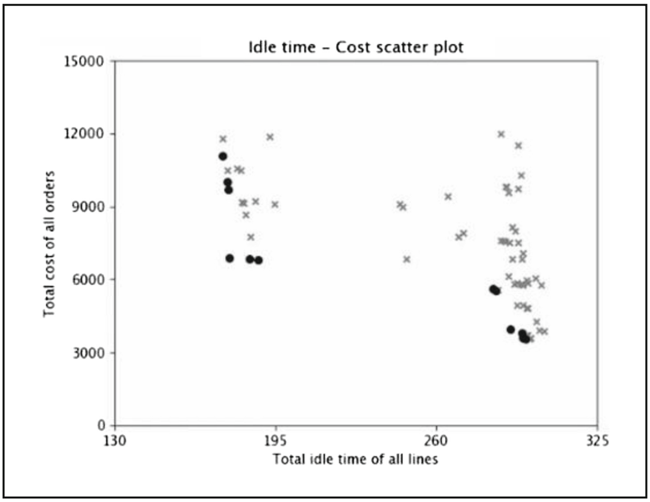

Fig. 3. Final Pareto front solutions

and the final Pareto front solutions were obtained based on the domination relationships between these solutions. The final Pareto front solutions are shown in Fig. 3, where the cross represents all Pareto front solutions generated from the 16 runs, and the circular points represent the final Pareto front solutions. As shown in Table 3, 12 Pareto solutions were finally obtained with their specific objective values and production sequences.

Table 4 shows that each production sequence is composed of a two-dimensional array (as there are only two production lines in this case). The first dimension represents the production sequence of the first production line, and the second dimension represents the production sequence of the second production line. For example, the solution with

Table 4. Objective values and production sequences of Pareto front solutions

sequence number	total idle time of pipeline (h)	total cost of all orders (yuan)	sequence of production
1	290	3960	([13, 8, 6, 2, 10], [9, 14, 7, 5, 12, 3, 11, 4, 1])
			([13, 8, 6, 7, 2, 10], [9, 14, 5, 12, 3, 11, 4, 1])
2	294.5	3780	([13, 8, 6, 2, 10, 11], [9, 14, 7, 5, 12, 3, 4, 1])
3	295.0	3600	([13, 8, 14, 6, 10, 3], [9, 5, 7, 1, 11, 4, 12, 2])
4	296.0	3555	([13, 8, 14, 6, 10, 3], [9, 5, 7, 2, 11, 4, 12, 1])
5	173.5	11070	([14, 10], [9, 5, 8, 6, 7, 13, 11, 12, 4, 3, 1, 2])
6	175.5	10012.5	([14, 10], [9, 13, 7, 8, 5, 4, 2, 12, 11, 3, 1, 6])
7	176.0	9697.5	([10, 14], [9, 7, 13, 8, 5, 12, 11, 3, 4, 1, 2, 6])
8	176.5	6885	([5], [14, 13, 9, 8, 10, 7, 12, 11, 4, 6, 3, 1, 2])
9	284.0	5535.0	([13, 8, 5, 10], [9, 14, 6, 7, 12, 3, 11, 4, 1, 2])
10	184.5	6862.5	([13, 8, 5, 10], [9, 14, 6, 7, 12, 3, 11, 4, 1, 2])
11	283.0	5625.0	([13, 8, 14, 6, 10], [9, 5, 7, 1, 11, 4, 12, 3, 2])
			([8, 13, 14, 6, 10], [9, 5, 7, 1, 11, 4, 12, 3, 2])
12	188.0	6817.5	([14, 5], [13, 9, 8, 10, 7, 12, 11, 4, 6, 3, 1, 2])

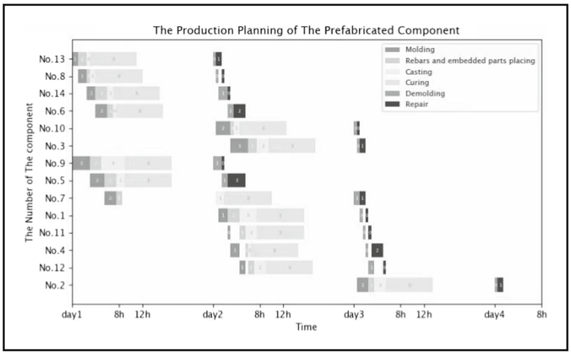

Fig. 4. Presents the production plan for the prefabricated components

serial number 3 in the table is ([13, 8, 14, 6, 10, 3], [9, 5, 7, 1, 11, 4, 12, 2]), which indicates that the production sequence of the first production line is components 13-8-14-6-10-3, and the production sequence of the second production line is components 9-5-7-1-11-4-12–2. Following this order, the total idle time of the two production lines is 295 h, and the total cost of storage and delay is 3600 yuan.

As shown in the table, there are two solutions for objective values corresponding to serial numbers 1 and 11. This is because the differences between the planned production times of each component in each process are small in this case, and the planned production time is estimated by the project manager based on experience, and the accuracy is difficult to quantify to the minute level. Therefore, there may be a many-to-one mapping relationship between feasible solutions and objective function values in the large feasible region of the case. Due to space limitations, only the Pareto result with serial number 3 was selected to arrange the production plan for the entire production line, as shown in Fig. 4.

8 Conclusions

Prefabricated component manufacturers are one of the core links in the supply chain of prefabricated buildings. Under the perspective of multiple orders, production scheduling of prefabricated buildings will become a common problem for prefabricated component manufacturers. In response to the multi-objective, multi-line prefabricated component mixed production problem, a dual-objective production scheduling model considering multiple order delivery punctuality and multiple production line idle time is established. The model distinguishes between component completion time and order completion time, considers the order agreed delivery time window, and provides guidance for production enterprises to deal with multiple orders.

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