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Research Article

Mixed Production Line Optimization of Industrialized Building Based on Ant Colony Optimization Algorithm

Xiaobo Chen,[1,2] Fangfang Yu,[1,2] Hengyu Zhou,[1,2] Zhengdao Li,[3] Kuo-Jui Wu,[4] and Xikun Qian[1,2]

[1]*School of Investment & Construction Management, Dongbei University of Finance and Economics, Dalian 116025, China*
[2]*Construction Management Research Center, School of Investment & Construction Management, Dongbei University of Finance & Economics, Dalian 116025, China*
[3]*College of Civil Engineering, Shenzhen University, Shenzhen, China*
[4]*School of Management, National Taiwan University of Science and Technology, Taipei, Taiwan*

Correspondence should be addressed to Xikun Qian; 451867306@qq.com

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Prefabricated components production line optimization is critical for improving industrialized building construction efficiency; however, few studies focus on the production line optimization problem in context of industrialized building construction. In order to optimize the large random orders in the prefabricated components production process, this research proposes a model to minimize variance of the production capacity utilization of prefabricated components in the production cycle, and the ant colony optimization algorithm is introduced to solve the mixed production line sequencing optimization problem. By optimizing the sequence, the production capacity of the component production is balanced, and the capacity utilization rate in the industrialized building construction process is improved. Finally, the effectiveness of the method is verified through a real case of fabricated building components production. The results show that the variance of daily production capacity utilization rate of the optimized hybrid component production line has reduced to 0.53%, which is significantly lower than the 2.45% before optimization. The proposed model could effectively achieve the production capacity balance of prefabricated components production line.

1. Introduction

Because of the potential advantages such as clean construction environment, improving quality performance, and reducing time and labor, the industrialized building (IB) is becoming more and more popular as a sustainable construction technology [1, 2]. With the popularization of building energy conservation technology and the concern for global warming, the energy conservation requirement has gradually shifted from the operation stage to the construction stage [3]. The traditional construction method of large-scale on-site pouring can no longer meet the current demand; in France, the United States, Japan, and many other developed countries, residential industrialization has become the main residential development model [4]. How to improve the production capacity utilization rate of IB in the construction stage is of great significance to the sustainable development of the construction industry.

IB system is a building system using prefabricated components to construct [5]. IB can be defined as introducing the industrial manufacturing theory into construction activities using factory production, transportation, and on-site assembly. IB is classified according to construction methods, which can be divided into factory construction and on-site construction. Among them, the buildings built by factory construction are called prefabricated construction. At present, the sustainability of IB has been confirmed in many studies [3, 6–9]. Organizational management for the macrolevel of IB has also attracted the attention of many scholars, such as stakeholder relationship and cooperative competition relationship between organizations and business model research of IB companies [5, 10–13]. In view of the optimization of IB production and construction, there are some related studies on technical aspects [4, 14, 15].

However, few studies focus on the prefabricated components production process optimization, and it is necessary to adopt the advance production line optimization method in operation management to improve the prefabricated components production efficiency. The issue of capacity utilization in the production of prefabricated components is still an important reason affecting the production efficiency of IB [16–18]. In order to improve the production capacity of prefabricated components in the production process, the production mode of hybrid production line is often used in IB construction production [17]. The hybrid production line is produced in batches and can produce a variety of different structural parts. Different structural parts have conversion time related to process when switching [18]. Due to the large demand gap of various structural components, a reasonable batch strategy must be adopted for production, that is, the scheduling of the mixed production line must be optimized, otherwise it will lead to uneven busy and idle of the mixed production line, long production cycle, and greatly reduce the production efficiency [19].

In order to meet the diversified and personalized needs of the construction market, construction manufacturers often adopt the production mode of mixed production line for multivariety, small batch, and large-scale customized production mode [20]. The scheduling optimization problem of hybrid production line directly restricts the production capacity of enterprises. In this paper, an ant colony optimization (ACO) algorithm-based optimization model is proposed to solve the production problem of mixed prefabricated components with limited production capacity. The IB adopts the standardized design, factory production of construction parts, as well as the spot mechanization assembly production pattern. This has transformed the traditional manual-based, on-site construction production model into a manufacturing production model based on factory production and on-site mechanized assembly. Thus, the advanced production theory in the manufacturing industry can be introduced and implemented in the IB. From this point of view, it is feasible to use the mature ACO algorithm to solve the production problem of mixed prefabricated components in IB. Based on the ACO theory and the characteristics of mixed prefabricated components production, this paper proposes the mechanism of the ACO algorithm. With the help of the proposed ACO algorithm, artificial ants will search for the best solution under the guidance of heuristic information and pheromone information. The solutions constructed by each ant should be checked through the daily production capacity of prefabricated components and matched with the objective function to minimize the variance of the daily production capacity utilization rate (DPCUR).

The contributions of this article are descried as follows:

In view of the complexity of scheduling and task allocation of the operation model of the prefabricated component hybrid production line, and in view of the production characteristics of small batch and large parts of prefabricated components, this paper constructs a production scheduling mathematical optimization model based on the minimum capacity utilization and designs an ant colony algorithm with good robustness and search ability to solve the model for optimizing the production planning and resource allocation of the prefabricated components to achieve the purpose of reducing cost and improve the production efficiency. The proposed mode expands researchers' understanding of the optimization of prefabricated component production process and provides an effective tool for production managers.

The rest of this paper is arranged as follows. In Section 2, a brief review of the status of research on IB and the sequencing problem mixed production lines is explained. In Section 3, we concretely describe the production process of prefabricated components and its mixed production line sequencing problem, and establish the corresponding mathematical model. In Section 4, the ACO mechanism for optimizing the production sequence of mixed prefabricated components is introduced in detail, and then the calculation process of the ACO algorithm for solving the production of mixed prefabricated components with limited production capacity is given. Section 5 gives a case made to illustrate the feasibility and applicability of the proposed optimization method. In Section 6, we further discuss the results and summarize the experiment results. Finally, we summarize the article and put forward some suggestions for future research in Section 7.

2. Literature Review

2.1. Industrialized Building. IB system is a building system using prefabricated components to construct [5]. In recent years, research on IB has focused on the following aspects: (1) Industrialized Building Assessment (IBA), primarily to assess sustainability in the construction process; (2) Technical optimization research on the construction stage of IB; (3) Organizational management of IB, e.g. cooperation and competition relationships among stakeholders.

Whether IB can achieve sustainable development and successful application is crucial. Therefore, IB needs to be evaluated. Through the sustainability potential of IB, the possibility of realization of IB can be determined. This research has attracted the attention of scholars from Brazil, Malaysia, and China, who analyzed the sustainable potential of IB in their country, and they believe that the IB has the possibility of implementation and the construction of IB should be strengthened as soon as possible [6–8]. IB has the advantage of improving the sustainable production process of buildings and effectively reducing the generation of on-site wastes [6]. In addition, CO_2 emissions are often used as performance indicators to assess the sustainability of IB [3, 9]. Zea Escamilla et al. [9] made low-carbon emissions a goal to find alternative industrialized materials, industrial bamboos, thereby increasing the sustainability of residential projects. Liu et al. [3] established a carbon emission evaluation model of prefabricated components in China, based on the method of production line. Jiang et al. [21] established a conceptual framework for the evaluation of IB and verified by exploratory factor and confirmatory factor analysis, arguing that efficiency improvement is the primary issue in the growth of IB.

In the technical optimization study of the construction stage of IB, the construction of IB is mainly based on prefabricated components [5]. The establishment of an open platform for industrialized housing construction to standardize design is conducive to improving the efficiency of IB [22]. Ogunde et al. [14] studied the influencing factors of the cost, time performance in the construction process of IB, and carried out data extraction analysis to prove that the construction of IB is a more economical way of construction. Nikolic [4] focuses on the technology-related content of the open-ended prefabricated industry and areas that should be focused on in large-scale residential renovations based on industrialization and energy efficiency. Besides, the optimization of the assembly process in the production site of prefabricated houses has also attracted the attention of researchers. Li et al. [1] proposed a constrained modeling service based on smart work packaging (SWP). In the process of constrained scenario analysis, it is pointed out that collision-free path planning is the most influential constraint on scheduling performance. To improve the construction efficiency of IB, Li et al. [15] proposed a new industrialized construction method, on-site industrialization, which expanded the theoretical knowledge system of industrialized construction.

In addition, the organizational management of IB has also attracted the attention of scholars. Firstly, the risk factors that influence the employees' attitude towards the implementation of IB and the problems existing in the management of the construction stage are analyzed [5, 10]. Secondly, the management among the various participants also affects the development of IB. Nursal et al. [11] proved the importance of supplier selection decision IB systems. Teng et al. [2] used stakeholder theory and industry symbiosis theory to define the stakeholder relationship in the industrialized construction industry chain. Xue et al. [12] used a combination of social network analysis (SNA) and structural equation modeling (SEM) to analyze the cooperative relationship between the technical innovation organizations of IB. Said and Bartusiak [23] analyzed the dynamic relationship of regional competition under the environment of industrialized housing construction. The adoption of different business models by industrialized construction companies also affects the development of IB [13].

The research on mixed production line scheduling in construction industry is still in its infancy. The main problems are as follows: (1) for IB, they mainly concentrated on the technology level, sustainability evaluation level, and macrolevel organization management of prefabricated components, and the research on the production management of prefabricated components is neglected to some extent. (2) the parallel production of hybrid production line is equivalent to the parallel production method of multiple machines; (3) unreasonable scheduling strategy; (4) most of the research on hybrid production line scheduling problem is single objective scheduling. Therefore, the key to solve the multiobjective hybrid production line scheduling problem is to find a reasonable batch strategy and propose a more effective new algorithm for the multiobjective hybrid production line scheduling optimization problem [24]. For solving this problem, this article proposes a model of mixed production line optimization of industrialized building based on the ant colony optimization algorithm. This algorithm can realize the maximum utilization of energy produced in the mixed production line of prefabricated components in the construction process of industrial buildings (Gui et al. 2021) [25].

Based on the literature review, it is necessary to increase the capacity utilization ratio of prefabricated components and assembly construction efficiency at the production stage in order to achieve sustainable development of IB. However, this aspect of research has not received enough attention. Currently, the construction of prefabricated components within IB is underutilizing its capacity. In this paper, the main focus will be on ensuring that the IB's production capacity can be maximized through effective utilization.

2.2. Sequencing Optimization Problems of Mixed Production Line.

The industrialized construction adopts the standardized design, factory production of construction parts, as well as the spot mechanization assembly production pattern, causes the traditional construction production pattern which mainly takes the handwork and the spot work transformation to the manufacture production pattern which mainly takes the mechanization production. The prefabricated component production process shares many characteristics with traditional manufacturing in terms of production scheduling. Therefore, the advanced research results of manufacturing production scheduling can be used for reference, and combined with the particularity of prefabricated components, the algorithms that have been maturely applied to manufacturing workshop schedule can be improved to improve the applicability of prefabricated component production scheduling.

This literature review analyses the methods to solve the mixed production line sequencing optimization problem as well as the objective function imposed by the mixed production line sequencing problem. Adding mixed prefabricated components to the IB production line poses a problem of mixed production line sequencing because the IB products are flexible. The traditional research method is to take time and cost-related information as the optimization goal in order to define the objective function of the optimization problem of the mixed production line. Concerning the time-related optimization objective, Abdul Nazar and Madhusudanan Pillai (2018) take the available maximum production time and the acceptable minimum free time of the machine as the objective function to provide decision makers with a basis for selection. The construction schedule was optimized by García-Nieves et al. [26]; considering the maximum time and space conditions, a multiobjective linear programming optimization model for repetitive job scheduling of construction projects was established. Rauf et al. [27] established a mathematical model with flow time, maximum completion time, and free time as indicators for the multicriteria problem of complex assembly lines, and proposed an improved simulation integration intelligence multicriteria algorithm to solve them. Biele and Mönch [28] in a given order of operations, take balancing the labor cost and minimizing the inventory holding cost as optimization objectives to solve the production planning problem of small-batch mixed assembly lines in aircraft manufacturing. Lv et al. [29] used utility work cost, production rate change cost, and setting cost minimization as objective functions, and proposed a ranking method based on genetic regulatory networks. Also, other researchers have positioned the objective function to maintain production stability. Abdul Nazar and Madhusudanan Pillai (2015) proposed minimizing the production rate change as the optimization objective to keep the production rate of each component on the production line constant. Zhong et al. [30] considered the assembly line ranking problem of the hull mixed model with manufacturing complexity, and minimizing the complexity brought about by frequent changes in system state is regarded as the optimization objective. Sun and Fan [31] took the minimum number of broken sorting rules as the main objective and the minimum level of total conversion complexity as the secondary objective. ACO was used to solve the problem. Zhang et al. [32] studied how to reduce the energy consumption of assembly line systems while maintaining system efficiency, and a multiobjective cell genetic algorithm was proposed to solve the energy balance-ranking problem of the mixed assembly line.

In sum, previous studies mostly took minimizing the difference between completion time and delivery time as the optimization goal, which achieved the purpose of improving on-time delivery rate to a certain extent. However, the relevant research model allows order delay and does not consider the actual constraints of various resources in the production scheduling process of prefabricated components, which is contrary to engineering practice. For example, when the delivery time is tight, the prefabrication factory often organizes workers to work overtime to ensure the delivery of orders on schedule, and the overtime also increases the labor cost, so this optimization model has certain limitations. Based on the premise of constant capacity utilization, this paper uses the mixed production sequence as the input of the optimization model. By comparing the change range ratio of daily energy utilization, this paper establishes the production scheduling optimization model under the mixed production line, which can reduce the waiting time of components on the production line and the idle time of machines, maximize the capacity and resource utilization of the whole production line, and save the production cost of prefabricated components. It plays a positive role in reducing the cost of prefabricated construction.

As is known to all, a metaheuristic algorithm can be used to solve such problems [20], and the manufacturing industry has done a lot of related research. According to the literature review, mainly including genetic algorithm (GA) [29, 32–37], particle swarm calculation (PSO) [30, 38, 39] and ant colony algorithm (ACO) [31, 34, 40], etc. At present, ACO has been proved to be an effective method to solve multiobjective optimization problems [31, 34, 40]. Kucukkoc and Zhang [40] proposed a flexible agent-based ACO algorithm to solve the mixed model parallel bilateral assembly line balance problem. This process can be used to generate mixed sequences of large products, which can reduce labor demand. Kucukkoc and Zhang [34] improved the existing agent-based ACO by introducing a genetic algorithm-based model ranking mechanism. Combining ACO with genetic algorithms, this study studies the balance scheduling problem of complex assembly lines and solves both the production line balance problem and model ranking problem. Sun and Fan [31] proposed the concept of transformation complexity caused by product diversity to optimize the sequencing problem of mixed model assembly lines in automotive manufacturing based on ACO.

Compared with other algorithms, it is found that ant colony algorithms have these advantages: (1) Performance of the solution is robust, and it can be applied to other problems with some modifications, and the solution is searchable for better solutions; (2) ACO can carry out global search. It is possible that the prefabricated components of IB can be subject to large computations and lengthy computation times, but these drawbacks can be avoided, since they, in principle, are small batches of large products. According to the above research, ACO is capable of solving the optimization problem of mixed production lines, especially regarding large products. Therefore, this paper chose ACO as the solution to solve the objective function.

From the above research content, the manufacturing industry has gradually begun to consider the maintenance of production stability into the optimization goal of mixed production lines. As one of the largest energy-consuming industries, the construction industry should consider how to achieve the balance of production capacity and maximize the effective application of production capacity as a production optimization goal, to accelerate the realization of the sustainable development of the construction. Therefore, this article will study how to achieve the production capacity balance of prefabricated components in the construction process of IB.

3. Problem Description and Model Formalization

3.1. Problem Statement of Prefabricated Component Production Optimization

3.1.1. The Production Process of Prefabricated Components. There is much overlap between the scheduling of prefabricated components and the scheduling of general manufacturing workshops. They both follow many production links to produce the required products. The production process of prefabricated components is mainly divided into a series of tasks such as component manufacturing, storage, and transportation. Production efficiency, as well as planning and flexibility of the entire production schedule, will be affected by the difficulty of prefabricated components production. The specific operation steps for the production of precast components can be carried out according to Figure 1.

The specific work content of these processes is shown in Table 1.

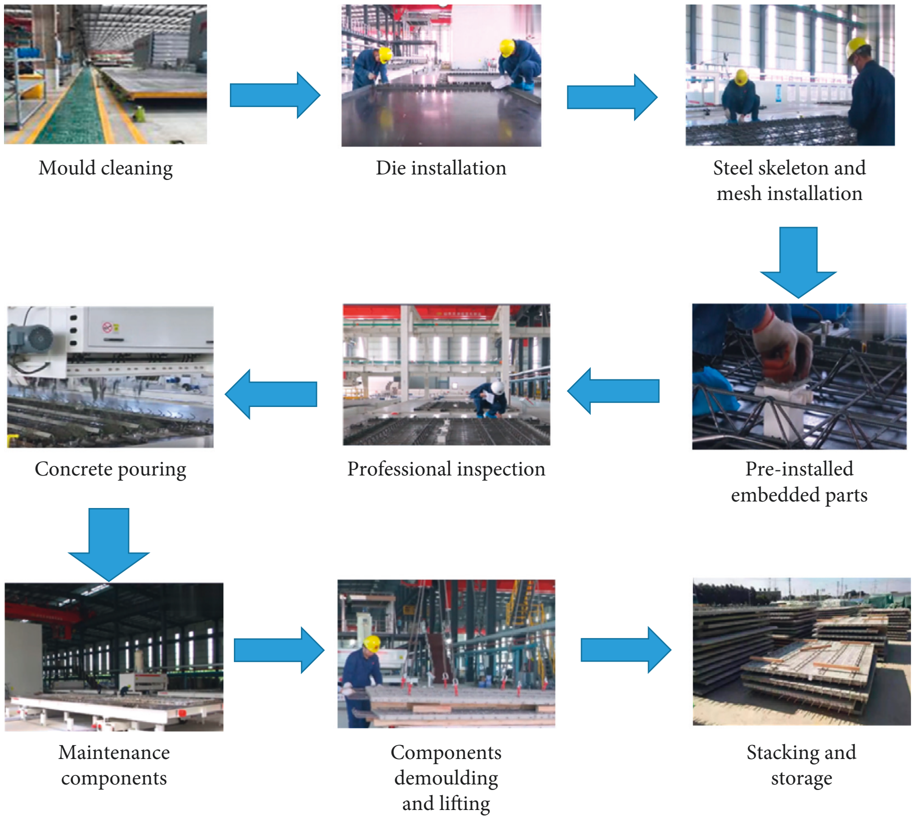

Figure 1: Process flowchart of prefabricated component production.

Table 1: The work content of the specific process.

Process	Activity	Description of activity content
1	Mould cleaning	Clean the contaminants remaining in the steel film, and clean the mold table, the mold is sprayed with isolating paint
2	Die installation	Install the mould of the production component
3	Steel skeleton and mesh installation	Place the steel skeleton in the mould for positioning and binding the mesh
4	Preinstalled embedded parts	Installation and fixing of embedded parts
5	Professional inspection	Confirm that the dimensions and positions of molds, embedded parts, holes, etc. are correct
6	Concrete pouring	Pour the concrete according to the production plan and fully vibrate it
7	Maintenance components	According to the requirements of components and construction period, adopt different maintenance strategies
8	Components demoulding and lifting	Strictly follow the order of technical disclosure requirements to demould and lift
9	Stacking and storage	Stack finished components that meet the strength requirements in the storage area

Different from the production scheduling of the manufacturing industry, it can be seen from the production process of the prefabricated components that the production of prefabricated components has the characteristics of weak process independence, high workgroup work, and high labor dependence. Therefore, we need to fully consider these characteristics when analyzing the production problems of prefabricated components.

3.1.2. Optimization Analysis of Mixed Production Line of Prefabricated Components. Common prefabricated components of residential buildings include floor slabs, solid walls, columns, beams, balconies, and stairs. In contrast with the production of general manufacturing products, different types of components can be produced simultaneously on a prefabricated component production line. The prefabricated component production lines are normally divided into two groups: multifunctional mixed production line and specific component production line.

Unlike traditional construction production, industrialized construction involves the supplier of prefabricated components as the key player of the process, and the prefabricated components are assembled at the building site after the factory production. Prefabricated component suppliers have a requirement to deliver different types of prefabricated components in a particular period of time to meet the assembly requirements of customized housing, so their entire manufacturing process has been transformed into a multifunctional mixed production line (sequencing mixed models on a multifunctional assembly line, SMMMAL). SMMMAL is shown in Figure 2(a), and this method can simultaneously produce different types of components on the same production line, such as floor slabs, insulation walls, beams, columns, balconies, stairs, and other planar components. Figure 2(b) represents a specific component production line, which is only aimed at the production of a certain component product with specific requirements. Since the specific component production line has a very high degree of specialization, it is temporarily not considered a research objective due to its high level of professionalism, high production efficiency, and large production capacity. SMMMAL is mainly the focus of the research in this article, and the main purpose is to solve the problem of uniform loading overall production line so that the various components can be balanced during production, and to achieve the efficient management of production of prefabricated components based on reasonable distribution during the construction process.

Prefabricated components are produced on construction sites with the constraints of production resources, such as daily production capacity, labor force, and materials. Production managers have to make sure that the full capacity of prefab plants is utilized in order to operate at optimal efficiency. In prefabricated plants, labour and materials are easier to obtain, so daily production capacity is a key constraint on capacity utilization. In order to maximize daily output by separating large prefabricated components from smaller prefabricated components as much as possible because of the different sizes of prefabricated components, the production manager arranges large prefabricated components in between smaller prefabricated components whenever possible. This article aims to attain precise prefabricated components production management in the production period, once the mixed production line of prefabricated components reaches a balance in production capacity. This paper proposes a mixed production optimization model of prefabricated components based on the ACO method to help the production manager choose the best production process for mixing prefabricated components during the production cycle.

3.2. The Establishment of Mathematical Models

3.2.1. Objective Function. Based on the above description, manufacturers of prefabricated components often accept large random orders in the process of providing prefabricated components for industrialized housing. Generally, prefabricated component manufacturers produce according to order, and owing to the constraints of component production line capacity, they take the highest daily utilization as the main production target. Under the condition of constant capacity, an increase in capacity utilization ratio will result in effective capacity utilization in the whole production cycle, which will improve the allocation of resources and the utilization rate of free labor and machine to other activities. In order to establish the following optimization model based on the manufacturer's point of view on prefabricated components mixed production, the objective function is the minimum variance of the production capacity utilization of the prefabricated components in the production cycle, established as follows:

$$f = \min\left(\sum_{j=1}^{d} \frac{\left(P_{d_j} - \overline{P}^2\right)}{d}\right), \tag{1}$$

where f is the objective function of prefabricated components production in one period under the daily production capability constraint, and P_{d_j} represents the mixed production capacity utilization rate of production period j.

$$P_d = \frac{\sum_{i=1}^{n} S_i}{F}\ , \tag{2}$$

where S_i represents the production amount of element i, F represents the maximum production capability, and n represents the maximum production amount under the constraint of the daily production capability.

$$\overline{P} = \frac{\sum_{i=1}^{N} S_i}{F d}\ , \tag{3}$$

where $\overline{P}$ is the average daily production capability rate in one production period, Fd represents the days in one production period, and N is the total amount of prefabricated components in one production period.

3.2.2. Assumption. Production of prefabricated elements was similar to construction on-site in a factory environment. Therefore, the "concreting" cannot be interrupted until the manufacturing process has completed its objectives. Therefore, the prefabricated element on the production line should also obey the basic rules of the "concreting." To build the mathematic optimization model, the following assumptions were made:

(1) Different size prefabricated elements production follows the series order

(2) Each works station cannot complete different prefabricated elements at the same time

(3) Different production procedure of one prefabricated elements cannot parallel completed at one moment

3.2.3. Constraints. To meet the above-optimized production objectives, the constraints are as follows:

Constraints 1:

$$\sum_{i=1}^{n} S_i < F. \tag{4}$$

Constraints 2:

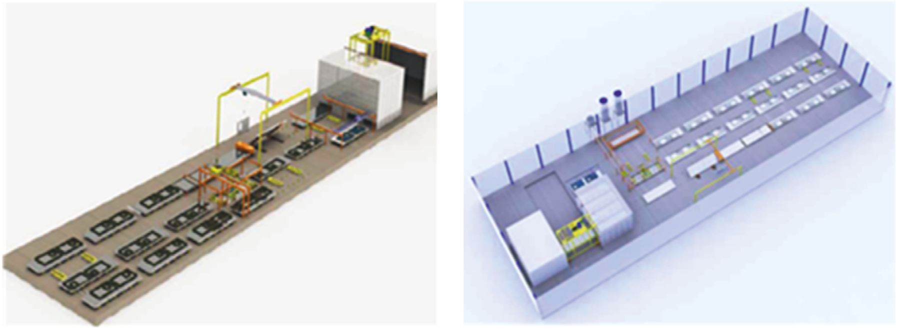
(a) (b)

Figure 2: The production line of prefabricated components. (a) multifunctional mixed production line and (b) specific component production line.

$$W > \sum_{i=1}^{N} S_i, \tag{5}$$

where W is the maximum demand for prefabricated components in a certain period. The first constraint means the actual daily prefabricated components production amount must be less than the maximum daily production capability. The second constraint means the industrialized housing projects demand must more than the total production amount in one production period; in another word, the prefabricated components cannot be produced more than demand.

4. Solution Approach

ACO algorithm is one kind of a metaheuristic method proposed by Dorigo (Dorigo, 1992). According to ACO, ant colonies leave pheromone along their foraging trails, and the amount of pheromone is proportional to how far an ant has to travel. The shorter the path, the greater the quantity of pheromone. The following ants choose the probabilistic route based on the pheromone strength left by the former ants. Due to the ants that will choose greater pheromone and shorter route, with several cycles, the ants will find the shortest route for their foraging [41, 42]. In an uncertain and complex environment, ACO is ideal for self-learning due to its features of positive feedback and self-organizing.

By imitating the foraging behavior of the ant colonies, the ACO has been extended to a wide area of optimization, such as Traveling Salesman Problem (TSP) [43], Job Shop Scheduling Problem (JSSP) [44, 45], Flow Shop Scheduling Problem (FSSP) [46, 47], Communication Network Routing Problem (CNRP) [48, 49], and Vehicle Routing Problem (VRP) [50, 51].

Due to the ACO methAn interesting question raised in this paper is how to optimize the load uniformity of prefabricated components in a multifunctional mixed production line so that the production of various prefabricated components can achieve a balanced production capacity and realize the effective application of production capacity. Aiming at the solution of this problem, the ACO algorithm is used to optimize the mixed production of prefabricated components.

Step 1. Pheromones update mechanism

The artificial ant was made to complete the prefabricated elements production task. Having completed element *i*, the artificial ant will select the next element *j* based on transition probability, and will generate pheromones along the route *ij*. The following artificial ants will then choose their routes according to the pheromones level on the routes. The more pheromones on the route, the higher probability of the ant choose the route. The pheromones update functions are defined as follows:

$$\begin{aligned} \tau_{ij}(t+n) &= (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij}(t) \\ \Delta\tau_{ij}(t) &= \sum_{i=1}^{n} \frac{Q}{\mathrm{STD}(Pd_i)} \end{aligned}, \tag{6}$$

where τ_{ij} is the pheromones information, $\rho\,(0<\rho<1)$ is the evaporation rate which applied to avoid an unlimited accumulation of the pheromones information, $\Delta\tau_{ij}$ is the increase of the pheromones information due to the artificial ant select the route *ij*, *STD* represents the variance of daily production capacity in one period, and *Q* is the strength of the pheromones information.

Step 2. The transition probability of artificial ant

When the artificial ant finish the prefabricated element *i*, it will use the heuristic information as well as pheromone information to choose the next element *j*. Therefore, the transition probability of artificial ant is determined by the pheromone information τ_{ij} and the heuristic information η_{ij}. The transition probability $P_{ij}^{k}(t)$ is defined as follows:

$$\mathrm{P}_{ij}^{k}(t) = \begin{cases} \dfrac{\left[\tau_{ij}(t)\right]^{\alpha} \times \left[\eta_{ik}(t)\right]^{\beta}}{\sum_{S\subset[k]_a}\left[\tau_{ij}(t)\right]^{\alpha} \times \left[\eta_{is}(t)\right]^{\beta}}, & j \subset [k]_a, \\ 0, & \end{cases} \tag{7}$$

Table 2: The size and amounts of different types of prefabricated walls.

Parameter Type	Size (Length × Height × Thickness)	Amount		
		Production period 1	Production period 2	Production period 3
Model 1	1.5 × 1.8 × 0.3	8	9	7
Model 2	2.4 × 1.8 × 0.3	6	8	8
Model 3	1.8 × 1.8 × 0.3	4	5	5
Model 4	3.6 × 1.8 × 0.3	8	10	8
Model 5	2.0 × 2.0 × 0.24	6	6	7
Model 6	1.6 × 2.0 × 0.24	8	6	7
Model 7	3.2 × 2.0 × 0.24	10	6	8
Model 8	3.0 × 2.0 × 0.24	8	8	8

where α and β are the parameters that determine the relative influence of the pheromone information and heuristic information, respectively, $[k]_\alpha$ is the set of the unfinished elements out of the Tabu list, and η_{ij} is heuristic information that is defined as follows:

$$\eta_{ij}(t) = \frac{1}{D_{ij}}, \tag{8}$$

Where D_{ij} represents production capability difference of element i and j. In the local, the artificial ants use greed guidelines to search the smaller production capability difference elements, and the smaller of D_{ij}, the larger of the heuristic information η_{ij}.

Step 3. Tabu list update

When the artificial ant finished one prefabricated element, the finished prefabricated element will be added into the Tabu list. Under this iteration rules, the artificial ant just can select the unfinished elements outside the Tabu list and keep finishing the remaining elements until the Tabu list was fully filled.

Step 4. Output the optimization results

Repeat the iteration steps above each time, recording the best-mixed production sequence, until the artificial ant route approaches the optimum route. Output the best-mixed production sequence based on the final calculation.

5. Case Study

5.1. Basic Parameters of the Case. An industrialized housing project in China was chosen to study the mixed prefabricated components optimization. There are several types of prefabricated components that prefabricated components factories can supply for industrialized housing construction such as prefabricated concrete floors, prefabricated concrete walls, and prefabricated balconies. In this study, the prefabricated concrete wall was selected. There are 8 types of prefabricated concrete walls that are needed in the industrialized housing construction; the basic size parameters were shown in Table 2. The height and thickness parameters of the wall are relatively simple, so the daily production capability is determined by the length parameters of the prefabricated concrete wall. The prefabricated components factory daily production capability was 30 m.

Table 3: Random order sequence of prefabricated walls of production period 1.

Day Model	Day1	Day2	Day3	Day4	Day5
Model 1	1	2	2	1	2
Model 2	2	1	1	1	1
Model 3	1	0	1	1	1
Model 4	1	1	2	2	2
Model 5	1	2	1	1	1
Model 6	2	2	1	1	2
Model 7	2	3	2	2	1
Model 8	2	1	1	2	2
DPCUR (%)	96.33	99.33	94.67	99.67	99.33

During the construction process, the prefabricated component factory received random orders from the construction site. From the perspective of the manager of a prefabricated component factory, the smaller the fluctuation of daily production capacity during the production period, the easier the scheduling of product management work. Therefore, to simulate the actual prefabricated construction process, a random order sequence of the prefabricated wall was generated as the input of the optimization model, as shown in Tables 3 to 5. The optimization code was developed by MATLAB, and the parameters in the ACO are $\alpha = 1$, $\beta = 2$, $\rho = 0.7$, iteration steps $N\_\max = 50$ and the ants' number is 38.

5.2. Optimization Results and Analysis. Based on the MATLAB code developed in this study, the random order sequence was optimized. The object of the optimization is to minimize the variance of DPCUR in one production period. The random order sequence in Tables 3 to 5 was inputted in the optimization code, and the optimization results were shown in Table 6.

To verify the optimization results, the five days DPCUR of the random order sequence were compared with the optimization sequence, as shown in Figure 3. And the black solid line represents the DPCUR of random mixed prefabricated walls, and the black dash line represents the DPCUR of optimization sequence mixed prefabricated walls.

6. Discussion

At present, the research on production scheduling optimization of hybrid production line mostly focuses on

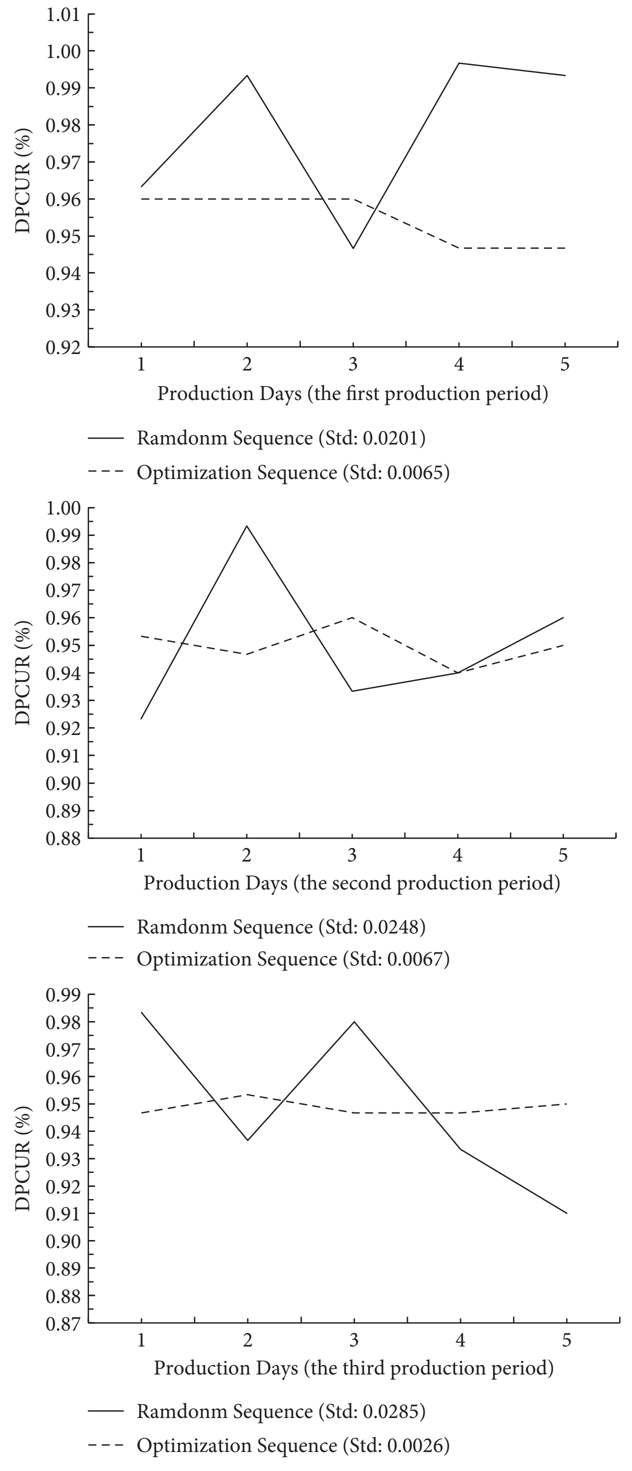

Figure 3: The comparison of DPCUR in the production periods.

Table 4: Random order sequence of prefabricated walls of production period 2.

Days Model	Day1	Day2	Day3	Day4	Day5
Model 1	1	2	2	2	2
Model 2	1	2	2	2	1
Model 3	1	1	1	1	1
Model 4	2	2	2	2	2
Model 5	2	1	1	1	1
Model 6	1	1	0	2	2
Model 7	1	2	1	1	1
Model 8	2	1	2	1	2
DPCUR (%)	92.33	99.33	93.33	94.00	96.00

Table 5: Random order sequence of prefabricated walls of Production period 3.

Days Model	Day1	Day2	Day3	Day4	Day5
Model 1	1	1	2	2	1
Model 2	1	3	1	1	2
Model 3	2	0	1	1	1
Model 4	2	1	2	1	2
Model 5	2	1	2	0	2
Model 6	1	1	3	1	1
Model 7	1	1	1	3	2
Model 8	2	3	1	2	0
DPCUR (%)	98.33	93.67	98.00	93.33	91.00

manufacturing industry, and there is few research in construction industry [52, 53]. The production scheduling optimization problem of prefabricated building components is a new production scheduling problem with resource constraints and production process characteristics. Compared with the traditional flow shop problem, it has its particularity of construction production. It is necessary to analyze the process characteristics and resource constraints in the production process, establish the corresponding mathematical model, and solve it. Therefore, the hybrid production line scheduling problem in traditional manufacturing industry is analyzed.

Based on the results of the case study, the proposed model is further discussed and analyzed. Under the condition that the total production capacity remains unchanged during the production period, we will mainly discuss the research results from two aspects. First, compared with the previous model, the variance of the DPCUR of the optimized model is significantly reduced. Before optimizing the production of prefabricated components, Tables 3 to 5 are work allocation plans. The random sequence reflects the actual production process, where the production manager schedules the mixed production based on his experience. And Table 6 reflects the work distribution plan of the optimized prefabricated components under the same conditions. From the comparative analysis of the data in Figure 3, it can be seen that the fluctuation of the optimized DPCUR is significantly smaller. As DPCUR changes are smaller, production capacity approaches equilibrium. The optimized sequence of mixed production lines is conducive to production managers to make more accurate production scheduling plans and effectively promotes the production management of IB prefabricated components.

Second, the optimized model can reduce the capacity limit during the same production period. To ensure the smooth progress of production, data in Tables 3 to 5 show that before optimizing the production of prefabricated components, the resources must be allotted based on a maximum limit of $L = 30\,\text{m}$. Nevertheless, the standard deviation of daily

Table 6: Optimization results of random order of prefabricated walls.

Time		Production Amount	DPCUR (%)	Variance
Production period 1	Day1	Model2 × 4; Model3 × 4; Model5 × 6	96.00	0.0065
	Day2	Model2 × 2; Model8 × 8	96.00	
	Day3	Model7 × 9	96.00	
	Day4	Model4 × 7; Model7 × 1	94.67	
	Day5	Model1 × 8; Model4 × 1; Model6 × 8	94.67	
Production period 2	Day1	Model3 × 5; Model5 × 5; Model6 × 6	95.33	0.0067
	Day2	Model2 × 8; Model4 × 2; Model5 × 1	94.67	
	Day3	Model4 × 8	96.00	
	Day4	Model7 × 6; Model8 × 3	94.00	
	Day5	Model1 × 9; Model8 × 5	95.00	
Production period 3	Day1	Model2 × 6; Model5 × 7	94.67	0.0026
	Day2	Model2 × 2; Model3 × 5; Model4 × 1; Model6 × 7	95.33	
	Day3	Model4 × 7; Model7 × 1	94.67	
	Day4	Model7 × 7; Model8 × 2	94.67	
	Day5	Model1 × 7; Model8 × 6	95.00	

capacity consumption for the optimized prefabricated component mixing production line has been significantly reduced to $L = 28.6$ m.

Therefore, after determining the maximum daily production capacity consumption, the production capacity limit can be appropriately adjusted to a certain range in the subsequent production period, with the savings in labor costs and idle machine time applied to other production lines for the production of other components, thus making the resources more fully utilized. To a certain extent, the effective use of resources has been realized.

According to our research, the production capacity fluctuations of prefabricated components are significantly reduced after using the ACO algorithm to optimize the sequential of the multifunctional mixing production line. This method is conducive to achieving a balance between production capacity for prefabricated components, and can be used more effectively, thereby greatly improving the construction efficiency of industrialized construction projects.

7. Conclusions

In construction, IB often faces the problem of producing mixed prefabricated components with limited daily production capacity. This paper develops an optimization model based on an ACO algorithm to achieve a balance in production capacity of prefabricated components. Using resources from recent literature reviews on the optimization of IB and mixed production lines, it is found that manufacturing prefabricated components in IB still has a lot of problems, and how to manage production effectively management during the construction process is the current development trend of the whole industry. Consequently, the purpose of this paper is to develop an objective function that ensures the minimum variance of the daily production capacity utilization of the prefabricated components under the condition that the total capacity is constant in the production period, which maximizes the production capacity utilization of the prefabricated components and reduces the labor cost and the idle machine time to a certain extent. In contrast, since the ACO algorithm has more obvious advantages when applied to solving the problem of production optimization of small-batch large products, the paper chooses to apply the ACO algorithm to solving the problem of mixed production line optimization of prefabricated components in IB.

Our optimization model is based on combining ACO theory with the characteristics of prefabricated components. An industrialized housing project is used to verify the optimization model. An optimized mixed production sequence is generated by using the output of the random mixed production sequence into the optimized model. The comparison of the variance of change of the daily productivity utilization shows that the optimized sequence results show more efficiency. These aspects provide a significant contribution to research in this paper based on a series of experimental findings: (i) In order to optimize this mathematical model, the order of the models and rational task allocation should be altered to obtain the lowest variance of DPCUR for prefabricated components. (ii) we propose an ACO algorithm to overcome this problem and make it targeted by lokking at the characteristics of prefabricated components (small-batches and large-components) in IB.

In contrast to previous studies, this paper proposed an optimization model that realizes uniform consumption in the production process while ensuring that the existing capacity utilization ratio is not decreased, which contributes to the achievement of the capability balance and the maximization of the resource utilization of the entire production line. It helps to balance the production capacity of the whole production line and maximize the utilization of resources. It facilitates the optimization of production capacity balance and resource utilization ratio of the entire system.

With the IB, conventional construction production has been transformed into a manufacturing mode based mainly on mechanized production, and thus is able to utilize the advanced production theories and management experience of the manufacturing industry as part of the production process of prefabricated components. Accordingly, the research in this paper is based on this background. However, there are still a few limitations of the study. On the one hand, there may be an issue with *t* restriction condition setting not being sufficiently comprehensive. Alternatively, for the selection of optimization methods, when the production scale is enlarged, the existing methods should be improved to some extent, which can be considered to combine with a variety of heuristic algorithms to improve the performance of the algorithm. To compensate for existing defects, future research will be expanded to include application of more advanced manufacturing skills, as well as a more industrialized construction production process.

Data Availability

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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