Journal of Civil Engineering and Management
ISSN 1392-3730 / eISSN 1822-3605
2022 Volume 28 Issue 3: 208–222
https://doi.org/10.3846/jcem.2022.16454

IMPROVED EIGHT-PROCESS MODEL OF PRECAST COMPONENT PRODUCTION SCHEDULING CONSIDERING RESOURCE CONSTRAINTS

Minhao RUAN, Feng XU*

School of Naval Architecture, Ocean and Civil Engineering, Shanghai Key Laboratory for Digital Maintenance of Buildings and Infrastructure, Shanghai Jiao Tong University, Shanghai, P. R. China

Received 29 June 2021; accepted 21 December 2021

Abstract. Reasonable production scheduling plays a vital role in the production of precast component factories. However, previous static scheduling models no longer fit actual production. In particular, some factors will cause errors in the actual delivery time of the components, including the lack or redundancy of processes in the model, resource constraints required by the core processes, and differences in transportation schemes. Moreover, the optimization goal of simply pursuing the minimization of fines from order delivery underestimates companies' emphases on reputation. Therefore, this study proposes an improved model for precast component production scheduling considering resource constraints. The number of production processes is adjusted to eight, and three resource constraints for mold, steel, and concrete are added. An enterprise decision-making coefficient is introduced into the optimization object function, and the constraints of the transportation scheme are improved. Finally, a real case study is conducted to verify the applicability of the model. Compared with previous models, the developed model fills the gap in considering production resource constraints and enterprise decisions in precast production, can better meet diverse production conditions and business needs of factories for scheduling, and help give full play to the advantages of prefabricated construction.

Keywords: production scheduling, precast concrete components, production resource constraints, enterprise decision-making, transportation scheme, genetic algorithm.

Introduction

A prefabricated building refers to a building constructed by transferring a large amount of the on-site work of traditional construction to a factory, transporting the building components processed in the factory to the construction site, and assembling them on site. As a representative of the sustainable development path of the construction industry, prefabricated buildings adopt integrated construction, which greatly saves human resources and building materials, speeds up construction progress, and meets the requirements for green buildings; thus, it has been vigorously promoted by many countries. However, the performance advantages of prefabrication technology are often restricted by the supply chain management of precast components. Generally speaking, the delayed or early delivery of prefabricated components is the main obstacle limiting the productivity of an entire project (Wang & Hu, 2017). In addition to the additional labor costs owing to the schedule adjustment, the potential risk of construction delays cannot be ignored if the components are delayed in delivery (Kazaz et al., 2012). Simultaneously, delayed delivery will also cause reputational damage to the precast component factory, and affect the company's subsequent operations. In contrast, if the components are delivered too early, valuable construction land will be occupied with on-site stacking. The construction company will need to hire additional storage personnel and bear the storage risk. From this point of view, a reasonable production scheduling plan plays a vital role in the production and operation of a precast component factory and in the prefabricated building, i.e., by giving full play to its advantages. At the same time, the production of precast components also involves a variety of production resources and diversified production scenarios. Therefore, it is necessary to conduct research on optimizing precast component production scheduling from the perspective of supply chain management (Wang et al., 2019).

*Corresponding author. E-mail: *F.Xu@sjtu.edu.cn*

In the past few decades, scholars have proposed a large number of theoretical models for the production scheduling of precast components, such as the traditional flow shop sequencing model (Chan & Hu, 2002), lasting time estimation model (Ko, 2011), multi-objective scheduling model for prefabricated component production (Ko & Wang, 2011), and flowshop scheduling model of multiple production lines for precast production (Yang et al., 2016). In general, according to the different production methods, the production of precast components can be divided into fixed-position production and flowshop production (Yang et al., 2016). The former is suitable for short-term, customized component production with low resource utilization. The latter is suitable for the long-term, batch production of components, and provides a larger production capacity. It is more suitable for the background of the development of prefabricated buildings, and has more practical application significance. Therefore, this study selects flowshop production as the study object. According to the number of assembly lines, a scheduling optimization problem can be divided into single assembly line workshop scheduling (Chan & Hu, 2002; Ko & Wang, 2011; Leu & Hwang, 2002) or multiple production line assembly scheduling (Yang et al., 2016). The above studies allocate the processing sequence and resources before component processing to achieve the expected optimization objective; they are considered as static scheduling approaches. Based on static scheduling research, some scholars have selected order demand changes, due date uncertainty or machine breakdown as interference factors, aiming to promote research progress in dynamic scheduling for precast component production (Ma et al., 2018; Wang & Hu, 2018; Kim et al., 2020; Wang et al., 2021). The static scheduling of a single production line is the basis of the optimization problem for precast component production scheduling. The process models used in previous studies can be mainly divided into two categories: a traditional six-process model, and an improved nine-process model considering the whole supply chain, as proposed by Wang and Hu (2017). The former ignores the pre-production and post-production steps throughout the entire supply chain, such as mold manufacturing, storing, and transportation. Although the latter approach has been improved regarding this point, problems remain. First, the improved nine-process model incorporates mold processing and manufacturing into the entire production process for each component, which is inconsistent with reality. Second, in the advancement of the core processes, insufficient supplies of some resources will lead to lags in the corresponding processes. For example, insufficient steel and concrete resources will affect the start time of steel bar binding and casting, respectively. Third, the optimization goal of simply pursuing the minimization of the total amount of fines for order delivery may violate the actual operating standards of some companies, leading to underestimations of the value of corporate reputation resources. Finally, depending on the different transportation schemes, the delivery times of precast components can vary greatly. Previous studies only considered three transportation scenarios: daytime transportation, nighttime transportation, and all-day transportation, and ignored transportation under overtime. Ignoring the above problems will lead to calculation errors in the production completion time and within the narrow application range of the model, affecting the science, accuracy, and practicability of the scheduling model. To eliminate these shortcomings, an improved eight-process model of precast component production scheduling considering resource constraints is proposed in this paper. Firstly, an eight-process model of precast component production is extracted from the entire supply chain of precast components. Secondly, new production resource constraints are added in the model, including those for molds, steel bars, and concrete, and important constraints that have been studied, such as process nature, worker working hours, and buffer space, are absorbed. In addition, the constraints of the transportation scheme are improved. Thirdly, an enterprise decision-making coefficient is innovatively introduced into the optimization objective. Finally, the genetic algorithm is utilized as the engine to select the optimal processing order of the precast components according to the optimization objective. This proposed model fills the gap in considering production resource constraints and enterprise decisions in precast production, which will enhance the accuracy of scheduling, enrich the application scenarios of production, and promote the development of prefabricated construction.

The remainder of this paper is organized as follows. Section 1 comprises a literature review. Section 2 proposes an improved eight-process model for precast component production scheduling, considering resource constraints. Section 3 comprises a demonstration of the model and discussion of the results. Final part presents the conclusions.

1. Literature review

The production of different precast components depends on different process models. In terms of concrete precast components, the traditional process model divides a complete assembly line into six processes, namely: mold assembly, placement of the embedded parts, casting, curing, mold removal, and surface treatment (Yang et al., 2016). However, the calculation of the completion time for the production of the precast components in the traditional process model only considers the processes directly related to production; however, the pre-production and post-production processes in the prefab supply chain will also affect the delivery time of the components. From the perspective of the entire supply chain, Wang and Hu (2017) proposed the nine-process model, supplementing the original model with the three additional processes of mold production, storage after production, and transportation. However, the improved nine-process model incorporates the manufacturing of the mold into the entire production process of each component; this is inconsistent with reality, and ignores the relationship between the resource constraints and core production line. Thus, the research results cannot be applied in actual production. Accordingly, this study proposes an eight-process production model for considering resource constraints based on factory surveys, which can better fit the conditions of actual production.

One precondition for optimizing the production scheduling of precast components is the selection of the optimization objectives. According to the different optimization objectives, research on the optimization of precast component production scheduling can be divided into three stages. The first stage of research on production scheduling optimization aimed at the shortest production completion time, such as in Leu and Hwang (2002); however, this is often not the only goal pursued by an enterprise. Ignoring the early delivery of precast components will cause many problems, such as increased on-site inventory and increased component damage rates. In the second stage, the optimization objective was revised to be on-time delivery, and the adverse effects of delayed and early deliveries were considered. Many scholars chose the minimization of the total fines for delays and early deliveries as the optimization objective (Chan & Hu, 2002; Ko & Wang, 2011; Wang & Hu, 2017; Jiang & Wu, 2021). However, simply pursuing the minimization of the total fines is not in line with corporate operating standards, and ignores the value of corporate reputation resources. The third stage of research concerns multi-objective optimization, and considers various issues such as providing on-time delivery, minimizing production costs, and maximizing resource utilization. Li et al. (2010) considered the multiple costs in a production process, including the molds, inventory, production space, labor, and materials, to pursue a minimization of the total production costs. Khalili and Chua (2014) focused on mold manufacturing, use, replacement, and conversion costs in the production process, and strove to minimize this part of the cost. Yang et al. (2016) aimed to minimize the workstation idle time and component type changes when considering multiple production line production scheduling. Ko (2010) developed a framework for precast fabricators to reduce the inventory. However, the optimization objectives from previous studies are often not adjustable, and cannot adapt to the flexible production needs of enterprises. To solve the above problems, this study introduces an enterprise decision-making coefficient into the optimization objective function; that is, the optimization objective function can be adjusted by changing the value of the coefficient, so that the precast component factory can make flexible decisions based on its own needs in terms of economic and reputation benefits.

The choice of constraints in the production scheduling model for precast components determines its applicability in actual production. Scholars have conducted continuous in-depth research based on the assumptions that a component of a traditional assembly line can only be processed on one machine at a certain time, and that a machine can only process one component at a certain time. Chan and Hu (2002) considered the limitation of workers' working hours and the parallel processing ability of a curing process. Ko and Wang (2011) considered the buffer size between production stations on the same basis. However, most of the above studies were based on a simple assumption of sufficient production resources in the production process, making these models impractical for the actual production of precast components. To solve this problem, scholars have further improved the model by considering constraints on production resources and production equipment. Leu and Hwang (2002) considered constraints on cranes and labor resources in a production process, and optimized a production scheduling plan to minimize the completion time for the components. Li et al. (2010) started from the perspective of minimizing production costs to optimize the production scheduling for prefabricated components, while considering the constraints on multiple resources, including production molds, labor numbers, inventory capacity, and production space. Yang et al. (2016) included multiple constraints in their model, such as those on the size of the curing room, number of molds, and number of pallets. Hu (2007) considered the influences of mold resources, and further analyzed the correspondences between mold types and prefabricated component types. Prata et al. (2015) optimized a production scheduling plan for precast beams and molds from the perspective of maximizing the utilization rate of the precast beam molds, and pursued maximum productivity under the premise of mold resource capacity constraints. Dan et al. (2021) established an optimization model for the production scheduling of precast components considering process connection and blocking. Wang and Hu (2017) added relevant constraints on the mold manufacturing, component storage, and transportation processes in the improved nine-process production scheduling model. However, in addition to mold resources, the other main resources involved in the production of precast components are steel and concrete, which were ignored. The component storage and transportation constraints in the previous models also have major defects. First, the end times of the storage and transportation processes are incorrectly defined; second, the default daily normal working time starts at 0 o'clock, which contradicts the actual situation. Finally, the proper boundary is not considered in the night transportation time period for large components. Therefore, this study absorbs important constraints that have already been studied, adds new resource constraints such as those concerning molds, rebars, and concrete, and improves component storage and transportation constraints, thereby making the model more applicable to actual production conditions.

2. Improved eight-process model of precast component production scheduling considering resource constraints

2.1. Eight-process model of precast component production

As mentioned in the literature review, early precast component production scheduling models divided the component production process into six steps: (1) mold assembly, (2) placement of embedded parts, (3) casting, (4) curing, (5) mold removal, and (6) surface treatment. The calculation of the completion time for the precast components only considers directly related production processes. From the perspective of the entire supply chain, Wang and Hu (2017) expanded the production process of precast components to nine major processes by implementing three additional procedures: mold manufacturing, component storage, and component transportation. However, according to actual factory survey results, not all of the molds of a precast component factory are manufactured in the factory. Customized molds are more common, and molds are reused during the mass production of the same type of components. The mold manufacturing production line and component production line are also often not the same assembly line. In such cases, a complete production chain for each component that considers the process of mold processing and manufacturing is evidently inappropriate. To solve this problem, based on combining survey results from precast component factories, a precast component production process from the perspective of the entire supply chain is shown in Figure 1. Part I comprises the production resource constraint part, and Part II comprises the prefabrication process. It can be seen from Figure 1 that the mold is regarded as a production resource. Mold manufacturing and mold transportation can be regarded as constraints on mold resources, and affect the start time of the mold cleaning process. In addition, it can also be seen from Figure 1 that the main resource constraints involved in the production of precast components concern steel and concrete, affecting the start times of the steel bar binding and casting, respectively. As also shown in Figure 1, the relevant steps of the steel bar resource constraints in-

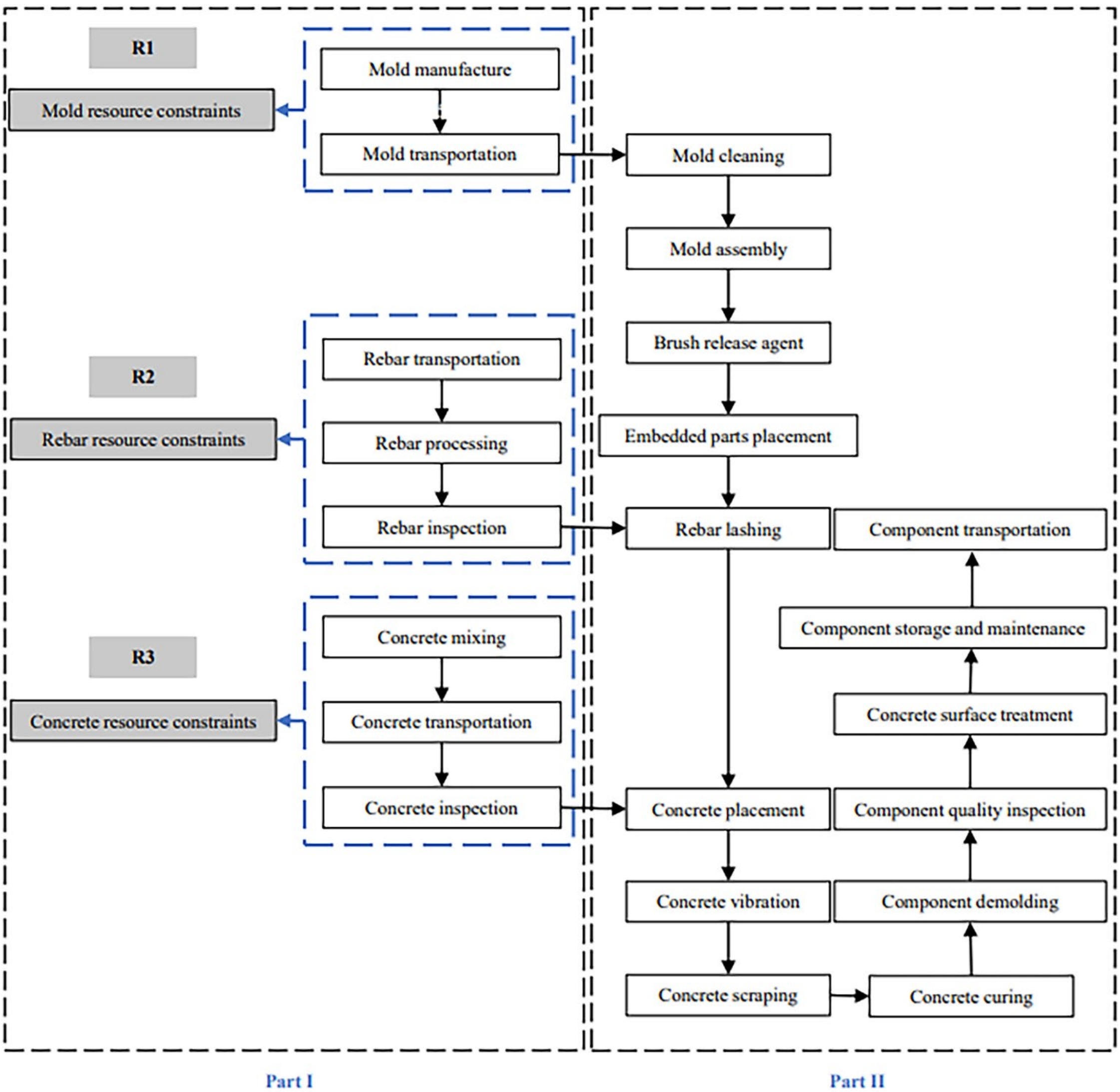

Figure 1. Precast component production process from the perspective of the entire supply chain

clude steel bar transportation, processing, and inspection, and the steps of the concrete constraints include concrete mixing, transportation, and inspection.

The processes with strong correlations and the same nature in Figure 1 (Part II) are integrated to form the precast component production eight-process model framework, as shown in Figure 2. As shown in Figure 2, the mold cleaning, mold assembly, and brushing release agent, which are all related to the mold, are integrated into the mold processing process. The embedded part setting and steel bar binding are similarly unified as the steel embedded part placement; the concrete placement, vibration, and scraping are integrated into the casting process; and the component quality inspection and component surface treatment are integrated into one process, i.e., the inspection and surface treatment. By integrating the resource constraints in Figure 1 (Part I) with the eight-process model framework for precast component production, an eight-process model for precast component production considering resource constraints from the perspective of the entire supply chain is obtained, as shown in Figure 2.

2.2. Buffer space constraints

Based on the model of buffer space constraints proposed by Ko and Wang (2011), this study combines the eight-process production model shown in Figure 2 with the actual precast component factory layout. By considering an independent curing room and sufficient storage warehouse space, there are only limited buffer zones between process one (mold processing) and process two (rebars and embedded parts placement), process two (rebars and embedded parts placement) and process three (casting), and process five (mold removal) and process six (quality inspection and surface treatment). Therefore, the completion time of component j on the k-th process can be re-expressed as follows:

$$C\left(J_j, N_k\right) = C\left(J_{j-1}, N_k\right) + WT_{j-1,k} + P_{j,k}, \quad k = 1; \qquad (1)$$

$$C\left(J_j, N_k\right) = \mathrm{Max}\left\{C\left(J_{j-1}, N_k\right) + WT_{j-1,k},\ C\left(J_j, N_{k-1}\right)\right\} + P_{j,k}, \quad k = 2,5, \qquad (2)$$

where $C(J_j, N_k)$ represents the production completion time

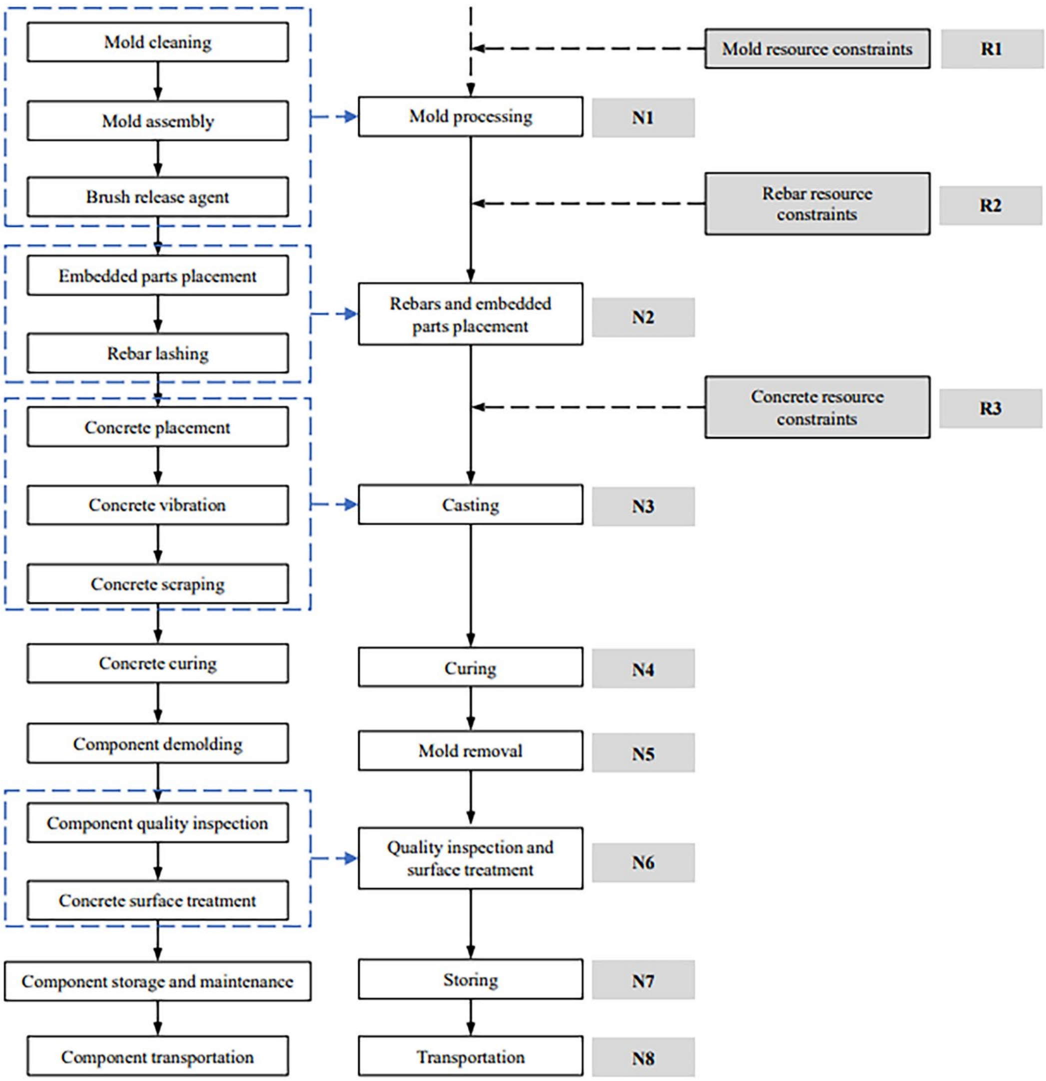

Figure 2. Precast component production eight-process model framework

of component j in the k-th process. $P_{j,k}$ represents the actual operation time of component j in the k-th process, and $WT_{j-1,k}$ represents the waiting time for component $j-1$ to be sent to the buffer in the k-th process. $WT_{j,k}$ can be calculated as follows:

$$WT_{j,k}=\begin{cases} C\left(J_{j-B_k},N_{k+1}\right)-P_{j-B_k,k+1}-C\left(J_j,N_k\right) \\ \qquad \text{if } C\left(J_j,N_k\right)\le C\left(J_{j-B_k},N_{k+1}\right)-P_{j-B_k,k+1} \\ 0 \\ \qquad \text{if } C\left(J_j,N_k\right)\ge C\left(J_{j-B_k},N_{k+1}\right)-P_{j-B_k,k+1} \end{cases}. \quad (3)$$

In the above, B_k is the number of precast components that can be stored in the buffer space between the k-th station and $k+1$-th station.

2.3. Mold resource constraints

The start time of the first process (mold processing) not only depends on the completion time of the mold processing of the previous component, but also relies on the time when the corresponding mold for the component is ready, as follows:

$$C\left(J_j,N_1\right)=\text{Max}\left\{C\left(J_{j-1},N_1\right)+WT_{j-1,1},\ C\left(J_j,R_1\right)\right\}+P_{j,1}, \quad (4)$$

where $C(J_j, R_1)$ represents the time when the mold of component j is ready. There may be ready-made molds in the factory. If not, they need to be made in the factory, or ordered from outside the factory. The time required for mold manufacturing and transportation must be considered.

If there are ready-made molds and the number of molds is sufficient, the molds are always ready, which can be:

$$C\left(J_j,R_1\right)=0. \quad (5)$$

If there is a certain quantity of molds but the quantity is insufficient, the next component using the certain kind of mold cannot start production until any one of the components currently using the certain kind of mold completes the sixth process, i.e., demolding. Yang et al. (2016) have given a detailed explanation for the above situation in their research.

If there is no ready-made mold, the mold must be manufactured or ordered. If the mold is ordered from outside the factory, the formula is as follows:

$$C\left(J_j,R_1\right)=C\left(J_j,M_b\right)+P_{t,m,j}, \quad (6)$$

where $C(J_j, M_b)$ is the time required to start ordering the mold for component j, and $P_{t,m,j}$ is the time required for the mold to be ordered and transported to the site.

If the mold is made in the factory, the formula is as follows:

$$C\left(J_j,R_1\right)=C\left(J_j,M_m\right)+P_{m,m,j}. \quad (7)$$

In the above, $C(J_j, M_m)$ is the time required to start making the mold for component j, and $P_{m,m,j}$ is the time required for the mold-making in the factory.

2.4. Rebar resource constraints

The start time of the placement of the rebars and embedded parts in the second process depends not only on the completion time for the first process of the component and the completion time of the previous component for the second process, but also on the premise of ensuring sufficient rebar resources, as follows:

$$C\left(J_j,N_2\right)=\text{Max}\left\{C\left(J_{j-1},N_2\right)+WT_{j-1,2},\ C\left(J_j,N_1\right),C\left(J_j,R_2\right)\right\}+P_{j,2}, \quad (8)$$

where $C(J_j, R_2)$ represents the completion time for the preparation of rebars required for component j; this may involve the time required for the transportation of rebars to the site, processing, and inspection. Rebar is a material that can be stored for a long time. Generally, more raw materials will be stocked when the price is low. Thus, priority is given to using stock rebar materials. When inventory resources are insufficient, rebars need to be purchased. The process of rebar processing and inspection does not affect the operations of the core production line for the precast components. Then the formula for the completion time is as follows:

$$C\left(J_j,R_2\right)=\begin{cases} C\left(J_j,S_s\right)+P_{m,s,j}, & j\le N_s \\ C\left(J_j,S_b\right)+P_{t,s,j}+P_{m,s,j}, & j>N_s \end{cases}, \quad (9)$$

where $C(J_j, S_s)$ is the time it takes to fetch the stock of rebar resources required for component j. $C(J_j, S_b)$ is the start time of ordering the rebar resources required for component j. $P_{m,s,j}$ is the processing and inspection time for the rebars required for component j. $P_{t,s,j}$ is the time taken by the rebars required for component j to be ordered and transported to the site. N_s is the number of components that can be produced by the factory stock rebar resources.

2.5. Concrete resource constraints

The start time of the third process (casting) not only depends on the completion time of the second process of the component and completion time of the previous component of the third process, but also on the premise of ensuring sufficient concrete resources. If the constraints of the concrete resources are considered, then the formula is as follows:

$$C\left(J_j,N_3\right)=\text{Max}\left\{C\left(J_{j-1},N_3\right),C\left(J_j,N_2\right),\ C\left(J_j,R_3\right)\right\}+P_{j,3}, \quad (10)$$

where $C(J_j, R_3)$ represents the preparation completion time of the concrete required for component j. Considering that concrete cannot be stored for a long time, it needs to be ordered in advance or prepared on site each time; the process of ordering, transportation, and on-site preparation does not affect the operation of the core production line of the precast components.

If ready-mixed commercial concrete is used, the calculation is as follows:

$$C\left(J_j,R_3\right)=C\left(J_j,C_b\right)+P_{t,c,j}, \tag{11}$$

where $C(J_j, C_b)$ is the time to start ordering the concrete required for component j, and $P_{t,c,j}$ is the time taken for the concrete to be ordered and transported to the site (including inspection).

If the concrete is prepared on site, the calculation is as follows:

$$C\left(J_j,R_3\right)=C\left(J_j,C_m\right)+P_{m,c,j}, \tag{12}$$

where $C(J_j, C_m)$ is the time required to start preparing the concrete for component j, and $P_{m,c,j}$ is the time required for the concrete on-site preparation (including inspection).

2.6. Constraints on worker working hours and process nature

This study absorbs the constraint model for the working hours of workers proposed by Chan and Hu (2002), and follows the classification of the natures of different processes by Wang and Hu (2017), as shown below.

In the eight-process model, the mold processing, placement of rebars and embedded parts, demolding, and quality inspection and surface treatment are all interruptible processes. The completion time of the process can be calculated as follows:

$$C\left(J_j,N_k\right)=\begin{cases}T_k & \text{if } T_k\le 24D+H_w\\ T_k+H_N & \text{if } T_k>24D+H_w\end{cases},$$
$$k = 1, 2, 5, 6, \tag{13}$$

where H_w is the normal working time of each working day. H_N is the non-working time of each working day. D is the number of complete working days. T_k is the cumulative completion time of the process, without considering the working time constraints. The calculation formulas are as follows:

$$D=\text{Integer}\left(T_k/24\right), \tag{14}$$

$$T_k=\text{Max}\left\{C\left(J_{j-1},N_k\right)+WT_{j-1,k},\ C\left(J_j,R_k\right)\right\}+P_{j,k},\quad k=1, \tag{15}$$

$$T_k=\text{Max}\left\{C\left(J_{j-1},N_k\right)+WT_{j-1,k},\ C\left(J_j,N_{k-1}\right),C\left(J_j,R_k\right)\right\}+P_{j,k},\quad k=2, \tag{16}$$

$$T_k=\text{Max}\left\{C\left(J_{j-1},N_k\right)+WT_{j-1,k},\ C\left(J_j,N_{k-1}\right)\right\}+P_{j,k},\quad k=5, \tag{17}$$

$$T_k=\text{Max}\left\{C\left(J_{j-1},N_k\right),\ C\left(J_j,N_{k-1}\right)\right\}+P_{j,k},\quad k=6. \tag{18}$$

Casting is an uninterruptible process. The calculation formula for the completion time of the casting process is as follows:

$$C\left(J_j,N_k\right)=\begin{cases}T_k & \text{if } T_k\le 24D+H_w+H_A\\ 24\left(D+1\right)+P_{j,k} & \text{if } T_k>24D+H_w+H_A\end{cases},$$
$$k=3, \tag{19}$$

$$T_k=\text{Max}\left\{C\left(J_{j-1},N_k\right),C\left(J_j,N_{k-1}\right),C\left(J_j,R_k\right)\right\}+P_{j,k},$$
$$k=3, \tag{20}$$

where H_A represents the allowable overtime during non-working hours, and $H_A < H_N$.

The curing process is a parallel process, and does not occupy any labor resources. Thus, the calculation formula for the completion time of the curing process is as follows:

$$T_k=C\left(J_j,N_{k-1}\right)+P_{j,k},\quad k=4, \tag{21}$$

$$C\left(J_j,N_k\right)=\begin{cases}T_k & \text{if } T_k\le 24D+H_w\\ 24\left(D+1\right) & \text{if } 24D+H_w<T_k\le 24\left(D+1\right)\end{cases},$$
$$k=4. \tag{22}$$

2.7. Improved storage and transportation process model

The completion time for the storage process depends on two factors. First, the strength of the precast components must meet the requirements for hoisting and transportation. Second, the storage process must cooperate with the transportation plan for the precast components. Previous studies considering storage and transportation processes have set up three different scenarios: daytime transportation, nighttime transportation, and all-day transportation (Wang & Hu, 2017). However, as the production process of precast components needs to consider the constraints of workers' working hours, the same is true for transportation, so daytime transportation also needs to be further classified according to workers' working hours. This study divides the transportation plans into four types, based on local traffic regulations and corporate transportation plans: transportation during normal working hours, transportation during overtime hours, night transportation of large components, and all-day transportation of urgent orders.

The storage process is also a parallel activity (multiple components can be stored simultaneously), and hardly occupies any labor resources. Therefore, the start time of the storage process depends only on the completion time of the previous process (quality inspection and surface treatment). That is, the cumulative completion time T_k of the storage process can be calculated as follows:

$$T_k=C\left(J_j,N_{k-1}\right)+P_{j,k},\quad k=7. \tag{23}$$

In the case of transportation during normal working hours, the transport driver will only load and depart during normal working hours. If the normal working hours of the worker are exceeded, the completion time of the storage process will need to be postponed to the work start time of the next working day. The calculation method for the completion time of the storage process is similar to that of the curing process, and can be represented as follows:

$$C\left(J_j, N_k\right) = \begin{cases} T_k & \text{if } T_k \le 24D + H_w \\ 24\left(D+1\right) & \text{if } 24D + H_w < T_k \le 24\left(D+1\right) \end{cases},$$
$$k = 7. \quad (24)$$

In the case where overtime is allowed for transportation, the transport driver can also load and depart within the allowed overtime. The calculation method for the completion time of the storage process can therefore be modified as follows:

$$C\left(J_j, N_k\right) = \begin{cases} T_k & \text{if } T_k \le 24D + H_w + H_A \\ 24\left(D+1\right) & \text{if } 24D + H_w + H_A < T_k \le 24\left(D+1\right) \end{cases},$$
$$k = 7. \quad (25)$$

In the case of urgent orders, the company allows loading and transportation at any time, so the completion time of the storage process is not limited by the working time. The storage completion time can be calculated as follows:

$$C\left(J_j, N_k\right) = T_k, \quad k = 7. \quad (26)$$

According to the provisions of the regional road traffic laws, if the height, volume, or weight of the precast components exceed certain limits, they can only be transported after 22 o'clock in the evening, i.e., to avoid affecting traffic. In this case, the night transportation of large components should be considered. The previous models that considered night transportation had major flaws. Wang and Hu (2017) defined the end time of the storage process based only on the storage time related to the lifting strength of the component, and then determined the start time of the transportation process according to different transportation schemes. This approach led to a gap between the end of the storage process and beginning of the transportation process. The start time of the transportation process should depend entirely on the end time of the storage process. It is more reasonable to model the storage process according to the transportation plan. In addition, the transportation process formula proposed by Wang and Hu (2017) implied that the daily normal working hours began at 0 o'clock, which contradicts the actual situation. To modify the model, this study introduces the parameter T_s for considering the start time of the factory's daily work; T_s is the length of time between the start of daily work and 0 o'clock. Furthermore, previous studies only focused on the left boundary of the restricted transportation time period, that is, 22 o'clock in the evening, and ignored the right boundary. In actual production, to reduce the costs of on-duty labor and wages and comprehensively address the legal restrictions on the transportation time period and actual required transportation time, factories often limit the allowable loading and transportation time for night transportation to a certain period of time. To improve the model, this study introduces the parameter H_L to consider this time period. H_L is the time period allowed for loading and transportation from 22 o'clock. That is, for night transportation, if the component storage process ends within this time period, there is no need to wait, the storage process ends, and the transportation starts (Scenario B in Figure 3). If the end time of the component storage process is outside this time period, the process must wait until the next 22 o'clock to perform the loading and transportation operations (Scenarios A and C in Figure 3). Therefore, the end time of the storage process can be expressed as follows:

$$C\left(J_j, N_k\right) =$$
$$\begin{cases} 24 * D + 22 - T_s & \text{if } Mod\left[T_k, 24\right] < 22 - T_s \\ T_k & \text{if } 22 - T_s \le Mod\left[T_k, 24\right] < 22 - T_s + H_L \\ 24 * \left(D+1\right) + 22 - T_s & \text{if } Mod\left[T_k, 24\right] \ge 22 - T_s + H_L \end{cases},$$
$$k = 7. \quad (27)$$

In actual production, as long as the transportation start time meets the limits of the four transportation plans, the transportation process can begin, and whether the completion time of the transportation process is within the working hours will not be used as a judgment condition for whether to start the transportation process. To simplify the model, it can be assumed that under the premise of sufficient transportation capacity, regardless of the transportation plan adopted, the transportation process can start immediately after the storage process ends. The end time of the transportation process is calculated as follows:

$$C\left(J_j, N_k\right) = C\left(J_j, N_{k-1}\right) + P_{j,k}, \quad k = 8. \quad (28)$$

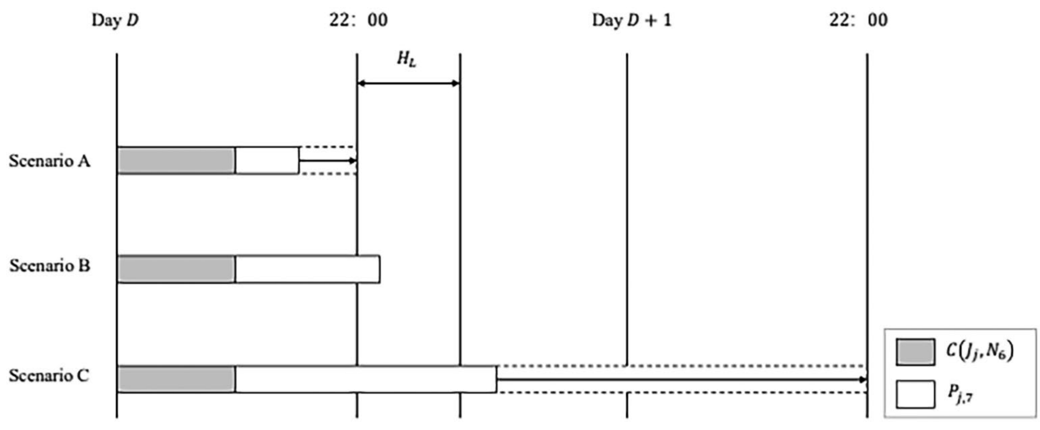

Figure 3. Scenarios

2.8. Adjustable optimization objective

As introduced in the literature review, in actual production, the increase in profits brought by minimizing the total fines for delayed and early delivery is not the only dimension of concern for the production and operation of a precast component factory. To remain competitive, companies should avoid delays in delivery for the sake of their industry reputation. Therefore, the optimization objective function is modified as shown in Eqn (29), which allows the precast component factory to make flexible decisions based on its own needs in regards to economic and reputation benefits, as follows:

$$\text{Min} \rightleftarrows f(\mu) = \text{Min} \rightleftarrows \sum_{j=1}^{n} \Big[\alpha_j \text{Max}\big(0, C_j - d_j\big) + \gamma \beta_j \text{Max}\big(0, d_j - C_j\big) \Big], \quad \forall \mu \in \pi; \tag{29}$$

$$C_j = C\big(J_j, N_8\big), \tag{30}$$

where π represents the set of all feasible component production sequences, and μ is any feasible solution. C_j is the total production completion time for component j, and d_j is the required delivery time for component j. α_j and β_j are the unit penalty fees for delayed and early delivery, respectively, which are objective and will not be changed by human will.

γ is the decision-making coefficient of the enterprise, and can be selected from 0 and 1, which reflects the subjective thoughts of the decision maker. When γ is 1, it means that the company pays more attention to economic benefits, and maximizes profits by minimizing the total penalties for late and early delivery. When γ is set to 0, it means that the company pays more attention to reputation, and ensures that there are as few delays as possible to deliver orders.

3. Empirical analysis

3.1. Data collection

Yangzhou Huasheng Engineering Construction Co., Ltd. is a factory with a mature industrial chain for the production of precast concrete components. Based on field research and interviews with production scheduling managers and engineers, a batch of order information including the types of precast components, operating time for each process of each component, due dates of components, and unit earliness and tardiness penalties is obtained as input data for the production scheduling model, as shown in Table 1.

The factory's normal working hours (H_w), non-working hours (H_N), and allowable overtime hours (H_A) are 10 hours, 14 hours, and 4 hours, respectively. As the cost of overtime work during non-working hours is doubled, overtime is only considered for non-interruptible processes. Under this order, the molds of component No. 1 and component No. 9 must be customized outside the factory, and will be delivered in 8 hours. The mold of component No. 10 must be made in the factory, and the manufacturing time is 4 hours. The remaining components have sufficient ready-made molds. The number of components that can be produced by the factory stock rebar resources is 1. The steel bars are ordered in two batches. The first batch will be delivered in 4 hours, enough to make four components; the second batch will be delivered in 24 hours, enough to make five components. The processing and inspection of the rebars required for each component takes 0.5 hours. The factory uses ready-mixed commercial concrete, and the transportation time is 0.5 hours. The buffer size (B_k) between the three sets of processes corresponding to the factory assembly line is 1 ($B_1 = B_2 = B_5 = 1$). The above data are obtained through field research.

Take a random set of component processing sequence 10-9-8-7-6-5-4-3-2-1 and transportation during normal working hours as an example, assuming that H_w. First, calculate the completion time of the first process of the first processed component, that is, the component No. 10, that is, $C(J_1, N_1)$. The above data show that the mold preparation completion time of component No. 10 is 4 hours, that is, $C(J_1, R_1) = 4$. Component No. 10 is the first component processed, so $C(J_0, N_1) = 0$ and $WT_{0.1} = 0$. The time required for mold processing of component No. 10 is 0.9 hours, that is, $P_{1.1} = 0.9$. $T_1 = 4.9$ can be calculated from Eqn (15), and then $D = 0$ can be calculated from Eqn (14). Summarizing the above data, $C(J_1, N_1) = 4.9$ can be ob-

Table 1. Input data of the production scheduling model

Components	Production time of each process (h)								Due dates (h)	Earliness and Tardiness penalties (¥/unit×h)	
Type number	N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8		Tardiness (α_j)	Earliness (β_j)
1	1.8	2.4	1.4	12	1	0.6	10	1.5	73	10	2
2	1.6	2.5	1.2	12	0.9	0.8	10	1.4	73	10	2
3	1.5	2.2	1	12	0.8	0.6	10	1	73	10	2
4	1.2	1.4	1.2	12	0.3	0.5	10	1.8	73	10	2
5	1.5	1.2	1.5	12	0.6	0.5	10	2.2	74	10	2
6	0.8	2.6	0.8	12	0.8	0.8	10	2	74	10	2
7	1.8	2.5	1.2	12	1	0.5	10	0.5	73	10	2
8	1.4	2.3	1.1	12	1	0.6	10	0.8	72	10	2
9	2.2	2.4	2	12	1.2	0.5	10	1.6	74	10	2
10	0.9	1	1.5	12	0.5	0.3	10	2.5	73	10	2

tained from Eqn (13). Similarly, T_2 to T_7 corresponding to component No. 10 can be calculated by Eqn (16), Eqn (20), Eqn (21), Eqn (17), Eqn (18), and Eqn (23), respectively, and then $C(J_1, N_2)$ to $C(J_1, N_7)$ can be calculated by Eqn (13), Eqn (19), Eqn (22), Eqn (13), Eqn (13), and Eqn (26), respectively. Finally, $C(J_1, N_8)$ is calculated by Eqn (28). In this way, the completion time of each process of component No. 10 can be obtained. Repeating the same calculation operation for the remaining components can obtain the completion time of each process of all components, and further obtain the value of C_1 to C_{10} from Eqn (30). Finally, the data is substituted into Eqn (29) to calculate the objective function value under the corresponding processing sequence.

This study develops algorithms based on the genetic algorithm processes in genetic algorithm-based decision support systems for precast production planning, as proposed by Ko and Wang (2010). The algorithm flow is shown in Figure 4. Parameters of genetic algorithm are adjusted based on the previous research findings. The population size and generation gap are determined in accordance with Grefenstette's (1986) recommendations, which are 10 to 160 and 0.3 to 1, respectively. The crossover probability and mutation probability are selected from (0.75, 0.95) and (0.005, 0.02), respectively (Schaffer et al., 1989). These are summarized as follows:

– Population size: 100;
– Number of iterations: 300;
– Probability of crossover: 0.8;
– Probability of mutation: 0.02; and
– Generation gap: 0.9.

The Microsoft Windows 10 system and Matlab R2019b are used for genetic algorithm solving. The execution time in the following cases is within 1 min.

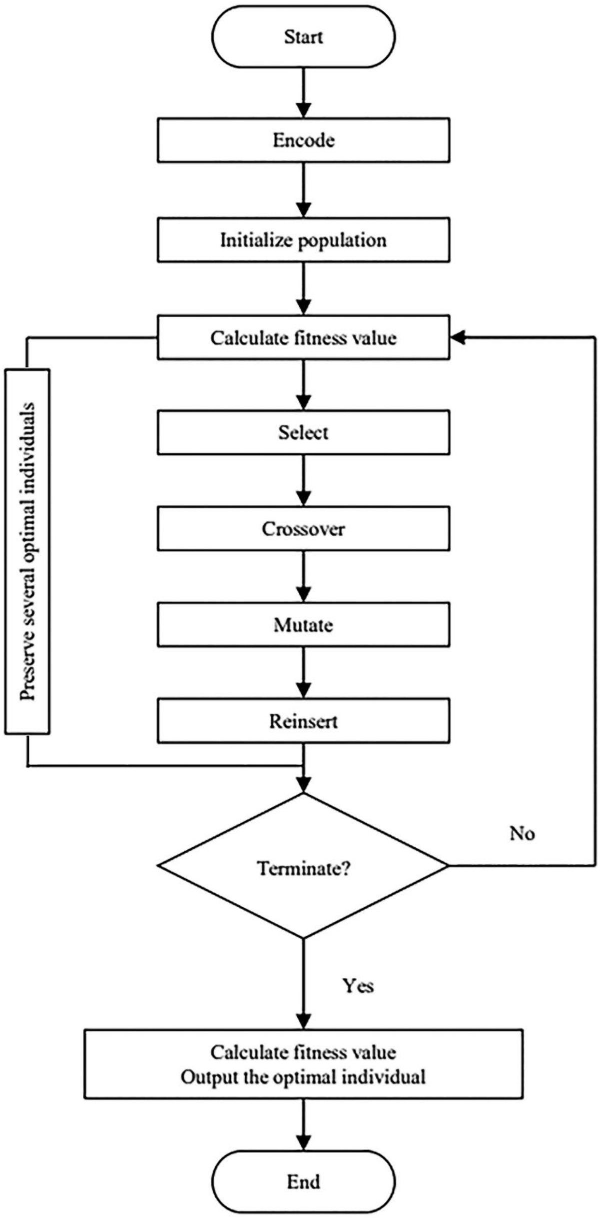

Figure 4. Flowchart of the algorithm

3.2. Results and discussions

To verify the accuracy of the calculation of the completion time of component production, three models are compared: the above data are input into the traditional six-process production scheduling model, the improved nine-process model considering the entire supply chain, and the improved eight-process model considering the resource constraints developed in this study, respectively. Taking transportation during normal working hours as an example, the shortest production completion time and corresponding processing sequence are respectively calculated; then, production is performed according to the processing sequence obtained from the model. The actual production completion time is recorded, and the error between the model output and actual time consumption is calculated. The results are shown in Table 2.

It can be seen from Table 2 that owing to the lack of processes in the traditional six-process production scheduling model, the calculated production completion time is 53.5 hours, which is far from the actual production completion time of 102.6 hours; the error is close to 50%. The improved nine-process model considering the entire supply chain ignores resource constraints. The output production completion time is 74.2 hours, and the error from the actual production completion time of 102.6 hours is also large, i.e., close to 30%. The production completion time obtained from the improved eight-process model considering resource constraints is 96.5 hours, which is less than a 5% error from the actual result of 101.5 hours. The error may come from fluctuations in the operating time of workers in each process. Smaller error is owing to the fit of the model to the actual production process, and reflects the science and accuracy of the production scheduling model.

To verify the applicability of the model in various transportation scenarios, this study takes an enterprise decision-making coefficient of 1 as an example and compares the differences in the optimization results of the four transportation schemes. Among them, in the scenario of

Table 2. Comparison of output results of three models

Models	Component processing sequence	Estimated completion time (h)	Actual completion time (h)	Error
Traditional six-process production scheduling model	8-5-1-10-4-6-3-2-7-9	53.5	102.6	47.9%
Nine-process model considering the whole supply chain	8-1-10-4-5-6-3-9-2-7	74.2	102.6	27.7%
Improved eight-process model considering resource constraints	8-4-10-2-6-3-1-9-5-7	96.5	101.5	4.9%

the night transportation of large components, according to factory regulations, the factory's normal work start time is 8 a.m. ($T_s = 8$), and the allowed loading time at night (H_L) is 4 hours. After 300 iterations, the optimization results under the four transportation scenarios are shown in Table 3 (Scenario 1: transportation during normal working hours; Scenario 2: transportation during overtime hours; Scenario 3: all-day transportation of urgent orders; Scenario 4: night transportation of large components). Taking scenario 1 as an example, the optimal scheduling plan is component No.2-No.8-No.10-No.3-No.5-No.9-No.4-No.1-No.6-No.7, the total production completion time is 96.5 hours, and the total penalty is 389.4 yuan. The start time of each process for each component is shown in Table 4. To further intuitively reflect the component production process, the start and end times of each process for each component are represented in the form of a Gantt chart, as shown in Figure 5. It can be seen that for a single component, different processes do not overlap. In terms of processes, curing, storing, and transportation are parallel processes, so there may be overlaps, whereas the other processes can only process one component at a time; thus, there is no overlap. These results are consistent with actual production. The applicability of the model in different transportation scenarios reflects the practicality of the production scheduling model under complex actual production conditions.

Table 3. Optimization results under four transportation scenarios ($\gamma = 1$)

Scenarios	Component processing sequence	Completion time (h)	Total penalty (¥)
Scenario 1	2-8-10-3-5-9-4-1-6-7	96.5	389.4
Scenario 2	6-8-4-2-10-1-9-3-5-7	84	388.4
Scenario 3	6-5-3-8-10-9-1-2-4-7	84	437.8
Scenario 4	6-5-3-8-10-9-1-2-4-7	86.5	443

To ensure the effectiveness of the model for large-scale production cases, this study adds a production case of 36 components of 10 types to further verify the model. Taking transportation during normal working hours and the enterprise decision-making coefficient as 1 as an example, the results are shown in Table 5. The Gantt chart for the optimal scheduling plan is shown in Figure 6.

To further verify the applicability of the model under different enterprise decision-making coefficients, this study takes transportation during normal working hours as an example and compares the influences of the different enterprise decision-making coefficients on the optimization results. The results are shown in Table 6. It can be seen from the table that when the enterprise decision-making coefficient is 1 (the enterprise pays more attention to economic benefits), the total penalty is the smallest, at 2407.2 yuan. When the enterprise decision-making coefficient is set to 0 (the enterprise attaches more importance to reputation resources), the total delay in delivery is the smallest, at 175.3 hours. The results verify the effectiveness of the model for adjusting a scheduling optimization objective by changing the enterprise decision-making coefficient, and reflects the practicality of the production scheduling model under complex actual production requirements.

To further demonstrate the applicability of the model

Table 4. Start time of each process for the optimal scheduling plan ($\gamma = 1$)

Scenarios	Component type number	Start time of each process (h)							
		N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8
Scenario 1	2	0	1.6	4.1	5.3	24	24.9	25.7	48
	8	1.6	4.5	6.8	7.9	24.9	25.9	26.5	48
	10	4	6.8	7.9	9.4	25.9	26.5	26.8	48
	3	4.9	7.8	24	25	48	48.8	49.4	72
	5	6.8	24	25.2	26.7	48.8	49.4	49.9	72
	9	8.3	25.2	27.6	29.6	49.4	50.6	51.1	72
	4	24	27.6	29.6	30.8	50.6	51.1	51.6	72
	1	25.2	29	31.4	32.8	50.9	51.9	52.5	72
	6	27.6	31.4	34	34.8	51.9	52.7	53.5	72
	7	29	34	50.5	51.7	72	73	73.5	96

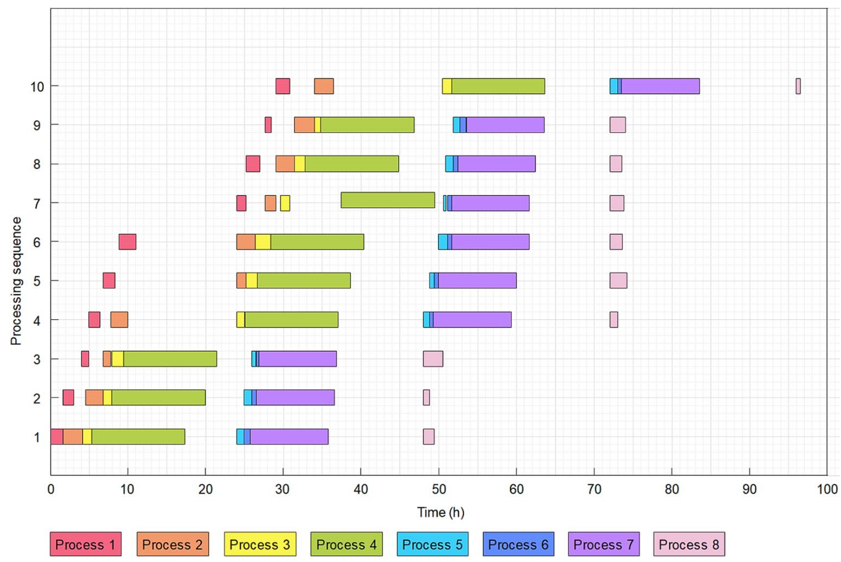

Figure 5. Gantt chart

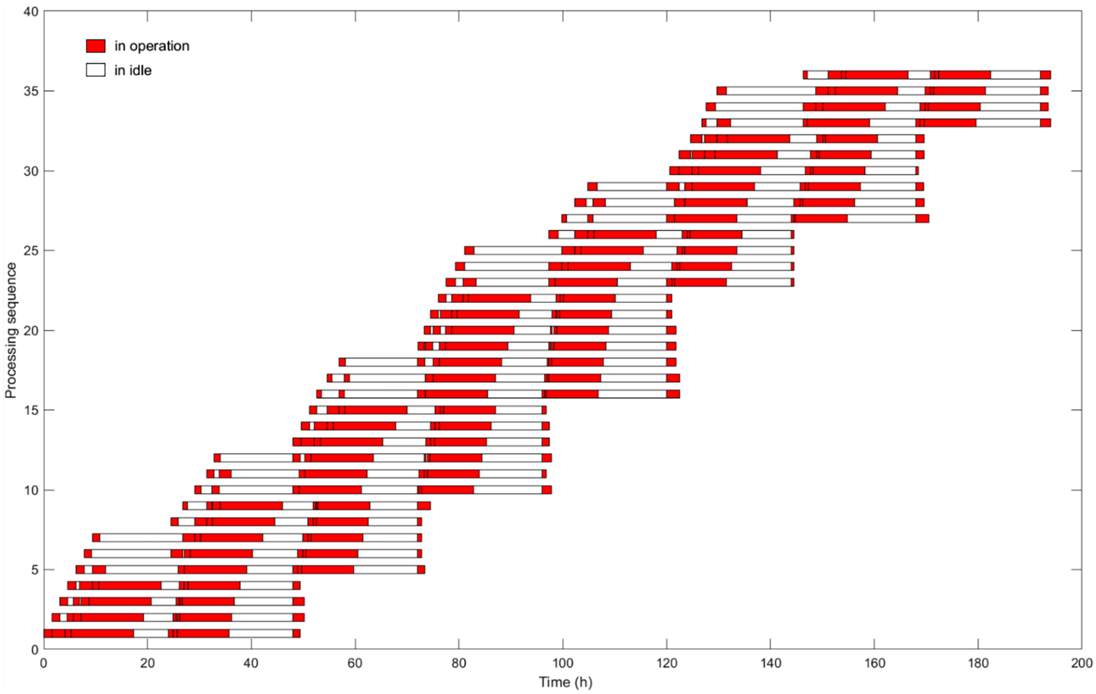

Figure 6. Gantt chart for the optimal scheduling plan

Table 5. Optimization results of the 36-component case in transportation scenario 1 (γ = 1)

Component type	Quantity	Due dates (h)	Completion time (h)	Total penalty (¥)
1	3	170	194	2407.2
2	5	80		
3	2	120		
4	5	120		
5	2	60		
6	2	200		
7	5	150		
8	5	80		
9	3	170		
10	4	150		

Note: The component type label has the same meaning as the 10-component case, and the production time of each process of each component is shown in Table 1.

Table 6. Optimization results under different enterprise decision-making coefficients

Enterprise decision-making coefficient	Component processing sequence	Completion time (h)	Total delivery delay (h)	Total penalty (¥)
1	5-8-17-16-6-27-29-25-34-14-4-26-28-7-11-10-9-13-12-20-15-33-36-23-31-35-32-30-24-22-21-1-3-19-2-18	194	178.3	2407.2
0	4-12-17-5-8-25-28-16-6-33-26-29-14-13-7-15-35-22-9-10-27-36-11-23-34-21-24-31-1-30-20-32-3-2-18-19	194	175.3	2563.2

Table 7. Input data and optimization results of the 8-component case

Basic production information										
Working hours						Buffer size				
$H_w = 9$	$H_N = 15$		$H_A = 3$			$B_1 = 2$		$B_2 = 1$	$B_5 = 1$	
Order information										
Components	Production time of each process (h)							Due dates (h)	Earliness and Tardiness penalties (¥/unit×h)	
Type number	N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8		Tardiness (α_j)	Earliness (β_j)
1	2	3	1.5	10	0.5	0.8	10	4	72	12	2
2	2.5	2.5	1.4	10	1	1	10	2.5	72	12	2
3	2	2.5	1.5	10	1	1	10	3	72	12	2
4	1.5	2	0.8	10	0.5	0.8	10	2	72	12	2
5	2.5	3	0.8	10	0.5	0.8	10	2.5	72	12	2
6	1.5	2	1.2	10	0.8	1	10	2.5	72	12	2
7	2	1.5	1	10	0.8	1	10	3	72	12	2
8	2	2	2	10	1	1.5	10	2	72	12	2
Optimization results											
Optimal component processing sequence	Completion time (h)			Total delivery delay (h)				Total penalty (¥)			
2-1-3-7-4-8-6-5	98.5			39				551			

Table 8. Input data and optimization results of the 12-component case

Basic production information											
Working hours						Buffer size					
$H_w = 11$	$H_N = 13$		$H_A = 3$			$B_1 = 2$		$B_2 = 2$	$B_5 = 2$		
Order information											
Components	Production time of each process (h)								Due dates (h)	Earliness and Tardiness penalties (¥/unit×h)	
Type number	N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8		Tardiness (α_j)	Earliness (β_j)
1	1.5	2.5	1	10	0.8	0.6	8	1.5	72	8	1
2	2	2.2	1.2	10	1.2	1	8	1	72	8	1
3	1.5	2.2	1.4	10	0.6	0.8	8	1.4	72	8	1
4	1.6	2	1	10	0.5	0.4	8	2.4	72	8	1
5	1.5	2.5	1.4	10	1.2	0.6	8	1.8	72	8	1
6	2	1.8	1.4	10	0.5	1	8	1.6	72	8	1
7	1.5	1.5	1	10	0.5	1	8	1.2	72	8	1
8	2.4	2.5	1	10	0.6	0.8	8	2.2	72	8	1
9	1.5	2.5	1.2	10	0.5	0.8	8	1.2	72	8	1
10	1.8	2.4	1.5	10	0.5	0.6	8	1.6	72	8	1
11	2	2.6	1.6	10	1.2	0.8	8	2	72	8	1
12	1.6	2.2	1.2	10	0.8	0.6	8	1	72	8	1
Optimization results											
Optimal component processing sequence	Completion time (h)			Total delivery delay (h)				Total penalty (¥)			
11-6-1-8-5-4-3-7-2-10-9-12	83.5			36.9				411.1			

in the production of different precast component factories, two other precast component factories are visited, and two sets of production case information (order A and order B) are collected. Under order A, the mold of component No. 4 must be customized outside the factory and will be delivered in 6 h. The mold of component No. 3 must be made in the factory, and the manufacturing time is 5 h. The remaining components have sufficient ready-made molds. The number of components that can be produced by the factory stock rebar resources is 3. The remaining required steel bars will be delivered in 24 hours. The processing and inspection of the rebars required for each component takes 1 hour. The factory uses ready-mixed commercial concrete, and the transportation time is 1 hour. The other input data and final optimization results of the 8-component case (transportation during normal workings hours, $\gamma = 1$) are shown in Table 7.

Under order B, the mold of component No. 5 must be customized outside the factory and will be delivered in 5 h. The molds of component No. 1 and component No. 8 must be made in the factory, and the manufacturing time is 4 h. The remaining components have sufficient ready-made molds. The number of components that can be produced by the factory stock rebar resources is 2. The remaining required steel bars will be delivered in 4 hours. The processing and inspection of the rebars required for each component takes 0.5 hour. The factory uses ready-mixed commercial concrete, and the transportation time is 1 hour. The other input data and final optimization results of the 12-component case (transportation during normal workings hours, $\gamma = 1$) are shown in Table 8.

Conclusions

This study adjusts the number of precast component production processes to eight. Based on the perspective of the entire supply chain, the redundant mold manufacturing process is removed and the constraints of three major resources of mold, steel, and concrete are added in the core production process. This makes the model more in line with the actual production process, and the calculated production completion time is more accurate. Starting from the actual operating needs of the precast component factory, an enterprise decision-making coefficient is innovatively introduced into the optimization objective, so that the precast component factory can flexibly balance the economic benefits and reputation benefits by adjusting the coefficient. As an integration and improvement of previous research, important constraints that have been studied are absorbed, such as the classification of processes, worker working hours, and buffer zones, and new resource constraints are supplemented, including those for molds, steel bars, and concrete. The constraints of the transportation scheme are also modified, making the model more applicable to actual production.

Based on actual case data, this study verifies the accuracy of the model in calculating the completion times of component production. The error between the model output and actual production time is only 4.9%. Compared with the traditional six-process model and nine-process model considering the whole supply chain, the accuracy increases by 43% and 22.8%, respectively. In addition, the differences in the optimization results under four transportation schemes and influences of the different enterprise decision-making coefficients on the optimization results are compared, verifying the practicability of the production scheduling model under complex actual production conditions and demands.

To summarize, this paper contributes to the body of knowledge from the perspective of both the research methodology and empirical evidence. The model proposed in this study belongs to the category of single-line static scheduling, and can be used as a basis for research on multi-line production scheduling and dynamic scheduling in future research. However, the enterprise decision studied in this paper is essentially a trade-off between total penalties and delivery delays. In face of actual production, companies may also consider various factors such as workers' salaries and equipment utilization. In addition, to further verify the advantages of the model, especially when a large number of resource constraints are involved, more cases are needed.

Acknowledgements

The authors express their sincere gratitude to Yangzhou Huazhong Engineering Construction Co., Ltd. for assistance in observation and conducting on-site interviews. They also appreciate the project engineers for valuable information and useful data.

Author contributions

Ruan Minhao and Xu Feng conceived the study and were responsible for factory investigation and data collection. Ruan Minhao established the model, performed the case analysis and wrote the first draft of the article. Xu Feng revised the first draft.

Disclosure statement

The authors do not have any competing financial, professional, or personal interests from other parties.

References

Chan, W. T., & Hu, H. (2002). Production scheduling for precast plants using a flow shop sequencing model. *Journal of Computing in Civil Engineering*, *16*(3), 165–174. https://doi.org/10.1061/(ASCE)0887-3801(2002)16:3(165)

Dan, Y. R., Liu, G. W., & Fu, Y. (2021). Optimized flowshop scheduling for precast production considering process connection and blocking. *Automation in Construction*, *125*, 103575. https://doi.org/10.1016/j.autcon.2021.103575

Grefenstette, J. J. (1986). Optimization of control parameters for genetic algorithms. *IEEE Transactions on Systems*, *Man*, *and Cybernetics*, *16*(1), 122–128. https://doi.org/10.1109/TSMC.1986.289288

Hu, H. (2007). A study of resource planning for precast production. *Architectural Science Review*, *50*(2), 106–114. https://doi.org/10.3763/asre.2007.5016

Jiang, W., & Wu, L. J. (2021). Flow shop optimization of hybrid make-to-order and make-to-stock in precast concrete component production. *Journal of Cleaner Production*, *297*, 126708. https://doi.org/10.1016/j.jclepro.2021.126708

Kazaz, A., Ulubeyli, S., & Tuncbilekli, N. A. (2012). Causes of delays in construction in Turkey. *Journal of Civil Engineering and Management*, *18*(3), 426–435. https://doi.org/10.3846/13923730.2012.698913

Khalili, A., & Chua, D. K. (2014). Integrated prefabrication configuration and component grouping for resource optimization of precast production. *Journal of Construction Engineering and Management*, *140*(2), 4186–4191. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000798

Kim, T., Kim, Y. W., & Cho, H. (2020). Dynamic production scheduling model under due date uncertainty in precast concrete construction. *Journal of Cleaner Production*, *257*, 120527. https://doi.org/10.1016/j.jclepro.2020.120527

Ko, C. H. (2010). An integrated framework for reducing precast fabrication inventory. *Journal of Civil Engineering and Management*, *16*(3), 418–427. https://doi.org/10.3846/jcem.2010.48

Ko, C. H. (2011). Production control in precast fabrication: considering demand variability in production schedules. *Canadian Journal of Civil Engineering*, *38*(2), 191–199. https://doi.org/10.1139/L10-123

Ko, C. H., & Wang, S. F. (2010). GA-based decision support systems for precast production planning. *Automation in Construction*, *19*(7), 907–916. https://doi.org/10.1016/j.autcon.2010.06.004

Ko, C. H., & Wang, S. F. (2011). Precast production scheduling using multi-objective genetic algorithms. *Expert Systems with Applications*, *38*(7), 8293–8302. https://doi.org/10.1016/j.eswa.2011.01.013

Leu, S. S., & Hwang, S. T. (2002). GA-based resource-constrained flowshop scheduling model for mixed precast production. *Automation in Construction*, *11*(4), 439–452. https://doi.org/10.1016/S0926-5805(01)00083-8

Li, S. H. A., Tserng, H. P., Yin, S. Y. L., & Hsu, C. W. (2010). A production modeling with genetic algorithms for a stationary pre-cast supply chain. *Expert Systems with Applications*, *37*(12), 8406–8416. https://doi.org/10.1016/j.eswa.2010.05.040

Ma, Z. L., Yang, Z. T., Liu, S. L., & Wu, S. (2018). Optimized rescheduling of multiple production lines for flowshop production of reinforced precast concrete components. *Automation in Construction*, *95*, 86–97. https://doi.org/10.1016/j.autcon.2018.08.002

Prata, B. D. A., Pitombeira-Neto, A. R., & Juca, D. M. S. C. (2015). An integer linear programming model for the multiperiod production planning of precast concrete beams. *Journal of Construction Engineering and Management*, *141*(10), 04015029.1–04015029.4. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000991

Schaffer, J. D., Caruana, R. A., Eshelman, L. J., & Das, R. (1989). A study of control parameters affecting online performance of genetic algorithms for function optimization. In *Proceedings of the Third International Conference on Genetic algorithms* (pp. 51–60). Morgan Kaufmann Publishers Inc., San Francisco, CA, USA.

Wang, Z. J., & Hu, H. (2017). Improved precast production scheduling model considering the whole supply chain. *Journal of Computing in Civil Engineering*, *31*(4), 04017013.1–04017013.12. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000667

Wang, Z. J., & Hu, H. (2018). Dynamic response to demand variability for precast production rescheduling with multiple lines. *International Journal of Production Research*, *56*(16), 5386–5401. https://doi.org/10.1080/09585192.2018.1511611

Wang, Z. J., Hu, H., Gong, J., Ma, X. P., & Xiong, W. Y. (2019). Precast supply chain management in off-site construction: A critical literature review. *Journal of Cleaner Production*, *232*, 1204–1217. https://doi.org/10.1016/j.jclepro.2019.05.229

Wang, Z. J., Liu, Y. S., Hu, H., & Dai, L. (2021). Hybrid rescheduling optimization model under disruptions in precast production considering real-world environment. *Journal of Construction Engineering and Management*, *147*(4), 04021012. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001976

Yang, Z. T., Ma, Z. L., & Wu, S. (2016). Optimized flowshop scheduling of multiple production lines for precast production. *Automation in Construction*, *72*, 321–329. https://doi.org/10.1016/j.autcon.2016.08.021