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Optimal single-machine batch scheduling for the manufacture, transportation and JIT assembly of precast construction with changeover costs within due dates

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ABSTRACT

The manufacture, transportation and on-site assembly sectors of precast construction projects are often considered separately and managed by rule of thumb, causing an inefficient use of resources and postponed delivery. This study views these sectors as a whole from the perspective of a single machine batch-scheduling problem. A dynamic programming algorithm, which aims to search for solutions that entail maximum production efficiency, was developed accordingly with the constraints of changeover costs and production deadlines. We tested the method's ability by processing as many products as possible simultaneously using real data collected from a precast factory in a simulation and compared the effect with a previous study. We found that our method possesses great potential to improve the efficiency of precast production.

1. Introduction

Precast construction is one of the newer technologies that can reduce construction waste effectively and is gradually being recognized as a more ecological and sustainable approach in large cities [1]. However, the previous research efforts primarily focus on the study of production sector and the effects of considering the Manufacture, transportation and on-site Assembly (MtA) sectors simultaneously in the scheduling plan and batching and lot-sizing are not being investigated. One of the reasons is the substantial equipment adjustments and operation changes that frequently occur in production when switching from one product class to another [2]. The longer time required in the design and manufacturing phases and much shorter time in the assembly phase complicates the production scheduling of precast components-forcing schedulers into the use of an overly subjective 'rule of thumb' approach [3]. Thus, large storage spaces are occupied in waiting for the last of a batch of components to be delivered, causing an inefficient use of resources and delays in deliveries [4]. This has led to the inefficient use of resources and overstocking in the precast industry [3,5], which, according to Tam et al. [6], is restricting its development by creating an additional expense that contractors and developers can ill afford. As a result, it is mostly confined to repetitive public housing due to its high initial costs, time in the initial design development and lack of experience of contractors, resulting in a lack of demand for precast components [6]. Therefore, maximizing the precast production efficiency is the key to promote the development of precast construction projects.

Many studies focus on applying computerized scheduling techniques to provide more appropriate production plans to enhance effective resource utilization and minimize cost. Since the fabricator usually deals with the orders one by one, this leads to inefficient resource utilization and overstocking in the precast industry [3,5]. The precast factory cannot process all the orders at the same time due to the lack of such resources as machines, workers and storage areas. Thus, different orders from different contractors for hundreds of different precast components may await production. Importantly, the production of different types of precast components takes a different amount of time, and some may take longer than those requiring on-site assembly. What is needed is to find a sequence of precast components on the fabricators' production line that minimizes the total changeover and inventory holding costs by considering the MtA sectors simultaneously, subject to maintaining Just-In-Time (JIT) deliveries for all contractors.

Therefore, the scenario is investigated where the precast manufacturer accepts only some of the orders from the contractors due to limited storage space available, and the precast components of each order have to be manufactured in one factory, transported to the respective construction sites separately and then assembled. The problem of defining the optimal order sequencing is analytically modeled with the aim

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of maximizing the production efficiency by reducing it to a single machine group-scheduling problem with deadlines by integrating the MtA sectors involved. An enhanced precast production scheduling method is developed to search for solutions with maximized production efficiency by coordinating production scheduling and delivery decisions with the JIT philosophy. This involves the development of an algorithm based on Cheng and Kovalyov [7] schema of dynamic programming algorithm. Finally, a simulated case based on a real-life Chinese precast factory is used to demonstrate and test the model's ability to improve the production efficiency by processing as many orders as possible.

The paper is organized as follows. In Section 2, the literature relating to scheduling problems for precast construction is briefly reviewed. Section 3 provides the notation and model formulation. Section 4 depicts the precast production process in mathematical form to maximum the production efficiency considering the changeover costs. In Section 5, a simulated case based on an actual Chinese precast concrete factory is used to demonstrate and validate the applicability of the model. Section 6 contains concluding remarks concerning the limitations of the study and prospects for future research.

2. Precast production scheduling

A great amount of research into precast production scheduling has been published to date in academic journals worldwide [8]. Leu and Hwang [9], for example, propose a flowshop scheduling model for resource-constrained mixed production of precast components and a Genetic Algorithm (GA)-based scheduling approach correspondingly to minimize the makespan. Benjaoran and Dawood [10] formulate a six step precast component production as a flowshop scheduling model with six machines in conjunction with GA-based optimization to minimize total flowtime, which provides statistically better schedules than from the traditional Earliest Due Date (EDD) of around 25% (total flowtime reduction). Zhai et al. [11] consider a scheduling model for make-to-order precast production based on a simulation technique and GA to minimize total costs. Ko and Wang [3] develop a multi-objective GA to solve the precast production scheduling model with minimum makespan and delay penalties, allowing for production resources and buffer size between workstations to store the work-in-processes. Tharmmaphornphilas and Sareinpithak [12] develop a heuristic approach to select concrete formulae and schedule jobs to minimize total product cost. Yang et al. [2] propose their Flowshop Scheduling Model of Multiple production lines for Precast production (MP-FSM) and apply GA optimization to minimize the changes in types of precast components during production. Another approach, by Arashpour et al. [13], models the problem of off-site construction producing multiple classes of products with multi-skilled resources to minimize changeover time in production when switching from one product class to another using the optimization-based metaheuristics-tabu search to find the optimal sequence in off-site production of $n$building elements. Their results indicate customer demand to be the most sensitive factor in obtaining the optimal sequence of multiple classes of products and the earliest due dates within product classes.

Although the MtA sectors of precast components are strongly linked and should be treated as a unified system [14], the few existing models that do this are either special cases of, or have a different structure to, our problem. For instance, Anvari et al. [14] use a GA-based optimization approach to a holistic MtA problem while sharing resources and the sequencing and timing of operations for a special case where the assembly area is also the manufacturing area, so that resources can be shared. In our research, the factory is in an inexpensive area far from the on-site assembly areas to save manufacturing costs [15] and therefore no resources can be shared between the two sectors. This is closer to the real problems of precast construction, where the MtA sectors need to be considered simultaneously.

Secondly, the prefabrication planning models of previous research consider precast components to be separate jobs with the same individually produced operations, with the GA being used widely to optimize the sequence of job operations to minimize total cost or reduce resource wastage. Hence, most studies do not take changeover cost into account. In reality, precast components can be generally grouped into several types, such as precast wall panels, beams, columns, slabs, balconies and staircases. Different orders of the same type of precast units may be produced with the same mold group with slight variations [16] or with different mold group. However, frequent production changes from one type of precast component to another can lead to substantial equipment adjustments and operation changes, which reduce production efficiency and increase costs [12]. Khalili and Chua [16], for example, establish a scheduling model for precast modular units that enables several building elements to be produced, transported and installed as units, and propose a mixed integer linear programming method to solve the scheduling problem involved. The difference in our research is that the scheduling of precast construction incorporates batching and lot-sizing. Precast components of the same type are classed as a group type as they are identical items with the same due date, with the changeover cost being minimized because the same concrete mix or formwork can be used. This is called the grouping concept [17]. On the other hand, a group type of precast components cannot be processed in one production batch, as the inventory holding cost is very high and other group types have to wait too long to be delivered. Therefore, a lot-sizing decision is made to split a production lot of the same type of components into sub-lots [18].

We model the MtA sectors as a whole from the perspective of a single machine batch-scheduling problem applying the batching and lot-sizing concepts. In our method, the deadline of each part type is rescheduled into many different sub-deadlines for each sub-lot, which considers the corresponding transportation times and assembly times. Thus, instead of producing a single large batch of each part type within its deadline, our method shows it's preferable to produce smaller batches of part type within their sub-deadlines so that the inventory storage areas can be released timely. We found that our method possesses great potential to improve the efficiency of precast production.

3. Model formulation

3.1. Problem description

The fabricator usually deals with the contractors' orders serially because frequently changing the type of precast components during production involves substantial equipment adjustments and operation changes [2]. Large quantities of precast components are piled orderly in a precast factory waiting for delivery, as it takes a long time to produce one order of components. Moreover, the precast components produced are usually bulky, large and heavy and need large storage areas; therefore, different orders from different contractors have to wait to be produced due to limited storage areas available prior to delivery to the construction site for direct assembly, where JIT delivery is advocated to improve customer service level. This involves the manufacturer incurring a storage cost that depends on inventory size and storage time. Thus, the cost of producing precast components can be very high if the manufacturing factory is located in an urban area. On the other hand, transportation costs will be much higher if it is located in a less expensive region outside the urban area. These are two of the main factors that make the direct cost of precast construction much higher than traditional construction and clearly a trade-off is needed. However, in reality, most precast factories are located where the costs of production are low irrespective of the transportation involved [15].

Here, we consider the scheduling problems of precast construction in which both changeover/delay-penalty costs of component manufacture and JIT deliveries apply. The orders of all the precast components are divided into several part types according to the types of components involved. Scheduling the resource of production orders allows fabricators to assess the effectiveness of resource utilization, reduce costs and analyze potential delivery delays. For example, steel molds are generally reused by the fabricators to save construction cost and time after they are stripped [2]. Other shared resources include a concrete mixer and vibrating table. Thus, the completion time of orders are sequence dependent and changeover cost is incurred in switching from one order of components to another. Because of the time-consuming and costly changeovers between different precast groups, production line efficiency is maximized by choosing a long run-length for each precast group. On the other hand, the urgency of orders for columns and slabs varies; some may be due imminently, while others may not be urgent. Customer service may then be improved by having smaller batches. For example, instead of producing a single large batch of wall panels in the current month and a single large batch of precast staircases the next month, it may be preferable to produce smaller batches of both wall panels and staircases in the current month to accommodate urgent orders and release the inventory storage areas with minimized inventory costs, and process the remaining orders the next month.

The precast components are delivered in batches to their respective contractors, the size of which is limited by the daily needs of their respective projects, as JIT delivery can both help achieve better customer services and reduce inventory holding costs. The batch delivery time depends on the schedule of the project to which the batch is delivered. This contains the times the contractors start their assembly activities, which are also the completion times of the production periods of the components. The objective is to find the sequence of precast components on the fabricators' production line to maximize the production efficiency, subject to maintaining JIT deliveries for all contractors.

3.2. Problem assumptions

To study such a complex decision-making problem, our notation is summarized in Table 1, and the following assumptions are made:

1) Delivery vehicles are fully loaded every trip to ensure the total delivery cost is fixed and each vehicle carries only one type of precast component. Because delivery vehicles with full capacity can deliver very limited precast components in the transportation sector, such as, a 20-foot truck with only two precast components of facades [19], the trucks carried only an average of 1.4 pieces per trip [20].
2) There is only one production line, with limited steel molds, in the factory. This assumption is based on the actual precast manufacturing factory (mentioned in section 5) where there is only one production line. Since the processing time for placing reinforcement and embedded parts and concrete casting is much shorter than the processing time needed for curing, single production line in one precast manufacturing factory is plausible.
3) Only the same component part type can be produced in a production batch - the maximum set of precast components that can be manufactured in the same time - and therefore there are no changeover costs within one production batch. Changeover time occurs in production when switching from one product class to another. The fabricators usually finish orders sequentially to minimize the delay and changeover costs. Therefore, it's plausible to produce only the same component part type in one production batch.
4) The two consecutive changeover cost between the same part type $c_{f,f}$, which is less than that between different part types $c_{g,f}, g \neq f$, is not considered. For example, mixing different kinds of concrete batch, preparation of formwork and cleaning of equipment are often required to switch from one class of product to another [13]. Thus, the changeover time between the same part type is much less than that between different part types. For simplicity, the two consecutive changeover cost between the same part type $c_{f,f}$ is set as 0.
5) The manufacturing time includes maintenance time. Equipment periodic maintenance is to prevent the stoppage of equipment. In this research, it's assumed that equipment maintenance needs a time interval in which precast components complete casting so that the maintenance time is part of production time.

Table 1
Notation used in this paper

SYMBOL	DESCRIPTION
F	Total number of orders demanded for production
M	A set of construction sites $M = \{M_1, M_2, \ldots M_F\}$
r_f	The start time for assembling precast component of part type f
t_f	The transportation time of part type f
D_f	The deadline for part type f on site M_f
p_f	The manufacturing time of a single precast component of part type f
P_f	The manufacturing time of one production batch of part type f
v_f	The assembly time of a single precast component of part type f
V_f	The assembly time of one delivery batch of part type f
b	The quantity size of one production batch
b_f	The quantity size of one delivery batch of part type f
q_f	The total number of precast components of part type f
n_f	The total number of production batches of part type f
N	The total number of all production batches;
m_f	The total number of delivery batches of part type f
qi_f	The quantity size of inventories of part type f
C_k	The completion time of the k th production batch
$c_{g,f}$	Changeover cost incurred when one production batch of part type f is produced after that of part type g, $(f \neq g)$
B	The sequence of production batches
T	The total changeover costs

3.3. Mathematical model

A set of F types of independent non-preemptive orders from the construction contractors, each belonging to one of the construction sites $M_1, M_2, \ldots, M_F$, has to be produced in a manufacturing factory M_0 in a single production line with limited steel molds. Each precast component of part type f is ready for manufacturing at time zero and has to be produced first in the factory M_0 and then transported to the construction site $M_f (f = 1, \ldots, F)$ for assembly. As is illustrated in Fig. 1, each precast component of part type f has a manufacturing time p_f in the factory M_0, a transportation time t_f, and an assembly time v_f on the construction site $M_f (f = 1, \ldots, F)$. The model description is as follows: There are q_f precast units of part type f that need to be produced first and then assembled on site. Each precast component of part type f has a processing requirement p_f on machine M_0 (manufacturing factory M_0) and a processing requirement v_f on machine M_f (construction site M_f) $f = 1, \ldots, F$. Thus, the above scheduling problem can be modeled as a single machine batch-scheduling problem [7].

A changeover cost $c_{g,f}$ is incurred if a production batch of part type f is manufactured immediately after a production batch of part type $g \neq f$. A maximum set of precast components manufactured at the same time is called a production batch. The precast components of a production batch are manufactured in a batch of the same size b, which is determined by the number of steel molds. Due to the high cost of steel molds, difficulty in shifting and the great variety of elements involved, fabricators usually produce all construction elements from a limited number of molds to effectively reduce the cost [4]. If the number of precast components of each part type, q_f is a multiple of b, such that $q_f = bn_f f = 1, \ldots, F$. Otherwise, $n_f = \text{int}[q_f/b] + 1$ (where int[X] means the integer part of X). Therefore, there are n_f production batches of part type f. Denote the total number of production batches as $N = \sum_{f=1}^{F} n_f$.

The precast components of the same part type f are delivered in a JIT philosophy with batches of the same size b_f, which is the daily consumption on construction site M_f because of the congested state of the site and expensive costs involved in second handling the bulky components. After the manufacture of all the precast components of a delivery batch of part type f is completed, they are immediately transported to the construction site M_f so as to relieve the factory storage areas of the consecutively manufactured components. Thus, the inventory cost is minimized. It is assumed that there are m_f delivery batches of part

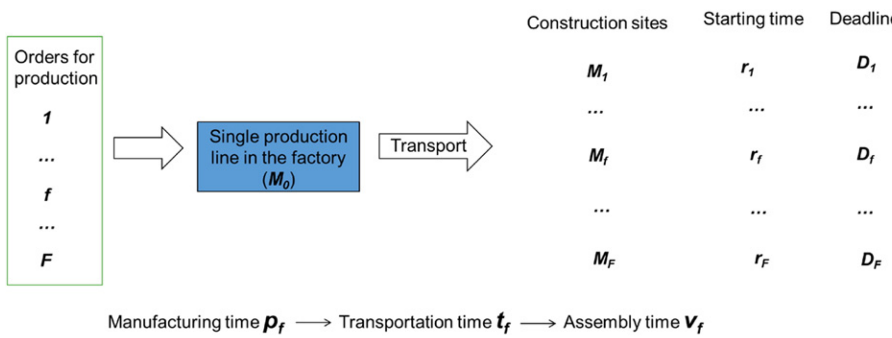


Fig. 1. Illustration of precast production considering transportation and assembly times.

type f, thus $q_f = bn_f = m_f b_f$. All numerical parameters are assumed to be non-negative integers.

The corresponding transportation time is equal to t_f. The precast components used for each construction site M_f have a start time r_f and deadline $F_f f = 1, \ldots, F$. The first delivery batch of part type f must be completed by time $r_f - t_f$. If started at time r_f, they will be completely assembled at time $r_f + b_f v_f$. Then, to maintain JIT delivery on construction site M_f, the manufacture of the second delivery batch of part type f must be completed by time $r_f - t_f + b_f v_f$. By continuing in a similar way, the latest possible completion times for all the precast components manufactured in the factory can be determined.

This problem is closely related to batch scheduling problems within limits. Here, the delivery costs are not considered as one of the optimal objectives, as the precast components are very bulky and therefore every delivery truck can deliver only a very limited amount [19,20]. Thus, the total transportation costs of the components are mostly related to the distance and type of vehicle used. However, irrespective of the size of one production batch b being larger than that of delivery batch b_f, a fabricator's inventory holding cost will occur. But the inventory cost is much smaller than that of a single larger size delivery. Thus, by adopting a smaller sized batch production and JIT delivery, the inventory holding costs are minimized. Reduction of inventories provides one of the ways of increasing production, and results in less initial production costs. Therefore, the problem is generalized to a batch delivery problem within deadlines to minimize the changeover and delay penalty costs involved.

The problem can be generalized to a batch delivery scheduling problem, which is known to be NP-hard. Existing studies are reported in Potts and Wassenhove [18] review of the types of models combining batching and lot-sizing decisions with scheduling; and Potts and Kovalyov [21] review of the literature on scheduling with batching, giving details of the basic algorithms and referencing other significant results. Many papers focus on the batch delivery single machine scheduling problem with a common due date to minimize flow times, or earliness/lateness penalties, inventory holding, due date and delivery costs. For example, Dvir Shabtay [22] proves a batch delivery single machine scheduling problem where the due dates are controllable is NP-hard and develops a polynomial time optimization algorithm for two special cases. Ji et al. [23] prove a batch delivery scheduling problem with batch delivery cost on a single machine remains strongly NP-hard and present a dynamic programming algorithm to minimize the sum of the total weighted flow time and delivery cost. Cheng and Gordon [24] also present a polynomial algorithm for a special case of a batch delivery scheduling problem on a single machine. Chen [25] considers a single machine scheduling problem involving both the scheduling of job processing and the scheduling of job delivery and presents a polynomial dynamic programming algorithm for solving this problem. Yin et al. [26] address a batch delivery single-machine scheduling problem in which jobs have an assignable common due window and present a dynamic programming algorithm to solve the problem. Yin et al. [27] consider a single-machine batch delivery scheduling and common due date assignment problem and present polynomial algorithms for some special cases.

The problem addressed in this research is closely related to the batch scheduling problems in Cheng and Kovalyov [7] except that, here, the precast components can be delivered only when the quantity produced reaches the required size of a delivery batch before the delivery date. In addition, the manufacturing time P_f of each production batch in the factory is usually larger than the actual assembly time V_f of each delivery batch. Therefore, special techniques have to be applied to deal with V_f when considering JIT delivery. Also, the assembly time V_f of each delivery batch is the same since the delivery batch size b_f is equal to the daily consumption of construction site M_f.

4. Dynamic programming algorithm

To simplify the terminology, each precast component is now called a *job*. Let delivery batches of part type f be numbered$(1,f)$, $(2,f)$, …,$(m_f,f) f = 1, \ldots, F$. For a job of a delivery batch $j = (i-1)$ $b_f + 1, \ldots, ib_f$, job (j,f) has a manufacturing time p_f and deadline

$$d_{i,j} := D_{i,f} = r_f - t_f + (i-1) b_f v_f, i = 1, \ldots m_f, f = 1, \ldots, F \tag{1}$$

(note that$D_{1,f} \leq \ldots \leq D_{m_f,f}, f = 1, \ldots, F$). The objective of the algorithm is to find a schedule, such that the total costs of changeover and inventory holding are minimized and each job is completed by its deadline.

Recall the total number of production batches is $N = \sum_f^F n_f$, and production batches (i,f) have manufacturing times $P_f = b * p_f$, $i = 1, \ldots, n_f$. Here, the delivery batch b_f is determined by the daily consumption of part type f on construction site M_f to achieve JIT delivery, thus the delivery batch b_f of part type f is different from production batch b. Three situations can occur: (1) $b_f > b$; (2) $b_f = b$; (3) $b_f < b$. If $b_f > b$, more than one production batches of part type f should be processed consecutively each time to ensure the total quantity of precast components produced (and stored as inventory if there is any) is equal or larger than the size of one delivery batch. The case in Cheng and Kovalyov [7], where $b_f = b$, the completion time to reduce the inventory can be exactly the same as the delivery time. When $b_f < b$, the size of one production batch can be set to that of a delivery batch, which is determined by the customers' demands.

The flowchart of the dynamic programming algorithm for the problem is illustrated in Fig. 2. In our dynamic programming formulation, production batches of each part type f are assigned in order $(1,f), \ldots, (n_f,f)$ to the end of partial schedules. With each partial schedule, we associate a set of state variables (state)$(a_1, \ldots, a_F, g)$, where g is the part type of the job scheduled last and a_f is the number of production batches of part type f that are scheduled so far, $f = 1, \ldots, F$and j_f is the number of delivery batches of part type f that are scheduled so far, where $j_f \leq \mathrm{int}[\frac{a_f * b}{b_f}]$, $j_f \in \{1, \ldots, m_f\}$ and its deadline $D_{j_f,f}$. Thus, the inventory of part type $f$is $qi_f = b^* a_f - b_f{}^* j_f$. We call a partial schedule corresponding to the state $(a_1, \ldots, a_F, g)$ feasible if deadlines $D_{j_g,g} j_g = 1, \ldots, m_g$, $g = 1, \ldots, F$, are met. Calculate

$$D_{j_g,g} = \min\{D_{jf,f}\}; C(a_1, \ldots a_F) = \sum_{f=1}^{F} a_f P_f, \text{for } a_f = 0, 1, \ldots, n_f, f = 1, \ldots, F \tag{2}$$

We call state $(a_1, \ldots a_F, g)$ feasible if for $f = 1, \ldots, F$.

$$j_f \le \operatorname{int}\left[\frac{a_f{}^* b}{b_f}\right], j_f \in \{1, \ldots, m_f\}, C(a_1, \ldots a_F) \le D_{j_g,g}, \tag{3}$$

if

$$\begin{aligned} &qi_f + b < b_f; \text{ then.} \\ &C(a_1, \ldots a_F) + P_f \le D_{j_f,f}; \end{aligned} \tag{4}$$

else

$$C(a_1, \ldots a_F) + P_f \le D_{j_f+1,f} \tag{5}$$

$$C(a_1, \ldots a_F) + \sum_{f=1}^{F} P_f \le \max\left\{D_{j_f+1,f} | f = 1, \ldots, F\right\} \tag{6}$$

For the latter inequality, $a_f = n_f - 1$ is assumed, $f = 1, \ldots, F$.

Let $(a_1, \ldots, a_F, g)$denote the minimum total changeover and inventory holding costs of all partial feasible schedules in the feasible state $(a_1, \ldots, a_F, g)$. It is clear that a partial feasible schedule corresponding to this value can be extended to a complete feasible schedule with minimum total changeover and inventory holding costs of all complete feasible schedules extended from partial feasible schedules in the state $(a_1, \ldots, a_F, g)$, if any such schedule exists. The minimum total setup cost for the problem is then equal to

$$T^* = \min\{T(n_1, \ldots, n_F, g) | g = 1, \ldots, F\} \tag{7}$$

where the initialization of the recursion is $T(0, \ldots, 0, 0) = 0$.

Recursive computations are carried out over all feasible states $(a_1, \ldots, a_F, g)$as follows. Penalty costs for delays need not be considered here since the constraints of inequalities (3) to (6) require the completion time of each delivery batch earlier than, or at least equal to, the deadline for each delivery batch. Nor are the inventory costs considered here. Thus, set $c_{g,g} = 0, g = 1, \ldots, F$ and denote $A = (a_1, \ldots, a_{g-1}, a_g - 1, a_{g+1}, \ldots, a_F)$. Then,

$$T(a_1, \ldots, a_F, g) = \min_{f \in \{0,1,\ldots,F\}} \begin{cases} T(A, f) + c_{f,g}, T(A, f) \ne \infty, \text{and} a_g \ge 1, \\ \infty, & \text{otherwise}. \end{cases} \tag{8}$$

All values $P(a_1, \ldots, a_F)$ can be recursively computed in $O(\prod_{f=1}^{F} n_f)$ time, which is proved in detail in Cheng and Kovalyov [7]. All feasible states can be determined in $O(F^2 \prod_{f=1}^{F} n_f)$ time. The same time is needed to recursively calculate all values $T(a_1, \ldots, a_F, g)$. Therefore, the time

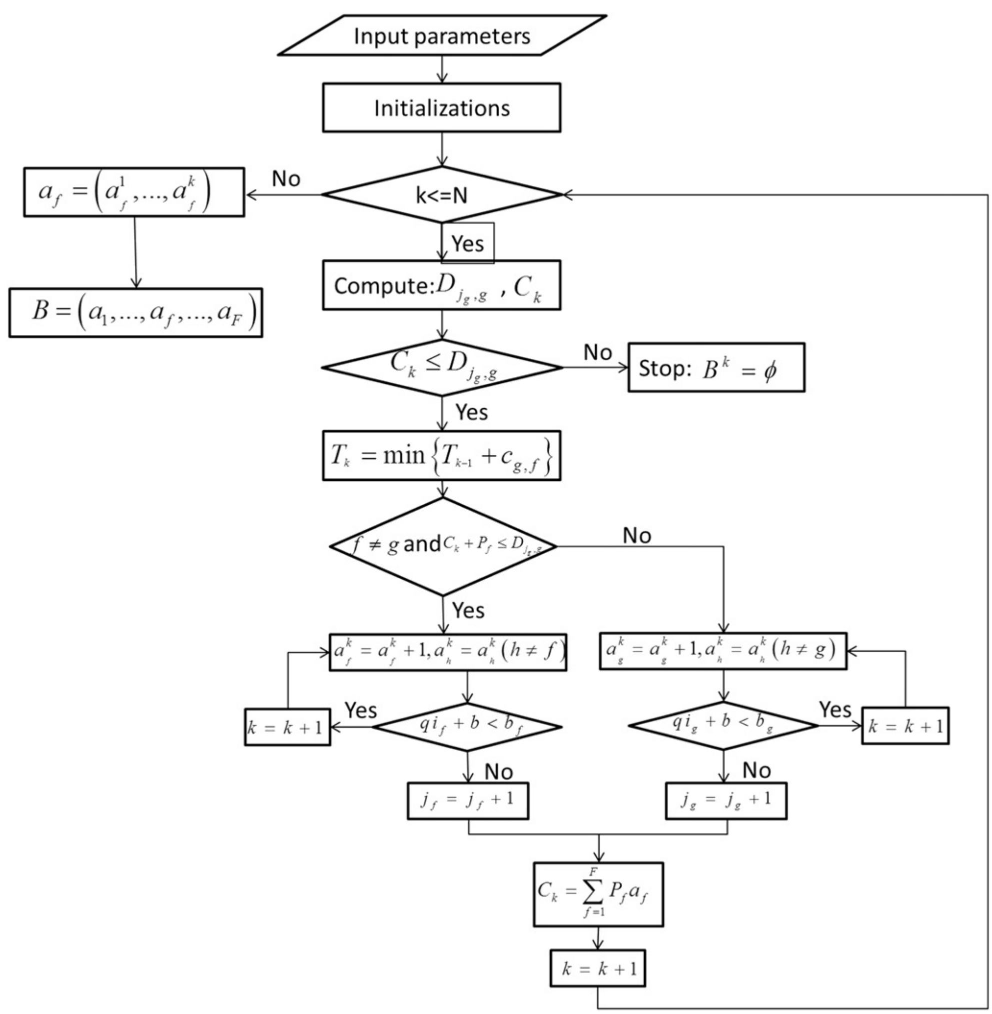


Fig. 2. The flowchart of the DP algorithm.

Table 2
Precast component orders (unit of time: day).

No.	PC type	Quantities per floor (total floors)	Manufacturing Time (P_f)	Starting time (r_f)	Transportation Time (t)
1	Façade 1	32 (16)	3	50	1
2	Façade 2	24 (10)	3	60	1
3	Façade 3	24 (12)	2	80	1
4	Façade 4	16 (20)	2	100	1
5	Bathroom 1	24 (15)	4	110	1
6	Bathroom 2	18 (18)	4	120	1

Note: P_f is the manufacturing time of one production batch.

needed to find T^* and the corresponding optimal schedule is $O(F^2\prod_{f=1}^{F} n_f)$. Since

$$\prod_{f=1}^{F} n_f \leq \left(\sum_{f=1}^{F} \frac{n_f}{F}\right)^F = \left(\frac{N}{F}\right)^F \tag{9}$$

Therefore, the running time of the dynamic programming algorithm can also be estimated as $O(N^F/F^{F-2})$.

5. Computational performance

A simulated case based on an actual precast manufacturing factory located in Shenzhen, China, with a single production line is applied to validate the formulated model and computational performance of the algorithm. Thus, the problem is formulated as a single processor ($m=1$) batch scheduling problem with changeover and delay penalty costs, and in which the MtA sectors are considered simultaneously.

5.1. Simulated case

The manufacture of the precast components generally involves a comprehensive method or a specialized method [4]. Due to its higher efficiency of labor utilization and resources, the specialized method has been used widely, especially with the introduction of automatic production systems in the precast industry [4] and is also adopted by the factory in this study. The general production periods of precast components are 2–5 days with a number of b(set,$b=30$) units in one production batch, which is mainly constrained by the steel molds. The problem is studied with six part types, with the corresponding changeover cost from one production batch to another of $c_{i,j}\{i,j=1,\ldots,6,i\neq j\}$. Detailed information of these orders is given in Table 2.

Here, there are four types of precast façades and two types of bathrooms in large quantities with different manufacturing times and start times for assembly. The manufacturing time of each order is presented in Table 3. In reality, the fabricators usually finish orders sequentially to minimize the delay and changeover costs. Therefore, as customer satisfaction is measured by on-time delivery [28], only some of these orders can be accepted. For example, due to the longer production time required by order 1 and order 5, only orders 2, 3, 4 and 6 can be accepted simultaneously if delays are unacceptable. The reason for the delay penalty costs being the first priority is that these are much higher than other direct costs, such as the changeover or inventory holding costs.

Now, the objective is to find a feasible production sequence by applying the JIT delivery philosophy with minimized changeover and delay penalty costs. The JIT deliveries are made by coordinating production and delivery decisions with the contractors' requirements so that delay penalty costs are minimized. For example, it theoretically takes six days to complete assembling one floor of a typical precast construction project. For a typical schedule, the first day involves installing the precast facades, the second day the precast bathroom, the third day the precast kitchen, the fourth day the interior walls, the fifth day the precast staircases, and the last day the semi-precast slabs. Finally, it takes 10 h–24 h to wait for the curing process of cast-in-place concrete connections to develop adequate strength and durability to start building the next floor. In other words, daily consumption is equal to the number of corresponding precast components required per floor. Therefore, two consecutive delivery batches of part type f should be completed in every seven days to ensure the JIT deliveries to construction site M_f and therefore the processing time V_f of part type f in a delivery batch b_f on construction site M_f can be defined as seven days. That is $V_f=7$ $days$, $f=1,\ldots,F$. Since there are six part types, the schedule is determined by the sequence of the part types and batch sizes.

As mentioned, if the fabricator completes the orders one by one according to the deadlines, then only some of the orders can be accepted, which actually increases the production costs. A huge amount of space will also be needed to store all the produced precast components before they are delivered, which increases inventory costs. To some extent, the production costs of the components can be reduced by processing as many orders as possible. Thus, the algorithm is developed to assign as many jobs to the current production batch of part type g as permitted by the latest possible starting time for the unassigned jobs of part types $f(f=1,\ldots,F,f\neq g)$. This latest time is equal to the earliest deadline of the unassigned jobs of part types $f(f=1,\ldots,F,f\neq g)$ minus the processing time of one production batch, i.e., $P_f(f=1,\ldots,F,f\neq g)$.

In iteration k (the total number of production batches $k=\sum_{f=1}^{F} a_f, f=1,\ldots,F$) of the algorithm, minimum deadlines $D_{j_g,g}$ and minimum changeover cost $\{T^{k-1}+c_{g,f}\}$ are computed, with $a_g'=a_g+1$ and $a_h'=a_h(h\neq g)$ being the cumulative numbers of production batches of part type f produced so far. Inventory qi_g+b is then computed, where $j_g'=j_g+1$ (if $qi_g+b>=b_g$) and $j_h'=j_h(h\neq g)$ are

Table 3
Total production times of orders.

No.	PC type	Total production times (d)	Starting times (r_f)
1	Façade 1	52	50
2	Façade 2	24	60
3	Façade 3	20	80
4	Façade 4	22	100
5	Bathroom 1	48	110
6	Bathroom 2	43	120

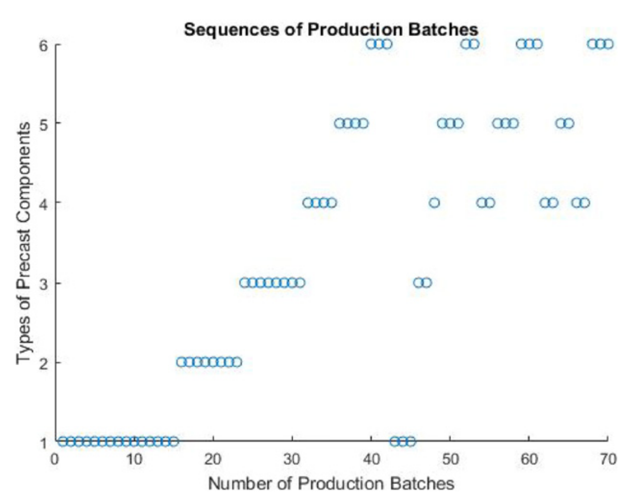


Fig. 3. Optimal sequence of production batches with minimized changeover costs.

the cumulative numbers of delivery batches of part type f, delivered so far. The **Algorithm 1** we use is shown as follows:

Algorithm 1

(Input parameters): $F, M_f, r_f, t_f, D_f, p_f, P_f, v_f, V_f, b, b_f, q_f, n_f, N, m_f, c_f, c_{g,f}$

(Initializations): $a_f = j_f = 0; T_0 = T_1 = 0; qi_f = 0; C_0 = 0; k = 1; l = 1$

(Recursive computation of production batches): **While** $k <= N$

compute $D_{j_g,g} = \min\{D_{j_f,f}\}; C_k = C_{k-1} + P_g$

If $C_k > D_{j_g,g}$

Then stop: $B^k = \phi$

Else: compute $T_k = \min\limits_{f=1,\dots,F}\{T_{k-1} + c_{l,f}\}$, record f

End if

If $f \neq g$ and $C_k + P_f \leq D_{j_g,g}$

Then: $a_f^k = a_f^k + 1, a_h^k = a_h^k\,(h \neq f)$, record current production type $l = f$

Else: $a_g^k = a_g^k + 1, a_h^k = a_h^k\,(h \neq g)$, record current production type $l = g$

End if

While $qi_l + b < b_l$

$k = k + 1$

$a_l^k = a_l^k + 1, a_h^k = a_h^k\,(h \neq l)$

End while

computation of delivery batches: $j_l = j_l + 1$

$a_f = (a_f^1, \dots, a_f^k), (f = 1, \dots, F); qi_l = b * a_l - b_l * j_l$

$C_k = \sum_{f=1}^{F} P_f a_f$

$k = k + 1$

End while

$B = (a_1, \dots, a_F)$

(Output): B, C_k, T

5.2. Results

Inventory costs are incurred when the customers' demands are larger than production capability, which requires manufacturing to take place a long time before assembly. To reduce inventory costs when one part type of precast component is manufactured in the production line, its manufacturing time should be no longer than the earliest deadline of other part types. Fig. 3 illustrates the sequence of the total production batches with minimized changeover costs produced by the model.

As is shown in Fig. 3, the orders for different part types are divided into many sub-lots to be processed. The total number of production batches is 70, which is less than the 91 delivery batches (equal to the total floors). The first 15 production batches are precast components of part type 1, the next 8 are part type 2, the next 8 part type 3 and so on. The changeover frequencies are 17 times so that the changeover costs are minimized by consecutive production batches of the same part type.

No feasible sequence exists when inequalities (3), (4), (5) and (6) are not met, as proved by Cheng and Kovalyov [7]. Therefore, if delaying jobs is acceptable, the constraints expressed by inequalities (3), (4), (5) and (6) need not be met in finding a feasible schedule with a minimum total completion time. Fig. 4(a) to (f) present the production performance of the feasible sequence. Since the number of each production batch b is not equal to that of the delivery batch b_f, the completion times of two delivery batches of the same part type can be the same, with the deadlines for the delivery batches all being met and no delay costs incurred.

As shown in Table 3, the part types 1 and 5 that can't be processed by the scheduling plan considering the production sector only require longer total production times than those of other part types. Compared with scheduling considering the production sector only, our model can process all part types within deadlines $D_f (f = 1, \dots, F)$. When considering the production, transportation and on-site assembly (MtA) sectors of precast construction projects simultaneously in our model, the deadlines $D_f (f = 1, \dots, F)$ of each part type are re-scheduled into many different sub-deadlines $D_{i,f}$ (as illustrated in Eq. (1)). The new sub-deadlines $D_{i,f}$ actually are the common deadlines D_f plus the corresponding transportation times and assembly times. Thus, instead of producing a single large batch of part type f within the common deadline D_f, our model shows it's preferable to produce smaller batches (i,f) of part type f within their sub-deadlines $D_{i,f}$ so that the inventory storage areas can be released timely. The longer production time of a single large batch of part type f requires, the better production ability our model shows (eg., more production of part types 1 and 5).

The more precast components produced in the same period, the higher efficiency use of resources (eg., machine, manpower, and storage areas, etc.) occurs and more profits generate. For instance, the profit of one single precast component is assumed as 1 unit and the changeover cost $c_{g,f} (g \neq f)$ as 10 units. The difference of total profit generated between the two methods should be the values by the total production profits minus changeover costs. Then, compared with scheduling considering the production sector only (3 times of changeover), our model considering the three sectors simultaneously resulted in increasing the total profits of 732 units, which is shown as follows:

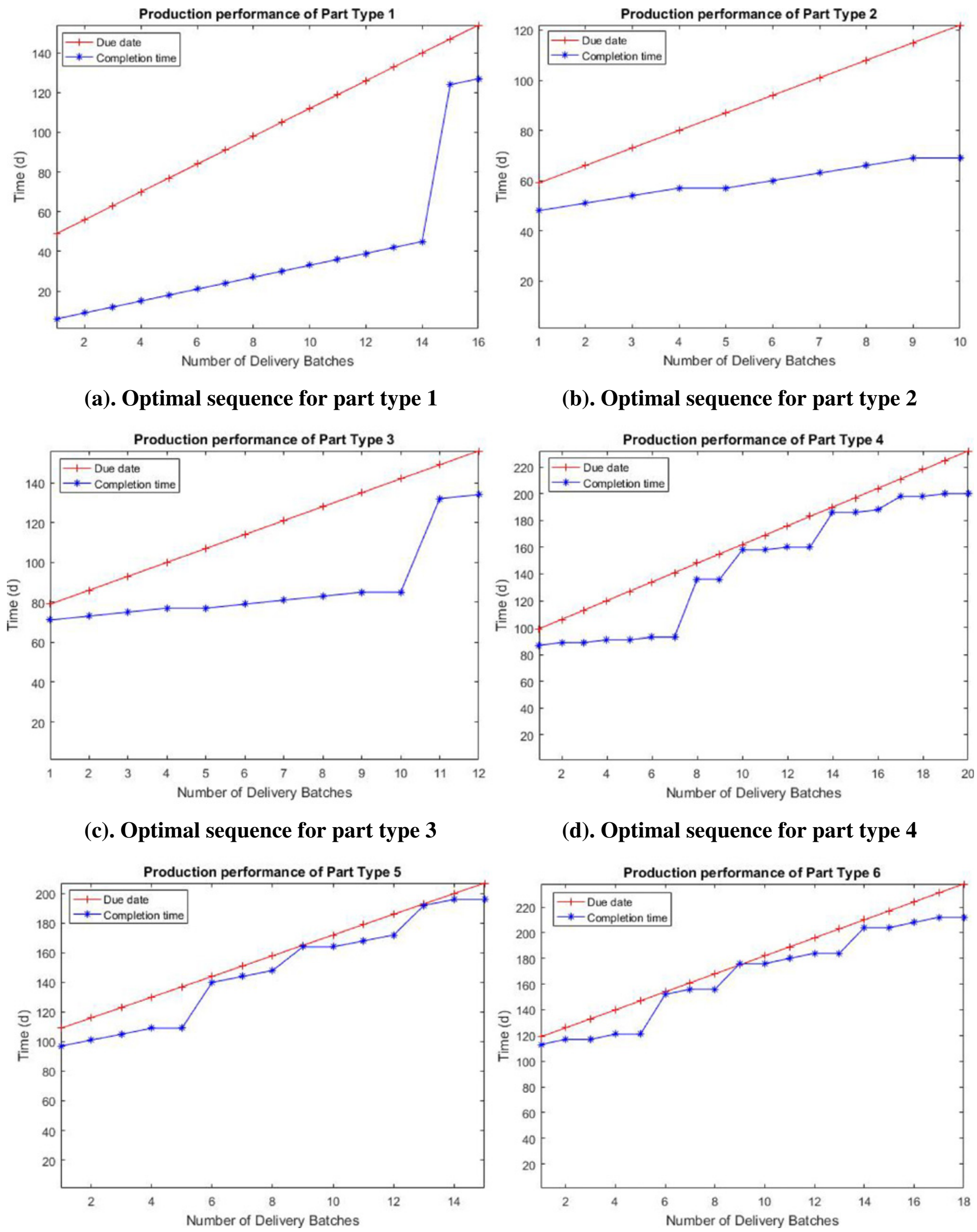
$$(32 * 16 + 24 * 15) * 1 - 17 * 10 + 3 * 10 = 732(\text{units}) \tag{10}$$

where the first part is the profit by processing part types 1 and 5, the second part changeover costs of our model, the third part changeover cost by scheduling considering the production sector only.

In addition, the more profits is made by producing more products, which can help reduce the production cost of precast components, resulting in a demand for precast components and then in return reducing the production costs. In the long term, this will create a virtuous cycle in the precast construction industry.

Finally, construction performance can be significantly improved using the proposed batch delivery scheduling strategy, due to the JIT delivery of precast components. Although the manufacturer can only accept some of the orders, computerized scheduling techniques provides more considered production plans than manual scheduling, which helps to process as many orders as possible with more effective resource utilization and minimized production costs. This has a positive outcome for both the manufacturers and the contractors, as the adoption of JIT delivery theory contributes to reducing the inventory holding costs of both. Moreover, JIT delivery adds to customer satisfaction, which can produce more orders.

The results also show that the coordination of decisions between manufacturers and contactors provides a good basis for JIT delivery. This corresponds with existing studies, which consider such coordination of decisions within the supply chain to be a critical issue in deterministic supply chain scheduling problems [7]. For instance, Hall and Potts [29] consider supplier-manufacturer cooperative decisions, where a supplier makes deliveries to several manufacturers, who also make deliveries to customers, while Tang and Gong [30] study the coordinated scheduling problem of hybrid batch production on a single batching machine and two-stage transportation connecting the production to minimize the sum of the makespan and total setup cost.



(a). Optimal sequence for part type 1

(b). Optimal sequence for part type 2

(c). Optimal sequence for part type 3

(d). Optimal sequence for part type 4

(e). Optimal sequence for part type 5

(f). Optimal sequence for part type 6

Fig. 4. Production performance of the optimal sequence.

5.3. Comparison with the previous algorithm

Arashpour et al. [13] consider different manufacturing factors to investigate a similar problem with two objectives to minimize total completion time and total energy consumption. And then, a optimization-based metaheuristics-tabu search is develop to find an optimal sequence for off-site construction producing multiple classes of products with multi-skilled resources to minimize changeover time. This production scheduling problem with due times considering the production sector only can't extend the due times with corresponding transportation times and assembly times. Apart from this, the problem considering changeover costs is still a special case of our problem, which can be solved by the algorithm developed in this research. Table 4 shows data from Arashpour et al. [13] for 20 jobs with different deadlines to be processed by a single machine.

As can be seen in Table 4, there are three product classes with a processing time of 5 h per job and an average changeover time of 8 h is required whenever switching from one product class to another. The starting time is at eight. The jobs are then sequenced in the earliest due date order to minimize the maximum delay, which causes an average delay of 32.2 h per job. The study of Arashpour, et al. [13] applies the metaheuristics-tabu search algorithm to reduce the average delay of 32.2 h per job to 5 h per job, which requires a time of $O(n!)$ to analyze all possible job sequences.

As stated in the previous section, the time effort to find T^* and the corresponding optimal schedule of our algorithm is $O(F^2\prod_{f=1}^{F} n_f)$. In this case, the jobs are firstly grouped into three product classes, that is $F=3$. Secondly, the jobs for each part type $f,(f=1,2,3)$ are reassigned in order $(1,f),\ldots,(n_f,f), N=\sum_{f=1}^{3} n_f=20$, $(n_1=8, n_2=5, n_3=7)$

Table 4
Arashpour et al.'s [13] sequence of 20 jobs in the earliest due date order (minimax decision rule).

Job ID	Product class	Due time (hour)	Completion time	Delay (hours)
1	Wall panel	1	13	12
2	Wall panel	8	18	10
3	Wall panel	15	23	8
4	Wall panel	22	28	6
5	Wall panel	29	33	4
6	Wet-room panel	36	46	10
7	Wall panel	43	59	16
8	Wet-room panel	50	72	22
9	Wall panel	57	85	28
10	Wet-room panel	64	98	34
11	Wall panel	71	111	40
12	Façade panel	78	124	46
13	Wet-room panel	85	137	52
14	Wet-room panel	92	142	50
15	Façade panel	99	155	56
16	Façade panel	106	160	54
17	Façade panel	113	165	52
18	Façade panel	120	170	50
19	Façade panel	127	175	48
20	Façade panel	134	180	46
			Average	32.2

according to the deadlines involved, so that $D_{1,f} \le \ldots \le D_{n_f,f} f=1,2,3$ as shown in Table 5. Therefore, the time needed to find the optimal sequence is $O(F^2 \prod_{f=1}^{F} n_f) = O(3^2 {}^* 8^* 5^* 7)$, which is much faster than $O(20!)$.

In this case, as the delivery number is equal to the production number, set $b_f = b = 1$. Thus, $a_f = j_f, (f=1,2,3)$. By applying the dynamic programming algorithm, the following constraints have to be relaxed to find a feasible sequence.

$$a_f \in \{0, 1, \ldots, n_f\}, C(a_1, \ldots a_F) \le D_{j_g, g} \tag{11}$$

$$C(a_1, \ldots a_F) + P_f \le D_{a_f+1, f} \tag{12}$$

$$C(a_1, \ldots a_F) + \sum_{f=1}^{F} P_f \le \max\left\{D_{a_f+1, f} | f = 1, 2, 3\right\} \tag{13}$$

Table 5
The sequence of 20 jobs grouped into three part types.

Part type (f)	Job ID	Product class	Due time ($D_{i,f}$)
1	1	Wall panel	$D_{1,1} = 1$
	2	Wall panel	$D_{2,1} = 8$
	3	Wall panel	$D_{3,1} = 15$
	4	Wall panel	$D_{4,1} = 22$
	5	Wall panel	$D_{5,1} = 29$
	7	Wall panel	$D_{6,1} = 43$
	9	Wall panel	$D_{7,1} = 57$
	11	Wall panel	$D_{8,1} = 71$
2	6	Wet-room panel	$D_{1,2} = 36$
	8	Wet-room panel	$D_{2,2} = 50$
	10	Wet-room panel	$D_{3,2} = 64$
	13	Wet-room panel	$D_{4,2} = 85$
	14	Wet-room panel	$D_{5,2} = 92$
3	12	Façade panel	$D_{1,3} = 78$
	15	Façade panel	$D_{2,3} = 99$
	16	Façade panel	$D_{3,3} = 106$
	17	Façade panel	$D_{4,3} = 113$
	18	Façade panel	$D_{5,3} = 120$
	19	Façade panel	$D_{6,3} = 127$
	20	Façade panel	$D_{7,3} = 134$

Note: Due time $D_{i,f}$ corresponds with the reassigned job number(i,f).

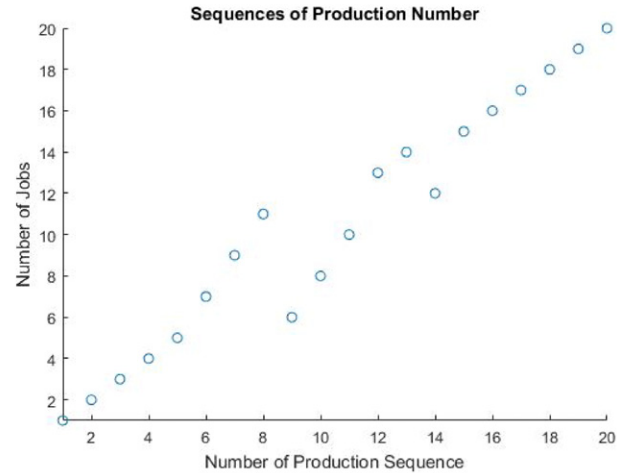


Fig. 5. Optimal sequence of jobs.

The optimal sequence of multiple classes of products in off-site construction is shown in Fig. 5, and Fig. 6 presents the completion times of jobs compared with the due dates.

As is shown in Fig. 5, the optimal production sequence is to produce three classes of products, that is, 8 jobs of wall panels, followed by 5 jobs of wet-room panels and then 7 jobs of façade panels. The optimal sequence involves only two changeover times. Group production can reduce the changeover times greatly. As is seen in Fig. 6, the number of delayed jobs is 9 compared with 17 in Arashpour et al. [13], the total completion time is 124 compared with 132, and the average delay per job is $\sum_{f=1}^{F} \sum_{i=1}^{n_f} (\max(C(i,f) - D(i,f), 0))/N = 5.2h$, which is very similar to Arashpour et al.'s average delay of 5.1$h$per job.

The results show that optimal sequencing for multiple classes of products can be achieved by group production and lot-sizing production, which first groups the same class of product into a part type and prioritizes jobs based on the earliest due dates within the same group. This agrees with Proposition 3 of Arashpour et al. [13].

6. Conclusions

The study contributes to the adoption of precast construction by expanding the insight into the JIT delivery theory and proposing a single machine batch scheduling model for production by integrating the MtA sectors. Most production planning for the MtA of precast components is managed by rule of thumb with the three MtA sectors considered

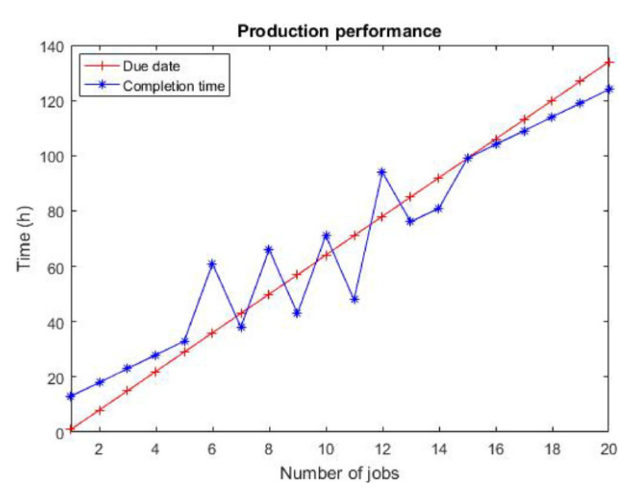


Fig. 6. Production performance of optimal sequence.

separately, which often results in the inefficient use of resources and delayed deliveries. This study applies an enhanced objective precast production scheduling method to search for solutions with maximum production efficiency, within an integrated MtA framework. With more precast components produced in the same period, the higher efficiency use of resources (eg., machine, manpower, and storage areas, etc.) occurs and more profits generate. The more profit is made by producing more products, which can help reduce the production cost of precast components, resulting a demand for precast components and then in return reducing the production costs. In the long term, this will create a virtuous cycle in the precast construction industry. Then an algorithm is developed based on the schema of Cheng and Kovalyov [7] dynamic programming algorithm $O(N\log F)$ with estimated running time $O(N^F/F^{F-2})$ to facilitate optimized scheduling. Compared to [Arashpour et al. [13]] optimization-based metaheuristics-tabu search algorithm for a similar scheduling problem, less delayed jobs occur, the total completion time is reduced and much less running time is required than analyzing all possible job sequences of $O(n!)$.

The proposed model has some limitations, however, which focus on single production line scheduling. The problem will be more complex when there is more than one production line, which requires more practical metaheuristics or hybrid algorithms. In addition, the proposed model does not consider maintenance intervals (e.g., periodic maintenance) as factors, which needs to be investigated in future studies. Since the main objectives are to minimize the changeover costs, inventory costs and delay costs, the changeover times between different part types are not considered specifically if total completion time is one of the objectives. However, minimizing changeover costs also minimizes the changeover times to some extent. A number of detailed practical constraints and optimization objectives are also identified and which are in need of further research:

1) the size of a production batch is limited by the number of steel molds, which is different from that of a delivery batch;
2) JIT delivery to construction sites (the size of delivery batch equals the daily consumption) makes the quantity of precast components in each production batch different for each delivery batch;
3) orders accepted by manufacturers have to be completed within due dates so that the delay penalty cost is zero, which helps promote customer satisfaction;
4) minimizing changeover costs is regarded as the main objective, which also minimizes total completion time.

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