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Optimized flowshop scheduling of multiple production lines for precast production

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ABSTRACT

The current approach in practice to produce the flowshop schedules of precast production is the dispatching rule technique, which does not guarantee optimal schedules. Some researchers have developed models for a single production line to optimize the scheduling, in which Genetic Algorithm (GA) is used to obtain the solution. However the models cannot be used for multiple production lines. Moreover, some optimization constraints and objectives were missing in the models, such as avoiding frequent type change of precast components during production. Both issues hinder their work to be applied to real precast plants. To overcome the problem, this paper proposes a Flowshop Scheduling Model of Multiple production lines for Precast production (MP-FSM) and develops a corresponding optimization approach to facilitate optimized scheduling by using GA. The approach was validated preliminarily by comparing with traditional scheduling approaches. The results demonstrated that optimized schedules can be obtained by using the proposed approach.

1. Introduction

Precast concrete structures have demonstrated better production efficiency and construction quality by employing highly effective manufacturing process compared to the in-site concrete structures. The components of this kind of structures need to be produced in factories and installed in site. Generally speaking, the production of the components, namely precast production, has dramatic impact on the construction, because it involves the most work load of construction projects. Obviously, production planning is the key elements for the precast production process. It consists of master production scheduling, material requirement planning and shop floor scheduling. Among them, the shop floor scheduling is the most detailed and difficult one, in which production tasks are assigned to specific workshop sections, teams or even operators. Furthermore, among all kinds of shop floor scheduling, flowshop scheduling is of the most importance, because the flow shop is often chosen as the shop floor organization form for precast production due to their high production capacity. In most cases, the flowshop schedules are prepared by sequencing the precast components based on the dispatching rule technique by using Enterprise Resource Planning (ERP) systems. However, it is a simplified approach regardless of many constraints [3] and does not guarantee optimal schedules [5].

A number of studies have been attempted to resolve the issues. Chan and Hu [4,5] proposed the Flow Shop Sequencing Model (FSSM) for precast production, in which such issues as the parallel processing capability of curing rooms and the requirement of uninterrupted activities like casting and curing are considered. While makespan minimization was employed in the traditional flowshop problems as the optimization objective, FSSM also targeted at minimizing the contract penalty and storage cost resulted from the tardiness or earliness of the production.

Benjaoran et al. [2] studied the impact of the quantity of molds on shop floor schedules of precast production and proposed a Flow Shop Scheduling Model for Bespoke Precast production (BP-FSSM) based on the FSSM. A scheduling system called "Artificial Intelligence Planner" was developed based on the BP-FSSM, which enables automatic quantity take-off, productivity estimation and scheduling generation for bespoke precast production [3].

Since the buffer size between workstations to store the work-in-processes is limited, which was not taken into account in the previous studies, Ko and Wang [8] modified the optimization constraints of the existing scheduling models and developed a Genetic Algorithm (GA) based decision support system for the production scheduling accordingly.

Some other researchers have also made some interesting contributions. Leu and Hwang [12] developed a scheduling model for the mixed production of precast components from multiple construction projects and proposed a GA based scheduling approach correspondingly. Tharmmaphornphilas and Sareinpithak [16] developed a scheduling model for precast production of fixed-location and proposed a heuristic

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approach to solve the model. Zhai et al. [21] proposed a scheduling model for make-to-order precast production based on simulation technique and GA. Khalili and Chua [7] established a scheduling model for precast modular units, which consisted of several building elements and can be produced, transported and installed as units, and a scheduling approach based on the model and the mixed integer linear programming method was proposed.

The authors carried out field studies into several factories of precast production and found out a number of practical issues in the above mentioned studies. The most crucial one is that the existing models cannot be directly applied to flowshops with multiple production lines, because the available quantity of molds for each production line, as an essential parameter of the existing models, cannot be determined before scheduling in that kind of flowshops. Moreover, some optimization objectives and constraints were not taken into account in the existing models.

This paper proposes a Flowshop Scheduling Model of Multiple production lines for Precast production (MP-FSM) and a corresponding optimization approach to facilitate effective and optimized scheduling by using GA. Section 2 analyses the flowshop scheduling problem and highlights some newly identified optimization objectives and constraints. Based on the analysis, Section 3 formulates the MP-FSM. Then, Section 4 establishes a MP-FSM based optimized flowshop scheduling approach by using GA and shows the feasibility of the approach via a case study. Section 5 verifies the approach preliminarily by comparing with the traditional one. Finally, Section 6 concludes the paper.

2. Analysis on flowshop scheduling of multiple production lines

Precast production can be divided into two categories according to the difference in production methods, namely flowshop production and fixed location production. The flowshop divides the precast production into six steps, namely molding (M1), placing of rebars and embedded parts (M2), casting (M3), curing (M4), mold stripping (M5) and finishing (M6). Each step is handled in a particular workstation by a particular team. For the fixed location production, the division of precast production is similar, while all steps of a component are handled in a fixed workstation by the same or different teams. Generally speaking, the production capacity and resource utilization rate of the fixed location production is lower than that of the flowshop production. This paper is focusing on the scheduling of multiple production lines for flowshop production, i.e. flowshop scheduling.

A precast flowshop is normally equipped with a limited number of molds of various types, production pallets and production lines with fixed production routing. There are six workstations in each production line for the aforementioned six steps of precast production respectively. The curing room, i.e. the curing workstation, in a production line is capable to handle a limited number of precast components simultaneously. When some precast components of multiple types are going to be produced in the flowshop, the aim of flowshop scheduling is to assign the tasks to the workstations and specify the time to start or end each production step of all the precast components.

Flowshop scheduling is essentially a multi-objective optimization problem. In this study, based on literature review and field study in a number of factories of precast components in China, the optimization objectives and constraints have been summarized as shown in Table 1. Since the items No.1, 2, 3 and from 5 through 8 have been presented in detail in the existing studies already [2,5,8], only the newly identified items, i.e. items No.4, 9 and 10 are discussed in this paper.

Table 1
Optimization objectives and constraints of flowshop scheduling of multiple production lines.

No.	Classification	Items
1	Optimization objectives	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	Optimization constraints	Constraint of productivity
6		Constraint of the size of curing rooms
7		Constraint of the eight-hour day working
8		Constraint of the buffer size between workstations
9		Constraint of the quantity of molds
10		Constraint of the quantity of production pallets

2.1. Type change of precast components during production

Frequent type change of the precast components in each workstation during production result in substantial equipment adjustments and operation changes which are detrimental to the production efficiency and quality. Therefore, it is critical to minimize the type change of precast components during production.

In most cases, a shift work system is used in the flowshops of precast production. A shift usually lasts 8 h, so minimizing the type change of precast components produced in each shift is the key to keep the type changes to the minimum as discussed above.

2.2. Constraint of the quantity of molds

Molds are the essential elements of precast production. However, the quantity of molds is often limited, especially for the bespoke precast components due to the high initial cost and limited demand. So it is important to ensure that the molds of each type are always more than the precast components of the same type being produced simultaneously.

Since molds are shared resources across all the production lines, they need to be allocated to the precast components during scheduling, especially to those produced in different lines. For example, two components of the same type A_1 and A_2 are going to be produced in two production lines respectively, but only one mold of the type is available. Then, a tradeoff is required to decide which of them use the mold first, which may make big difference in the contract penalty and storage cost eventually.

2.3. Constraint of the quantity production pallets

Production pallets are the platforms where the precast components with molds are placed on during production. However, the quantity of the pallets are also limited, so it is important to ensure that the production pallets are always more than the precast components being produced simultaneously in each production line.

Production pallets are shared across all production lines, so the allocation of them is also necessary. Moreover, the production pallets have to work with the molds in pairs. Therefore, the allocation of production pallets has to be coordinated with the molds to avoid the conflict and resource waste.

3. Flowshop scheduling model of multiple production lines

This section describes how the MP-FSM, which consists of the optimization objectives and constraints, are formulated.

3.1. Optimization objectives

All the optimization objectives in Table 1 are adopted in the MP-FSM. The Workstation Idle time (WI) and the Contract penalty and Storage cost (CS), which are the targets in the first two optimization objectives, will increase linearly with the number of production lines. Thus, the corresponding indices f_{WI} and f_{CS} of multiple production lines can be obtained by summing up those of each single production line. Their calculation methods for a single production line are presented in an existing research already [2]. Accordingly, the first two optimization objectives are expressed as Eqs. (1) and (2). Moreover, the makespan of multiple production lines f_{MS} is the maximum of that of each single production line. The calculation of the makespan of a single production line is presented in an existing study already [5]. Accordingly, the third optimization objective is formulated as Eq. (3).

$$\text{Min } f_{WI} = \sum_{l=1}^{L}\sum_{k=1}^{6}\left[C\left(J_{l,n_l}, M_{l,k}\right) - S\left(J_{l,1}, M_{l,k}\right) - \sum_{i=1}^{n_l} P_{l,i,k}\right] \quad (1)$$

$$\text{Min } f_{CS} = \sum_{l=1}^{L}\left\{\sum_{i=1}^{n_l}\tau_{l,i} * \text{Max}\left[0, C\left(J_{l,i}, M_{l,6}\right) - d_{l,i}\right] + \sum_{i=1}^{n_l}\varepsilon_{l,i} * \text{Max}\left[0, d_{l,i} - C\left(J_{l,i}, M_{l,6}\right)\right]\right\} \quad (2)$$

$$\text{Min } f_{MS} = \text{Max}_{\forall l\epsilon N^+|l\le L} C\left(J_{l,n_l}, M_{l,6}\right) \quad (3)$$

Where: f_{WI}, f_{CS} and f_{MS} represent the workstation idle time, contract penalty and storage cost, makespan during production respectively;

N^+ stands for all positive integers;

L is the total quantity of production lines;

n_l is the total quantity of precast components produced in production line l ($l \le L$), while N is the total quantity of precast components to be produced and $\sum_{l=1}^{L} n_l = N$;

$J_{l,i}$ is the serial number of the precast component produced in production line l at the sequence i ($i \le n_l$);

$M_{l,k}$ is the serial number of the workstation handling the kth ($k \le 6$) step;

$S(J_{l,i}, M_{l,k})$, $P_{l,i,k}$ and $C(J_{l,i}, M_{l,k})$ is the entering time, duration and leaving time of the precast component $J_{l,i}$ in the workstation $M_{l,k}$ respectively;

$\text{Max}_{\forall l\epsilon N^+|l\le L} f(l)$ is the maximum of f(l), where l is a positive integer and $l \le L$;

$\tau_{l,i}$ and $\varepsilon_{l,i}$ are the rates of contract penalty and storage cost of precast component $J_{l,i}$ respectively. In the Eq. (3) the f(l) represents $C(J_{l,n_l}, M_{l,6})$; and

$d_{l,i}$ is the due date of precast component $J_{l,i}$.

The optimization objective of minimizing type change of precast components during production is derived as follows.

The type change of precast components during production in a single production line can be minimized in two steps. First, the quantity of the types of the precast components in each shift should be minimized. For example, if 6 precast components of type A (A) and 6 precast components of type B (B) are produced in a single production line, all the As should be assigned to a shift and Bs to another. Second, if the types of the precast components produced in a shift cannot be the same after the previous step, the ones of the same type should be sequenced next to each other. Therefore, the quantity of the type changes of precast components in each shift should also be minimized. For instance, 2 As and 1 Bs have to be produced in a single production line in the same shift. Comparing to the sequence of A, B, A with 2 type changes of precast components, those in the sequences of A, A, B or B, A, A are only 1. So the first sequence should be avoided.

Based on this analysis, the optimization objective for a single production line is expressed as Eq. (4).

$$\text{Min } f_{TCL} = \sum_{s=1}^{S}\left(TQ_{l,s} + CQ_{l,s}\right) \quad (4)$$

Where: f_{TCL} represents the degree of the type change of precast components produced during production in the production line l;

l is the serial number of a production line;

s is the serial number of a shift;

S is the total quantity of shifts;

$TQ_{l,s}$ is the total quantity of the types of the precast components in the shift s of the production line l; and

$CQ_{l,s}$ is the total quantity of the type changes of precast components during production in the shift s of the production line l.

The smaller the f_{TCL} is, the less type changes of precast components are, and vice versa. Therefore, the Eq. (4) means that minimizing the type change of precast components during production in a single production line equals minimizing both the quantity of the types and the quantity of the type changes of precast components during production in each shift.

The optimization objective for multiple production lines can be achieved by minimizing that of each single production line. So the optimization objective is expressed as Eq. (5).

$$\text{Min } f_{TC} = \sum_{s=1}^{S}\left\{ETQ_s + ECQ_s\right\} \quad (5)$$

Where: f_{TC} represents the average degree of the type change of precast components during production in multiple production lines;

$ETQ_s = \sqrt{\sum_{l=1}^{L} TQ_{l,s}^{\ 2}/L_s}$ is the equivalent quantity of the types of the precast components in the shift s per production line, where L_s is the quantity of production lines actually participating in the production in shift s; and

$ECQ_s = \sqrt{\sum_{l=1}^{L} CQ_{l,s}^{\ 2}/L_s}$ is the equivalent quantity of the type changes of precast components during production in the shift s per production line.

ETQ_s and ECQ_s represent the average quantity of the types and type changes of precast components in shifts in the production lines. Therefore, the Eq. (5) means that minimizing the type change of precast components during production in multiple production lines equals minimizing both the average quantity of the types and the average quantity of the type changes of precast components in multiple production lines in each shift.

It deserves to explain that apart from optimizing the objective in a global perspective, the experience and efficiency of all operators have to be considered to avoid the local deterioration in certain production lines. Hence, instead of using the algebraic mean of $TQ_{l,s}$ and $CQ_{l,s}$ of each production line, the ETQ_s and ECQ_s need to be calculated by using their quadratic mean [15], namely the square root of the mean of their squares. This can be explained in detail by taking ETQ_s as an example.

Assume that four precast components of different types (A, B, C, D) are produced in two production lines. In plan 1, A is produced in line 1 and B, C, D are produced in line 2. In plan 2, A, B are produced in line 1 and C, D are produced in line 2. If the ETQ_s is calculated by averaging the $TQ_{l,s}$ of each production line, namely by $\sum_{l=1}^{L} TQ_{l,s}/L_s$, then the $\sum_{l=1}^{L} TQ_{l,s}/L_s$ of the both plan are 2, which means to select either of them is equivalent if the other optimization objectives are not considered. But actually it is easier for operators to make operation mistakes in the plan 1, so the plan 2 should be selected. However, if the ETQ_s is calculated by using the quadratic mean of $TQ_{l,s}$, namely by $ETQ_s = \sqrt{\sum_{l=1}^{L} TQ_{l,s}^{\ 2}/L_s}$, to amplify the difference in the quantity of the types of precast components among production lines, the ETQ_s of the plan 1 is $\sqrt{5}$ and that of the plan 2 is 2. The result means the plan 2 should be selected, which agrees with the actual requirement of and production experience. The quadratic mean method is thus chosen.

3.2. Optimization constraints

All the optimization constraints in Table 1 are adopted in the MP-FSM. The first three optimization constraints in Table 1 for a single production line have already been presented in the existing studies [2,5,8]. For the MP-FSM, only small changes need to be made in the equations. For example, a precast component can be located based on the sequence of production in a single production line and, therefore, denoted as J_i. Nevertheless, the serial number of the production line, in which the precast component is produced, is also required to locate the precast component in multiple production lines. Hence, the precast components are denoted as $J_{l,i}$ for the MP-FSM. The first three optimization constraints in Table 1 are presented in the following Eqs. (6) to (11), where Eqs. (6) and (7) stand for the constraint of productivity; Eq. (8) stands for that of the size of curing rooms; Eq. (9) stands for that of the eight-hour day working for the casting step; Eq. (10) stands for that of the eight-hour day working for the curing step; and Eq. (11) stands for that of the eight-hour day working for the other steps.

$$S(J_{l,i}, M_{l,k}) \geq \begin{cases} \mathrm{Max}\left[C\left(J_{l,(i-1)}, M_{l,k}\right), C\left(J_{l,i}, M_{l,(k-1)}\right)\right], & \text{if } k \neq 4 \\ C\left(J_{l,i}, M_{l,(k-1)}\right), & \text{if } k = 4 \end{cases} \tag{6}$$

$$C(J_{l,i}, M_{l,k}) \geq S(J_{l,i}, M_{l,k}) + P_{l,i,k} \tag{7}$$

$$S(J_{l,i}, M_{l,4}) \geq \mathrm{Max}^{Y_l^{th}}_{\forall y \in N^+ | y<i} C\left(J_{l,y}, M_{l,4}\right) \tag{8}$$

$$C(J_{l,i}, M_{l,3}) \geq \begin{cases} T, & \text{if } T \leq 24D + H_W + H_E \\ 24(D+1) + P_{l,i,k}, & \text{if } T > 24D + H_W + H_E \end{cases} \tag{9}$$

$$C(J_{l,i}, M_{l,4}) \geq \begin{cases} T, & \text{if } T < 24D + H_W \\ 24(D+1), & \text{if } 24D + H_W \leq T \leq 24(D+1) \\ T, & \text{if } T > 24(D+1) \end{cases} \tag{10}$$

$$C(J_{l,i}, M_{l,k}) \geq \begin{cases} T, & \text{if } T < 24D + H_W \text{ and } k = 1,2,5,6 \\ T + H_N, & \text{if } T \geq 24D + H_W \text{ and } k = 1,2,5,6 \end{cases} \tag{11}$$

Where: $Max^{Y_l^{th}}_{\forall y \in N^+ | y<i} f(y)$ is 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 $y \leq i$,. In the Eq. (8) the f(y) represents $C(J_{l,y}, M_{l,4})$;

T is the $C(J_{l,i}, M_{l,k})$ calculated without considering the constraint of eight-hour day working;

$D = \text{integer}(T/24)$ is the total quantity of days passed from the start of the production to the $C(J_{l,i}, M_{l,k})$;

H_W, H_N and H_E are the working hours, non-working hours and overtime hours allowed per day; and

$J_{l,i}$, $M_{l,k}$, $S(J_{l,i}, M_{l,k})$, $P_{l,i,k}$ and $C(J_{l,i}, M_{l,k})$ are the same as in the previous equations.

The constraint of buffer size is referring to that the space required for the work-in-progresses temporarily stacked between two adjacent workstations must be less than the storage capacity. It is originally proposed by Ko and Wang [8], but their equations are too complicated. Therefore, based on the definition of the constraint, the authors proposed the Eq. (12). It means that if the storage capacity between workstations $M_{l,k}$ and $M_{l,(k+1)}$ is $B_{l,k}$, then the leaving time of the precast component $J_{l,i}$ from the $M_{l,k}$ must be later than the entering time of the precast component $J_{l,(i-B_{l,k})}$ into the $M_{l,(k+1)}$, so that it can be guaranteed that less than $B_{l,k}$ components are stacked between the two workstations.

$$C(J_{l,i}, M_{l,k}) \geq S\left(J_{l,(i-B_{l,k})}, M_{l,(k+1)}\right) \tag{12}$$

Where: $B_{l,k}$ is the maximum quantity of precast components that can be stacked between workstation $M_{l,k}$ and $M_{l,k+1}$; and

$J_{l,i}$, $M_{l,k}$, $S(J_{l,i}, M_{l,k})$ and $C(J_{l,i}, M_{l,k})$ are the same as in the previous equations.

3.2.1. Constraint of the quantity of molds

As introduced in Section 2, to generate schedules, it is essential to allocate the molds to the components and ensure that the components being produced simultaneously are not more than the molds of the same type, as corresponds to the item No.9 of the Table 1.

In order to formulate the constraint of the quantity of molds, the concept of priority of precast components to use molds is introduced. Namely, the precast components with higher priorities can get molds earlier than the others of the same type. If all the molds of the type are occupied, the precast components with lower priorities cannot be produced until the molds of the type are released from the precast components with higher priorities. For instance, three components of the same type A_1, A_2 and A_3 are produced in three production lines respectively with only 2 molds of the type. It is assumed that the priorities of the components are 7, 4 and 3 respectively, namely A_1 has the highest priority while A_3 has the lowest priority. Then A_1 and A_2 get molds and start to be produced first, while A_3 cannot get mold until A_1 or A_2 is completed and releases its mold. In this way, molds are allocated.

It deserves to emphasize that the priorities of precast components should be consistent with the production sequence of precast components in each production line. Otherwise, the production may be interrupted because all the molds may be occupied by precast components that are not yet produced. But the precast components produced in the different production lines do not have to comply with this rule. For example, if the due date of the precast component at the sequence 3 in the line 1 is earlier than the one at the sequence 2 in the line 2, it is reasonable for the former to have higher priority, although it may be produced later.

If the priorities of precast components to use molds are given, the constraint of the quantity of molds is expressed as the Eq. (13) based on the rule that the precast components with higher priorities get

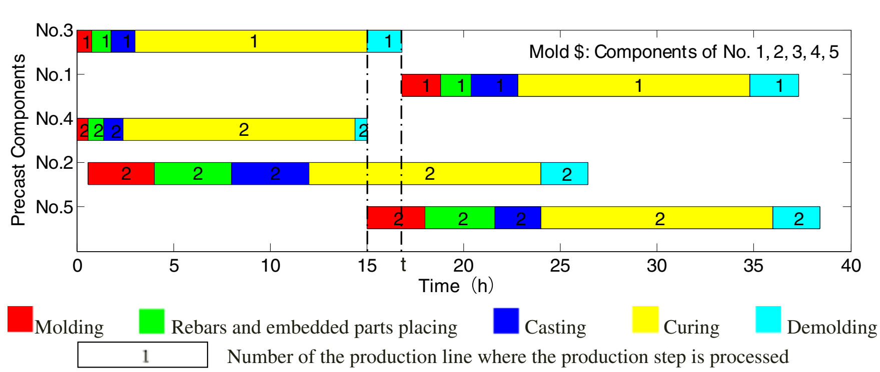

Fig. 1. Gantt chart of a schedule generated based on the MP-FSM.

Table 2
Schedule for precast component No.3 in Fig. 1.

	M1	M2	M3	M4	M5
Start time	0:00	0:46	1:47	3:00	15:00
End time	0:46	1:47	3:00	15:00	16.49

molds earlier than the others of the same type.

$$S\left(J_{l,i}^{j,\$}, M_{l,1}\right) \geq \mathrm{Min}\left\{\mathrm{Max}^{Q_\$}_{\forall l' \epsilon N^+|l' \leq L, \forall y \epsilon N^+|y \leq N, \forall x \epsilon N^+|x<j}\left[C\left(J_{l',y}^{x,\$}, M_{l,6}\right)\right]\right\} \tag{13}$$

Where: $J_{l,i}^{j,\$}$ is the serial number of the precast component of type \$ produced in production line l at the sequence i, the priority of which is the integer j (The bigger j is, the higher the priority is);

$Q_\$$ is the total quantity of molds of type \$ in the flowshop, where \$ represents the type of the molds such as type A or type B;

$Max^{Qs}_{\forall l' \in N^+|l' \leq L, \forall y \in N^+|y \leq N, \forall x \in N^+|x<j} f(l', y, x)$

stands for the first $Q_\$$ maximum values of $f(l', y, x)$, where the domain of variables is $\forall l' \epsilon N^+|l' \leq L$, $\forall y \epsilon N^+|y \leq N$, $\forall x \epsilon N^+|x<j$. 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 $Q_\$ = 4$. In the Eq. (13) the $f(l', y, x)$ represents $C(J_{l',y}^{x,\$}, M_{l,6})$; and

L, N, N^+, $M_{l,k}$, $S(J_{l,i}^{j,\$}, M_{l,k})$ and $C(J_{l,i}^{j,\$}, M_{l,k})$ are the same as in the previous equations.

The meaning of Eq. (13) is that a new component of type \$ cannot be produced before any of the \$-type molds is released and become available to use, where the release time of each mold can be calculated by

$Max^{Qs}_{\forall l' \in N^+|l' \leq L, \forall y \in N^+|y \leq N, \forall x \in N^+|x<j} f[C(J_{l',y}^{x,\$}, M_{l,6})]$, namely the complete time of the last $Q_\$$ components of type \$ being produced before the new component.

As a typical example of the optimization constraint, five \$-type precast components numbered from 1 to 5, namely J_1, J_2, J_3, J_4 and J_5, are produced in two production lines equipped with 3 molds of the type. Their priorities to use molds follows $J_4 > J_2 > J_3 > J_5 > J_1$. The Gantt chart of a feasible flowshop schedule is shown in Fig. 1.

In the Gantt chart, the horizontal axis stands for the time and the vertical axis stands for the serial number of the precast component. The colored bars represent the production steps of the precast components, so the starts and the ends of them represent the start time and end time of the production steps. The serial numbers inside the bars represent the production lines in which the steps are processed. Taking the precast component No.3 in Fig. 1 as an example, it is produced in the first production line, while the start time and the end time of its production steps is shown in Table 2 if the initial time for production is assumed as 0:00.

In the example as shown in Fig. 1, the molds are not enough at the moment 15 h, because only 3 molds exist. Precast component No.5 occupies the mold released from precast component No.4 in preference to precast component No.1, because the priority of precast component No.5 is higher. Therefore, precast component No.1 has to wait until the precast component No.3 is completed, namely the moment t, because the precast component No.3 is the earliest one to be completed and release its mold among the last three precast components produced before precast component No.1.

Table 3
Information of precast components.

Component		Processing time (h)						Penalty (\$) rate per hour	
ID	Mold family	M1	M2	M3	M4	M5	Due date (h)	Earliness	Tardiness
1	A	2	1.6	2.4	12	2.5	112	2	10
2	B	3.4	4	4	12	2.4	112	2	10
3	A	0.8	1	1.2	12	0.8	112	2	10
4	A	0.6	0.8	1	12	0.6	112	2	10
5	C	3	3.6	2.4	12	2.4	144	2	10
6	A	3	3.2	3	12	3	128	2	10
7	C	1.3	0.9	2.4	12	1.9	144	2	10
8	B	1.7	1.4	1.1	12	0.9	144	2	10
9	A	2.2	1.8	1.2	12	2.3	144	2	10
10	C	1.6	3.2	2.3	12	2.1	240	2	10

3.2.2. Constraint of the quantity of production pallets

As mentioned in Section 2, it is essential to allocate the pallets to the components and ensure that the available pallets are always more than the precast components being produced simultaneously, as corresponds to the item No.10 in Table 1.

In the MP-FSM, production pallets are allocated according to the aforementioned priorities of precast components to use molds in order to guarantee that the precast components assigned with molds will have production pallets. Hence, unnecessary occupancy of molds and production pallets can be avoided in this way. This paper only presents the equation of the optimization constraint as shown by Eq. (14) without further explanation, due to its similarity to the constraint of the quantity of molds.

$$S\left(J_{l,i}^{j}, M_{l,1}\right) \geq \mathrm{Min}\left\{\mathrm{Max}^{P}_{\forall l' \epsilon N^+|l' \leq L, \forall y \epsilon N^+|y \leq N, \forall x \epsilon N^+|x<j}\left[C\left(J_{l',y}^{x}, M_{l,6}\right)\right]\right\} \tag{14}$$

Where: $J_{l,i}^{j}$ is the serial number of the precast component produced in production line l at the sequence i, the priority of which is j;

P is the total quantity of production pallets in the flowshop; and

L, N, N^+, $M_{l,k}$, $S(J_{l,i}^{j,\$}, M_{l,k})$ and $C(J_{l,i}^{j,\$}, M_{l,k})$ are the same as in the previous equations.

4. Flowshop scheduling based on the MP-FSM

Based on the MP-FSM, optimized flowshop schedules of multiple production lines for precast production can be generated by using optimization algorithms. In the section, the principle for flowshop scheduling based on the MP-FSM is introduced and a scheduling approach by using GA is presented through a case study.

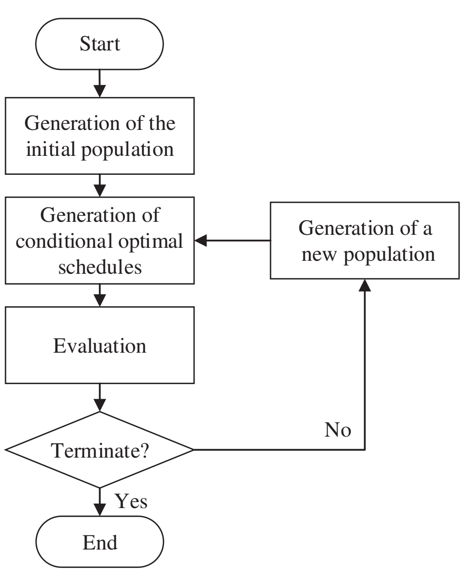

Fig. 2. Flowchart of the proposed scheduling approach.

Component serial No.	6	2	3	1	5	4	10	8	7	9
Line serial No.	1	2	2	2	2	1	1	1	2	1

Fig. 3. Encoding schema.

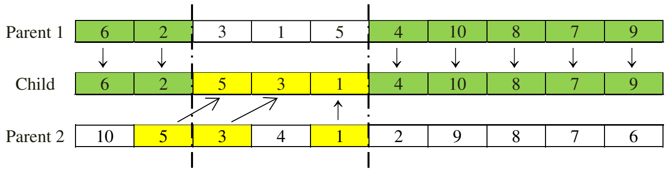

Fig. 4. Cross over operator for the line of component-serial-No.

4.1. Principle for flowshop scheduling based on the MP-FSM

In most cases, the production requirements (such as the quantity of precast components of each type) and conditions (such as the buffer size) can be pre-determined, the only variables in the optimization objectives and constraints are the allocation plan of the precast components to the production lines, their production sequences, and their priorities to use molds, which are totally called production arrangements in this paper.

Generally, optimal flowshop schedules can be generated based on the MP_FSM by the following steps.

Step 1. Enumerate all the possible production arrangements of the precast components;

Step 2. For each production arrangement, generate the conditionally optimal schedule based on the Eqs. (1), (2), (3) and from (5) to (14) in the way described in the following paragraph, because even if the production arrangement is given, more than one feasible schedule can be generated according to it;

Step 3. Evaluate the schedules by the optimization objectives, namely the Eqs. (1), (2), (3) and (5), and select the optimal one from them.

The conditionally optimal schedule corresponding to a given the production arrangement can be generated by calculating the most suitable start time and the end time of each production step of each component which is obviously the earliest moment to start and end the steps but satisfies the optimization constraints, namely the Eqs. from (6) through (14).

4.2. Approach for flowshop scheduling based on the MP-FSM by using GA

Since the calculation is complex and onerous in the aforementioned steps, optimization algorithms have been used in the existing studies to reduce the quantity of enumeration required in the principle. By reviewing relevant publications, it was concluded by Wall [18] and Tormos et al. [17] that GA is ideal for solving such nonlinear scheduling problems, where the search space is large and the number of feasible solutions is small, because it operate on a population of solutions rather than on one individual and use no gradient or other problem specific information. Other studies also support the conclusion. For instance, Wu et al. [20] compared GA and local search heuristics in generating robust schedules and found that schedules generated by using GA had shorter makespan. Lei [11] concluded that GA performs better than Simulated Annealing (SA) and Particle Swarm Optimization (PSO) for stochastic job shop scheduling problems by conducting computational tests.

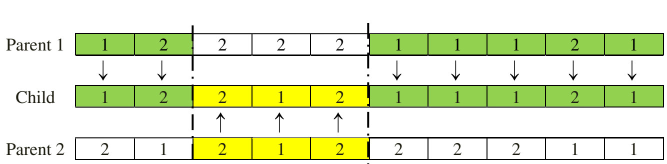

Fig. 5. Cross over operator for the line of line-serial-No.

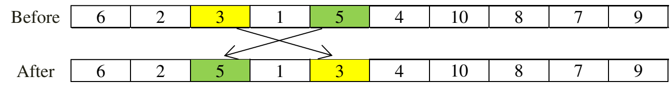

Fig. 6. Mutation operator for the line of component-serial-No.

Thus, in this research, GA is selected for the scheduling of precast production based on the MP-FSM.

The flowchart of the proposed approach for flowshop scheduling based on the MP-FSM by using GA is shown in Fig. 2, including following steps.

Step 1. Generate the initial population of chromosomes, each of which represents a production arrangement;

Step 2. Generate the conditional optimal schedules corresponding to the chromosomes by following the step 2 in the principle for flowshop scheduling based on the MP-FSM as mentioned in Section 4.1;

Step 3. Evaluate them based on the optimization objectives and determine whether to terminate;

Step 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 second step; otherwise, end the calculation and output the optimal schedule selected by step 3.

The optimization terminates when the quantity of iterations reaches the limit given by schedulers. All the steps are introduced in detail via a case study as follows.

The case is shown in Table 3. It was derived by referring to the case used by Benjaoran et al. [2] for scheduling a single production line, which was also used in the validation of Ko et al.'s study (2010). In the case, 10 precast components are produced in a plant with 2 production lines. The precast components share 7 production pallets and 7 molds, of which 3 molds are of type A, 2 molds are of type B and 2 molds are of type C. 3 shifts are applied in the production, which guarantee the continual production during the whole day. To highlight the objectives and constraints proposed in the research, the size of the buffer between workstations and curing rooms is set as 10 to be large enough to handle all the precast components at the same time.

4.2.1. Generation of the initial population

Based on the GA theory, the production arrangements are required to be encoded into chromosomes. Then, the initial population of chromosomes should be generated to start the GA iteration.

The encoding of production arrangements is designed as follows. As mentioned in Section 3.2.1, the priorities of precast components should be consistent with the production sequence of precast components in each production line. Thus, the production sequence of precast components in a production line is dependent only upon the other two variables in the production arrangement, i.e. the allocation plan of the precast components to the production lines and their priorities to use molds. Hence, this research encodes the production arrangements by using only the allocation plan of the precast components to the production lines and their priorities to use molds as 2*n matrixes, where n is the quantity of precast components. The serial numbers of components are listed as genes in the first line of the matrixes and their sequence represents their priorities to use molds. For example, 6 stands for the precast component whose serial number is 6, namely J_6. The serial numbers of production lines, which are listed as genes in the second line of

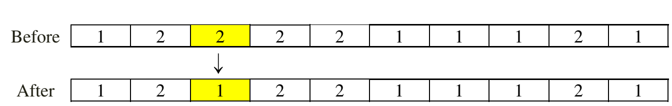

Fig. 7. Mutation operator for the line of line-serial-No.

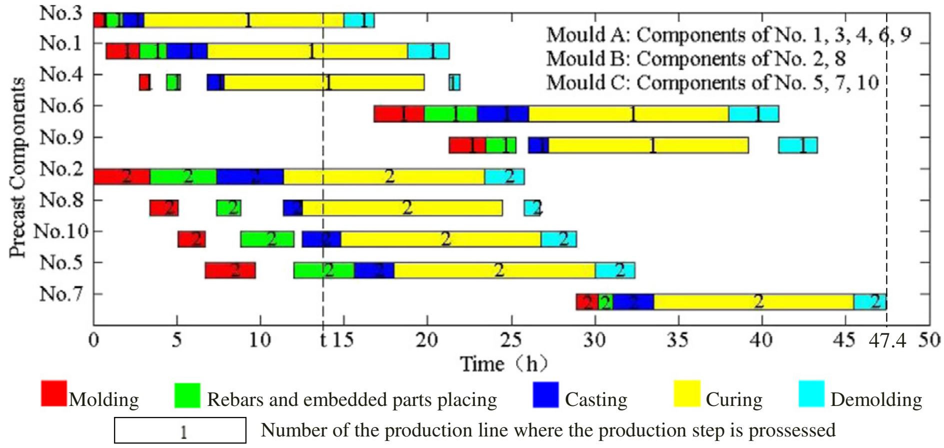

Fig. 8. Generated Gantt chart of the case.

the matrixes, represent the production lines where the components right above the serial numbers are produced. In this way, convergence speed of the scheduling can be increased because the size of each chromosome is reduced so that the searching space of GA is reduced [19].

The initial population of chromosomes is determined by randomly generating the aforementioned matrixes. The quantity of chromosomes in a population including the initial one was determined as 100, which had been decided by trial and error to minimize the computation time. As an example, Fig. 3 is a typical chromosome in the initial population during the scheduling of the case. It represents a production arrangement as follows. The sequence of production in production line 1 is J_6, J_4, J_{10}, J_8, J_9 and that in production line 2 is J_2, J_3, J_1, J_5, J_7. Besides, the priorities of the 6 precast components to use molds follow $J_6 > J_2 > J_3 > J_1 > J_5 > J_4 > J_{10} > J_8 > J_7 > J_9$.

4.2.2. Generation of conditional optimal schedules

The conditional optimal schedule of each chromosome in a population can be generated based on the Eqs. (1), (2), (3) and from Eq. (5) to (14) by following the step 2 in the principle for flowshop scheduling based on the MP-FSM as described in Section 4.1.

4.2.3. Evaluation

All the schedules obtained in the above step need to be evaluated by the optimization objectives. Since more than one objective are used in the MP-FSM, a multi-objective function is used as a combination of them, which is presented as Eq. (15).

$$f = w_{WI} * \left(\frac{f_{WI}}{f_{WI}^*}\right) + w_{CS} * \left(\frac{f_{CS}}{f_{CS}^*}\right) + w_{MS} * \left(\frac{f_{MS}}{f_{MS}^*}\right) + w_{TC} * \left(\frac{f_{TC}}{f_{TC}^*}\right) \qquad (15)$$

Where: f is the unfitness value of the evaluated schedule;

w_{WI}, w_{CS}, w_{MS} and w_{MS} are the weights of the optimization objectives WI, CS, MS and TC respectively;

f_{WI}, f_{CS}, f_{MS} and f_{TC} are the values of the optimization objectives WI, CS, MS and TC respectively calculated by the aforementioned equations; and

f_{WI}^*, f_{CS}^*, f_{MS}^* and f_{TC}^* are the smallest values of the optimization objectives WI, CS, MS and TC respectively among the schedules in the last population;

In the equation, weights of the optimization objectives are given by the schedulers to reflect the difference in the importance of the objectives. Moreover, since the range of the value of each optimization objective is different, f_{WI}^*, f_{CS}^*, f_{MS}^* and f_{TC}^* are used to normalize them.

After evaluation, the conditional optimal schedule with the lowest unfitness value is adopted as the optimal schedule, when the quantity of iterations reaches the predetermined limit 500 which was decided by analyzing the convergence curve of unfitness values during the iteration of previous scheduling experiments. Otherwise, 50 chromosomes are selected as the parents for the next population. The Roulette Wheel selection is used to select the chromosomes, where the chance of them to be selected is inversely proportional to the unfitness value [13].

4.2.4. Generation of a new population

Based on the parents selected in the last step as described in Section 4.2.3, 50 new chromosomes can be obtained by crossing over as follows. First, divide the 50 parent chromosomes into 25 pairs randomly. Second, determine two cut points are randomly for each pair. Third, cross over the two parent chromosomes in each pair to generate a child chromosome according to the cut points. During the cross over, the first line of the child chromosome is generated by following the order-based crossover operator, namely the OX2 [10] as shown in Fig. 4, while the second line of the child chromosome is generated by following the

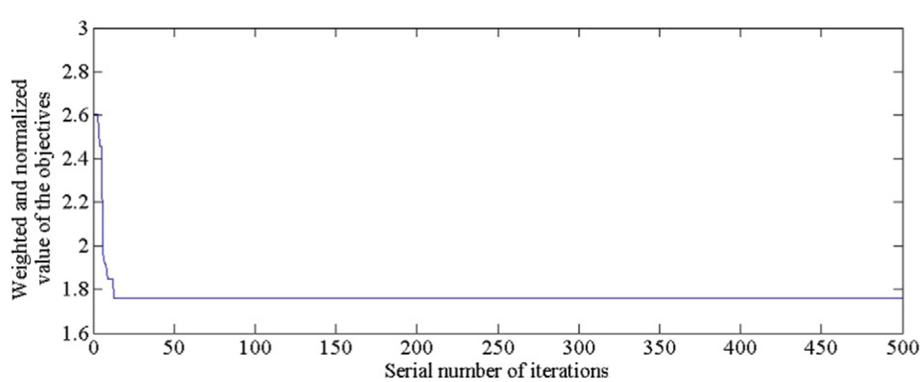

Fig. 9. Convergence curve of the case.

Table 4
Parameters and makespan of seven scheduling cases.

Case	Quantity of components			Quantity of molds			Quantity of production pallets	Quantity of production lines	Makespan			
	Type A	Type B	Type C	Type A	Type B	Type C			EDD	SPT	LST	MP-FSM
1	7	8	5	5	3	3	10	3	83.4	82.2	77.4	77.4
2	3	7	5	4	3	3	11	4	79.4	79.4	77.4	77.4
3	5	5	6	2	2	3	9	2	79.4	80.2	79.4	77.4
4	4	3	6	3	3	3	8	4	41	41	46.4	41
5	7	8	7	4	4	4	15	4	61.8	56.4	57.6	54.4
6	10	11	7	3	5	3	15	3	84.6	82.8	82	82
7	9	4	10	5	4	3	10	3	67.2	67.2	86	67.2

basic two point cross over operator [6] as shown in Fig. 5. Since both cross over operators are well used and have already been applied in many other studies, the detail explanation about them is hence not included in the paper. Finally, interchange the two parent chromosomes in each pair and cross over them again to generate another child chromosome. Thus, 50 new child chromosomes are generated after the cross over of the 25 chromosome pairs.

A 0.5% chance of mutation is adopted for each chromosome as recommend by Ko and Wang [9]. During the mutation, the position of two randomly selected genes is interchanged if the mutation happens in the first line of the chromosomes as shown in Fig. 6. Meanwhile, if the mutation happens in the second line, the value of a randomly selected gene is changed as shown in the Fig. 7.

Thus, a new population is generated by combining these 50 new chromosomes and their parent chromosomes. Then, the new population goes back to the step 2, namely generation of conditional optimal schedules, until the quantity of iterations reached its limit.

In this way, the optimization of production sequence and the allocation of the shared resources (such as molds and production pallets) and production tasks (namely precast components) can be done by optimizing the production arrangements based on the MP-FSM by using GA. Hence the optimized schedule is generated in the case.

The above-mentioned steps were realized in Matlab software [14]. After setting the weights of each optimization objectives as $w_{WI} = 0\%$, $w_{CS} = 72\%$, $w_{MS} = 14\%$ and $w_{MS} = 14\%$, the optimal schedule of the case was generated and its Gantt chart is shown in Fig. 8. The production of all the precast components can be completed in 47.4 h according to the schedule. It is obvious that all the optimization objectives were achieved. Take the objective of minimizing type change of precast components during production, namely, the item 4 in the Table 1, as an example. In the schedule, all the precast components of the same type were sequenced next to each other. For instance, all the components produced in the production line 1, namely precast components No.3, 1, 4, 6 and 9, are of type A. Then, the objective was achieved. Moreover, all the optimization constraints were satisfied in the schedule. Take the constraints of the quantity of molds, namely, the item 9 in the Table 1, as an example. In the schedule, the total quantity of precast components of type A being produced simultaneously was ≤3, which were the quantities of molds of the type. Similarly, those of precast components of type B and C are not more than the quantities of the molds of the type respectively. It can be directly checked by drawing a vertical line at any time t in the chart and comparing the quantity of the components of each type which cross the line of time t with the total quantity of molds of the type.

The minimum of the weighted and normalized value of the objectives in each population during calculation is depicted in the convergence curve of Fig. 9. Based on the curve and the principle of GA, the schedule in the Fig. 8 can be trusted as the optimal solution of the case within limited calculation loads.

5. Preliminary validation

To validate the performance of the proposed approach preliminarily, comparative experiments with the scheduling based on the dispatching rule technique using Earliest Due Date (EDD) rule, Shortest Processing Time (SPT) rule and Least Slack Time (LST) rule, were conducted, where only the optimization objective of makespan minimization was used to simplify the comparison.

Seven scheduling cases were carried out to compare the performance of the two approaches. Moreover, as mentioned in the Section 3.2, except the constraints of the quantity of molds and production pallets for multiple production lines, the other constraints in MP-FSM are not originally proposed in the research. Therefore, only the parameters relative to the proposed constraints, namely, the quantity of precast components of each type, molds of each type, production pallets and production lines are set to be variables and determined randomly to construct the seven different the cases as shown in Table 3. They are the quantity of components, molds and production pallets. Meanwhile, the due time for components of type A, B and C was 112 h, 144 h and 112 h respectively. The other parameters remained constant and are the same as the aforementioned case in the last section. To minimize only the makespan, the weights of each optimization objectives were set as $w_{WI} = 0\%$, $w_{CS} = 0\%$, $w_{MS} = 100\%$ and $w_{MS} = 0\%$. Moreover, the dispatching rule technique based schedules in the seven cases were generated by using Asprova [1].

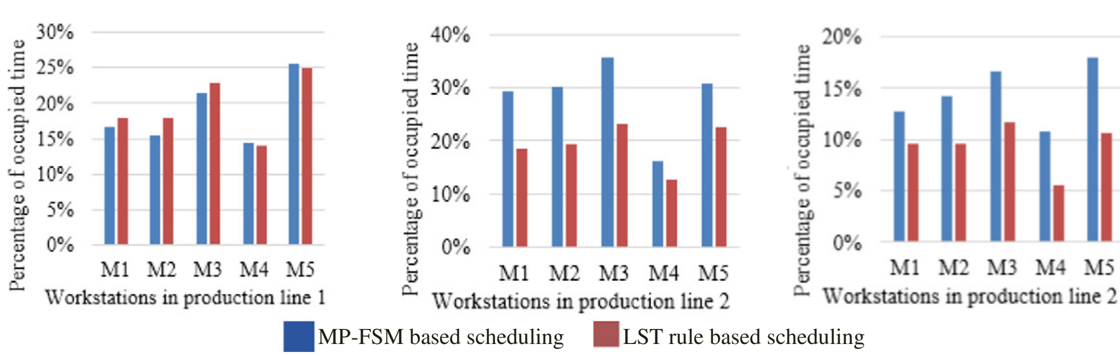

Fig. 10. Percentage of resource occupied time in Case 7.

Table 4 reveals that the MP-FSM based schedules have shorter makespan than the dispatching rule technique based ones in the most cases. For instance, compared with the EDD rule based scheduling, the MP-FSM based scheduling demonstrates better performance in the >70% cases.

Moreover, Table 4 shows that in the same case, the performance of schedules generated by various dispatching rules is different, but no clear conclusion can be drawn about which rule is always the best. It indicates that the performance of dispatching rule technique based scheduling highly depends on the experience of schedulers in selecting dispatching rules and sometimes trial and error is necessary for the rule selection. On the contrary, the MP-FSM based scheduling is not only optimized but also friendly to beginners, because the schedule is optimized by using GA.

The percentage of occupied time of workstations in the MP-FSM based schedule and the LST rule based one in case 7 were analyzed and visualized in Fig. 10. In the figure, the horizontal axis stands for the workstations in each production line and the vertical axis stands for the percentage of occupied time of each workstation during the whole production process. It is easy to find that the percentage of resource utilization in the schedule based on the MP-FSM is higher than that of the schedule based on LST rule in most cases. Yet, percentage of resource utilization in some workstations in production line 1 is not consistent with the trend, which is because the objective of the calculation is to minimize the total makespan but not that of a specific production line.

6. Conclusion

This paper proposes a Flowshop Scheduling Model of Multiple production lines for Precast production (MP-FSM) and a corresponding optimization approach to facilitate optimized scheduling by using GA with preliminary validation. The key contributions to the body of knowledge are summarized as follows.

- A number of practical optimization objectives and constraints were identified, such as the objective of minimizing type change of precast components during production and the constraint of the quantity of production pallets, which have not been considered in the previous studies.
- The MP-FSM, the mathematic model of the proposed optimization objectives and constraints for multiple production lines was established in contrary to the previous studies which are based on the production scenario of a single production line,
- An optimized approach for flowshop scheduling of precast production was also proposed based on the MP-FSM, in which the allocation of the shared resources (such as molds and production pallets) can be traded off by using the GA method. The experiments also concluded the proposed approach was able to achieve optimized schedules comparing to the traditional one.

When the schedules are not optimized, the unpredicted flexibility of production capability during scheduling can works as the buffer for unexpected conditions. Therefore, the control of the process is increasingly difficult and important when the schedules become increasingly precise and optimal. Thus, advanced and effective production control, especially dynamic method to maintain and realize the optimal schedules, is the future direction of the research.

Acknowledgement

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