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Research Article

Optimization of Flow Shop Scheduling in Precast Concrete Component Production via Mixed-Integer Linear Programming

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The increasing number of prefabrication projects has increased the demand for precast concrete (PC) components. The production cost of PC components significantly affects the development of the precast industry and the progress of prefabrication projects. To reduce the production cost, both the delivery delay time and component storage time must be reduced. Flow-arrangement optimization is generally performed using the genetic algorithm. However, this method cannot always yield a perfect optimal solution. Moreover, the traditional optimization model does not consider the impact of the overtime hours of workers on the project costs. In this study, a mixed-integer linear programming (MILP) model was developed to optimize the production scheduling by minimizing the storage and delay times. The total delay time for the components was reduced by 55.3%, from 3.8 to 1.7 h, and the total storage time for finished components was reduced by 20.3%, from 6.4 to 5.1 h. Then, the use of the MILP model was extended to optimize the production scheduling by minimizing overtime. Finally, the feasibility and effectiveness of MILP were verified by comparing the results. The total overtime decreased by approximately 24.5%, from 11.5 to 9.3 h. It has been demonstrated that the proposed MILP model can achieve a better production sequence with less overtime. The findings of this research can be deployed in optimizing efficiency in the real-life scheduling of production sequence.

1. Introduction

Because of the drawbacks of conventional on-site construction approaches, the construction sector consumes approximately 40% of the total global energy, uses 40% of the global materials, and produces 50% of the global waste [1]. Many countries or regions, in recent years, have shown increasing interest in prefabrication as an "efficient" production strategy to meet their enormous construction demands [2]. Prefabrication is an off-site construction method, and prefabricated buildings are a branch of industrial architecture that transfers some or all components of a building into the precast factory.

Compared with traditional construction methods, the advantages of prefabricated buildings include (1) standardization of mass production, (2) reducing material waste and carbon emissions during the construction process, (3) decreasing the impact of the environment on the production of prefabricated components in the factory, and (4) the flexibility of production of prefabricated components when construction schedules change [3–5]. However, the cost of prefabrication projects is higher than that of cast-on-site projects [6]. The precast concrete (PC) components account for more than 40% of the total cost. These costs are mainly caused by transportation costs and waiting costs for construction [7–9]. Therefore, efficient control of precast component production is important to reduce the construction cost.

A primary difficulty in PC production is how to manage PC completion times and delivery times across the assembly line when the orders received by the factory are approaching the work limit load. The overdue delivery of PC causes serious problems, such as degraded component quality, higher labor costs, rescheduling of construction activities, and project delays. Therefore, delivering the components to the construction site on time is critical to ensure the smooth construction of the prefabrication project. The delay time caused by the prefabricated component manufacturer is the

most common situation in prefabrication projects. Previous researchers only focused on minimizing the work completion time to avoid the delay time. They ignored early delivery, which also causes huge cost waste. The long storage of components in the factory also increases the storage cost. Therefore, reasonable planning of the completion time of each component requires simultaneous reduction of delay time and storage time [10]. Chan and Hu [6] considered delay time and storage time as optimization goals and proposed a modified flow shop sequencing model (FSSM). The aim of some studies [7, 11, 12] was to minimize the delay time and optimize the scheduling scheme using the genetic algorithm (GA). However, these studies focused on the use of the GA for optimization. Owing to the characteristics of the GA, the optimization results obtained are not necessarily the optimal solution. Another straightforward criterion is the minimization of machine idle time to increase machine utilization or productivity [13]. Idle time is relevant to the waste of production cost—for example, equipment and labor waste—directly. Practically, for the crucial components that cannot be delayed, working overtime is sometimes necessary and inevitably leads to additional costs. Thus, optimizing the production scheduling to reduce the amount of overtime is significant for reducing cost [14].

In this study, the production scheduling plan was formulated as a mixed-integer linear programming (MILP) model. First, the minimum sum of the storage time and delay time is taken as the optimization objective. Compared with the FSSM, the MILP model can obtain a better schedule of prefabricated component production with less penalty cost. Then, the model was extended by setting the minimization of labor overtime as the objective function subject to nondelay delivery. It was demonstrated that the model can effectively optimize the production sequence of components to reduce the overtime cost.

2. Literature Review

2.1. Research Scope. In production practice, most prefabrication plants adopt the order-type production mode. The construction unit agrees to the delivery time, and the prefabrication plant guarantees the delivery on time [15]. At the planning stage, the determination of resource supply quantities depends largely on the experience of project managers, schedulers, and superintendents, without any analytical decision support [16]. Addressing the need to plan workflows for individual craft persons is not possible [17]. Therefore, a perfect production scheduling scheme is important to balance the resource supply and resource demand of the project.

Few studies related to production scheduling have attempted to satisfy the constraints of prefabricated component resources and delivery time [18]. The primary goal of a prefabricated component production plan is to meet customer requirements at the lowest cost. Warszawski and Ishai [19] considered the long-term planning required in a production plant and the decisions involved in the production planning process. Chan and Hu [6] proposed a modified FSSM. A standardized production process for PC components was specified, and a distinction was made between working time and nonworking time. Production planning based on this model can reduce production costs and improve production efficiency. Benjaoran and Dawood [20] analyzed the impact of changes in operation time on machine idle time, completion time, component storage time, and delay time.

Although researchers have studied the relationship between delivery time and completion time, they have not considered the limited quantity of production resources. Hu [21] considered the mold usage problem and used the FSSM to level the mold usage. Wang and Hu [7] further considered the impact of links between storage and transportation on punctual delivery of orders and developed a production scheduling model for an entire supply chain. Liu and Lu [22] proposed a multiproject scheduling framework to reduce resource dependence. Li et al. [23] established a production planning model that meets the requirements of production cost and satisfies constraints related to on-site construction and internal resources. Yang et al. [11] conducted field studies on precast production in several factories and found that the existing models cannot be directly applied to flow shops with multiple production lines. They then developed a model for multiple production lines to minimize workstation idle time and the contract penalty, storage cost, and changes in the type of precast components.

Most previous studies have taken minimizing the difference between the completion time and the delivery deadline as the optimization objective while taking limited production resources as the restrictive condition. Although the objective of improving the on-time delivery rate has been achieved to a certain extent, the above-mentioned model does not consider the impact of worker behavior on completion time. Techera et al. [24] studied the relationship between working hours and worker fatigue at extreme temperatures. Chan et al. [25] studied how to balance work in the context of labor shortages in the construction industry and the living time that attracts the labor force. Chan and Hu [26] divided the total working hours of workers into normal working hours, overtime hours, and other hours, which can be occupied by overtime hours. The impact of worker behavior on production efficiency has been studied. In practice, when the delivery deadline is tight, prefabrication factories often organize workers to work overtime to ensure that ordered components are delivered on time. In this research, the minimum overtime hours of workers are taken as one of the objectives, as well as improving the utilization of normal working hours, shortening overtime hours, and improving production efficiency.

2.2. Research Methodology. The production scheduling problem involves the allocation of resources over a period. Production scheduling is a nondeterministic polynomial problem [12]. For human decision makers, a theoretically strict and optimal production scheduling plan can be obtained through operations research. However, owing to performance issues, it is difficult to solve practical problems involving a large number of constraints and variables.

Therefore, to solve complex mathematical models in a limited time, researchers have applied heuristic algorithms to solve production scheduling problems. The principle of heuristic algorithms (metaheuristics) is based on experience or law and involves searching for feasible solutions to the problem under a specific set of conditions. The GA has been widely used to ensure on-time delivery and optimize resource allocation [27]. Many researchers have applied the GA to scheduling problems. Anvari et al. [28] proposed a flexible job shop scheduling problem using a multiobjective GA-based searching technique to solve unified manufacturing, transportation, and assembly resource scheduling problems in precast construction. Wang and Hu [7] modified the traditional production planning model from the perspective of the entire PC supply chain and verified the effectiveness of the proposed model based on GA. Chan and Wee [29] analyzed the reasons for the midway failure of production scheduling plans and included the GA in the planned repair model. Liu et al. [30] proposed an improved GA that assists in the scheduling of prefabricated factory production and vehicle transportation. Shang et al. [31] adopted the GA to perform and optimize assembly-related block space scheduling. Using the GA, a family of optimal or near-optimal solutions could be efficiently obtained in a short time. In addition, the GA was reliable and stable and could provide suitable solutions under different practical conditions.

The aforementioned scholars have applied the GA to solve scheduling problems. The algorithm simulates the operation mechanism of genetic inheritance, mutation, and recombination and uses natural selection to establish a screening mechanism. Finally, an acceptable solution is obtained through a large number of iterations, but it is difficult to guarantee the optimality of the solution. In the actual production process, the production scheduling scheme in the design stage requires a highly accurate result. To obtain the optimal solution, dynamic programming is introduced to solve the model. MILP is an algorithm that decomposes a multistage optimization problem into a single-stage problem step by step according to the principle of optimization [32]. The GA is characterized by a short computation time and yields near-optimal solutions. MILP is characterized by a long computation time and can yield optimal solutions. However, the PC scheduling problem is a small-sample problem; the calculation time of MILP is similar to that of the GA, but its accuracy is higher than that of the GA.

MILP has been widely used in many fields because it offers flexible modeling and provides optimal solutions. Huang et al. [33, 34] used the MILP model to optimize the use of material storage units in high-rise buildings. The MILP model is also used to optimize the layout design and planning of facilities on construction sites. Khalili and Chua [35] incorporated prefabricated components and connectors into the MILP model to determine the best possible production plan. In this study, an optimization model for MILP was established. The binary variables were set as decision variables to control the production sequence of the components in the model. The solution space was delineated with linear constraints indicating the relationships in the process flow. Finally, the optimal solution was obtained using the branch-and-bound method. The model was built using the *Python* language, and the optimization model was established and solved using the commercial software Gurobi [36].

3. Problem Description

With continuous innovations in the production technology of PC components, most precast factories adopt a mobile assembly line. Each PC component is completed sequentially on the assembly line through a standardized production process. Figure 1 shows the six steps of a typical production line: (1) mold assembly, (2) reinforcement setting, (3) casting, (4) curing, (5) mold removal, and (6) finishing and repairing. The production scheduling of precast components can be abstracted as flow shop sequencing. In this process, m machines arranged in sequence on the assembly line are used to produce n types of components. The production schedule presents the work to be performed and the timeframes in which the work must be completed. The corresponding process of each component is completed sequentially by each machine. Owing to the difference in operating time, the production line cannot maintain a stable flow rate; therefore, components must wait on the production line, and the machines are forced to idle. An inappropriate production scheduling plan increases the component waiting time on the production line, and the idle time of the machine prolongs the production time. The components waiting time and machine idle time must be minimized to obtain the shortest completion time through reasonable adjustment of the production sequence.

To illustrate the characteristics of the production sequencing problem in the flow shop, a case in which three machines are used to produce three types of component is shown in Figure 2(a). The production process of components A, B, and C follows the initial component production sequence. Afterward, the production sequence is adjusted to the sequence C, B, and A. As shown in Figure 2(b), the comparison reveals that the completion time is reduced from 21 to 15 h by adjusting the production sequence of the components. The optimized production scheduling has an obvious effect on improving production efficiency.

4. Model Development

In the production scheduling problem, the main factors that affect the production cost of the prefabricated factory include the storage cost caused by the premature production and by the occupation of the space and the delay cost caused by the completion time being later than the delivery time. Figure 3 depicts the process of the MILP model, and the related mathematical expression is detailed subsequently.

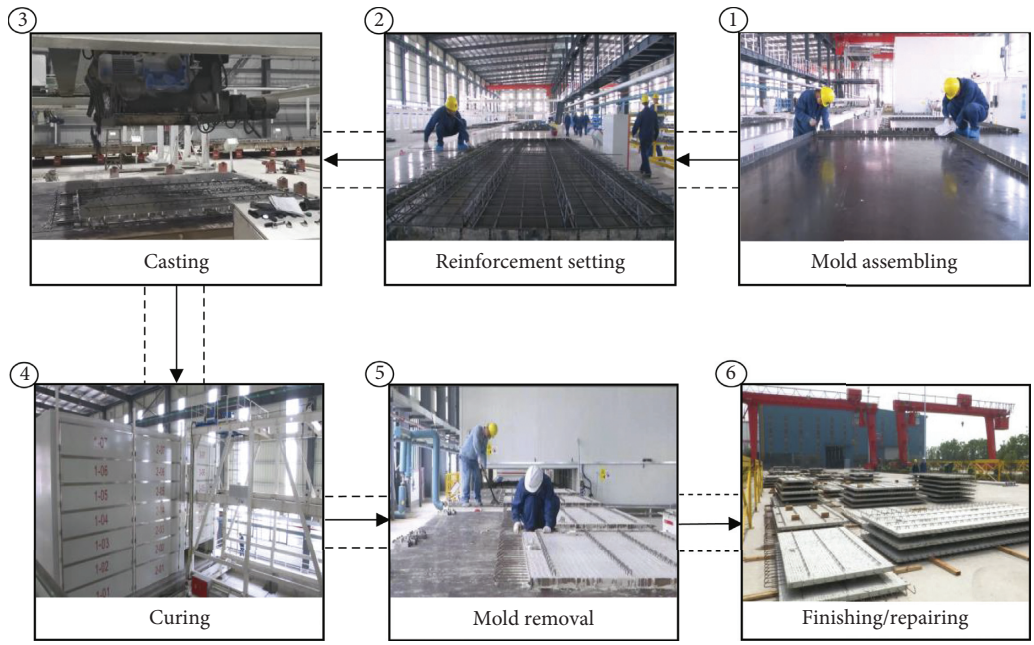

Figure 1: Production flowchart of PC components.

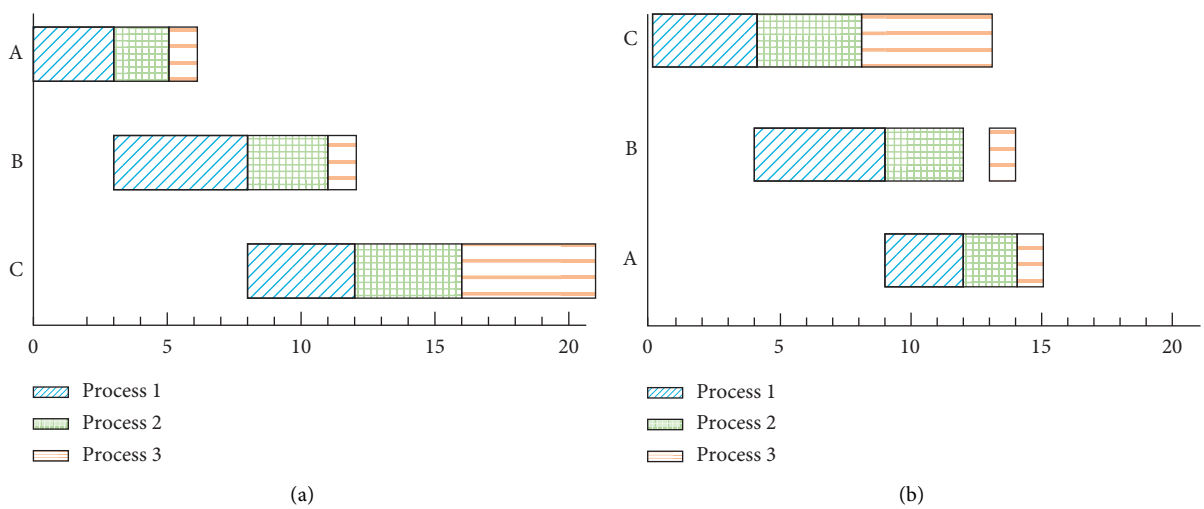

Figure 2: (a) Production sequence scheme (1) and (b) production sequence scheme (2).

4.1. Step 1: Introduction of the Two Objective Functions and Variables. The first objective function is to minimize the storage time and delay time of all components.

$$\text{Minimize}\left(\sum_{i}^{I}\left(\alpha_i \times ET_i + \beta_i \times TT_i\right)\right), \tag{1}$$

where I represents the total number of components required as per the order, i represents the production order of the component, $ET_i$and TT_i represent the storage time and postponement time of component i, respectively, α_i and β_i represent the weights of the storage time and delay time of component i, respectively, and $\alpha_i \times ET_i$ and $\beta_i \times TT_i$ represent the weighted penalty of the storage time and delay time of component i, respectively. To minimize the extra cost, the purpose of the objective function is to minimize the total costs of the storage time and delay time penalty.

To deliver components on time, the second objective of this model is to optimize the prefabricated component production sequence and reduce the total overtime. The constraint in (2) ensures that every component is delivered on time.

$$CT_{i,j} \le DT_i, \quad \forall i \in \{1, 2, 3, \cdots, I\}, j = 6, \tag{2}$$

where j represents the operation sequence of the machines, $CT_{i,j}$ represents the completion time for the i component on the j machine, and DT_i represents the due time of component i. When $j = 6$, $CT_{i,6}$ represents the total completion time of component i, and $CT_{i,6}$ represents the notion that component i can be completed before the due time.

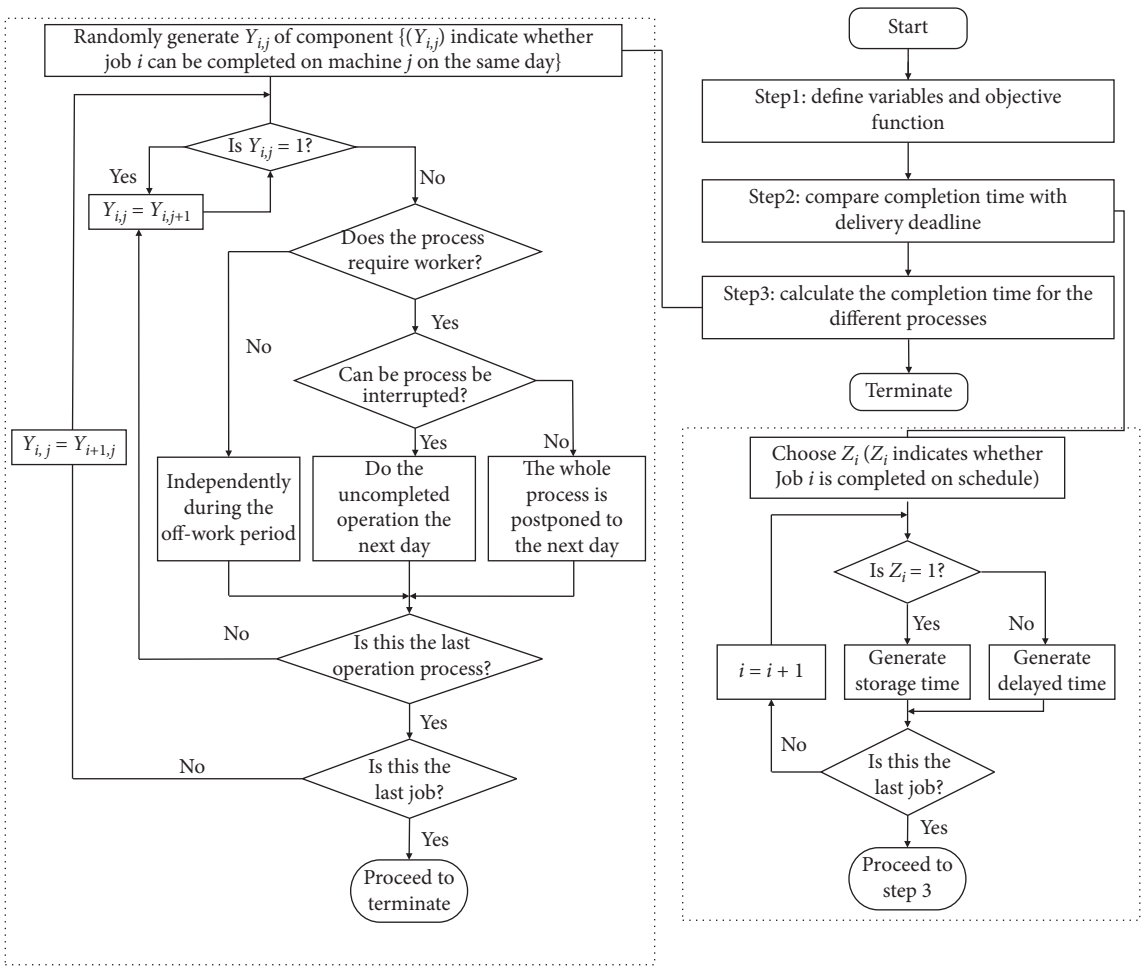

Figure 3: Algorithm flowchart.

Considering (2), storage time and delay time will not waste. Simultaneously, the following equation, the objective function, minimizes the total overtime to ensure the minimum production cost:

$$\text{Minimize}\left(\sum_{i}^{I}\sum_{j}^{J}\left(\gamma_j \times OT_{i,j}\right)\right), \tag{3}$$

where $OT_{i,j}$ represents the overtime of component i on machine j, γ_j is the weight of overtime for component i, and $\gamma_j \times OT_{i,j}$ represents the weighted overtime penalty.

4.2. Step 2: Comparison of the Completion Time with the Delivery Deadline. In the production process, efficiency can be improved and costs can be reduced by reducing the delivery waiting time. The waiting time includes both delay time and storage time. The first objective function is to explore how to balance the waiting time to minimize the production cost.

First, one component is assigned to one sequence, and the sequence is fixed. This means that the production sequence of components can be changed, but the order of the operations for one component cannot be changed. Second, the operation process of the component needs to be completed within the working hours; this is represented by the constraints in the following equations:

$$\lambda \times SD_{i,j} + \delta \le ST_{i,j}, \quad \forall i \in \{1, \cdots I\}, \forall j \in \{1, \cdots\cdots, 6\}, \tag{4}$$

$$\lambda \times CD_{i,j} + \varepsilon + OT_{i,j} \ge CT_{i,j}, \quad \forall i \in \{1, \cdots, I\}, \quad \forall j \in \{1, \cdots, 6\}. \tag{5}$$

The parameter λ represents the 24 hours in a day. Moreover, $SD_{i,j}$ and $CD_{i,j}$ are the start date and completion date of component i on machine j, respectively. The date here is a point in time, so it needs to be multiplied by 24 to represent a time period. Furthermore, $OT_{i,j}$ is the overtime of component i on machine j, and $CT_{i,j}$ is the time when component i completes operation on machine j. The parametersδ and ε represent the working hours and off-working hours of each working day, respectively.

The storage time ET and the delay time TT in the objective function in (1) can be calculated using the following equations:

$$ET_i = \left(DT_i - CT_{i,j}\right) \times \left(1 - Z_i\right), \quad \forall i \in \{1, 2, 3 \cdots I\}, j = 6, \tag{6}$$

$$TT_i = \left(CT_{i,j} - DT_i\right) \times Z_i, \quad \forall i \in \{1, 2, 3, \cdots, I\}, j = 6. \tag{7}$$

The parameter DT_i represents the delivery deadline of component i. The binary variable Z_i indicates whether the component has expired by the time of completion. By comparing the component completion time and the delivery deadline, it can be judged whether completion before the delivery deadline is possible. In (8) and (9), when $j = 6$, $CT_{i,6}$ represents the completion time of the sixth operation of component i, and it also represents the total completion time of component i. When $Z_i = 0$, component i will end before the completion deadline and there will be a storage time penalty. When $Z_i = 1$, component i is overdue and will have a delay time penalty.

$$CT_{i,j} \geq DT_i - \left(1 - Z_i\right) \times N, \quad \forall i \in \{1, 2, 3, \ldots, I\}, j = 6, \tag{8}$$

$$CT_{i,j} \leq DT_i + Z_i \times N, \quad \forall i \in \{1, 2, 3, \ldots, I\}, j = 6. \tag{9}$$

4.3. Step 3: Calculation of the Completion Time for the Different Processes. The completion time has a significant impact on production costs. In the actual production process, it takes several days for the component to be completed. To achieve optimal sequencing, progress in producing components is required every day. The binary variable $Y_{i,j}$ indicates whether the operation of component i on machine j can be completed on that day. In (10) and (11), N represents an extremely large number, and $ST_{i,j}$ is the start time of component i on machine j. The variable $PT_{i,j}$ is the operation time of component i on machine j. By comparing the remaining time and process operation time of the day, it can be determined whether the operation of each component on the machine can be completed on that day.

$$24 \times SD_{i,j} + \delta \geq ST_{i,j} + PT_{i,j} - \left(1 - Y_{i,j}\right) \times N, \quad \forall i \in \{1, \ldots, I\}, \forall j \in \{1, \cdots, 6\}, \tag{10}$$

$$24 \times SD_{i,j} + \delta \leq ST_{i,j} + PT_{i,j} + Y_{i,j} \times N, \quad \forall i \in \{1, \ldots, I\}, \forall j \in \{1, \cdots, 6\}. \tag{11}$$

In the production process, the daily working hours and overtime hours are limited. If the operations of the process cannot be completed on that day, different continuous processes are treated with different measures. Subject to the technology difference, processes are divided into interruptible processes and uninterruptible processes. When the process cannot be completed on that day, the interruptible process (including model assembling, reinforcement setting, model removal, and repair) interrupts the operation and waits until the next day to perform unfinished operations. Different types of process have different constraints. The constraints of interruptible processes are given in the following equation:

$$CT_{i,j} = ST_{i,j} + PT_{i,j} + \left(1 - Y_{i,j}\right) \times \left(NT - OT_{i,j}\right), \quad \forall i \in \{1, \ldots, I\}, \forall j \in \{1, 2, 5, 6\}. \tag{12}$$

In the formula, NT denotes "beyond normal working hours," including overtime and other hours. When $Y_{i,j} = 1$, the operation can be completed on the same day, and the completion time is the sum of the start time and operation time. When $Y_{i,j} = 0$, the operation cannot be completed on that day. The completion time consists of the start time, operation time, and time off work. $PT_{i,j}$ is divided into two parts, with both the first and second days covering the operating time.

The uninterruptible process is the casting model process, and its constraints are as follows:

$$CT_{i,j} = ST_{i,j} + PT_{i,j}, \quad \forall i \in \{1, \cdots, I\}, j = 3. \tag{13}$$

The meaning of (13) is that, if this operation cannot be completed that day, the operation starts the next day.

When $j = 6$, it is a curing process. The curing process is carried out independently when the workers are off duty, and the operation is completed the next day. The new curing process is carried out after the previous curing process ends, and its constraint conditions are shown in (14). The calculations of the completion time for the interruptible, uninterruptible, and curing processes are different, as illustrated in Figure 4.

$$CT_{i,j} \geq ST_{i,j} + PT_{i,j}, \quad \forall i \in \{1, 2, 3, \cdots, I\}, j = 4. \tag{14}$$

The first objective of the proposed model is to minimize the penalty caused by the storage time and delay time. The problem is formulated by the objective function in (1) and subjected to constraint sets in (4)–(14). The second objective is to minimize overtime without delivery. The problem is formulated by the objective function in (2) and subjected to constraint sets in (3)–(5) and (8)–(14). The two MILP models were solved using the commercial software Gurobi™.

5. Numerical Example

5.1. Verifying the Effectiveness of MILP. To prove the effectiveness of MILP in optimizing the production scheduling problem of PC components, the optimization results of this model and the FSSM for the same batch of component production scheduling schemes are compared. The data of component type, process operation time, delivery date, and weight value are shown in Table 1 [6]. The production process of PC components of this model includes six processes: formwork assembly, steel tying, concrete pouring, autoclave curing, formwork removal, and cleaning and repairing. The operation time of each process varies depending on the component type. Table 1 specifies the time required for each work to complete each component and

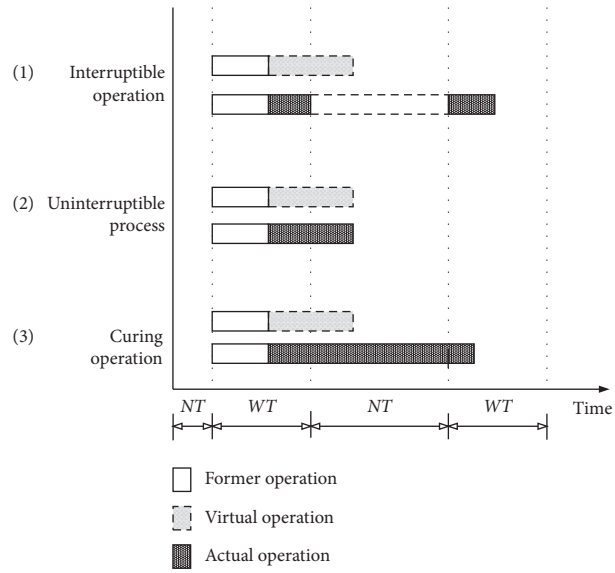

Figure 4: Process arrangement chart.

Table 1: Operation time and weight value of the six components in each process.

Component number	Process operation time (h)					Delivery period (h)	Weight value (unit/h)	
	Mold assembling	Reinforcement setting	Concrete casting	Mold removal	Finishing/ repairing		Restoring time	Delay time
1	1	0.8	1.2	1.5	0.5	28	2	10
2	1.7	2	2	1.5	2.5	28	2	10
3	0.4	0.5	0.6	0.5	0	28	1	10
4	0.3	0.4	0.5	0.4	1	28	1	10
5	1.5	1.8	1.2	1.5	1.5	52	2	10
6	1.5	1.6	1.5	1.8	0.8	32	2	10

weight value. The curing time of all components is not less than 12 h. In addition, the normal working hours of workers are eight hours a day. The optimization objective is to minimize the storage time and delivery delay time of finished components, as shown in (1).

In the optimization results of the FSSM and MILP models, the completion time of each process is shown in Tables 2 and 3. The completion times of the processes are listed in columns 2–7. The completion time of each component is the completion time of the final process (cleaning and repairing), listed in column 7. The total time to complete the order is the completion time of the final process (cleaning and repairing) of the final component. The delay time of each component (column 9) is the actual completion time of the component (column 7) minus the specified delivery period of the component (column 8). The storage time of each component (column 10) is the specified delivery period of the component (column 8) minus the actual completion time of the component (column 7).

The optimization results of the FSSM include a component production sequence of 4-2-6-1-3-5, order form completion time of 51 h, total component delay time of 3.8 h, and total component storage time of 6.4 h. The beginning and completion times of each process for each element type are also illustrated in Figure 5. The optimization result of this model includes the component production sequence 4-2-3-1-6-5, order completion time of 51 h, total delay time of components of 1.7 h, and total storage time of components of 5.1 h. The beginning and completion times of each process for each element type are also illustrated in Figure 6. With the order completion time unchanged, comparing Tables 1 and 2 shows that the delay time of component 1 is reduced from 1.7 to 0.9 h, and the delay time of component 3 is reduced from 1.7 to 0.4 h. The storage time of component 6 is shortened from 2.8 to 1.5 h by adjusting the production sequence of components 1, 3, and 6. The total delay time of components is shortened from 3.8 to 1.7 h, a decrease of approximately 55.3%. The total storage time of finished components is shortened from 6.4 to 5.1 h, a decrease of approximately 20.3%. These results prove that, compared with the local optimal solution by two models, MILP can provide better results for optimizing the production scheduling problem of PC components and has a smaller time penalty.

5.2. Verifying the Viability of MILP considering the Overtime of Workers. Most previous studies have had the objective of minimizing the difference between component completion time and the delivery deadline. In these studies, order delays

Table 2: Completion time of each process based on the FSSM.

Component production sequence	Process completion time (h)						Delay time (h)	Restoring time (h)
	Mold assembling	Reinforcement setting	Concrete casting	Curing	Mold removal	Finishing/ repairing		
4	0.3	0.7	1.2	24	24.4	25.4	—	2.6
2	2	4	6	24	25.9	28.4	0.4	—
6	3.5	5.6	7.5	24	27.7	29.2	—	2.8
1	4.5	6.4	8.7	24	29.2	29.7	1.7	—
3	4.9	6.9	9.3	24	29.7	29.7	1.7	—
5	6.4	24.7	25.9	48	49.5	51*	—	1
		Total delay time (h)					3.8	—
		Total restoring time (h)					—	6.4

*Orders complete time.

Table 3: Completion time of each process based on MILP.

Component production sequence	Process completion time (h)						Delay time (h)	Restoring time (h)
	Mold assembling	Reinforcement setting	Concrete casting	Curing	Mold removal	Finishing/ repairing		
4	0.3	0.7	1.2	24	24.4	25.4	—	2.6
2	2	4	6	24	25.9	28.4	0.4	—
3	2.4	4.5	6.6	24	26.4	28.4	0.4	—
1	3.4	5.3	7.8	24	27.9	28.9	0.9	—
6	4.9	6.9	9.3	24	29.7	30.5	—	1.5
5	6.4	24.7	25.9	48	49.5	51*	—	1
		Total delay time (h)					1.7	—
		Total restoring time (h)					—	5.1

*Orders complete time.

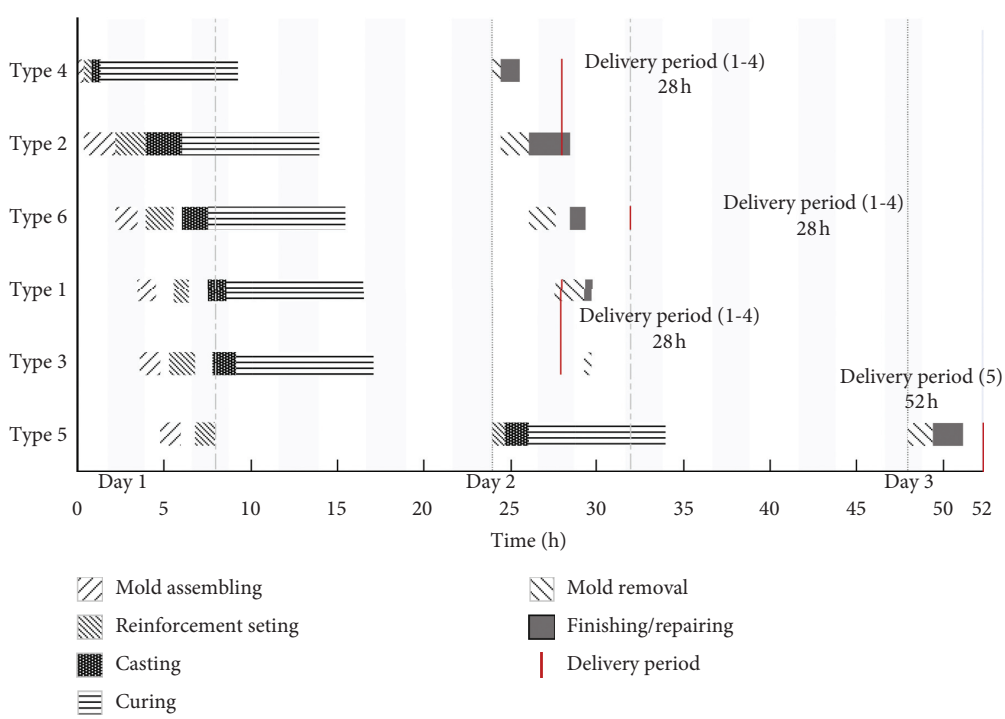

Figure 5: Gantt chart of completion time of each process based on the FSSM.

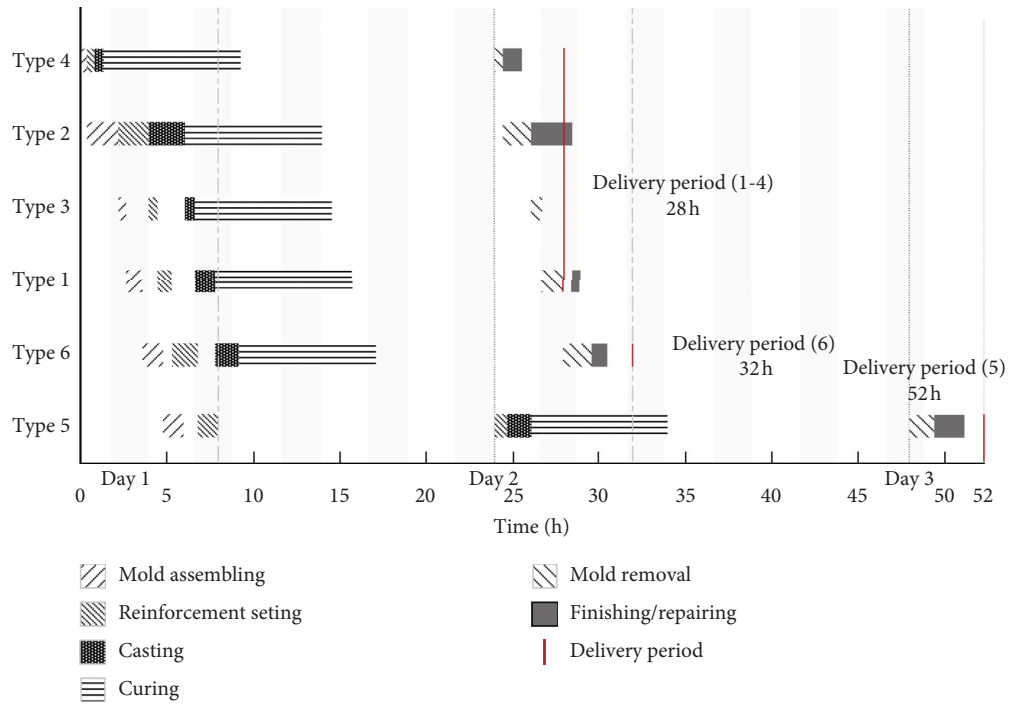

Figure 6: Gantt chart of completion time of each process based on MILP.

are allowed, which is contrary to real projects. When the delivery deadline is approaching, prefabricated component factories often organize workers to work overtime to ensure that orders are delivered on time. In the traditional production process, owing to the large number of components and the large variety of types, it is difficult to arrange the production sequence of components to obtain higher production efficiency based on the experience. Subject to on-time delivery, the second objective function in (3) aims to minimize the total overtime time.

The data of the component types and process operation time are used in Table 1. The normal working time is eight hours a day. To protect workers' rights and ensure efficiency, the daily overtime cannot exceed 4 h. Because of the limitation of the delivery period, shown in Table 1, the delivery cannot be achieved on schedule with overtime. To solve this problem and highlight the optimization effect of the model, some adjustments are made to the production data, including (1) increasing the number of components to 10 and (2) adjusting the delivery period of each component. Table 4 shows the adjusted operating time and delivery time of each component process.

The production sequence of each component in scheme (1) is 1-2-3-4-5-6-7-8-9-10. Scheme (1) is arranged according to the fixed component production sequence. According to the production sequence of scheme (1), the overtime plan is optimized by the model, and the specific times of the components in each process are shown in Table 5. According to Table 6, the shortest overtime that is needed to complete the order is 11.5 h. Scheme (2) considers the optimal objective of the shortest overtime hours, and the results are listed in Table 7. The production sequence of each component is 3-4-2-5-1-6-7-8-9-10. Scheme (2) is arranged according to the objective of the shortest overtime. The overtime plan and the specific time of the components in each process are listed in Table 8. According to Table 7, the shortest overtime required to complete the order is 9.3 h.

When the overtime schedules (Tables 6 and 7) were compared, it was found that scheme (2) adjusts the production sequence of components 3, 4, 2, 5, and 1. These adjustments played a significant role in reducing the overtime. From the perspective of components, the overtime of component 5 in the concrete casting process decreased from 1 to 0.8 h. Simultaneously, the final process for component 6 no longer required overtime, and the total overtime of all components was reduced. From the perspective of production processes, the overtime for reinforcement setting, concrete casting, and repairing processes decreased to 0.8, 0.6, and 0.8 h, respectively, and the total overtime decreased to 9.3 h, a reduction of approximately 19.1%. In summary, scheme (2) reduces overtime in most processes by adjusting the component production sequence.

The waiting time is the time when the component waits for the next process after completing the previous process. It is caused by an imbalance in the operating time of each process. According to statistics, after the optimization of scheme (2), the waiting time was reduced by 24.5% from 52.3 to 39.5 h. The waiting time changes specific production steps, as can be seen by comparing Figures 7 and 8. This proves that scheme (2) improves the utilization of normal working

Table 4: Operating time and delivery deadline of each process for 10 components.

Component number	Process operation time (h)					Delivery period (h)
	Mold assembling	Reinforcement setting	Concrete casting	Mold removal	Finishing/repairing	
1	1	0.8	1.2	1.5	0.5	32
2	1.7	2	2	1.5	2.5	32
3	0.4	0.5	0.6	0.5	0	32
4	0.3	0.4	0.5	0.4	1	48
5	1.5	1.8	1.2	1.5	1.5	48
6	1.5	1.6	1.5	1.8	0.8	48
7	1	0.8	1.2	1.5	0.5	52
8	1.7	2	2	1.5	2.5	52
9	0.3	0.4	0.5	0.4	1	56
10	1.5	1.8	1.2	1.5	1.5	56

Table 5: Completion time of each process for scheme (1).

Component production sequence	Process completion time (h)					
	Mold assembling	Reinforcement setting	Concrete casting	Curing	Mold removal	Finishing/repairing
1	1	1.8	3	24	25.5	26
2	2.7	4.7	6.7	24	27	29.5
3	3.1	5.2	7.3	24	27.5	29.5
4	3.4	5.6	7.8	24	27.9	30.5
5	4.9	7.4	9	24	29.4	32
6	6.4	9	10.5	24	31.2	32.8
7	7.4	9.8	11.7	24	32.7	48.5
8	25.1	27.1	29.1	48	49.5	52
9	25.4	27.5	29.6	48	49.9	53
10	26.9	29.3	30.8	48	51.4	54.5

Table 6: Overtime plan for scheme (1).

Component production sequence	Process operation time (h)				
	Mold assembling	Reinforcement setting	Concrete casting	Mold removal	Finishing/repairing
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	1	0	0
6	0	1	2.5	0	0.8
7	0	1.8	3.7	0.7	0
8	0	0	0	0	0
9	0	0	0	0	0
10	0	0	0	0	0
Overtime of each process (h)	0	2.8	7.2	0.7	0.8
Total overtime (h)			11.5		

Table 7: Overtime plan for scheme (2).

Component production sequence	Process operation time (h)				
	Mold assembling	Reinforcement setting	Concrete casting	Mold removal	Finishing/repairing
3	0	0	0	0	0
4	0	0	0	0	0
2	0	0	0	0	0
5	0	0	0.8	0	0
1	0	0	0	0	0
6	0	0.6	2.3	0	0
7	0	1.4	3.5	0.7	0

Table 7: Continued.

Component production sequence	Process operation time (h)				
	Mold assembling	Reinforcement setting	Concrete casting	Mold removal	Finishing/repairing
8	0	0	0	0	0
9	0	0	0	0	0
10	0	0	0	0	0
Overtime of each process (h)	0	2.0	6.6	0.7	0
Total overtime (h)			9.3		

Table 8: Completion time of each process for scheme (2).

Component production sequence	Process completion time (h)					
	Mold assembling	Reinforcement setting	Concrete casting	Curing	Mold removal	Finishing/repairing
3	3	0.4	0.9	1.5	24	24.5
4	4	0.7	1.3	2	24	24.9
2	2	2.4	4.4	6.4	24	26.4
5	5	3.9	6.2	7.6	24	27.9
1	1	4.9	7	8.8	24	29.4
6	6	6.4	8.6	10.3	24	31.2
7	7	7.4	9.4	11.5	24	32.7
8	8	25.1	27.1	29.1	48	49.5
9	9	25.4	27.5	29.6	48	49.9
10	10	26.9	29.3	30.8	48	51.4

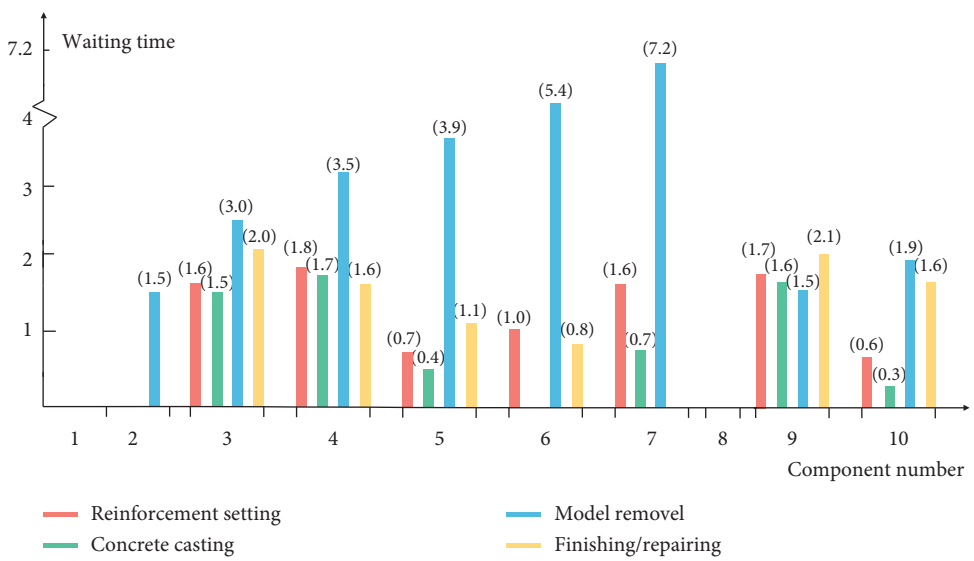

Figure 7: Waiting time chart for scheme (1).

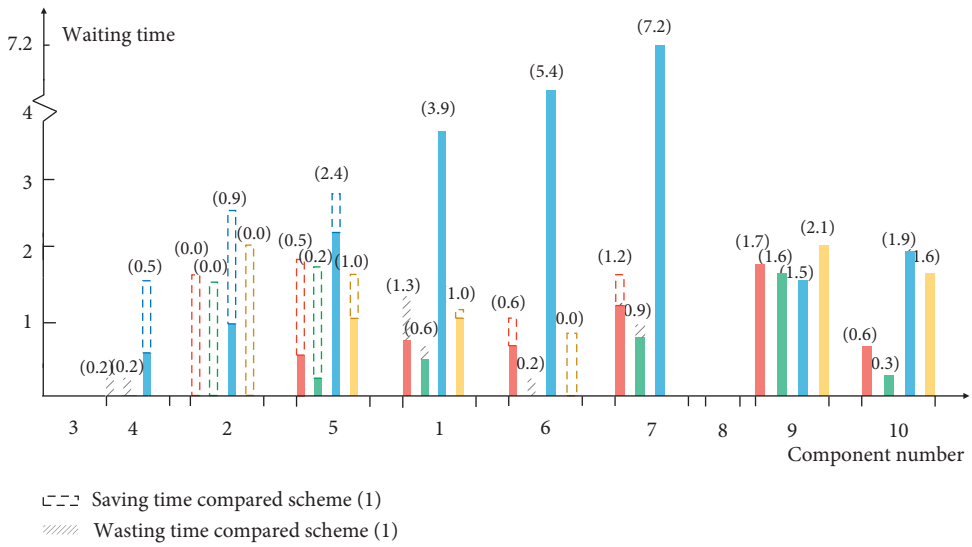

Figure 8: Waiting time chart for scheme (2).

hours by adjusting the production sequence of components and reducing the invalid waiting time of components on the production line.

6. Conclusions and Further Work

Saving the production cost of PC components can reduce the cost of prefabricated buildings, which promotes the development of prefabricated buildings. Improving production efficiency by optimizing production scheduling is an effective way to reduce component production costs. GA has been used in the production scheduling problem in the previous research, but it is not an accurate optimal solution. At the same time, previous research models allow the occurrence of delayed delivery, which is contrary to engineering practice and has certain limitations. In this study, the results of the MILP model were compared with the results of the FSSM. The result shows that MILP can provide better results. This proves the feasibility of MILP to solve such optimal problems. Then, MILP was used to establish a prefabricated component production scheduling model based on the shortest overtime. A case comparison revealed that the effectiveness of MILP results in a better solution, and its feasibility for minimizing overtime was verified.

This study contributes to the research on prefabricated component production from two aspects: calculation methods and influencing factors. (1) Taking the minimum storage time and delay time as the minimum objective function, the MILP method was adopted for calculation, and a better scheduling scheme was obtained than the traditional calculation results. (2) The minimization of overtime hours of workers was considered as one of the objective functions, and an effective optimal scheduling scheme was obtained by MILP calculation. Combining the production scheduling problem with the characteristics of PC production, a better scheme was obtained by using the algorithm. The optimized solution reduces costs and promotes on-time delivery of PCs.

In future research, it should be possible to increase other constraints, such as resource constraints, the number constraints of workers, and environmental influence constraints. Different resource types can make the optimization-based precast scheduling mechanism more perfect, accurately reflecting the actual production state, and it can reflect the actual production status and further improve the application value of the model. Managers can reduce the number of scheduling errors based on personal experience. Moreover, the model should include the entire supply chain of component production, including the transport phase and material preparation phase.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Zhansheng Liu contributed to the conception of the study. Zisheng Liu performed the experiment, performed the data analyses, and wrote the manuscript. Meng Liu contributed significantly to analysis and manuscript preparation. Jingjing Wang provided research guidance and research funding.

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