Mathematical Modeling and Algorithm Application
ISSN: 3006-0842 | Vol. 6, No. 1, 2025

Prefabricated Component Production Scheduling Optimization Using Simulated Annealing

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Abstract: With the rise of assembled buildings, precast concrete components have become the focus of the industry, and their production scheduling as a key link to the healthy and green development of the industry plays a crucial role. Nowadays, with the diverse demands of the construction market, the production of components is characterised by multiple varieties and small batches, and covers multiple closely related processes from raw material supply to maintenance and demoulding, facing complex scheduling dilemmas, and the problems of rationally allocating the processing sequence of the workpieces, improving the utilisation rate of the equipment, and shortening the production cycle still exist. This study shows that on the premise of ensuring that the proposed production scheduling model meets the needs of the assembly construction site, using the calculation results of the simulated annealing method, the rational planning of the production sequence of the components and the allocation of resources can significantly reduce the completion time of the prefabricated components and improve their production efficiency.

Keywords: Prefabricated Components; Simulated Annealing; Production Scheduling; Combinatorial Optimization; Makespan.

1. Introductory

With the acceleration of urbanisation, the demand for construction of neighborhoods is continuously on the rise. The traditional on - site pouring construction mode has significant drawbacks: on the one hand, the construction process is time-consuming; on the other hand, it is very susceptible to the interference of weather conditions, which seriously affects the progress and efficiency of the project. At present, prefabricated component production can be carried out in a factory environment, without excessive restrictions imposed by the natural conditions of the construction site, thus effectively shortening the overall construction period of the building. In the prefabricated components production line, automated equipment can also be used for steel processing, concrete pouring and other operations to improve the production efficiency of prefabricated components, and at the same time, automated equipment can reduce the original labour costs. However, with the increasing demand for prefabricated components in the current era, the rationality of their scheduling directly affects the project schedule, cost and quality. The production of prefabricated components is characterised by complex processes, restricted resources, diverse orders, etc., and the traditional scheduling methods are difficult to meet the demand for efficient production. Simulated Annealing Algorithm (SA), which belongs to the category of intelligent optimisation algorithms, shows outstanding advantages when dealing with combinatorial optimisation problems, and provides a new way to optimise the scheduling of prefabricated component production.

2. Domestic and international research status of prefabricated components

In recent years, China has actively promoted the development of prefabricated buildings, with prefabricated components being their core elements, and the production - related problems of prefabricated components have been increasingly drawing attention. Nowadays, the production scheduling of prefabricated components is more complicated, and the scheduling plan of prefabricated components has a direct impact on the progress and cost of prefabricated buildings. Therefore, many scholars have carried out research on this issue.

In their research, Chan and Hu[1]constructed a Flow Shop Scheduling Model (FSSM) that integrates the actual prefabricated component production constraints, used genetic algorithms to find the optimal solution, minimizing the completion time and penalty cost as the optimization objectives of the model. Based on this, Benjaoran[2]developed a Based-on -Order Flow Shop Scheduling Model (BP - FSSM) considering the instability of the order factor in real production. In addition, they constructed a multi - objective prefabricated component scheduling model to explore the effects of parameter variations on the model results for the three core parameters: the number of moulds, the length of time of the process, and the weights of the multi - objective function. This analysis aims to provide a solid theoretical basis for managers to make more scientific and efficient decisions when planning production programmes. Phanden et al.[3] applied genetic algorithms as well as SA to the case - study problem. They carefully set the parameters and designed the coding strategies during the implementation of the algorithms. The purpose was to explore the optimal or near - optimal scheduling solutions. This process usually involves iterative search techniques and may include optimization or integration of algorithms, and they strive for excellence with the aim of improving the speed and accuracy of the solution. Zhang[4]proposed a mixed - integer planning model with the core objective of minimizing the maximum completion time of the project. Immediately after that, given the properties presented by the problem, they innovatively proposed a co - evolutionary algorithm which incorporates the idea of SA. A three - linked integer string was designed to represent the three parts of the solution, namely plant assignment, machine

assignment and sequence of operations. Three populations were constructed to search for the above three parts by genetic operations and SA respectively. A cooperative strategy was designed to generate the scheduling solution.

In terms of domestic research, scholars based on the reality of prefabricated component production, comprehensively considered a variety of constraints such as the supply of raw materials, conditions of production equipment, manpower and technical level, and launched an in-depth discussion. For example, for the flow limitation problem caused by the non-linear assembly line in prefabrication yard, a corresponding production scheduling model was constructed, and heuristic algorithms such as simulated annealing are used to solve the problem, which improves the production efficiency and optimises the use of resources. Yang Dinsheng[5]introduced the Metropolis criterion, described the basic way and process of using SA to deal with the production scheduling problem, and also verified the effectiveness of the algorithm. Jing Huicheng[6]and other researchers conducted an in-depth analysis of the shortcomings of genetic algorithms in the application of flexible flow shop scheduling problems, and in order to solve the problems of inefficient search and easy to fall into the local optimum of the existing methods, they innovatively proposed a hybrid optimisation strategy integrating the SA and the Particle Swarm Genetic Algorithm (PSG). This strategy significantly improves the overall performance of the algorithm by organically combining the two algorithms. Yang Rongzheng [7]team focused on the flow constraints faced in the production of prefabricated components for assembly buildings, and they constructed an optimisation model for production scheduling with the optimisation objective of achieving the shortest total duration, based on the full consideration of the interface constraints between the processes and the efficiency of the use of workstation resources. Although the study mainly used genetic algorithms to solve this model, it was also mentioned that heuristic algorithms such as SA have a wide range of applications in multi-objective optimisation and efficient solution of such problems [8].

3. Precast Production Scheduling Problem Description

3.1. Production of prefabricated components

The production process of precast components covers six key steps: mould assembly, reinforcement assembly, concrete pouring, steam curing treatment, demoulding operation and finishing and repair of the components [9]. According to the difference in the organisation of production, it can be divided into two modes of production: flow-through and fixed. Fixed production is carried out on a fixed pedestal for concrete pouring, which has a flat surface to ensure the dimensional accuracy of the components. During production, the mould is fixed on the pedestal, and the reinforcement and concrete are processed and poured in the mould, which is suitable for all kinds of prefabricated components, and has obvious advantages for the components with complicated shapes, large sizes and small quantities.

Flow-through production belongs to the highly automated production mode, which integrates the prefabricated component production process on one assembly line through automated production equipment and transmission system. From steel processing, mould splicing, concrete pouring to component maintenance, all are operated by automated equipment in accordance with preset procedures, with continuous and efficient production, suitable for large-scale standardised prefabricated component production, such as prefabricated wall panels and laminated panels in industrialised housing.

In this study, we will discuss the flow-shop production scheduling, which is called the Hybrid Flow-shop Scheduling Problem (HFSP) if there is one or even more processes that can be carried out simultaneously in the production process. The Hybrid Flow-shop Scheduling Problem (HFSP) exhibits the following typical characteristics: there are n workpieces to be processed sequentially on multiple stages $(c \geq 2)$, where each stage is equipped with a certain number of machines, i.e., there are $m_i \left(m_i \geq 1, i = 1,2,3,...,c\right)$ machines in stage i, and there exists at least one stage with multiple machines [10]. where m_i denotes the total number of machines in the current stage, and $\left(M_c, m_i\right)$ tabulates the m_ith machine of stage i. For example, $\left(M_1, m_1\right)$ is the first machine of stage 1. This is shown in Fig. 1.

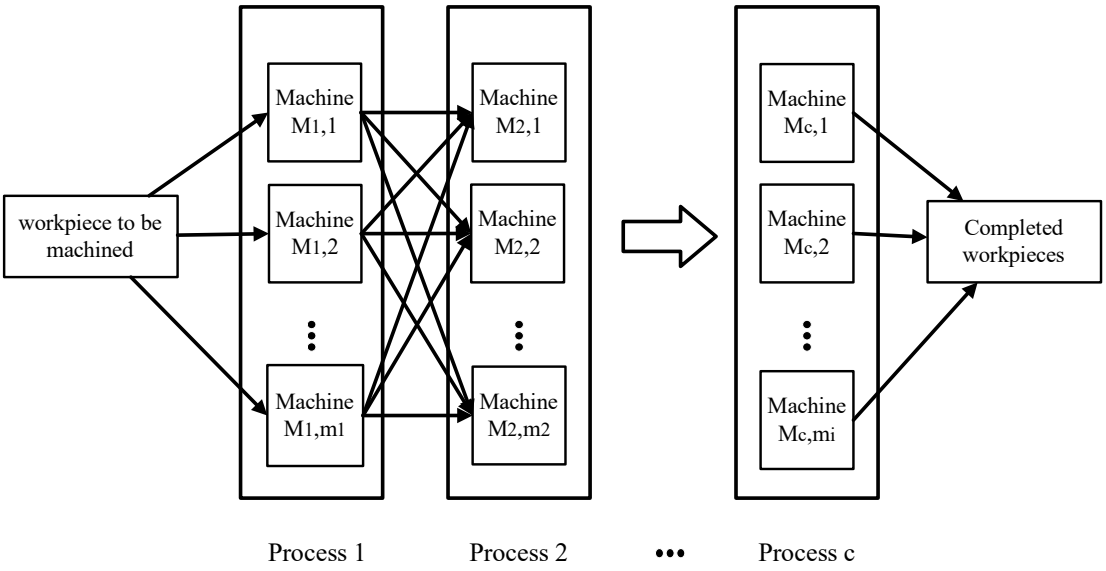


Fig. 1 Schematic diagram of the hybrid flow shop problem

At different stages of machining, HFSPs need to optimise single or multiple performance indicators based on workpiece sequencing and machine allocation schemes. This process involves arranging the sequence of workpieces and machine resources to maximise productivity or optimise a particular objective. This optimisation leads to increased productivity and flexibility in the shop floor, making it one of the most interesting research topics in the shop floor scheduling field.

3.2. Production scheduling issues

After systematic research on the precast component production link, the following constraints that need to be focused on are common in the industry: at the basic management level, there is a dynamic deviation between the production plan and the market demand, and the demand forecast model has not yet formed an effective linkage with the project progress, resulting in the insufficient match between production capacity and actual demand; at the same time, the equipment maintenance mechanism and the resource allocation strategy need to be optimized, and occasional mechanical failures will still affect production continuity.

But the most prominent contradiction, which is also the focus of this article, lies in the production process system itself: that is, there is an efficiency loss in process convergence, the buffer time between various processes is too long, there is a stagnation in material turnover, the workpiece production sequence and site layout planning are not scientific, the layout of the shop floor line and the configuration of the yard need to follow the principle of lean production, otherwise, the high - frequency secondary handling of materials directly increases the time and manpower costs. This problem has become the core constraint on improving production efficiency.

In addition, the cross-departmental coordination mechanism needs to be optimized. The information sharing between the Purchasing Department and the Production Department is not synchronized. Moreover, when it comes to quality control and delivery response from external suppliers, there is also a lack of more effective communication channels. It is recommended to take the reengineering of the production process as an entry point. With the help of digital tools, build a standardized system and systematically improve the overall efficiency of precast component production.

In conclusion, the precast production process involves the coordination of multiple processes and resources. From the procurement of raw materials, processing, assembly to the storage and transportation of finished products, each link has its specific time requirements and resource constraints. The production scheduling problem is directly related to production efficiency. Therefore, it is of great practical significance to explore effective production scheduling methods. SA is classified into the global optimization algorithm category by virtue of its probability - based characteristics and presents unique advantages in solving combinatorial optimization - related problems. It can search for better solutions in the complex solution space. At the same time, it realizes the visualization of system tracking, which provides new ideas for solving the problems of prefabricated components production scheduling and quality control.

4. Simulated annealing algorithm

4.1. Principle of simulated annealing method

Simulated annealing algorithm, whose mathematical principles are based on the annealing process of solid matter. Unlike some deterministic algorithms, SA carries a significant stochastic character, which is one of the key features that distinguish it from other traditional algorithms, and belongs to an algorithm with probabilistic properties[11]. The operation mechanism of the algorithm is similar to the solid annealing process: initially, the solid is heated to a sufficiently high temperature, and then it is allowed to cool down gradually at a slow rate. In the warming process, as the temperature steadily climbs, the particles inside the solid begin to slowly break free from the original regular arrangement of the binding, into a disordered, active state. As a result, the internal energy increases, and the stability of the molecules and atoms decreases. While in the slow cooling process, the particles will gradually become organized. At the same time, the energy continues to decrease, and the stability of atoms can be improved. As the temperature is gradually reduced, the solid is able to maintain equilibrium in a variety of different temperature environments. As the cooling process continues, the solid enters the ground state when the temperature drops to room temperature, in which the internal energy of the solid is minimized. However, the problem of

local optimization may be encountered. As shown in Fig. 2, there are many local optimal solutions in the solution space of the objective function[12]. A locally optimal solution means that in a certain neighborhood in the solution space, the solution corresponds to a better value of the objective function than all the other solutions in the neighborhood, however, there may be a more advantageous globally optimal solution in terms of the whole range of the solution space. For example, as shown in Fig. 2, points B, C, and E may be the optimal solution for one of the ups and downs at that time, but looking at the whole picture, point D is the optimal solution for the whole process.

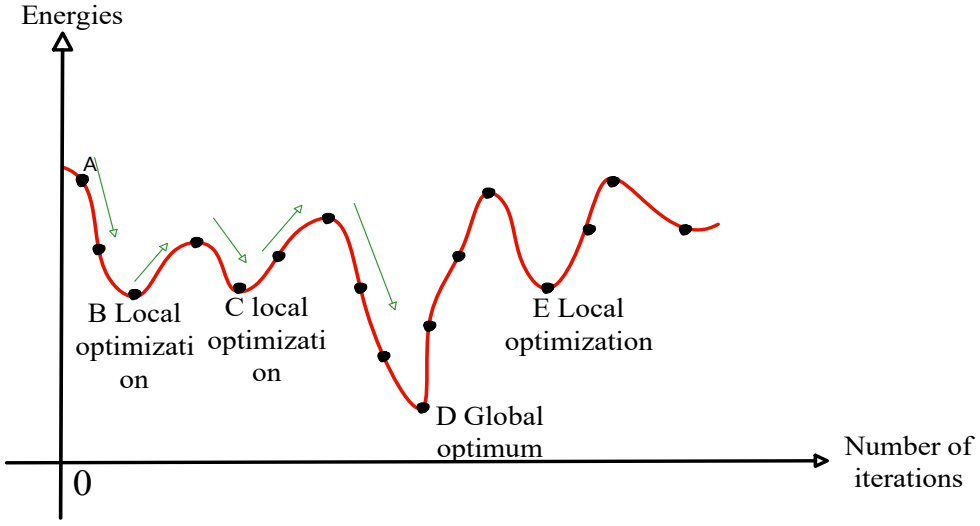


Fig. 2 Limitations of local optimal solutions faced by the simulated annealing method

According to the Metropolis criterion, the algorithm does not just accept the better solution, but will accept the new solution with a specific probability. Even if the new solution is inferior to the current solution in terms of the objective function value, there is still a possibility that it will be adopted. This unique mechanism gives the algorithm the ability to break out of the local optimization dilemma, allowing it to conduct a more comprehensive and extensive search in the solution space. As the algorithm iterates, the temperature decreases gradually, which makes the probability of the algorithm accepting an inferior solution decrease accordingly, and eventually, the algorithm will converge to a relatively ideal solution, thus completing the optimization process.

4.2. Mathematical model

Objective function:

$$\min k_{\max} = \max i\left\{\sum_{j=1}^{m} C_{\sigma(i)j} x_{ijt}\right\} \tag{1}$$

$\min k_{\max}$: Minimized maximum completion time;

x_{ijt} : Decision variable indicating whether processing of the i -th prefabricated component starts at the j -th process at moment t. If processing starts then $x_{ijt}=1$, otherwise $x_{ijt}=0$;

$C_{\sigma(i)j}$: The completion time of the i -th prefabricated component at the j -th process;

restrictive condition:

$$\sum_{t=1}^{T} x_i j_t \le \sum_{t=1}^{T} x_i \left(j+1\right)_t, i=1,2,...,n; j=1,2,...,m-1 \tag{2}$$

$$S_{\sigma(i),j} = \max\left(C_{\sigma(i-1),j}, C_{\sigma(i),j-1}\right);\ \ C_{\sigma(0),j}=0,\ \ C_{\sigma(i),0}=0, j\neq 4 \tag{3}$$

$$C_{\sigma(i),j} = S_{\sigma(i),j} + P_{\sigma(i),j};\ \ j\neq 4 \tag{4}$$

$$S_{\sigma(i),4} = C_{\sigma(i),3};\ \ j=4 \tag{5}$$

$$C_{\sigma(i),4} = S_{\sigma(i),4} + P_{\sigma(i),4};\ \ j=4 \tag{6}$$

$S_{\sigma(i)j}$ The start time of the i -th prefabricated component at the j -th process;

$p_{\sigma(i)j}$: Processing time of the i -th prefabricated component at the j -th process;

Equation (2) for the process sequence constraints: for each prefabricated component production task, there is a sequential relationship between its processes, which must be processed in accordance with the specified process route, i.e., only after the mold assembly process is completed can the processing enter the rebar assembly process, etc., but note that in the fourth process, it is possible for some operations to be carried out in parallel, i.e., after the completion of the process of process three directly into the process of process four without the waiting time for the machine, this problem is reflected in the following four formulas. In this study, there are 6 steam maintenance molds, as shown in Figure 3 below.

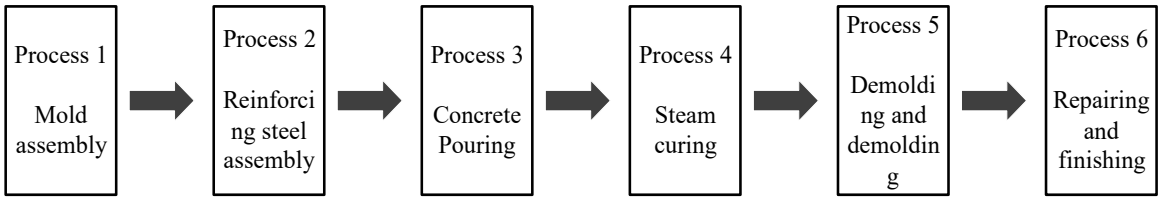


Fig. 3 Prefabricated components production process

Equation (3) is a time constraint: it indicates that the start time and completion time of the tasks must meet the time requirements in actual production except for the fourth process, and the start time of the job must meet the completion time of the preceding job in the same machine, i.e., the start time of the j -th process of prefabricated component i is equal to the maximum value of both the time of the completion of the j -th process of the previous prefabricated component $(i-1)$ after the completion of the completion of the previous process $(j-1)$ and the completion time of the jth process of the previous prefabricated component $(i-1)$. The maximum of the two times.

Equation (4) indicates that, except for the fourth process, the completion time of the j -th process for the i -th prefabricated component of the remaining processes = the start time of the j -th process for the i -th prefabricated component plus its processing time.

Equation (5) , (6) indicate that the precast component process constraints: in order to ensure that the precast components to meet quality standards, in the completion of the concrete pouring process, the need to immediately carry out steam curing operations, that is, the two processes need to be seamless, which does not allow any time gap between.

4.3. Algorithm design

The basic steps of SA are as follows[13]and the detailed flowchart[14]is shown in Fig. 4

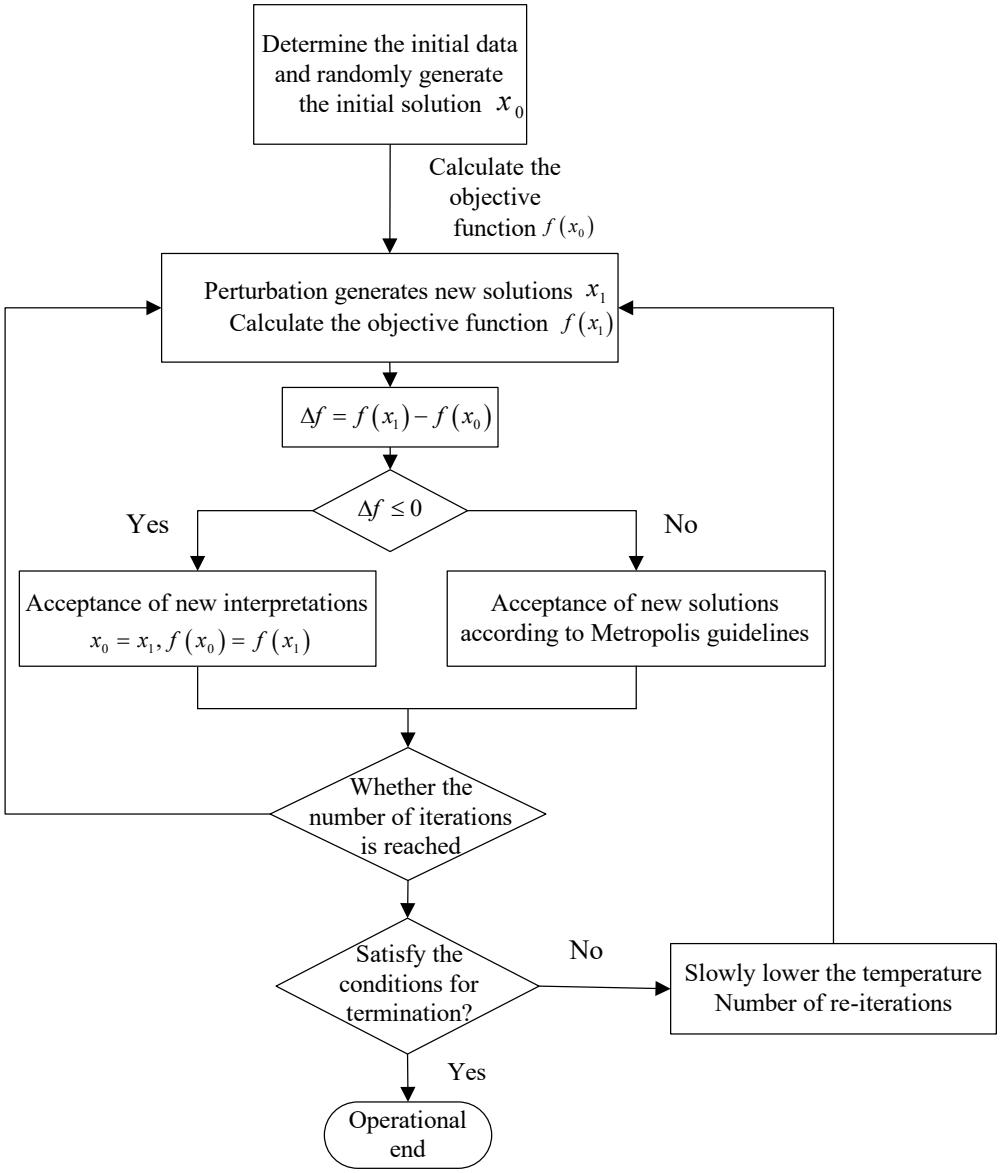


Fig. 4 Flow of simulated annealing algorithm

Step1: Initialize the annealing temperature T, set the basic cooling coefficients and the number of iterations, and generate a random initial solution x_0;

Step2: The following operations are performed continuously at temperature T until an equilibrium state is reached at temperature T;

Step3: Generate a new feasible solution x_1 within the neighborhood of the solution x;

Step4: Calculate the energy difference, which is the difference Δf between the objective function value $f(x_1)$ of the new solution x_1 and the objective function value $f(x_0)$ of the original solution x_0, i.e., $\Delta f = f(x_1) - f(x_0)$;

Step5: According to the Metropolis criterion to determine whether to admit a new solution or not, i.e., $\Delta f < 0 \,||\, \exp(-\Delta f / T) > \text{random}[0,1]$, where random[0, 1] is a random number in the interval [0, 1].

Step6: Execute the annealing operation, $T = T * n$, which is the cooling coefficient in n ($0 < n < 1$), and $n = 0.98$ is selected in this article. If the convergence judgment condition is satisfied, then the annealing process is finished; if it is not satisfied, then jump to Step2 to continue the execution.

4.4. Decoding by simulated annealing

(1) A coding method based on the order of tasks is used, in which an arrangement of prefabricated component production tasks is taken as a solution. The decoding process then determines the start time, processing time and completion time of each task based on the encoding, while considering various constraints to calculate the production cycle corresponding to the solution.

(2) Initial solution generation: randomly generate an initial arrangement of tasks as the initial solution i.e. x_0.

(3) Neighborhood structure design: using the strategy of exchanging neighborhood structure, two tasks are randomly selected from the solution space and their

positions are exchanged[15], so as to derive a brand new solution. As shown in Fig. 5, the coding of the initial solution is presented as 1-3-2-5-6-4. This coding corresponds to the meaning that the production sequence of prefabricated components starts from prefabricated component 1, followed by prefabricated component 3, then prefabricated component 2, then prefabricated component 5 and prefabricated component 6, and finally ends with prefabricated component 4. In which 2 and 4 in the initial solution are exchanged to obtain a new solution x_1, and so on, as the iteration process progresses gradually, each iteration can produce more new feasible solutions, and the number of feasible solutions grows cumulatively as a result, which greatly improves the coverage of the search space, and thus significantly increases the probability of discovering the globally optimal solution.

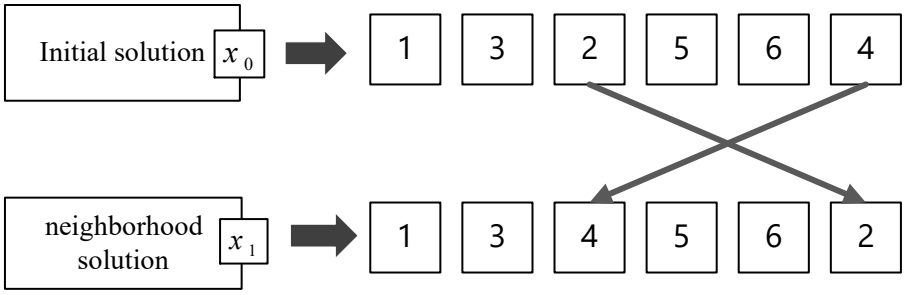


Fig. 5 Neighborhood solutionMetropolis

(4) Metropolis criterion: Assuming that the current solution is x_0, whose corresponding objective function value is $f(x_0)$, and the new solution is x_1, whose objective function value is $f(x_1)$, and the current temperature is T. First, we calculate the difference between the two objective function values, $\Delta f = f(x_1) - f(x_0)$. If $\Delta f < 0$, then we accept the new solution x_1 as the solution of the moment; on the contrary, if $\Delta f > 0$, then we decide whether to accept the new solution x_1 according to the probability $e^{\frac{-\Delta f}{T}}$.

(5) The exponential cooling strategy is adopted, i.e., $T_{k+1} = nT_k$, where T_k is the temperature of the k th iteration and n is the cooling coefficient, $0 < n < 1$. The values of the initial temperature T_0 and the cooling coefficient n have a large impact on the performance of the algorithm, and $n = 0.98$ is taken in the present experiments, while the others need to be adjusted through experiments.

(6) The termination rule is as follows: if the temperature drops to a certain threshold, or has reached the maximum number of iterations specified in advance, the algorithm terminates the operation and outputs the best solution currently found.

5. Practical calculation

In order to verify the effectiveness of the simulated annealing method in precast component production scheduling, the actual production data of a precast component production plant in Zigong City is selected for example calculation. The factory has 12 different types of prefabricated components to be produced in a certain time period, and the processing procedures, processing time and required equipment of each type of construction are shown in Table 1.

Table 1 Prefabricated components data sheet

No.	Assembling Molds/h	Reinforcement Installation/h	Concrete Pouring/h	Steam Curing/h	Demoulding/h	Tidying up and repairing/h
1	1.7	1.9	2.3	15	2.3	0.5
2	1.8	1.8	2.5	15	2.4	0.4
3	2.0	2.2	2.6	15	2.7	0.5
4	1.9	2.2	3.0	15	3.0	0.5
5	2.6	2.7	2.8	15	3.1	0.4
6	2.5	2.8	2.9	15	3.0	0.5
7	1.4	1.6	2.1	15	1.8	0.5
8	1.6	1.7	2.0	15	1.9	0.5
9	1.5	1.3	1.9	15	1.8	0.4
10	1.4	1.6	1.1	15	1.7	0.5
11	1.2	1.7	1.0	15	1.6	0.5
12	1.1	1.5	0.9	15	1.4	0.5

The data related to precast component production were collected from a precast component production plant in Zigong City, and the simulation test work was carried out based on the mathematical model constructed in subsection

3.3, combined with the algorithm in subsection 3.2. The key parameters of this algorithm are set as follows: the value of particle dimension is equal to the total number of prefabricated components, and its dimension value is set to 12; the initial temperature is set to 1000; and the number of iterative steps is constant at 200 during a single cycle. the algorithm is run using MATLAB2016b software, and the final results obtained are shown in Fig. 6 and Fig. 7.

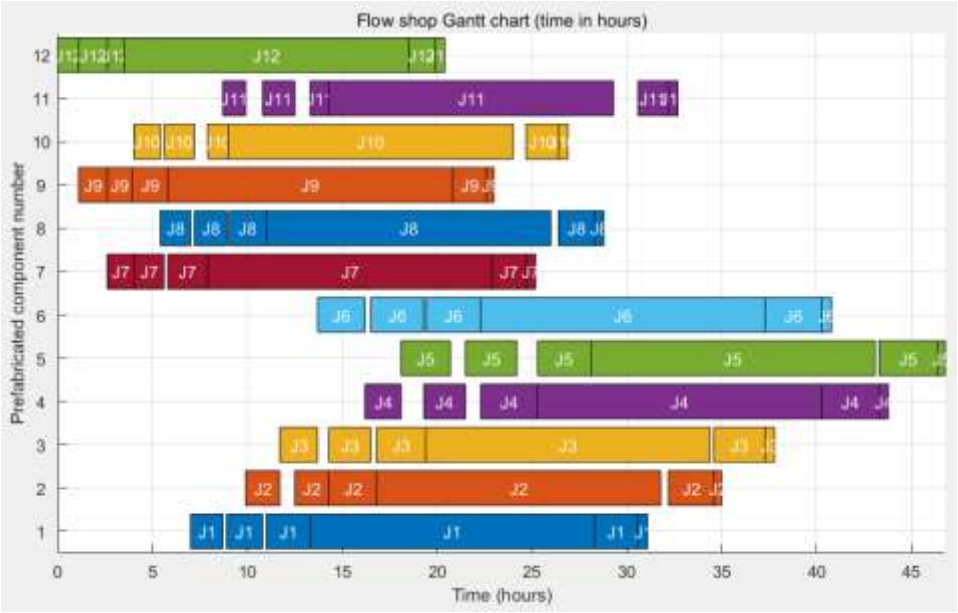


Fig. 6 Scheduling Gantt chart

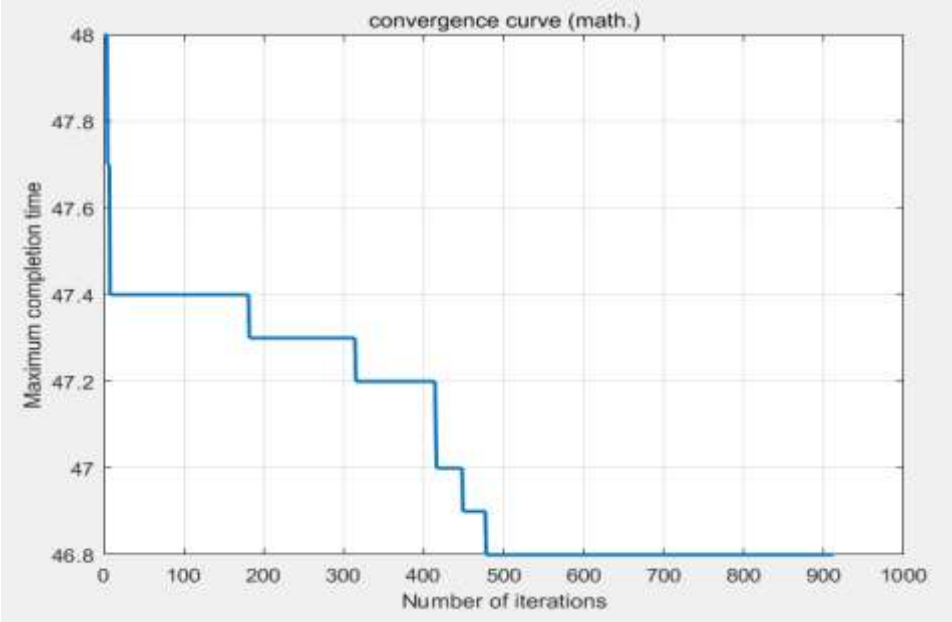


Fig. 7 Algorithm search process

As can be seen from Fig. 6, the prefabricated components are arranged in compact rows, and the utilization rate of the machine is significantly improved. The adjacent processes of the same workpiece are connected naturally, and the white space, i.e., its waiting time, is less, and the final completion time is 46.8 hours. As can be seen from Figure 7, at the beginning of the iteration, the process of finding the optimal solution is very smooth, but in the middle of the iteration, there is a period of time caught in the local optimal solution trap. As a result, the convergence curve briefly fell into a smooth state. According to the Metropolis criterion, with the increase in the number of iterations, the algorithm successfully gets rid of the constraints of the local optimal solution and gradually explores to the global optimal solution. As the iteration process advances to a later stage, the maximum completion time is basically maintained in a stable state. The optimal prefabricated component production sequence is finally derived as shown in Fig. 8 below:

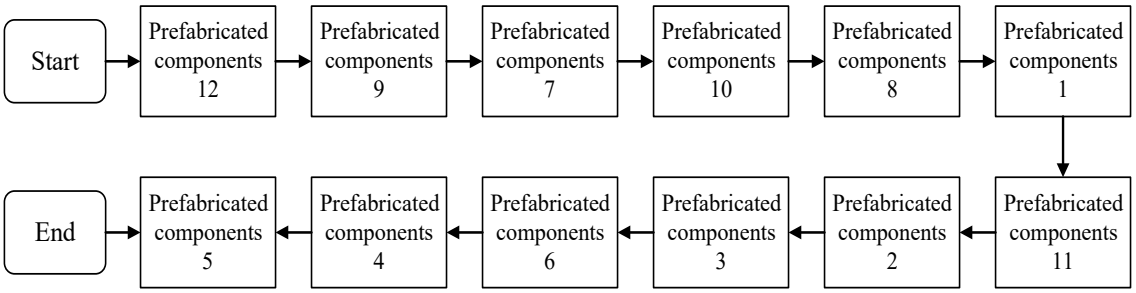


Fig. 8 Optimal production sequence

6. Concluding remarks

In this paper, the simulated annealing algorithm is used to solve the problem of prefabricated component production scheduling. In order to check the effectiveness of the algorithm, we use examples to verify the results, which clearly show that the algorithm is not only feasible but also significantly superior. In the process of in - depth research, the key feature of parallel maintenance in real production is fully considered, and a production scheduling model based on the simulated annealing algorithm is successfully constructed. The model and algorithm proposed in this article have been verified through a large number of example tests and can accurately generate more advantageous scheduling schemes. In practical applications, the model and algorithm significantly shorten the task completion time and effectively improve the efficiency of prefabricated components production.

The current study has not yet reached a perfect state and there are still some limitations that need to be further optimized and improved. In future research, more in - depth optimization of the model can be carried out, taking full consideration of more complex and variable factors in the actual production process, such as fluctuations in raw material supply, sudden equipment failures, and manpower allocation issues. This can further enhance the adaptability and accuracy of the model. At the same time, we can try to combine it with other intelligent algorithms to further improve the algorithm's solution performance, as well as develop a visualization scheduling system to assist enterprise production management. In the future, with the in - depth development of construction industrialization, optimizing prefabricated components production scheduling will continuously enhance the competitiveness of the construction industry and provide strong support.

Acknowledgment

This research was funded by the Research on the optimization method of resource scheduling for the production of assembled prefabricated components (Project number: S202310622088). The study is supported and funded by the Innovation and Entrepreneurship Training Program for College Students, Sichuan University of Science & Engineering (Project No. S202410622087).

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