Optimized Rescheduling of Multiple Production Lines for Flowshop Production of Reinforced Precast Concrete Components

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Abstract

Flowshop production is adopted as the major type of production of reinforced precast concrete components and it has higher requirements on shop floor schedules than other types, especially that from rescheduling. However, up to now, very few approach for the optimization of the shop floor rescheduling has been proposed in spite of its vital importance. This research proposes an approach for optimizing shop floor rescheduling of multiple production lines for flowshop production of reinforced precast concrete components. The approach comprehensively utilizes the over-assigned time, which is the difference value between the assigned production time and the estimated one of a production step for a precast component to deal with production emergencies. Meanwhile, it keeps the adjustment of schedules at minimum to avoid massive material re-dispatch. First of all, the optimization objectives and constraints of optimized shop floor rescheduling of multiple production lines for flowshop precast production are analyzed and a mathematic model is thus formulated. Then, the solver of the model is established by using genetic algorithm. Finally, the approach is validated by case studies. It is concluded that the approach contributes to the effective and efficient optimized rescheduling of multiple production lines for flowshop precast production.

Keywords: precast production; optimization; flowshop; reschedule; genetic algorithm

1 Introduction

The adoption of reinforced precast concrete components (precast components for short hereafter) enables the application of advanced industrial production and management approaches in construction and thus enhances the construction quality and efficiency. In general, scheduling is crucial for the production of precast components (precast production for short hereafter), which consists of master production scheduling, material requirement planning and shop floor scheduling. Among them, shop floor scheduling is the most detailed and difficult one, in which production tasks are assigned to specific workshop sections, teams or even operators (Yang et al., 2016). Moreover, flowshop production is adopted as the major type of precast production and it has higher requirements on shop floor schedules than other types, because its production steps are closely linked to each other.

Since shop floor schedules should be coordinated with the assembly ones of construction sites, precast production is sensitive to production emergencies that may result in delay in precast production process, such as resource shortage, machinery breakdown, rush orders, etc. Over-assigned time for each precast step is always included in the planned shop floor schedules for production emergencies. Namely, during scheduling, the required production time of each production steps is assigned slightly more than the estimated one in case of production delay (General Administration of Quality Supervision, Inspection and Quarantine of P.R.C., 2009).

The current operation procedure for the production emergency is shown as Figure 1 (General Administration of Quality Supervision, Inspection and Quarantine of P.R.C., 2009, Sheng et al., 2008, Yao, 2014). First, the emergency information is collected by site supervisors. Then, the operators and site supervisors try to eliminate its negative influence by using the over-assigned time of the corresponding workstation and slightly adjusting the production schedule of the workstation. Third, if the order requirements can be fulfilled just by doing so, the procedure ends and precast components are produced according to the new schedule. Otherwise, such counterplans as outsourcing orders, activating backup production lines, extending working hours, adding workers and reducing production requirements (Sheng et al., 2008, Yao, 2014), will be adopted by schedulers. Fifth, rescheduling is conducted based on the heuristic rules such as the right shift, left shift, opportunistic insertion, deterministic insertion and overall adjustment (Chan et al., 2003) and then go back to the third step.

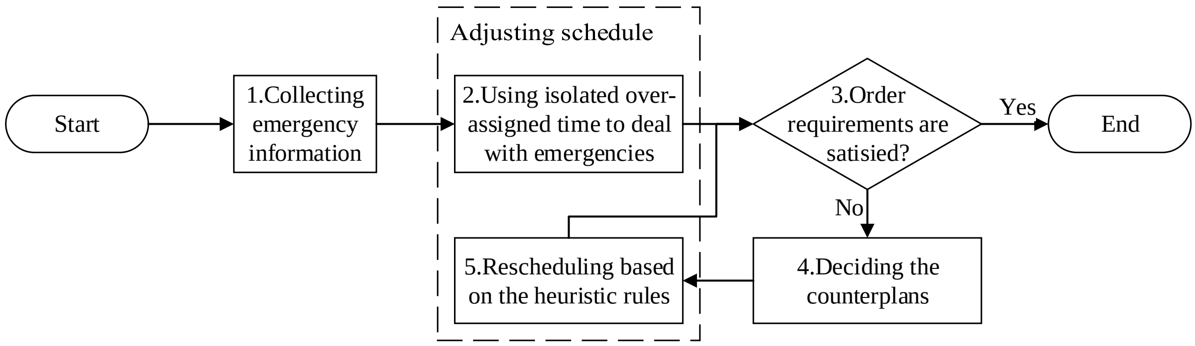
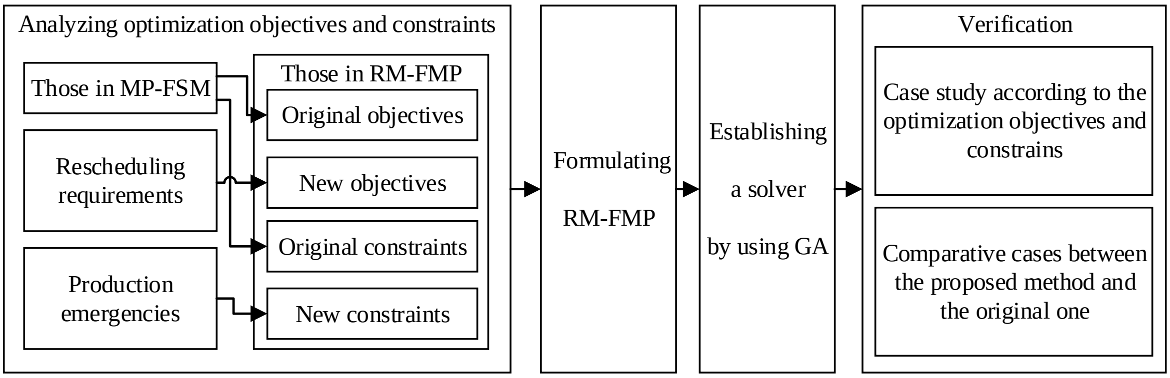


Figure 1. Current operation procedure for production emergencies

However, the procedure cannot satisfy the current production requirements in the following two aspects. For one thing, because the over-assigned time among all the production steps in the plant is not fully utilized, schedulers rely on counterplans to deal with production emergencies, which lead to rise in production cost or failure in fulfillment of order requirements. For another, the heuristic rule based rescheduling approach do not guarantee optimal schedules theoretically and is significantly influenced by the experience of schedulers so that it may result in waste of production capacity, increase of inventory demand and consequential rise of cost (Chan et al., 2003).

This research proposes an approach for the optimized shop floor rescheduling (the optimized rescheduling hereafter for short) of multiple production lines for flowshop precast production. The approach can not only take into account the traditional ways for schedule adjustment, such as outsourcing orders, activating backup production lines and/or extending working hours, but also make use of the over-assigned time of each production step as a whole to deal with serious production emergencies.

The flow chart of the main part of the paper is shown in Figure 2. First, the optimization objectives and constraints of the shop floor rescheduling of multiple production lines for flowshop precast production are analyzed based on the MP-FSM (Flowshop Scheduling Model of Multiple production lines for Precast production) that the authors proposed previously. Second, the corresponding mathematic model, i.e., optimized Rescheduling Model of Multiple production lines for Flowshop Precast production (RM-MFP), are formulated accordingly. Third, a solver for the model is established by using Genetic Algorithm (GA for short hereafter). Finally, the way to apply the approach is introduced and the approach is validated by case studies. For better understanding, all the symbols of the paper are listed as an appendix of the paper with their units.



Notes. MP-FSM is the abbreviation for Flowshop Scheduling Model of Multiple production lines for Precast production. RM-FMP is the abbreviation for optimized Rescheduling Model of Multiple production lines for Flowshop Precast production

Figure 2. Flow chart of the paper

2 Relevant studies

The existing relevant studies of this research can be divided into two aspects, i.e., scheduling and rescheduling of precast production. It is obvious that rescheduling is essentially the scheduling with additional constraints.

As far as scheduling is concerned, Chan et al. (2002) introduced an artificial intelligence based flowshop scheduling approach utilized in manufacturing industry and formulated the FlowShop Sequencing Model (FSSM) for precast production by analyzing the characteristics of precast production. Benjaoran et al. (2005) studied the impact of the quantity of moulds on shop floor schedules of precast production and proposed the FlowShop Scheduling Model for Bespoke Precast production (BP-FSSM). Ko et al. (2010) improved the feasibility of the schedules using artificial intelligence by including the constraint of the buffer size, namely size of the temporary storage place, between workstations for the partially finished precast components waiting for completion (work-in-processes for short hereafter) storing into the optimization model and developed a corresponding scheduling system. Yang et al. (2016) proposed the Flowshop Scheduling Model of Multiple production lines for Precast production (MP-FSM) to facilitate optimized scheduling of precast production with multiple production lines.

As far as rescheduling is concerned, Chan and Zeng proposed schedule adjustment approach of precast production based on the heuristic rules and Genetic Algorithm (GA for short here after) (Chan et al., 2003, Zeng, 2007). Although the existing research development can be applied to improve shop floor rescheduling of multiple production lines for flowshop precast production, the optimization of the schedules still cannot be guaranteed.

3 Analyzing optimized rescheduling

During rescheduling, the over-assigned time utilization as well as counterplans, if they are applicable, contributes to deal with production emergencies. According to literature (Sheng et al., 2008, Yao, 2014), common counterplans include outsourcing orders, activating backup production lines, extending working hours, adding workers and reducing production requirements. However, counterplans application should be decided by schedulers before rescheduling, because they lead to extra cost or is contract-related so that normally it needs to be approved by multiple managerial departments. Moreover, by using the proposed approach to empower the software to optimally reschedule the precast production with the over-assigned time used as a whole, the step two and step five in the current operation procedure, as shown in Figure 1, can be combined so that a new procedure is formulated as shown in Figure 3.

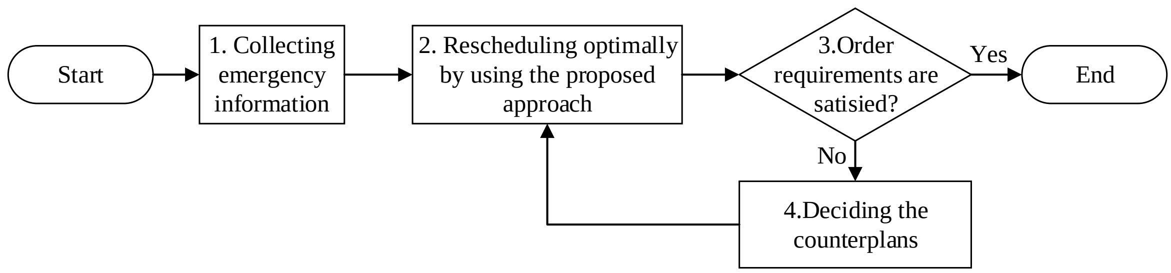


Figure 3. New operation procedure for production emergencies

After collecting the emergency information, schedulers adjust the schedule optimally by using the proposed approach in which the over-assigned time of multiple production steps in multiple precast components is utilized as a whole to deal with production emergencies. If it fails, one can decide applying such counterplans as outsourcing orders, activating backup production lines and/or extending working hours. Then the counterplans are input along with the production condition, production organization, emergency information and original schedule into the software and conducting rescheduling by using the proposed approach again.

According to the new procedure, the step two, namely “rescheduling optimally by using the proposed approach” is crucial and is where the proposed approach mainly activated. Since it is an optimization process essentially, its problem definition, optimization objectives and constraints are introduced in the following.

3.1 Problem definition

The optimized rescheduling of multiple production lines for flowshop precast production is defined as follows. The plant is equipped with a number of moulds of various types, production pallets and production lines with fixed production routing. In each production line, precast components go through five production steps, namely moulding, placing rebars and embedded parts, casting, curing and demoulding. Each production step is handled in a particular workstation by a particular team. Among the workstations, the curing workstation, i.e. the curing room, in a production line is capable of handling a number of precast components simultaneously. Precast components of multiple types are produced according to the original shop floor schedule (original schedule hereafter for short) and the shift work system that specifies the working hours of a day and the way the work team shifts before rescheduling is carried out when production emergencies occur.

3.2 Optimization objectives

As rescheduling is essentially the scheduling with additional constraints, some of its optimization objectives can be inherited from those of scheduling. The optimization objectives of rescheduling were thus established, as shown in Table 1, where item 1 to item 4 are from scheduling (Yang et al, 2016), and the rest are obtained by analyzing the requirements that are specific to rescheduling. The latter is explained in detail in the following.

Table 1 Optimization objectives

Item number	Optimization objective	Remark
1	Minimization of Workstation Idle time (WI)	—
2	Minimization of Contract penalty and Storage cost (CS)	—
3	Minimization of MakeSpan (MS)	—
4	Minimization of Type Change of precast components (TC)	—
5	Minimization of Material Re-dispatch complexity and workload (MR)	New
6	Using the minimum amount of Over-assigned time for production emergencies (UO)	New

Note. Type changes of precast components is an index to quantize the frequency of the changes in production operation of a workstation.

3.2.1 Minimization of material re-dispatch complexity and workload

During flowshop precast production, materials such as rebar cages and embedded parts are pre-dispatched to the production lines and different type of precast components are assigned different set of materials. It is obvious that during re-dispatch, the complexity and workload of material re-dispatch should be minimized.

3.2.2 Using the minimum amount of over-assigned time for production emergencies

In practice, schedulers need to assign the required time for each production step of each precast component by around 20% more than the estimated time in case of delay of the production step (General administration of quality supervision, inspection and quarantine of P.R.C., 2009). Although the effect for using the over-assigned time of a single production step in a single component is limited, it is possible to deal with even serious production emergencies by utilizing the over-assigned time of multiple production steps in multiple precast components as a whole. In order to deal with the further uncertainty in production, schedulers should ensure that the amount of over-assigned time used for production emergencies is minimized. Besides, since the curing steps are executed in automatic curing rooms with high reliability, their corresponding over-assigned time is not considered. Moreover, the rest of the production steps should share all the over-assigned time equally during scheduling for better coordination.

3.3 Optimization constraints

Table 2 shows the optimization constraints of rescheduling established in this study. A number of optimization constraints of rescheduling are inherited from those of scheduling (Yang et al., 2016), i.e. from item 2 to item 6 in Table 2. The remaining items in the table are established by analyzing the changes of production conditions resulting from production emergencies (Sheng et al., 2008, Yao, 2014) including production step delay, resource shortage, machinery problem, machinery breakdown, order change and quality problem. For instance, since resource purchase is after scheduling, the amount of resource is not a constraint for scheduling. However, when the production emergency of resource shortage occurs, production of all the precast components that use the resource of this kind pauses and it becomes the domain constraint.

Table 2 Optimization constraints

Number	Content	Remark
1	Constraint of workstation productivity	Revised
2	Constraint of the size of curing rooms	—
3	Constraint of the eight-hour day working	—
4	Constraint of the buffer size between workstations	—

5	Constraint of the quantity of moulds	—
6	Constraint of the quantity of production pallets	—
7	Constraint of the amount of resources	New

The details of the new or revised optimization constraints are explained in the following.

3.3.1 Constraint of workstation productivity

During rescheduling, not only the constraint of workstation productivity that resulted from normal production but also that resulted from production emergencies should be considered. The former aspect of the constraint is the same as that of the MP-FSM (Yang et al., 2016). The latter aspect of the constraint depends upon the reasons for the change of production condition. For example, a production step delay could lead to the increase in production time of a production step of a precast component, while a machinery problem could result in the increase in production time of a production step of multiple precast components.

3.3.2 Constraint of the amount of resources

Resources such as concrete are essential for flowshop precast production. During rescheduling, it is necessary to ensure that the resource supply is always more than the resource consumption.

4 Formulating RM-MFP

Based on the analysis in Section 3, the RM-MFP is formulated by mathematically modeling the aforementioned optimization objectives and constraints. In order to make the model easy to understand, the known quantities and variables are described in advance in the following.

4.1 Known quantities, independent variables, dependent variables and their notations

4.1.1 Known quantities

For the optimized rescheduling of flowshop precast production, the known quantities are divided into five parts.

(1) Parameters of plant condition

The total quantity of production lines is denoted as L. The maximum quantity of precast components that can be handled in the curing room of production line l is denoted as Y_l. The total quantity of moulds of type \$ in the flowshop is denoted as $Q_\$$. The total quantity of production pallets in the flowshop is denoted as P. The serial number of the workstation for production step k $(k \leq 5)$ in the production line l is denoted as $M_{l,k}$.

(2) Parameters of production organization

The working hours, non-working hours and overtime hours allowed during the working day are denoted as H_W, H_N and H_E respectively.

(3) Parameters of order

The total quantity of precast components is denoted as n. Some other parameters such as the total quantity of precast components of each type in the original orders are also known.

(4) Parameters of original schedule

The earliest beginning time for the first production step of the first precast component to be produced the production line l is denoted as $S(J_{l,1}, M_{l,1})$. The total quantity of precast components of type \$ be produced in the production line l during period (t_0, t_0+T_p) according to the original schedule is denoted as $Sum_{l,\$}^{O}(t_0, t_0 + T_p)$.

(5) Parameters of production emergency

The estimated duration delay is denoted as h_a. The duration of machinery breakdown is denoted as (t_{bs}, t_{be}). Some other parameters such as the total quantity of precast components of each type in the rush orders are also known.

4.1.2 Independent variables

The RM-MFP inherits the independent variables from the MP-FSM for the allocation plan of the precast components to the production lines and their priorities of resource utilization (Yang et al., 2016). In addition, the objective of using the minimum amount of over-assigned time for production emergencies brings new independent variables, i.e., the duration for using the over-assigned time and the proportion of the used over-assigned time to the assigned production time. These 4 variables determine the new schedule for precast production and are called production arrangement in this paper.

The representation of the variables is as follows. The allocation plan of the precast components to the production lines is represented by production line number AL_c ($AL_c \in N^+$, N^+ stands for all positive integers), where the precast component c is produced. The priorities of resource utilization of precast components is represented by j ($j \in N^+$). The precast components with higher priorities can get resources earlier than the others. The duration for using the over-assigned time is represented by T_r. Thus, given that t_0 is the initial time for using the over-assigned time, the over-assigned time is used during the period [t_0, t_0+ T_r]. The proportion of the used over-assigned time to the assigned production time, which equals the estimated production time plus the over-assigned time, is represented by φ.

4.1.3 Dependent variables

The other dependent variables can be inferred from the known quantities and variables.

As the allocation plan of the precast components to the production lines and their priorities of resource utilization is represented by the variables, the serial number of the precast component produced in production line l at the sequence i can be determined and represented by $J_{l,i}$.

The total quantity of precast components produced in the production line l (l ≤L) can be determined and represented by n_l and $n = \sum_{l=1}^{L} n_l$.

As the contract penalty is given in the order or contracts and the storage cost of each precast component should also be known, the contract penalty and storage cost of the precast component produced in production line l at the sequence i can be determined and represented by $\tau_{l,i}$ and $\varepsilon_{l,i}$ respectively.

Similarly, the due time of the precast component produced in production line l at the sequence i can be determined and represented by $d_{l,i}$.

The production time of the step k of the precast component produced in production line l at the sequence i can be determined and represented by $P_{l,i,k}$.

4.2 Optimization objectives

Since all the optimization objectives in Table 1 should be applied in the RM-MFP, the method of weighting and normalizing is used to combine all the optimization objectives as Equation (1).

$$\text{Min } f = w_{WI} * \left(\frac{f_{WI}}{f_{WI}^*}\right) + w_{CS} * \left(\frac{f_{CS}}{f_{CS}^*}\right) + w_{MS} * \left(\frac{f_{MS}}{f_{MS}^*}\right) + w_{TC} * \left(\frac{f_{TC}}{f_{TC}^*}\right) + w_{MR} * \left(\frac{f_{MR}}{f_{MR}^*}\right) + w_{UO} * \left(\frac{f_{UO}}{f_{UO}^*}\right) \quad (1)$$

In the equation, f is the unfitness value of the evaluated schedule. w_{WI}, w_{CS}, w_{MS}, w_{TC}, w_{MR} and w_{UO} are the weights of the optimization objectives WI, CS, MS, TC, MR and UO, respectively, and the sum of them is 1. f_{WI}, f_{CS}, f_{MS}, f_{TC}, f_{MR} and f_{UO} are the values of the optimization objectives respectively. f_{WI}^*, f_{CS}^*, f_{MS}^*, f_{TC}^*, f_{MR}^* and f_{UO}^* are the values of each optimization objective, respectively, under the condition that the shop floor rescheduling problem is optimized by only using the corresponding optimization objective. The unfitness value grows with the value of each optimization objective linearly, so that the change of each optimization objective can be directly reflected as the change of the unfitness value, which makes the equation suitable as the multi-objective function for precast scheduling or rescheduling problems. Such a technique has been applied in similar researches such as that of Benjaoran (2005).

It is necessary to noted that the weights of the optimization objectives, namely w_{WI}, w_{CS}, w_{MS}, w_{TC}, w_{MR} and w_{UO} should be decided by the user according to his perception on relative importance of the optimization objectives. An investigation and determination method of weights in decision making problems with multiple objectives has been proposed by Zhen (1987), in which the preference of schedulers and the interaction effect between all the objectives have been concerned. Many other mature studies about impact analysis has also been concluded by Porter (1980).

The values of the optimization objectives from 1 to 4 in Table 1 inheriting from the MP-FSM are formulated as Equation (2) to Equation (5).

$$f_{WI} = \sum_{l=1}^{L}\sum_{k=1}^{5}\left[C\left(J_{l,n_l}, M_{l,k}\right) - S\left(J_{l,1}, M_{l,k}\right) - \sum_{i=1}^{n_l} P_{l,i,k}\right] \tag{2}$$

$$f_{CS} = \sum_{l=1}^{L}\left\{\sum_{i=1}^{n_l} \tau_{l,i} * \mathrm{Max}\left[0, C\left(J_{l,i}, M_{l,5}\right) - d_{l,i}\right] + \sum_{i=1}^{n_l} \varepsilon_{l,i} * \mathrm{Max}\left[0, d_{l,i} - C\left(J_{l,i}, M_{l,5}\right)\right]\right\} \tag{3}$$

$$f_{MS} = \mathrm{Max}_{\forall l \in N^+ | l \le L} C\left(J_{l,n_l}, M_{l,5}\right) \tag{4}$$

$$f_{TC} = \sum_{s=1}^{S}\left\{\sqrt{\sum_{l=1}^{L} {TQ_{l,s}}^2 / L_s} + \sqrt{\sum_{l=1}^{L} {CQ_{l,s}}^2 / L_s}\right\} \tag{5}$$

In the equations, $S\left(J_{l,i}, M_{l,k}\right)$, $P_{l,i,k}$ and $C\left(J_{l,i}, M_{l,k}\right)$ are the entering time, duration and leaving time of the precast component $J_{l,i}$ in the workstation $M_{l,k}$ respectively. $\mathrm{Max}_{\forall l \in N^+ | l \le L} f(l)$ is the maximum of $f(l)$, where l is a positive integer and $l \le L$. $TQ_{l,s}$ is the total quantity of the types of the precast components in the shift s of the production line l. $CQ_{l,s}$ is the total quantity of the type changes of precast components during production in the shift s of the production line l. S is the total quantity of shifts. L_s is the quantity of production lines actually participating in the production in the shift s.

The equations for the new optimization objectives are introduced in the follows.

4.2.1 Equation of minimization of material re-dispatch complexity and workload

As mentioned in Section 3.1.1, to achieve the optimization objective, the complexity and workload of material re-dispatch should be minimized. The more production lines are involved in rescheduling, the easier the operators make mistakes during production. The complexity of that can be measured by f_{MR1}, namely, the quantity of production lines whose schedules are changed by rescheduling. Because exchanging two precast components of the same type between different production lines does not result in material re-dispatch, the workload of material re-dispatch can be measured by $f_{MR2,}$ namely, the sum of absolute change of component quantity of each type in each production lines by rescheduling. For example, the original production sequence of 2 production lines is components of type A, A, A and B, B, B, respectively, while the new production sequence of them is components of type A, B, A and B, A, B, respectively, so both f_{MR1} and f_{MR2} are equal to 2.

The difference between the quantity of production lines whose schedules are changed by rescheduling and the sum of absolute change of component quantity of each type in each production lines by rescheduling is huge, so it is further divided into two sub-objectives accordingly, as shown in Equations (6) and (7). Then they are combined as Equation (8) by using the normalization method.

$$f_{MR1} = L_r \tag{6}$$

$$f_{MR2} = \sum_{l=1}^{L}\left[\sum_{\$=\$_1}^{\$_{MN}} \left|Sum_{l.\$}(t_0, t_0 + T_p) - Sum_{l.\$}^{O}(t_0, t_0 + T_p)\right|\right], \$ \in (\$_1, \ldots \$_{MN}) \tag{7}$$

$$f_{MR} = \frac{f_{MR1}}{f^*_{MR_1}} + \frac{f_{MR2}}{f^*_{MR_2}} \tag{8}$$

In the equations, L_r is the quantity of production lines whose schedules are changed by rescheduling. \$ represents a type of the precast component, while $\$_1$ and $\$_{MN}$ represents the first and the last type of precast component, respectively. T_p is the duration from the initial time of rescheduling. $Sum_{l,\$}(t_0, t_0 + T_p)$ is the quantity of precast components of type \$ in the production line l from time t_0 to $t_0 + T_p$ according to the new schedule, while $Sum^O_{l,\$}(t_0, t_0 + T_p)$ is that according to the original schedule. $f^*_{MR_1}$ and $f^*_{MR_2}$ are the values of each sub-objective, respectively, under the condition that the shop floor rescheduling problem is optimized by only using the corresponding sub-objective.

4.2.2 Equation of using the minimum amount of over-assigned time for production emergencies

During the period (t_0, t_0+T_r), the used over-assigned time for production emergencies in production line l can be measured by f_{uo}, namely the time difference of finishing a certain amount of job before and after using the over-assigned time. The average efficiency increases by $1/(1-\varphi)$ times and the time for finishing a certain amount of job decreases by $\varphi * T_r$ times in a single production line. Hence, the value of the optimization objective can be formulated as equation (9). For the example shown in Figure 4, the over-assigned time of the workstations in 1 production line is utilized from 12:00 to 14:00 in a day, with the proportion φ being 6.8%, so the f_{UO} is 0.136.

$$f_{UO} = \varphi * T_r * L_r \tag{9}$$

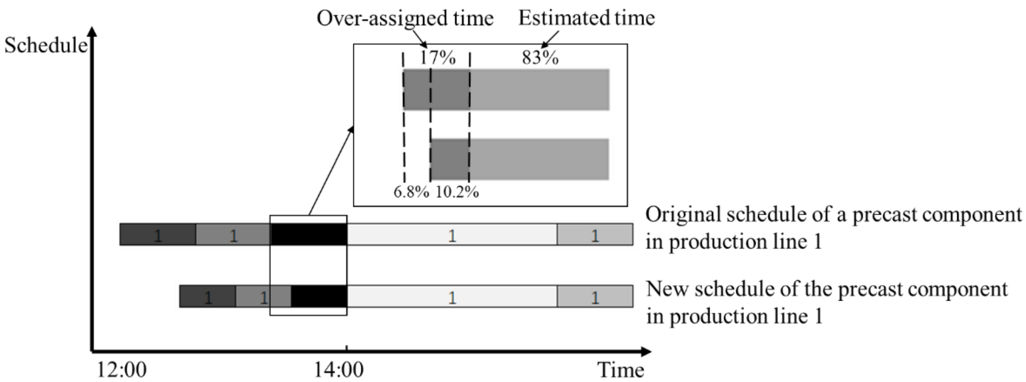


Figure 4. Optimization objective of using the minimum amount of over-assigned time for production emergencies

4.3 Optimization Constraints

All the optimization constraints in Table 2 are adopted in the RM-MFP. Constraint of workstation productivity, that of the size of curing rooms, that of the eight-hour day working, that of the buffer size between workstations, that of the quantity of moulds, that of the quantity of production pallets, that of the amount of resources inherit from the MP-FSM and are formulated as Equation (10) to Equation (16), respectively.

$$S\left(J_{l,i}, M_{l,4}\right) \geq \mathrm{Max}^{Y_l^{th}}_{\forall y \in N^+ | y<i} C\left(J_{l,y}, M_{l,4}\right) \tag{10}$$

$$C\left(J_{l,i}, M_{l,3}\right) \geq \begin{cases} T, & \text{if } T \leq 24D + H_W + H_E \\ 24(D+1) + P_{l,i,k}, & \text{if } T > 24D + H_W + H_E \end{cases} \tag{11}$$

$$C\left(J_{l,i}, M_{l,4}\right) \geq \begin{cases} T, & \text{if } T < 24D + H_W \\ 24(D+1), & \text{if } 24D + H_W \leq T \leq 24(D+1) \\ T, & \text{if } T > 24(D+1) \end{cases} \tag{12}$$

$$C\left(J_{l,i}, M_{l,k}\right) \geq \begin{cases} T, & \text{if } T < 24D + H_W \text{ and } k = 1,2,5,6 \\ T + H_N, & \text{if } T \geq 24D + H_W \text{ and } k = 1,2,5,6 \end{cases} \tag{13}$$

$$C\left(J_{l,i}, M_{l,k}\right) \geq S\left(J_{l,(i-B_{l,k})}, M_{l,(k+1)}\right) \tag{14}$$

$$S\left(J_{l,i}^{j,\$}, M_{l,1}\right) \geq \mathrm{Min}\left\{\mathrm{Max}^{Q_\$}_{\forall l' \in N^+ | l' \leq L, \forall y \in N^+ | y \leq N, \forall x \in N^+ | x<j} \left[C\left(J_{l',y}^{x,\$}, M_{l,6}\right)\right]\right\} \tag{15}$$

$$S\left(J_{l,i}^{j}, M_{l,1}\right) \geq \mathrm{Min}\left\{\mathrm{Max}^{P}_{\forall l' \in N^+ | l' \leq L, \forall y \in N^+ | y \leq N, \forall x \in N^+ | x<j} \left[C\left(J_{l',y}^{x}, M_{l,6}\right)\right]\right\} \tag{16}$$

In the equations, $\mathrm{Max}^{Y_l^{th}}_{\forall y \in N^+ | y<i} f(y)$ represents the Y_lth maximum value of $f(y)$, where Y_l is the maximum quantity of precast components that can be handled in the curing room of production line l, and y is a positive integer and $y \leq i$. $\mathrm{Max}^{Q_\$}_{\forall y \in N^+ | y<i} f(y)$ stands for the first $Q_\$$ maximum values of f(y), where y is a positive integer and $y \leq i$. For example, given that $f(y) = y^2$, $i = 3$, its value is the set {4, 9} if $Q_\$ = 2$, while its value is the set {0, 1, 4, 9} if $Q_\$ = 4$. T is the $C\left(J_{l,i}, M_{l,k}\right)$ calculated without considering the constraint of eight-hour day working. D=integer(T/24) is the total quantity of days passed from the start of the production to the $C\left(J_{l,i}, M_{l,k}\right)$. $B_{l,k}$ is the maximum quantity of precast components that can be stacked between workstation $M_{l,k}$ and $M_{l,k+1}$. $J_{l,i}^{j,\$}$ is the serial number of the precast component of type \$ produced in production line l at the sequence i, whose priority is j (The bigger j is, the higher the priority is). $J_{l,i}^{j}$ is the serial number of the precast component produced in production line l at the sequence i, whose priority is j.

The equations for the new optimization constraints are introduced as follows.

4.3.1 Equation of constraint of workstation productivity

As mentioned in Section 3.3.1, the constraint is divided into two aspects, the constraint of workstation productivity under normal production condition and that resulted from production emergencies. The former inherits from the MP-FSM, as Equation (17) and Equation (18). Equation (17) means production step $\left(J_{l,i}, M_{l,k}\right)$ does not start if the precast component $J_{l,i}$ does not finish its last production step in workstation $M_{l,(k-1)}$ or the workstation $M_{l,k}$ does not finish its last job, namely precast component $J_{l,(i-1)}$. Equation (18) means the leaving time of the precast component $J_{l,i}$ in the workstation $M_{l,k}$ cannot be earlier than the entering time of that plus the production duration of the production step.

$$S(J_{l,i}, M_{l,k}) \geq \begin{cases} \mathrm{Max}\left[C(J_{l,(i-1)}, M_{l,k}), C(J_{l,i}, M_{l,(k-1)})\right], & \text{if } k \neq 4 \\ C(J_{l,i}, M_{l,(k-1)}), & \text{if } k = 4 \end{cases} \tag{17}$$

$$C(J_{l,i}, M_{l,k}) \geq S(J_{l,i}, M_{l,k}) + P_{l,i,k} \tag{18}$$

The latter depends on the production emergencies causing the productivity change.

Production step delay increases the production time of a single step of a single precast component. The delay duration is represented by h_a, and the corresponding equation is (19), which means that the leaving time of the precast component $J_{l,i}$ in the workstation $M_{l,k}$ cannot be earlier than the entering time of that plus the production duration of the production step and plus delay duration.

$$C(J_{l,i}, M_{l,k}) \geq S(J_{l,i}, M_{l,k}) + P_{l,i,k} + h_a \tag{19}$$

Machinery problem, adding workers, using over-assigned time and reducing production requirements change the production time of one or several steps of multiple precast components as formulated as Equation (20), which means if production step $(J_{l,i}, M_{l,k})$ is influenced by these production emergencies, the leaving time of the precast component $J_{l,i}$ in the workstation $M_{l,k}$ cannot be earlier than the entering time of that plus the production duration of the production step and plus the extra time for the production step because of the influence.

$$C(J_{l,i}, M_{l,k}) \geq S(J_{l,i}, M_{l,k}) + P_{l,i,k} + h_b, \text{if } (J_{l,i}, M_{l,k}) \in \mathrm{ConditionComps} \tag{20}$$

In the equations, $\mathrm{ConditionComps}$ is a set of the combination of precast components and workstations that are directly influenced by the production emergencies, while h_b is the extra time for the production step because of the influence.

Machinery breakdown stops production in a single workstation in a production line and the corresponding jobs delay until the machinery is repaired. Hence, the corresponding equation is Equation (21) and (22). Equation (21) means that no precast component enter the workstation $M_{l,k}$ when it is breakdown. Equation (22) means that the duration of machinery breakdown adds to the production duration of production step $(J_{l,i}, M_{l,k})$, when machinery breakdown happens during it.

$$S(J_{l,i}, M_{l,k}) \geq t_{bs}, \text{if } S(J_{l,i}, M_{l,k}) \in (t_{bs}, t_{be}) \tag{21}$$

$$C(J_{l,i}, M_{l,k}) \geq P_{l,i,k} + t_{be} - \mathrm{Max}\{[t_{bs} - S(J_{l,i}, M_{l,k})], 0\}, \quad \text{if } (t_{bs}, t_{be}) \cap [S(J_{l,i}, M_{l,k}), C(J_{l,i}, M_{l,k})] \neq \text{null} \tag{22}$$

In the equations, (t_{bs}, t_{be}) is the duration of machinery breakdown.

Activating backup production lines changes the quantity of production lines, but it results in no extra constraints.

Taking production step delay as an example, a production step starts as 9:30, namely, $S(J_{l,i}, M_{l,k}) = 9{:}30$. It takes 0.5 hours, namely, $P_{l,i,k} = 0.5h$. But production emergencies delay it by 0.3 hours, namely $h_a = 0.3h$. Hence, the finish time for the step $C(J_{l,i}, M_{l,k})$ should be later than 10:18 as shown in Figure 5.

It is worth noting that during rescheduling by using the RM-MFP, users can simply apply all the equations of constraint of workstation productivity, because the equation is objective so that actually it has nothing to do with whether the corresponding production emergency occur or not. Taking the Equation (21) as an example, if the production emergency of machinery breakdown does not happen, t_{bs}=0 and the equation becomes $S(J_{l,i}, M_{l,k}) \geq 0$, which obviously can be satisfied.

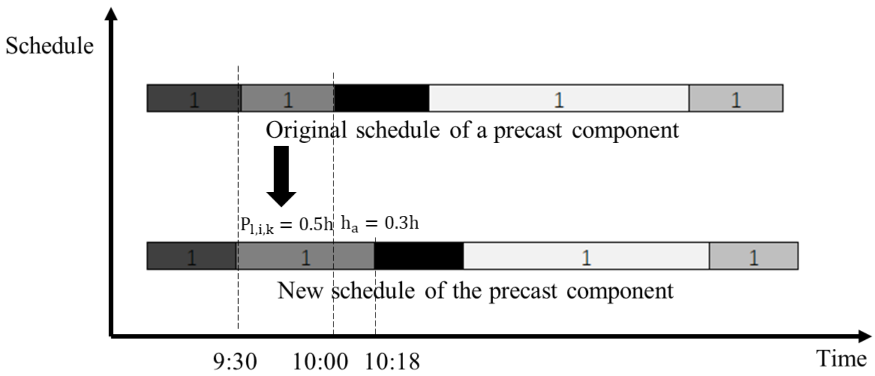


Figure 5. Example of constraint of workstation productivity

4.3.2 Equation of constraint of the amount of resources

As mentioned in Section 1.2.2, the optimization constraint can be described as the resource supply in the plant should not be less than the resource consumption. The resource supply is determined by the procurement plan, which can be formulated as an increasing function, $y = \text{Msupply}(t)$. The bottleneck of resource supply is the start time for producing any precast component, $t = S(J_{l,i}^{j}, M_{l,1})$. Thus, the total supply is $\text{Msupply}[S(J_{l,i}^{j}, M_{l,1})]$. The production of precast components follows the priorities of resource utilization of precast components (Zeng, 2007). $\text{Mconsume}(J_{l,i}^{j})$ is the resource consumption of the precast component $J_{l,i}^{j}$. Thus, until the start time for producing $J_{l,i}^{j}$, the resource consumption is $\sum_{x=1}^{j} \text{Mconsume}(J_{l,i}^{j})$. In this way, the optimization constraint is formulated as Equation (23). It can be depicted by Figure 6, which means the curve of resource consumption should always be within the envelope diagram of the curve of resource supply.

$$\text{Msupply}[S(J_{l,i}^{j}, M_{l,1})] \geq \sum_{x=1}^{j} \text{Mconsume}(J_{l,i}^{x}) \tag{23}$$

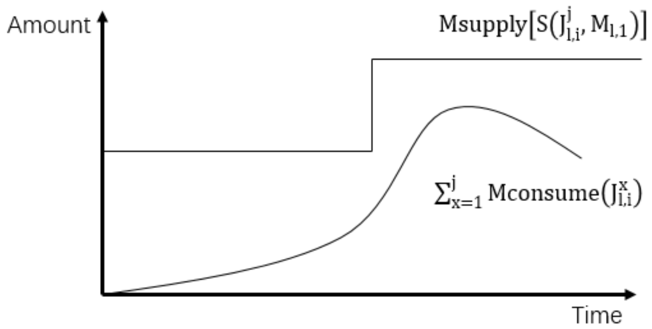


Figure 6. Constraint of the amount of resources

5 Establishing a solver by using Genetic Algorithm

Ma et al. (2015) proposed an exhaustion based solver for a similar problem, namely, shop floor scheduling model of multiple production lines for flowshop precast production, but the calculation load is extremely large. Since GA can be utilized to operate on a population of solutions rather than on one individual and uses no gradient or other problem specific information, it is ideal for solving such nonlinear scheduling problems, where the search space is large and the number of feasible solutions is small (Wall, 1996, Tormos et al, 2008). Wu et al. (1993) and Lei et al. (2012) compared GA, Particle Swarm Optimization (PSQ for short hereafter) and Simulated Annealing (SA for short here after) with similar scheduling cases and verified that GA is the best among them. Hence, the research uses GA to establish the solver for the RM-MFP.

Solving the RM-MFP by using GA is similar to solving the MP-FSM (Yang et al., 2016), which contains the following steps as shown in Figure 7. 1) Generate the initial population of chromosomes randomly according to the coding method, each of which represents a production arrangement. The size of population is set by schedulers and is denoted as m, which is even. 2) Calculate the conditional optimal schedule for each production arrangement represented by a chromosome based on the Equations from (1) to (23) in the method described by Yang et al. (2016). This step is needed because even if production arrangement is given, more than one feasible schedule can be generated according to it. Thus, m conditional optimal schedules can be achieved; 3) Evaluate the m conditional optimal schedules and find the best one based on the optimization objectives and determine whether to terminate; and 4) If it is to continue, generate a new population of chromosomes based on the previous one by mutating and crossing over and go back to the step 2), otherwise, terminate the calculation and produce the best schedule selected by step 3) (Yang et al., 2016).

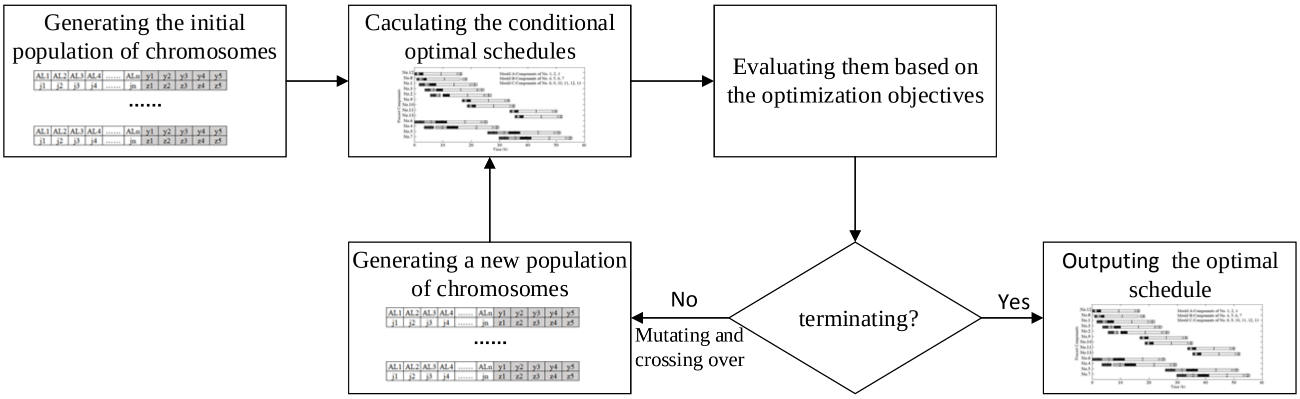


Figure 7. Flow chart of the RM-MFP solver

Because the RM-MFP has different optimization variables compared with the MP-FSM, its coding, mutation and crossing over method needs to be developed accordingly. Due to space limitation, the paper only describes the parts of the solver which are different from those in the MP-FSM. Moreover, as the calculation load of scheduling and rescheduling are comparable according to the form of the mathematic models, the calculation parameters such as population size and mutation chance for solving the RM-MFP can be determined by referring to those for solving the MP-FSM (Yang et al., 2016).

5.1 Coding method of chromosomes

All the 4 variables mentioned in Section 4.1.2 should be represented in a chromosome to describe a specific production arrangement for rescheduling. Thus each variable is represented as a group of genes in a chromosome respectively. The total quantity of the genes which represent the first two variables, namely the allocation plan of the precast components to the production lines and their priorities of resource utilization, is n, which is the total quantity of precast components. The representation of the genes corresponding to the two variables is decimal. For better mutation and crossing over, the representation of the genes corresponding to the last two variables, the proportion and duration of releasing over-assigned time, is binary and ternary respectively to increase the length of chromosome part. The number of genes is designed as 5 according to production practice (General administration of quality supervision, inspection and quarantine of P.R.C., 2009) for both variables. The chromosome design is as follows.

A chromosome is a 2*(n+5) matrix of genes, which can be divided into two parts as shown in the Figure 8. The left part is further divided into two sections, which are coded decimally. The genes in the top left section, namely $AL_{1, \ldots,}$ AL_n, are serial numbers of precast components arranged according to their priorities of resource utilization. The values of the genes are not repeated with the range [1, n]. The genes in the bottom left section, namely j_1, …, j_n, are the serial number of production lines where the precast components right above the serial numbers are produced. The values of the genes can be repeated with the range [1, L]. The right part is also divided into two sections, which are coded in the binary and ternary respectively. The values of the genes of the part can be repeated. The ternary number constituted by the genes of the top right section, namely $y5+3*y4+3^2*y3+3^3*y2+3^4*y1$, is the duration for using the over-assigned time, T_r. The binary number constituted by the genes of the bottom right section over 100, namely $(z5+2*z4+2^2*z3+2^3*z2+2^4*z1)/100$, is the proportion of the used over-assigned time to the assigned production time of each step, φ. $\varphi \leq \phi$, where ϕ is the proportion of the over-assigned time to the assigned production time.

AL1	AL2	AL3	AL4	……	ALn	y1	y2	y3	y4	y5
j1	j2	j3	j4	……	jn	z1	z2	z3	z4	z5

Figure 8. Coding method of chromosomes

5.2 Crossing over and mutation method of chromosomes

The different sections of the chromosomes cross over following different cross over operators.

Since the genes in the top left section are not repeated, the order-based crossover operator, namely OX2, is applied for the section as illustrated in Figure 9 (Yang et al., 2016). First, a continuous subsection of chromosome, which is shorter than the parent section, is randomly selected within a parent section and all the rest genes in the parent section are inherited by the child section. Then the genes in the selected subsection are rearranged according to the appearance order of the equivalent genes in the other parent section and inherited by the child section. Thus the top left section of the child chromosome is created.

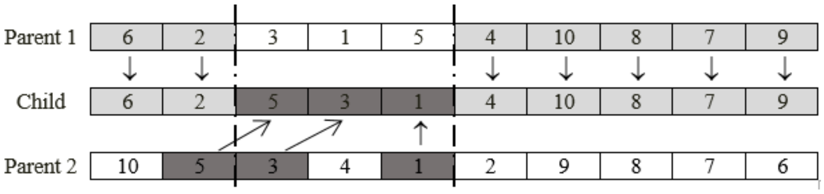


Figure 9. Cross over operator for the top left section

Since the genes in the bottom left section can be repeated, the basic two-point cross over operator is applied for the section as illustrated in Figure 10 (Yang et al., 2016). First, a continuous subsection of chromosome, which is shorter than the parent section, is randomly selected within a parent section and all the rest genes in the parent section are inherited by the child section. Then the corresponding subsection in the other parent section, the position of which is the same as the selected subsection, is directly inherited by the child section. Thus the bottom left section of the child chromosome is created.

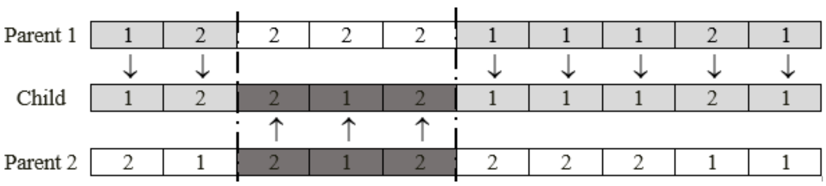


Figure 10. Cross over operator for the bottom left section

Since the two sections in the right part of the chromosomes are short, the basic one-point cross over operator is applied for the sections as illustrated in Figure 11 (Crossover, 2016). First, a cut point is randomly selected within the both parent sections and the parent sections are cut as four subsections. Then, the right subsection of a parent section and the left subsection of another parent section is inherited by the child section. In the way, the right part of the child chromosome is created.

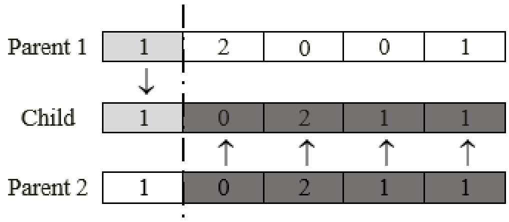


Figure 11. Cross over operator for the top right section and the bottom right section

The different sections of the chromosomes mutate following different mutation operators.

Since the genes in the top left section are not repeated, the genes in the section follows the mutation operator by which the position of two randomly selected genes are interchanged as illustrated in Figure 12. First, two different genes are selected in the section. Then, the section is mutated by exchanging the position of them.

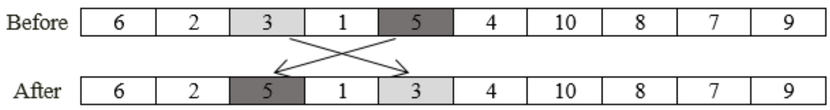


Figure 12. Mutation operator for the top left section

Since the genes in the rest sections are repeatable, the genes in the sections follows the mutation operator by which the value of a randomly selected gene changes randomly within the corresponding value range as illustrated in Figure 13.

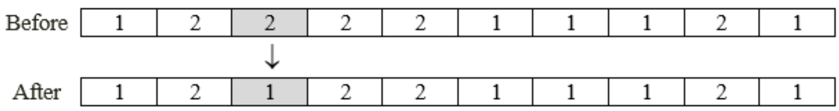


Figure 13. Example of the mutation operator for rest sections

The best chromosome recording strategy is used during the generation of new population for better convergence performance. That is, the best chromosome in the current population is selected and recorded as C^0 according to the optimization objectives. After generating the new population by using the crossing over and mutation operators, the best chromosome in the new population is selected and recorded as C^1. Then, C^0 and C^1 are compared and the one of better performance is reserved in the new population (Li, 2004, Zhou, 1999). Such a process goes on until the convergence criterion is met and the optimal plan is thus obtained.

6 Verification

Based on the procedure as shown in Figure 3, the proposed approach is verified in two steps after a corresponding program was developed and used. In the first step, a production case of the production emergency of duration delay is used, and a widely used software is used for preliminary comparison where the overall adjustment rule is applied. The results are analyzed according to the optimization objectives. In the second step, seven production cases of the production emergency of rush order arrival is used, and the same software is used for further comparison, where Earliest Due Date (EDD) rule, Shortest Processing Time (SPT) rule and Least Slack Time (LST) rule are applied, respectively.

6.1 Step 1: a production case

Ten precast components produced in two production lines are rescheduled in the case. The precast components share 7 production pallets and 7 moulds, among which 3 moulds are of type A, 2 moulds are of type B and 2 moulds are of type C. Three shifts are applied in the production, which guarantee the continual production during the whole day. Resource supply follows the Equation (24). The buffer size between workstations and curing rooms is set as 3 and 20 respectively. The production information of the precast components is derived by referring to the case used by Benjaroran et al. (2005) as shown in Table 4, which was also used in the validation of Ko et al.'s study (2010) and Yang et al. (2016). The production time of each step in the table includes the over-assigned time with the over-assignment proportion of 20%. The original schedule is depicted in Figure 14. All the precast components are finished within 55.6h. The production emergency is assumed to be that the No. 4 precast component in the production line 2 doubles its production time of the second production step due to extra requirement from the customer, namely h_a=4h. Hence, the shop floor rescheduling is necessary or the precast components cannot be delivered on time.

$$y = \mathrm{Msupply}(t) = \begin{cases} 15, \text{if } 0 \le t < 20 \\ 20, \text{if } 20 \le t \end{cases} \tag{24}$$

Table 4. Production information of precast components

Component		Production time of each step (hour)					Due date (hour)	Penalty rate per hour (Dollar/Component)		Resource consumption (unit)	Quantity (piece)
Id	Type	M1	M2	M3	M4	M5		Earliness	Tardiness		
1	A	2	1.6	2.4	12	2.5	57	2	10	1	3
2	B	3.4	4	4	12	2.4	57	2	10	2	4
3	C	0.8	1	1.2	12	1.8	53	2	10	1	6

M1: moulding, M2: placing of rebars and embedded parts, M3: casting, M4: curing, M5: demoulding

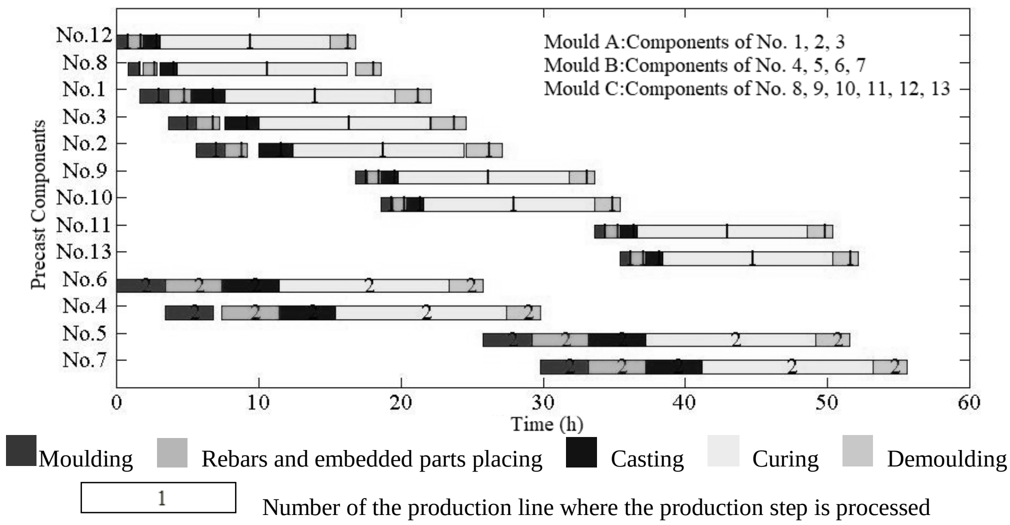


Figure 14. Original schedule

In the case, the production emergency is solved only by using the over-assigned time as a whole. The new schedule generated by using the proposed approach is shown in the Figure 15. It is obvious that all the objectives were achieved. For instance, all the precast components are produced within 56.9h and can be delivered in time. Moreover, because only the production jobs in the production line 2 are adjusted in the new schedule, the material re-dispatch is not necessary. In addition, the period for using the over-assigned time, T_r, is only 39h and the decrement rate of the estimated production time of the steps, φ, is only 6.7%, which means that little over-assigned time for production emergencies are used to solve the production emergency. Moreover, all the optimization constraints were satisfied in the schedule. As the RM-MFP is inherited from the MP-FSM, the first six constraints are inevitably satisfied. The curves of resource consumption and supply are depicted in Figure 16, which shows the resource supply is enough for production according to the schedule.

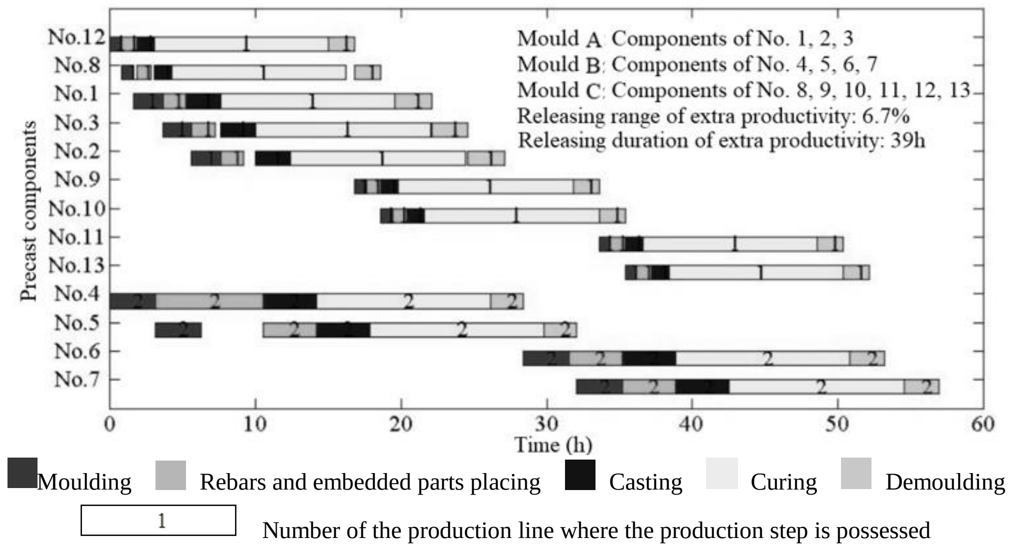


Figure 15. New schedule by RM-MFP

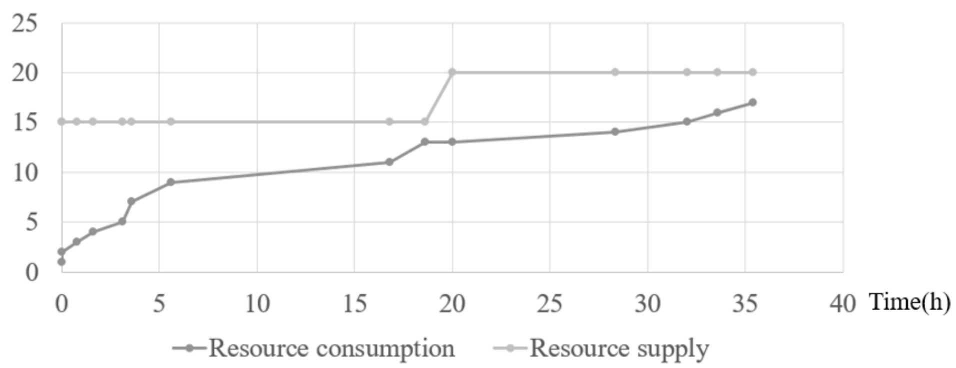


Figure 16. Resource consumption and supply according to the new schedule by RM-MFP

Next, Asprova APS is selected as a comparison to adjust the schedule based on the heuristic rule, where the over-assigned time within the production steps is not utilized as a whole, namely, the assigned production time is regarded as the estimated production time. The software is developed by a Japanese company called Asprova in 1994. Currently it is leading in the market in Japan and is used worldwide. The overall adjustment rule is applied, because theoretically it performs the best. The new schedule obtained by using Asprova APS is shown as Figure 17. Some objectives are not achieved in the schedule. For instance, all the precast components have to been produced in 61.8h, which is beyond the requirement of the customer as shown in Table 4. Moreover, according to the schedule, the

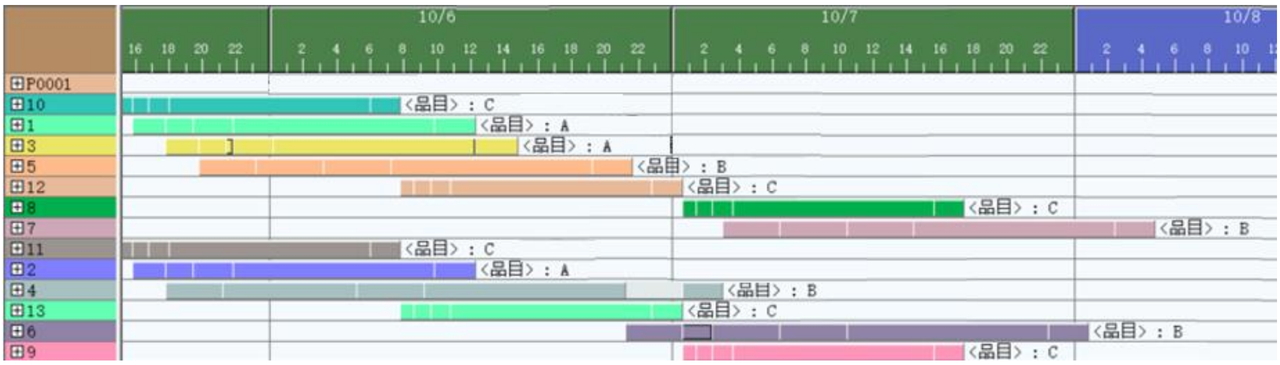


Figure 17. New schedule by Asprova APS

material re-dispatch is inevitable because the production adjustment is within the two production lines. The result indicates that, comparing with the heuristic rule based method, the proposed approach gives better results in solving the production emergencies, because it can utilize the over-assigned time as a whole and keep the adjustment of schedules at minimum to avoid massive material re-dispatch.

The minimum of the weighted and normalized value of the objectives in each population during calculation is depicted in the convergence curve of Figure 18. The calculation converges within 30 iterations, which shows the high calculation efficiency of the solver for the RM-MFP. Based on the curve and the principle of GA, the schedule in the Figure 15 can be trusted as the optimal solution of the case within limited calculation loads.

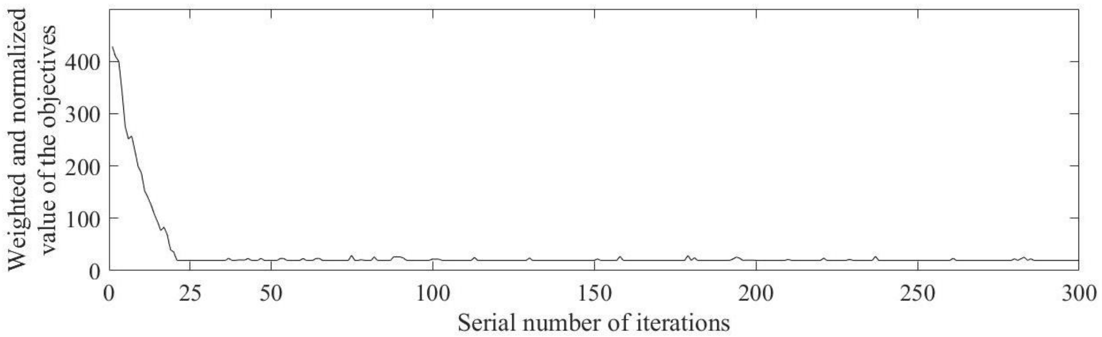


Figure 18. Convergence curve of the case

6.2 Step 2: seven production cases

Seven cases of rescheduling was further carried out to compare the performance of the proposed approach with the heuristic rule based ones. Asprova APS was also applied as a comparison to generate the heuristic rule based schedules. The arrival of new rush order is selected as the reason for rescheduling. It is common in practice and little experience is required for rescheduling as most software provides the functionality. The new order contains 5 precast components of Type A. Since the software does not support quantitative multi-objective optimization, the minimization of makespan is selected as the only optimization objective, because it is one of the most significant objectives of rescheduling. To minimize the makespan, the weights of optimization objectives is W_{WI}=0%, W_{CS}=0%, W_{MS}=100%, W_{TC}=0%, W_{MR}=0%, W_{RC}=0% in the proposed approach and the overall adjustment is selected as the heurist rule for rescheduling in Asprova APS. Three widely used dispatch rules, namely Earliest Due Date (EDD) rule, Shortest Processing Time (SPT) rule and Least Slack Time (LST) rule are applied in each case respectively as calculation parameters in Asprova APS to determine the production sequence (Yang et al., 2016).

The seven cases that were used in a previous study (Yang et al., 2016) are used, in which, the quantity of each type of component, quantity of production lines, quantity of pallets are varied. The schedules of the seven cases that were scheduled by using Asprova APS by Yang et al. (2016) are used to determine the original schedules. The original schedule for each case in the study is adopted as the best one among the 3 schedules of each case. Since the production emergency is set as rush order arrival, the resource supply is enough in the 7 cases. The other parameters follow the cases of Yang et al. (2016). The makespans of both the original schedules and the new schedules that are obtained by using the proposed approach are shown in Table 5.

Table 5. Makespan of the original and new schedules of the comparative cases

Cases	Component quantity (piece)			Makespan of original schedules (hour)	Dispatch rule of original schedules	Makespan of new schedules (hour)			
	Type A	Type B	Type C			SPT	EDD	LST	RM-MFP
1	12	8	5	77.4	LST	82.2	83.4	83.4	77.4
2	8	7	5	77.4	LST	79.4	80.2	80.2	77.4
3	10	5	6	77.4	EDD	102.5	104.9	104.1	102.5
3	9	3	6	41	SPT	61.5	62.3	62.3	61.5
5	12	8	7	56.4	SPT	61.5	66.2	64.8	61.5
6	15	11	7	82	LST	102.5	107.6	105.8	102.5
7	14	4	10	67.2	EDD	86	67.2	68.7	67.2

Note: the quantity of precast components in Table 5 is the total quantity in the new schedules

Table 5 shows that the proposed approach is more optimal than the heuristic rule based ones. It shows better or equal performance in 100% of the comparative cases. To be specific, 43%, 86% and 100% of the schedules adjusted by the proposed approach has shorter makespan compared with those adjusted by Asprova APS by using the dispatch rules of SPT, EDD and LST respectively. For the rest of the cases, the performance of the two approaches is the same. Moreover, the performance of the heuristic rule based rescheduling approach is highly depended on the experience of schedulers, because many calculation parameters, such as the heuristic rules and dispatch rules, need to be determined manually. The proposed approach is also more efficient because less trial and error processes are necessary.

7 Conclusions

This paper proposes and verifies an approach which includes an optimized Rescheduling Model of Multiple production lines for Flowshop Precast production (RM-MFP) and a corresponding GA-based solver to realize the optimized rescheduling. The RM-MFP includes a number of new optimization objectives and constraints that were identified through literature review and field investigation. Morever, the proposed method can make use of the over-assigned time of multiple production steps in multiple precast components as a whole in the rescheduling process. Furthermore, a GA based solver is proposed to achieve the optimization.

Compared with the existing approaches, the proposed approach is less dependent on the experience of schedulers to enable the scheduler to deal with production emergencies more effectively and efficiently. To be specific, in the comparative cases of the study, the proposed approach shows better performance in 76.3% of them and performs equally in the rest. The proposed approach contributes to the innovation of body knowledge on the way to carry out optimized rescheduling of multiple production lines for flowshop precast production.

Since fixed-location production is also an important type for precast production especially for big, heavy or special designed precast components and the scheduling of such type can be classified as open shop scheduling, most of existing research achievements in the scheduling or rescheduling of precast production cannot be directly applied in the problem. So scheduling or rescheduling of precast production of fixed-location is another further research direction.

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Appendix: Symbols

Symbols	Meaning	Unit
\$	A type of the precast component	-
$B_{l,k}$	Maximum quantity of precast components that can be stacked between workstation M_k and M_{k+1}	Piece
ConditionComps	A set of the combination of precast components and workstations that are directly influenced by the production emergencies	-
$CQ_{l,s}$	Total quantity of the type changes of precast components during production in the shift s of the production line l	1
$d_{l,i}$	Due time of the precast component produced in production line l at the sequence i	Hour
h_a	Estimated duration of delay	Hour
h_b	Extra time for the production step because of the influence	1
H_E	Overtime hours allowed during the working day	Hour
H_N	Non-working hours during the working day	Hour
H_W	Working hours during the working day	Hour
$J_{l,i}$	Total quantity of precast components produced in the production line l	Piece
$J_{l,i}^{j,\$}$	Serial number of the precast component of type \$ produced in production line l at the sequence i, whose priority is j	1
$J_{l,i}^{j}$	Serial number of the precast component produced in production line l at the sequence i, whose priority is j	1
L	Total quantity of production lines	Set
L_r	Quantity of production lines whose schedules are changed by rescheduling	Set
L_s	Quantity of production lines actually participating in the production in shifts	Set
$M_{l,k}$	The serial number of the workstation for production step k in the production line l	1
n	Total quantity of precast components	Piece

Symbols	Meaning	Unit
n_l	Total quantity of precast components produced in the production line l	Piece
P	Total quantity of production pallets in the flowshop	Set
$P_{l,i,k}$	Production time of the step k of the precast component produced in production line l at the sequence i	Hour
$Q_\$$	Total quantity of moulds of type $ in the flowshop	Set
T_p	Duration from the initial of rescheduling to the end of the schedule	Hour
$TQ_{l,s}$	Total quantity of the types of the precast components in the shift s of the production line l	1
T_r	The duration for using the over-assigned time	Hour
Y_l	Maximum quantity of precast components that can be handled in the curing room of production line l	Piece
φ	Proportion of the used over-assigned time to the assigned production time	1
$\tau_{l,i}$	Contract penalty of the precast component produced in production line l at the sequence i	Dollar/hour
$\varepsilon_{l,i}$	Storage cost of the precast component produced in production line l at the sequence i	Dollar/hour