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Sustainable performance of just-in-time (JIT) management in time-dependent batch delivery scheduling of precast construction

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ABSTRACT

Despite a great deal of research into precast production scheduling published in academic journals worldwide, little attention has been given to environmental performance related to precast construction transportation and assembly scheduling problems. To address this issue, this paper studies the Just-in-Time (JIT) strategy for supply chain management of precast construction while considering time-dependent transportation time and on-site assembly time. There are two main contributions of our work. First, our analysis expands the current batch-scheduling model of minimizing earliness/tardiness penalties, by incorporating environmental impact considering the time-dependent transportation time and economic impact of resources wasted by waiting for on-site assembly. Second, we quantify the economic and environmental performance using our research objective, consisting of earliness/tardiness penalties, an additional transportation time penalty, and a resource waste penalty. The optimal results show that, compared with the supplier's intuitive minimax optimization with deliveries on the earliest due date, there is an average 10.7% reduction of the objective value of a one-day assembly task by our proposed method. The results also show that the objective of achieving additional environmental performance conflicts with that of obtaining economic performance. However, sensitivity analysis further shows it is not always true to consider only additional environmental performance for the suppliers to achieve 'green' value. For a sustainable business, the customer's service-JIT delivery should also be considered. Thus, when the policy makers assign importance weights to different objectives, they should fully consider both the economic and environmental impacts. The research contributes to batch delivery theory by expanding the approach to a time-dependent delivery model by considering both the economic and environmental effects. The method developed is of practical value for precast building projects to help in the successful implementation of sustainable development.

1. Introduction

Compared with conventional construction, precast construction has the main advantages of higher productivity, less workload and less complex work, with the improved quality of precast products in a specialized facility with well-controlled environmental conditions (Yin et al., 2009). In addition, precast components are fabricated in controlled conditions in areas away from crowded city centers with adequate operational and storage space; thus, only one trip is needed to the construction site for direct assembly (as is shown in Fig. 1) (Ko, 2010). The quicker erection times, superior quality and less manpower required, make precast construction the most suitable option for housing construction in areas such as Hong Kong (Wong et al., 2003). Today, an additional motive for using precast construction - especially in large congested urban areas - is the heightened awareness of traffic congestion, environmental pollution, natural resource depletion and accompanying social problems (Chen et al., 2010; Li et al., 2014; Yee et al., 2001). A great

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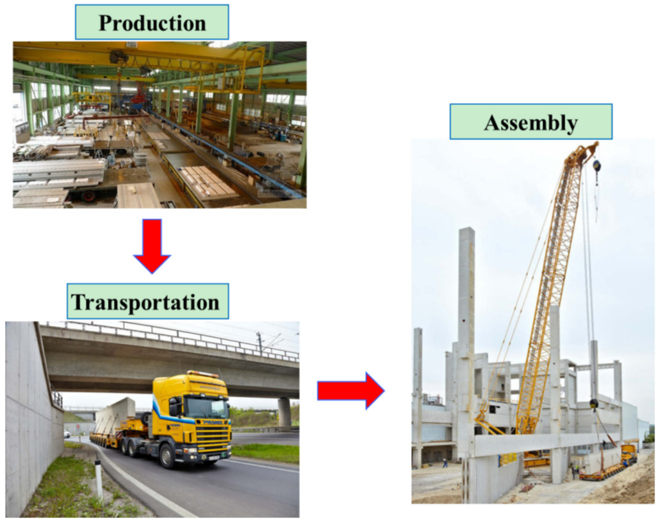

Fig. 1. Supply chain processes of precast construction.

deal of research into the precast production scheduling has been published extensively worldwide (Li et al., 2014). However, the studies involved mainly focus on the economic performance of production in a narrow or broad sense. Little attention has been given to environmental performance related to the transportation and assembly scheduling problems of precast construction.

This paper focuses on the JIT delivery of precast components with emphasis on time-dependent transportation and the wasted time of truck drivers queuing on site. It incorporates both economic and environmental performance into the objectives to minimize earliness/tardiness, resource waste and environmental emission penalties of an optimal batch delivery-scheduling problem. Precast components are mostly bulky, large and heavy, and often need expensive cranes for lifting (Pheng and Chuan, 2001) and sufficient space for temporary storage. In addition, the high transportation cost of precast components mainly confines the application of precast construction (Jaillon and Poon, 2008). However, this additional cost may be off-set by the Gross Floor Area (GFA) exemptions granted for buildings adopting green features, according to the incentive schemes implemented by the Buildings Department since 2001 (Jaillon and Poon, 2009). Therefore, full consideration of both environmental and economic performance in the supply of precast components can have a significant effect on the development of precast construction, so that the construction cost of precast buildings can be reduced in the long term, which will contribute to a wider use of precast techniques. The reverse is also true: a wider use of precast techniques can contribute to a decreasing cost of precast construction, which could contribute to sustainable construction in a dense urban environment (Jaillon and Poon, 2008).

Nowadays, as the importance of environmental protection is increasingly emphasized (Liu et al., 2014), integrating environmental concerns into supply chains (referred to as Green Supply Chain Management) has received greater attention for supply chain management (Zhao et al., 2017). Green Supply Chain Management (GSCM) seeks to reduce the consumption of resources and environmental waste (Sharma et al., 2017). In response, this paper addresses the optimum delivery-scheduling problem using just-in-time (JIT) principles to minimize delivery resources and environmental emissions. The delivery resources comprise workers, equipment, and other resources (e.g., delivery trucks, cranes and on-site storage areas) related to the delivery of precast components. Precast components can be delivered in JIT mode, which advocates smaller sized and more frequent deliveries (Min and Sui Pheng, 2007). In precast construction, no additional delivery costs are incurred by more frequent deliveries. This is because delivery vehicles with full capacity can deliver a very limited number of precast components - a 20-foot truck with only two precast façade components (Ng et al., 2009). For another example, most precast concrete units used in the Aurora Municipal Center project were very large, weighing upwards of 28 tons, and hence the trucks carried only an average of 1.4 pieces per trip (Polat, 2008). In this case, delivery time is the most relevant factor to reduce the high transportation cost of precast components.

On the other hand, if too many precast components are delivered at once, the limited on-site resources cannot handle all of them at the same time, which causes site congestion and thus prolongs total delivery time. In addition, without taking great care over the storage process, significant construction waste can be generated by re-hardened concrete and all pre-fabricated materials (Lu and Yuan, 2013). Moreover, construction sites in such high density cities as Hong Kong do not have enough space to store precast components before they are assembled (Ko, 2010). For example, more than 80% of Hong Kong's precast construction contractors face a common challenge of storage space constraints (Pheng and Chuan, 2001). Therefore, contractors do not want precast components delivered ahead of the installation schedule, and delivery drivers have to wait for the time window of these precast components. Nor do contractors want precast components delivered after the due date, because this will cause a loss for the whole project. It is highly desirable for the exact type of precast component to be delivered of the right quantity and quality at the right time for assembly, which involves having neither inventory nor double handling (Lu and Yuan, 2013). Thus, resources related to the use of cranes for double handling can be saved greatly. Meanwhile, by delivering the right quantities at the exact time, delivery drivers can return earlier with less waiting time on-site. Although the applications of the JIT philosophy in construction projects has been well documented, little attention has been paid to its application in precast construction. Therefore, JIT principles should be applied in the precast delivery process so that delivery resources can be saved, and environmental emissions reduced by the corresponding energy saving.

Environmental emissions generated by transportation of bulky precast components in the delivery process can also be reduced by minimizing transportation time. This is because transportation times can vary greatly in a congested urban environment depending on the time of day (Dabia et al., 2013). Road congestion results in substantial environmental emissions, as longer driving time and frequent restarting vehicles involve extra fuel consumption. According to the “Annual Report of Transportation Development of Beijing City in 2011” by the Transportation Development Research Center of Beijing, China, traffic congestion can cause additional daily emissions of 16,700 tons of carbon dioxide and 9.5 tons of such other pollutants as nitrogen oxide, particulate matter and sulfur dioxide. Delivery time can be reduced greatly by avoiding heavy traffic congestion so that environmental emissions can be reduced correspondingly. Therefore, it is necessary to develop strategies such as the optimal number of delivery batches, optimal number in each delivery batch and optimal delivery time in the JIT delivery process to improve sustainable performance.

The remainder of the paper is organized as follows. Section 2 reviews the current literature concerning the supply chain scheduling of precast construction. Detailed modeling of the proposed problem is given in Section 3. Then, Section 4 presents a polynomial time algorithm for the optimal solution. A precast building project in Hong Kong considering four different situations is applied to verify the proposed method and computational results are provided in Section 5. Finally, Section 6 presents a discussion and the study's limitations, while Section 7 contains the conclusion.

2. Literature review

Despite precast construction being inherently superior to other forms of construction, its management has generated many problems - from precast component production to transportation and assembly (Li et al., 2014). An unavoidable research question is concerned with the supply chain problems of precast construction - how to produce, transport and assemble the precast components JIT due to their bulky, large, and heavy characteristics. The JIT strategy promotes more frequent deliveries with smaller number of precast components in each batch. The JIT philosophy is one of the management techniques contributing to eliminating waste caused by overproduction, waiting, transportation, processing, stocks, motion and producing defective products (Akintoye, 1995). Pheng and Hui (1999), for example, apply the JIT philosophy to site layouts to improve productivity and quality by eliminating on-site waste, controlling the movement of inventory and the usage of equipment; Sui Pheng and Chuan (2001) conducted a survey to show that precasters in Singapore are ready and able to deliver JIT; Min and Sui Pheng (2006) examine the effects of JIT purchasing policy on the ready-mixed concrete industry in Singapore; Min and Sui Pheng (2007) model the JIT purchasing approach and testify with cases conducted in the ready-mixed concrete industry in Chongqing and Singapore; Pheng and Jayawickrama (2012) provide anecdotal evidence of a project successfully applying JIT principles to improve productivity and quality standards, which helped the main contractor to achieve the target completion date; Ocheoha and Moselhi (2013) study the joint effect of BIM and JIT on quality control, eliminating waste and inventory reduction by analyzing and comparing data from case studies; and Viana et al. (2015) apply the JIT philosophy to delivery, to facilitate integration between off-site fabrication and on-site installation in an action research study conducted with a HVAC subcontractor. Although the increasing applications of the JIT philosophy in construction projects has been well documented, little attention has been paid to the application of JIT philosophy in precast construction considering the bulky, large, and heavy characteristics of precast components. Thus, there is a practical demand to apply the JIT strategies to find out the optimal number of delivery batches, optimal number in each delivery batch and optimal delivery time in the construction process to improve sustainable performance.

In the application of the JIT philosophy in the precast construction industry, it is necessary to examine the main processes of precast construction, such as production, transportation and site assembly. There is a fast growing body of studies centering on the production scheduling problem with time constraints, which is known to be NP-complete (Chan and Hu, 2001). Despite the increasing academic interest in this domain (Li et al., 2014), the main focus is on economic performance in a narrow or broad view, such as in minimizing mold usage (Hu, 2007), earliness/tardiness of production (Ip et al., 2000), production resources and costs (Khalili and Chua, 2013), production cost and processing time (Liu et al., 2014), production makespan (Chan and Hu, 2001), production makespan and resource utilization (Leu and Hwang, 2002), earliest due date rule (Chan and Hu, 2002), production changeover cost and times (Arashpour et al., 2016a; Yang et al., 2016), project costs and completion time in a unified manufacturing, transportation and assembly systems (Anvari et al., 2016). Following an increasing awareness of environmental protection, manufacturing plants are becoming increasingly pressured to reduce their carbon footprint (Shrouf et al., 2014). Although the deleterious effects of carbon dioxide emissions is beginning to be recognized by a number of manufacturers as one of the critical factors in supply chain management, there have been few studies of this to date (Lee, 2011). Of these, Shrouf et al. (2014) provide a mathematical model of single machine production scheduling to minimize total energy consumption costs, considering time-dependent energy prices; Liu et al. (2014) formulate a multi-objective optimization model to simultaneously minimize total carbon dioxide emissions and total completion time, solved by a non-dominated sorting genetic algorithm; Rajemi et al. (2010) develop an energy footprint model for a machined product using an optimization methodology, by analyzing energy use in turning operations to minimize the manufacturing resources involved; Cao et al. (2012) present a carbon efficiency approach to quantitatively characterize two kinds of emissions (fixed and varied) during the life-cycle of machine tools and apply a case study to show the different methods that can be used to reduce the emissions; Mouzon and Yildirim (2008) propose a framework to minimize a multi-objective optimization by considering total energy consumption and total tardiness and develop a greedy randomized adaptive search metaheuristic to obtain an approximate Pareto front; while, according to the linear structure of inter-industry production linkages, Oliveira and Antunes (2004) provide a multi-objective model to the assess environmental burden by considering changes in economic activities.

These studies mainly focus on the scheduling problems of the production process by considering energy consumption in the manufacturing industry. Transportation operations are also important operational characteristics that affect the green supply chain however (Sarkis, 2003), but little attention has been given to the transportation and assembly scheduling problems of precast construction by considering environmental performance. Therefore, this study expands the current batch-scheduling model of minimizing earliness/tardiness penalties, incorporating environmental impact considering time-dependent transportation time and resource waste by waiting for on-site assembly. Both economic and environmental performance are considered as our research objectives. In analyzing resource saving and environmental emissions during the delivery process, the waiting time for the assembly of on-site precast components and time-dependent transportation time are considered simultaneously. Existing research studies consider neither time-dependent transportation time nor the assembly time as scheduling variables. Thus, no tailored solution has yet been proposed in the context of precast building projects. The two factors affect both production operations and the site construction schedule. The delivery and assembly of precast components needs to be correctly planned and executed to avoid the negative effects of excessive deliveries waiting for assembly or assembly waiting for deliveries of precast components. An optimal batch delivery scheduling approach will enable both manufacturers and contractors to improve productivity within due dates and thus realize sustainable business practices.

3. Model formulation

3.1. Problem description

For precast construction projects in such congested urban areas as Hong Kong, different types of precast components are delivered by different suppliers from various origins. There is no precast manufacturing factory in Hong Kong because it is believed that the free market economy would drive capitalists to move the place of production from costly regions to places with a lower cost of manufacturing (Wong et al., 2003). The schedules for transport of the precast components to the job site are developed based on the construction installation schedule (Cheng and Chen, 2002). Construction projects may vary between each other, but common parameters can be shared by most construction activities (Christian and Hachey, 1995). For instance, in precast building construction, the erection schedule of prefabricated components mainly involves one day for the precast façade, one day for the precast bathroom, another day for the semi-precast slabs, etc. In other words, the erection schedule for the project is divided into many daily erection schedules; those for different construction tasks can be demonstrated by parametric modeling as:Nprecast components should be installed within a due date $[a_0, b_0]$.

We assume truck drivers deliver precast components in batches to the construction site for assembly directly, which means the driver can return only after the precast components he delivers are assembled. There is no capacity limitation for a batch delivery. As the precast components are large in volume, every truck with a full capacity can deliver a very limited number of precast components. Thus, it is assumed the total cost of all deliveries is fixed (the number of trucks required is fixed) whether they are delivered in a single time (all trucks for one delivery) or several times (one or two trucks for one delivery). However, the more precast components delivered to the construction site in one time, the longer the truck drivers have to queue for assembly. This is then accompanied by site congestion, waste of resources, and additional resource (e.g. manpower, cost and time) consumption for second unloading, storing and lifting if the driver wants to leave ahead of the assembly schedule. Thus, the problem is to develop optimal strategies to find the optimal number of delivery batches, optimal number in each delivery batch and optimal delivery time, so that the penalties for earliness/tardiness, resource waste and carbon dioxide emissions can be minimized.

3.2. Problem assumptions

To study such a complex decision-making problem, we first introduce the indices, sets, parameters and decision variables (shown in Table 1.), and make the following assumptions:

(1) The delivery time from the manufacturing factory to the construction site during time interval $j(j = 1,\ldots,M$, one day is divided into$M$intervals) is independent of the type of vehicle (Malandraki and Daskin, 1992).
(2) The transportation time is a function (say, a step function) of the starting time during the day (Malandraki and Daskin, 1992).
(3) Environmental emissions are related to transportation time if the distance is the same.
(4) The manufactory has sufficient capacity to meet periodic demand (Arashpour et al., 2016b), therefore precast components can be delivered at any time if the construction site has enough assembly ability within the due date.
(5) Delivery vehicles are full loaded for every trip (except the last and only one) to ensure that the total delivery cost is fixed, and each vehicle carries only one type of precast component. This is very close to reality for, as mentioned previously, a very limited number of precast components can be carried by one vehicle.
(6) Resource waste is measured based on the time lost by truck drivers on-site waiting for the assembly to be completed.

3.3. Mathematical model

According to Tam's (2003) study, floor concreting takes from four to six days if large and bulky precast components are used (Li et al., 2014). For a typical precast construction project in Hong Kong, the average time to complete one floor takes six days, which means that time is tightly scheduled in the assembly process. Fig. 2 illustrates the several processes involved in a precast construction project, which shows two kinds of precast components (precast walls and precast PCF slabs) required to be delivered JIT with separate time constraints. The daily assembly schedule, as mentioned before, involves a certain number of precast components transported by$N$trucks from one place (e.g., one supplier in Dong Guan, China) to the job site (e.g., Hong Kong) and then assembled in one day.

$\{J_1, \ldots, J_N\}$Is the number sequence of trucks. Trucks carrying different types of precast components are sequenced by different numbers according to the assembly schedule (if the task requires more than one kind of precast component) and trucks with precast components of the same type are randomly sequenced. We partition the delivery trucks into m batches$\{J_1, \ldots, J_{l_1}\}\{J_{l_1+1}, \ldots, J_{l_2}\}, \ldots, \{J_{l_{m-1}+1}, \ldots, J_{l_m}\}$, where $l_i$is the sequence of trucks in the ith batch for $i = 1, \ldots, m$, with $l_0 = 0$ and $l_m = N$.

Workers have fixed daily working hours, with a given common due date $[a_0, b_0]$for all batch deliveries and rest time interval $[T_1, T_2]$. The precast components must be delivered and assembled onsite during the workers' working time. Therefore, the working intervals are $[a_0, T_1]$ and $[T_2, b_0]$, witha_0, b_0, $T_1$and T_2 being given parameters. Since the assembly work is done continuously with a common due date ($[a_0, T_1]$ and $[T_2, b_0]$), the delivery deadline of each batch should be the completion time of assembly for last batch, i.e.,

$$D_j = a_0 + \sum_{k=1}^{l_i} p_k, \text{ or } D_j = a_0 + (T_2 - T_1) + \sum_{k=1}^{l_i} p_k, \text{ for } j \in [J_{l_{i-1}+1}, \ldots, J_{l_i}] \text{ and } i = 1, \ldots, m, \tag{1}$$

where $p_k$is the assembly of precast components delivered by truck k.

For the sake of simplicity, set $D_j = b_0 j \in [J_{l_{i-1}+1}, \ldots J_{l_i}]$, $i = 1, \ldots, m$ and n_i as the total number of vehicles utilized in the ith delivery batch, thus

$$l_i = \sum_{j=1}^{i} n_j, i = 1, \ldots, m \tag{2}$$

In a congested urban environment, environmental emissions from transportation between two locations are not a function of the distance traveled alone because travel time may differ even over the same distance. Traffic density may cause big changes in travel time and result in different amounts of emissions. Considering time-dependent transportation time can to some extent reduce the environmental emissions of ignoring the changing environment (Wang and Lin, 2013). Many unexpected factors account for this, such as accidents, weather conditions or other random events. An expected variation, which may also cause travel time to increase dramatically during rush hours, is the temporal variation that results from the hourly, daily, weekly or seasonal cycles in the average traffic volume. The transportation time between two locations can be predicted according to traffic conditions (light traffic, normal traffic, heavy traffic and major traffic jams) (Han et al., 2014). Malandraki and Daskin (1992) first formulated the time-dependent VRP (TDVRP) and divided the time horizon into$M$ slices with a constant travel time t_{ij}^m for each arc$(i,j)$and slice$m$. In this research, transportation time is represented by a known step function of the time of day the delivery takes place (Malandraki and Daskin, 1992).

Table 1
Indices, sets, parameters and decision variables related to the proposed problem.

Indices and sets	
N	total number of precast components needed for the construction task
J_i	type of trucks in the ***i***th order
l_i	sequence of trucks for the ith batch delivery
M	number of time intervals in the day for the transportation time
a_0	starting time for assembly on site
b_0	deadline for assembly
T_1, T_2	time interval for rest
v	assembly time of precast components in a single truck
P_i	assembly time of the ***i***th batch delivery
t_i	tardiness of the ***i***th batch delivery
e_i	earliness of the ***i***th batch delivery
S_i	starting time for assembly of the ith batch delivery
w_i	waiting time for assembly in the ***i***th batch delivery
F_i	completion time of assembly for the ***i***th batch delivery
D_i	deadline of assembly for the ***i***th batch delivery
Constants	
α	earliness penalty coefficient
β	tardiness penalty coefficient
γ	resource waste penalty coefficient
δ	emission penalty coefficient
Variables $(i\in\{1,m\})$	
m	number of delivery batches, $m\in\{1,N\}$
n_i	number of precast components delivered in the ***i***th delivery
r_i	starting time for the ***i***th delivery
$C(r_i)$	transportation time starting at r_i for the ***i***th batch delivery
A_i	arrival time on site of the ***i***th transportation

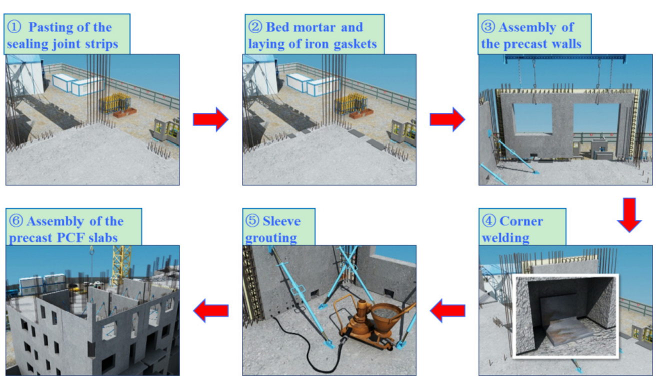

Fig. 2. An example of precast construction.

Thus, the day is divided into time intervals. The delivery time $C(r_i)$ is defined as

$$C(r_i) = \begin{cases} s_1, TI_0 \le r_i < TI_1 \\ \ldots\ldots \\ s_M, TI_{M-1} \le r_i < TI_M \end{cases} \tag{3}$$

where M is the total number of time intervals and $[TI_{j-1}, TI_j]$, $(j = 1, \ldots, M)$ is the time interval.

Therefore, once the time when the delivery takes place is known, the delivery time is a known constant. Obviously, environmental emissions can be reduced if deliveries of the precast components avoid traffic congestion. The transportation time, $C(r_i)$, is a function of starting time r_i for transportation:

$$\text{Set } C_0 = \min(C(r_i)), i = 1, \ldots, m. \tag{4}$$

where $(C(r_i) - C_0)$ means the additional transportation time incurred by traffic congestion. For instance, it might take C_0(e.g. 3 h) to move from one place to another place when the traffic is the lightest, but $C(r_i)$ (e.g. 5 h) in heavy traffic. Thus, environmental

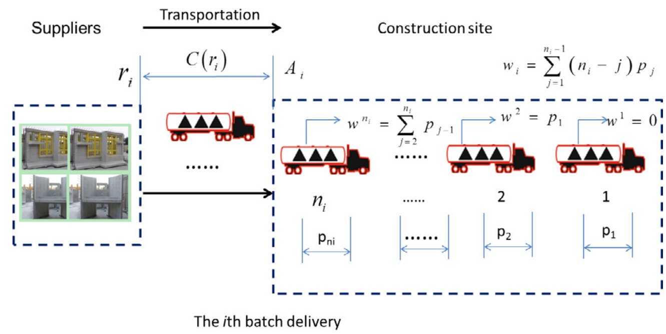

Fig. 3. Simplified wasted time of delivery drivers in the ith delivery batch.

emissions will increase with the additional travel time $(C(r_i) - C_0)$ (e.g. 5−3 = 2 h) due to traffic congestion.

The arrival time, A_i , of the ith delivery batch at the construction site is

$$A_i = r_i + C(r_i) \tag{5}$$

Fig. 3 illustrates the relationships between the starting time (r_i) for delivery, transportation time $(C(r_i))$, arrival time (A_i) and the wasted time of truck drivers (w_i) waiting for theith delivery batch to be assembled.

As shown in Fig. 3, the arrival time (A_i) of the delivery batch should match the assembly schedule (S_i). The on-site arrival time of a precast components is called ‘early’ when its rendition time is before its start time for assembly (i.e., $A_i < S_i$) and ‘on-time’ when it is delivered on its due date for assembly (i.e., $A_i = S_i$). Otherwise, it is called a ‘tardy’ or ‘delayed’ precast component. For an early delivery, the trucker resource will be wasted, while the assembly schedule will be delayed for a tardy one, which will cause a final overrun of project costs and time. When it is time to assembly the precast components, w_i is the total waiting time of the delivery drivers for the ith batch delivery. w_i becomes longer as the quantity of theith delivery batch (n_i) becomes larger, because the delivery trucks must queue for assembly (the delivered precast components have to be assembled one by one). It is desired to find a balance between the delivery time and the total assembly time for the ith delivery batch. The objective is to simultaneously determine the optimal number of delivery batches m $(\{J_1,\ldots,J_{l_1}\}\{J_{l_1+1},\ldots,J_{l_2}\}, \ldots, \{J_{l_{m-1}+1},\ldots J_{l_m}\})$, the optimal quantity of each batch n_i $(\pi = (n_1, n_2, \ldots, n_m))$, and the optimal delivery time of each batch $r_i(R = (r_1, r_2, \ldots, r_m))$. This involves minimizing the objective function

$$z(m,B,R) = \alpha \sum_{i=1}^{m} \sum_{j=1}^{n_i} e_i + \beta \sum_{i=1}^{m} \sum_{j=1}^{n_i} t_i + \gamma \sum_{i=1}^{m} \sum_{j=1}^{n_i-1} (n_i - j)p_j + \delta \sum_{i=1}^{m} \sum_{j=1}^{n_i} (C(r_i) - C_0) \tag{6}$$

where α is the earliness penalty coefficient, β is tardiness penalty coefficient, γ is the resource loss penalty coefficient and δ is the environmental emission penalty coefficient. The objective function z considers both the truck drivers' transportation time, $C(r_i)$, and queuing time,w_i. The values of the first two parts in Eq. (6) are the earliness and tardiness penalties, which depend on the arrival and completion times of the precast components assembled in the previous batch. The arrival time of the ith delivery batch $A_i(A_i = r_i + C(r_i))$ on site should be equal to the completion time of assembly$(S_{i-1} + P_{i-1})$ for the $(i-1)$th delivery batch, otherwise, an earliness or tardiness penalty will occur. The value of the third part in Eq. (6) is resource waste. The corresponding time-loss w_i is $w_i = \sum_{j=1}^{n_i}(j-1)v = \frac{v}{2}n_i(n_i-1)$. It is obvious that larger m means smallerw_i. However, larger m also means the delivery time $C(r_i)$becomes more complex, which increases the probability of causing earliness/tardiness penalties and additional environmental emissions from traffic congestion - the value of the 4th part in Eq. (6).

Taking one delivery batch as a unit, therefore, Eq. (6) can be simplified to

$$\min z(m,B,R) = \alpha\sum_{i=1}^{m} n_i{*}e_i + \beta\sum_{i=1}^{m} n_i{*}t_i + \gamma\sum_{i=1}^{m} w_i + \delta\sum_{i=1}^{m} n_i{*}(C(r_i) - C_0) \tag{7}$$

$$\text{where } w_i = \sum_{j=1}^{n_i-1}(n_i - j)p_j. \tag{8}$$

Eq. (7) shows the total penalty consisting of earliness/tardiness penalties, the resource waste penalty and the environmental emission penalty.

The constraints are:

$$A_1 \le a_0, A_1 \le A_2 \le \ldots \le A_m, (i = 1, \ldots, m); \tag{9}$$

$$A_i = r_i + C(r_i), (i = 1, \ldots, m); \tag{10}$$

$$S_i = \max(A_i, F_{i-1}); \tag{11}$$

$$e_i = \max(0, S_i - A_i); \tag{12}$$

$$t_i = \max(0, F_i - b_0); \tag{13}$$

$$F_i = S_i + P_i; \tag{14}$$

$$P_i = \sum_{k=1}^{n_i} p_k; \tag{15}$$

$$\sum_{i=1}^{m} n_i = N; \tag{16}$$

$$a_0 \le S_i + P_i \le T_1 \text{ or } T_2 \le S_i + P_i \le b_0 (i = 1, \ldots, m). \tag{17}$$

In this formulation, Eq. (8) gives the on-site waiting time of truck drivers in each batch; (9) denotes that the arrival time of the first batch at the construction site is earlier than, or equal to, the starting working time, and that the subsequent batch cannot arrive at the construction site before the previous one; (10) states that the arrival time is the sum of the starting time and transportation time for the delivery; (11) ensures the subsequent batch can be assembled only when it arrives at the construction site and the previous assembly is completed; (12) shows that the earliness penalty is generated when the arrival time is earlier than the starting time for assembly; (13) shows that the tardiness penalty occurs when the completion time is greater than the common due date; (14) states that the completion time is the sum of the starting time and processing time for the assembly; (15) denotes that the assembly time of each batch is the sum of the assembly time by all precast components in one batch; (16) indicates that N trucks of precast components are partitioned into m delivery batches with n_i trucks of precast components in each batch; and (17) states that the assembly work in the same batch should be done continuously.

4. A polynomial time algorithm for optimal batch delivery

The proposed problem is to find the optimal batch delivery schedule to minimize the sum of earliness/tardiness, resource waste and emission penalties with time constraints. Two steps could be taken to solve the objective function. First, to determine the optimal number of delivery batches m. Then, the optimal quantity of each delivery batch (n_i) and the optimal delivery time of each batch (r_i) should be solved. Note that once n_i is determined, the completion time (F_i) can be calculated. Thus, the optimal delivery time of each batch (r_i) can be computed. For a given m, the value of Eq. (6) depends only on $C(r_i)$and n_i.

Several earlier papers have dealt with batch delivery scheduling problems with an objective function of minimizing earliness/tardiness penalties and batch delivery costs. Mason and Anderson (1991), for example, has examined weighted flow time minimization problems in batch delivery systems and proposes a branch and bound solution. Herrmann and Lee (1993) has studied the single-machine batch delivery problem considering all jobs with a common due date and uses a pseudo-polynomial dynamic programming algorithm to solve the problem. Cheng and Gordon (1994) present a dynamic programming approach to a batch delivery-scheduling problem on a single machine and apply a polynomial algorithm to a special case of the problem. Chen (1996) considers a single machine batch-scheduling problem with a common due date and presents a polynomial dynamic programming algorithm to minimize the sum of earliness/tardiness penalties, due date penalty and delivery costs. Hall and Potts (2003) provide dynamic programming algorithms for a range of batch delivery scheduling problems from the viewpoint of the supplier only, or manufacturer only or both. Mazdeh et al. (2007) address a single machine batch scheduling problem, and suggest branch and bound algorithms to minimize the sum of flow time and delivery costs. Shabtay (2010) provides some properties of the optimal schedule for a batch delivery single machine-scheduling problem considering the controllable due dates and prove the problem is NP-hard. Yin et al. (2013a) provide a dynamic programming algorithm to solve a single-machine batch delivery scheduling problem to minimize the total cost of earliness/tardiness, job holding and due date assignment, considering an assignable common due date and controllable processing times. Yin et al. (2013b) also consider a batch delivery single-machine scheduling problem with an assignable common due window, and develop a dynamic programming algorithm to find the optimal size and location of the window, the optimal dispatch date for each job and an optimal job sequence to minimize a cost function. While Potts and Kovalyov (2000) review research into two types of scheduling problems, comprising jobs that are processed or delivered in batches - showing that the dynamic programming approach is a useful solution technique.

No literature addresses the same objective as this study, which is to minimize earliness/tardiness, resource waste and environmental emission penalties. Some important manufacturing factors, such as waiting time and time-dependent delivery time, have also not been considered previously. In this research, waiting time, time-dependent transportation time, number of delivery batches and the assembly time of each batch are considered as variables. If the problem is solved in one of the working intervals$[a_0, T_1]$, the others are likewise because the working intervals are similar to each other. To be general, therefore, the notation of the problem stated above is the same except the working intervals are changed from $[a_0, T_1]$and$[T_2, b_0]$to$[W_0, W_1]$. Thus, the batch delivery and assembly work are completed on a common due date$[W_0, W_1]$with the same objective function. If the final delivery batch can be assembled within due date W_1 (the arrival time of the first delivery batch should be W_0 or earlier), no tardiness penalty will occur. Therefore, the tardiness penalty part can be simplified to

$$\beta \sum_{i=1}^{m} t_i = \beta \sum_{i=1}^{m} \max(0, A_i - S_i) = \beta \sum_{i=1}^{m} \max(0, S_i + P_i - W_1) \tag{18}$$

and when the assembly time of each precast component is identical, say$p_k = v$, the delivery drivers' waiting time for assembly in the ***i***th batch delivery$w_i$is

$$w_i = \sum_{j=1}^{n_i} (j-1)v = \frac{v}{2} n_i (n_i - 1). \tag{19}$$

The assembly time of the$i$th batch P_i is

$$P_i = n_i{*}v. \tag{20}$$

Thus, Eq. (6) can be reformulated as

$$z(m, n_i, r_i) = \alpha \sum_{i=1}^{m} n_i{*}\max(0, A_i - S_{i-1} - P_{i-1}) + \beta \sum_{i=1}^{m} n_i{*}\max(0, S_i + P_i - W_1) + \frac{v\gamma}{2} \sum_{i=1}^{m} n_i(n_i - 1) + \delta \sum_{i=1}^{m} n_i{*}(C(r_i) - C_0) \tag{21}$$

This problem is very similar to the special case of batch delivery scheduling problems with an identical processing time to minimize earliness/tardiness, holding, due date assignment and costs (Shabtay, 2010). In Shabtay's (2010) study, the objective function of the special case with identical processing time is

$$z(\pi, B, d) = \alpha \sum_{i=1}^{m} \sum_{j=l_{i-1}+1}^{l_i} \max\left(0, d_j - \sum_{k=1}^{l_i} p_k\right) + \beta \sum_{i=1}^{m} \times \sum_{j=l_{i-1}+1}^{l_i} \max\left(0, \sum_{k=1}^{l_i} p_k - d_j\right) + \frac{\theta p}{2} \sum_{i=1}^{m} (l_i - l_{i-1}) \times (l_i - l_{i-1} - 1) + \delta m \tag{22}$$

Comparing Eq. (21) with Eq. (22), the first and second parts in Eq. (21) are corresponding to those in Eq. (22), both of which are the earliness/tardiness penalties. The third part in Eq. (21) is corresponding to that in Eq. (22), the values of which are related to the number of batches and number of elements in each batch. The fourth part in Eq. (21) is corresponding to that in Eq. (22), for both are related to minimizing the total number of batches. The special case of identical processing time has been proved to be solvable in polynomial time (Shabtay, 2010), which is solvable in $O(n^2)$ time by applying a polynomial time optimization algorithm with a given job sequence (n is the number of jobs). This research uses the algorithm without a proof (see Shabtay (2010) for more details). The difference is that we apply their algorithm, which builds the optimal batch sequence in forward order from the front instead of in reverse order from the back.

The batch-partitioning scheme is therefore: Given Ntrucks of precast components, partition Ninto$m$delivery batches ($\pi = (n_1, \ldots, n_m)$), where$1 \le m \le N$. The objective is to determine simultaneously the optimal number of delivery batches m, the optimal quantity of each batch n_i, and the optimal delivery time of each batch $C(r_i)$. For $0 \le l < j \le N$,$F(l,j)$ denotes the minimum partial value of the objective value given by Eq. (6) for a partial schedule that includes trucks $1, \ldots, j$, assuming $l+1$ indexes the start of the second batch, i.e., that the partial sequence includes $1, \ldots, l$ in the same batch and continues with another batch starting with truck $l+1$, giving

$$F(l,j) = (j-l) \times \left(\alpha\max\left(0, S_{l+1,j} - A_{l+1,j}\right) + \beta\max\left(0, S_{l+1,j} + v \times (j-l) - W_1\right)\right) + \frac{v\gamma}{2}(j-l-1)(j-l) + \delta(j-l)\left(C_{l+1,j} - C_0\right) + G_l \tag{23}$$

where $C_{l+1,j}$, $A_{l+1,j}$and$S_{l+1,j}$denote the transportation time, arrival time and the starting time of assembly work for the partial trucks $l+1, \ldots, j$, respectively. For$1 \le j \le N$, let $G_j$denote the minimum partial value of the objective value given by Eq. (23) for a partial schedule that includes delivery trucks $1, \ldots, j$. $G_j$can be recursively calculated in the reverse order as explained below

$$G_j = \min_{j>l} F(l,j) \tag{24}$$

Combining Eqs. (23) and (24), we obtain the recursion

$$G_j = \min_{j>l} \left\{ (j-l) \times \left(\alpha\max\left(0, S_{l+1,j} - A_{l+1,j}\right) + \beta\max\left(0, S_{l+1,j} + v \times (j-l) - W_1\right)\right) + \frac{v\gamma}{2}(j-l-1)(j-l) + \delta(j-l)\left(C_{l+1,j} - C_0\right) + G_l \right\}, 1 \le j \le N \tag{25}$$

with the initialization

$$G_0 = 0 \tag{26}$$

The goal is to find G_N. An optimal schedule for the pair $l, \ldots, j$ consists of the first batch$\{1, \ldots, l\}$, followed by an optimal batch with trucks$\{l+1, \ldots, j\}$. The developed algorithm is shown in Table 2.

5. Computational results

The project chosen for this study is a 30-storey-high residential building with car parking facilities. The project is characterized by the extensive use of precast reinforced concrete components with almost 120 precast units per typical floor including precast wall panels, beams, columns, slabs, balconies and staircases. Tower cranes are utilized for transporting and lifting the components on the site after the delivery trucks arrive. The construction site is located in the center of a very congested city, such as Hong Kong, which indicates the need for JIT delivery. One construction activity related to the erection of precast wall panels was selected as an example. To test the completeness, reliability and scalability of the proposed method, different situations were considered, using several criteria such as different traffic levels, various types of trucks, and changeable assembly times, which were demonstrated by four cases. The parameters relating to Cases 1 and 2 are shown in Table 3, Case 3 in Table 4 and Case 4 in Table 5. Compared with Case 1 (shown in Tables 3–5), Case 2 has different traffic levels

Table 2
The polynomial time optimization algorithm.

//Input: a_0, b_0, T_1, $T_2 \nu N\alpha,\beta$ γ, C_1, $\ldots C_M TI_1$, $\ldots, TI_M$;
//Initializations:$S_1 = a_0$; $e_1 = S_1 - A_1$; $t_1 = 0$;$G_{n+1} = 0$
//Calculate:
For$x \in [0, 24]$
Find$C_0' = \max(C(x))$
$r_1 = W_0 - C_0'$
End for
For$j = 1, \ldots, 2N$
$A_j = C(r_j) + r_j$
$C_j = C(r_j)$
$r_j = r_j + \nu/2$
End for
For $1 \le j \le N$
For$j < l \le N + 1$
For $1 \le i \le 2N$
$A_{j,l} = A_i$
$C_{j,l} = C_i$
//An optimal solution value is given by
$$G_j = \frac{\min}{j > l} \left\{ (j-l) \times (\alpha \max(0, S_{l+1,j} - A_{l+1,j}) + \beta \max(0, S_{l+1,j} + \nu \times (j-l) - W_1)) + \frac{\nu\gamma}{2}(j-l-1)(j-l) + \delta(j-l)(C_{l+1,j} - C_0) + G_l \right\}$$
End for
End for
End for
//Determine the optimal batch delivery time for each batch
For $1 \le j \le m$
$r_j = A_j - C(r_j)$
End for
//Determine the optimal number of delivery batches
For $1 \le m \le N$
Calculate $z(m, G_j)$
End for
//Output: $z(m, G_j)$, $A_{j,l}$,$C_{j,l}$

Table 3
Parameters relating to Cases 1 and 2.

Notation	Description	Value	Unit
a_0	starting time for assembly on site	8	h
b_0	deadline for assembly	18	h
T_1	time interval for rest	12	h
T_2	time interval for rest	14	h
n	total number of precast components	60	item
N	total number of trucks	15	1
M	time intervals of the transportation time	6	1
ν	assembly time of 4 pieces of precast units (one truck)	0.5	h/truck

Table 4
Parameters relating to Case 3.

Notation	Description	Value	Unit
a_0	starting time for assembly on site	8	h
b_0	deadline for assembly	18	h
T_1	time interval for rest	12	h
T_2	time interval for rest	14	h
n	total number of precast components	60	item
N	total number of trucks	10	1
M	time intervals of the transportation time	6	1
ν	assembly time of 6 pieces of precast units (one truck)	0.75	h/truck

considering the different precast manufacturers, Case 3 employs different types of trucks and Case 4 utilizes different lifting resources for on-site assembly.

When considering multi-objective optimization problems, decision makers should be aware of the importance of each individual objective in advance (Liu et al., 2017). For the problem in this study,

Table 5
Parameters relating to Case 4.

Notation	Description	Value	Unit
a_0	starting time for assembly on site	8	h
b_0	deadline for assembly	18	h
T_1	time interval for rest	12	h
T_2	time interval for rest	14	h
n	total number of precast components	40	item
N	total number of trucks	10	1
M	time intervals of the transportation time	6	1
ν	assembly time of 4 pieces of precast units (one truck)	0.8	h/truck

the penalty coefficient indicates the importance weight of the corresponding objective. Considering the schedule problem, decision makers are managers of transportation companies, or supplier companies with their own transportation equipment, who should consider the importance of the earliness/tardiness penalties, resource waste penalty and environmental emission penalty. Energy efficient scheduling that considers environmental issues in traditional operational studies - regarded as one of the most important means of achieving a company's sustainable competitive advantage - has attracted considerable attention over the last decade (Liu et al., 2017). On the other hand, customer satisfaction is measured by on-time delivery (Ko, 2010). Therefore, in this research, if the earliness/tardiness penalty coefficients are set at a standard level such as 1.0, then the resource waste penalty coefficient γ is set from 0 to 1.0, and environmental emission penalty coefficient δ is set from 1.2 to 3.0, which is shown in Table 6. In other words, compared with the earliness/tardiness penalties, the resource waste penalty caused by the truckers' waiting time is set to be less important, but the environmental emission penalty incurred by the extra transportation time is set to be more important.

For simplicity, three traffic levels are considered (light, normal and heavy traffic) in Cases 1, 3 and 4. The transportation time $C(r_i)$from one supplier to the construction site can be defined as

$$C(r_i) = \begin{cases} 2.1, 0 \le r_i < 5 \\ 3.5, 5 \le r_i < 7 \\ 4.2, 7 \le r_i < 9 \\ 3.5, 9 \le r_i < 16 \\ 4.2, 16 \le r_i < 19 \\ 2.1, 19 \le r_i < 24 \end{cases} \tag{27}$$

where r_i denotes the starting time for transportation. Four traffic levels are considered (light, normal, heavy and major traffic jams) in Case 2. The transportation time $C(r_i)$from one supplier to the construction site can be defined as

$$C(r_i) = \begin{cases} 2.5, 0 \le r_i < 5 \\ 3.2, 5 \le r_i < 6 \\ 4.5, 6 \le r_i < 7 \\ 5.0, 7 \le r_i < 9 \\ 3.2, 9 \le r_i < 16 \\ 4.5, 16 \le r_i < 18 \\ 2.5, 19 \le r_i < 24 \end{cases} \tag{28}$$

Table 6
Parameters of penalty coefficients.

α	earliness penalty coefficient	1.0	unit cost/h
β	tardiness penalty coefficient	1.0	unit cost/h
γ	resource waste penalty coefficient	0–1.0	unit cost/h
δ	environmental emission penalty coefficient	1.0–3.0	unit cost/h

where r_i denotes the starting time for transportation.

The above expressions illustrate the distribution of delivery time at different starting times. In the delivery practice of precast components, the maximum delay is usually minimized because the precast manufacturer intuitively arranges deliveries in earliest due date (Arashpour et al., 2016a). In this situation, all the precast units required in Cases 1, 3 and 4 will be delivered at 4.9 a.m. because it takes 2.1 h and will arrive at 7 a.m. for assembly (1 h earlier thana_0, the start working time of the workers). For Case 2, all the precast units required will be delivered at 4.8 a.m. so that it takes 3.2 h and will arrive on time at 8 a.m. for assembly. It is obvious that no delay occurs, which seemingly causes no waste of on-site resources. However, not all precast components can be assembled at the same time, because on-site resources are limited. In fact, precast components have to be assembled one by one, which means that they have to queue for assembly. The due date here is $b_0 = 18$ (at 6:00 p.m.), which means the truck driver with the last precast components to be assembled needs to wait almost 10 h, otherwise, a second handling will be needed, related to temporary unloading and lifting. If time is saved, the resource of truck drivers can be shared with other activities. Therefore, the assembly time of each precast component should be considered, defined here as an identical constant for the same type of precast component.

The objective of this research is to minimize the earliness/tardiness, resource waste and emission penalties by finding the optimal number of delivery batches m, optimal quantity of each batch delivery n_i, and the optimal delivery time of each batch r_i. As illustrated in Section 4, the problem can be dealt with in two steps. The first is to determine the total number of delivery batches$m$, and the second problem is formulated as a time-dependent batch-scheduling problem within common due dates. What should be noted is that the common due dates in the problem are$[a_0, T_1]$and$[T_2, b_0]$with a time interval$[T_1, T_2]$. It is assumed that the assembly work cannot be carried out during time interval $[T_1, T_2]$, and the precast components in one batch are assembled without any interruption, otherwise the time interval involved causes the truck driver to lose time. Thus, the delivery batches m should be larger or at least 2. In Cases 1, 2, 3 and 4, the m delivery batches of precast components can be divided into two parts (m_1 and m_2) according to the working intervals$[a_0, T_1]$and $[T_2, b_0]$, due to the identical assembly time of each precast component. Then the problem is divided into two independent sub-problems. In this way, the problem can be formulated as time dependent batch scheduling problems with a common due date without a time interval. Since the working interval $[a_0, T_1]$ is equal to working interval $[T_2, b_0]$, then we reset $N = 8$ for Cases 1 and 2, and $N = 5$for Cases 3 and 4.

5.1. Performance assessment

To assess the capability of providing a convenient decision-making tool, the above cases were analyzed to test the effectiveness and reliability of the solution obtained. The algorithm first calculates any possible optimal delivery batch with trucks from l to$j$, and $1 < = l < j < = N$, by calculating one optimal delivery batch consisting of a different number of trucks with a different starting time. Then, for a given m, the objective of each permutation $P(m)$is calculated. Theoretically, the partition permutation $P(m)$ of trucks related to m delivery batches is given by

$$P(m) = \frac{(N-1)!}{(m-1)!(N-m)!}, (1 < m < N) \tag{29}$$

When the number of delivery batches$m$equals 1 or$N$, there is only one permutation ($P(m) = 1$) and the objective values can vary differently, even in this situation. For example, when $m = 1$, the waiting time penalty is the largest and a constant. Thus, the optimal objective value is determined by the starting time for transport of the delivery, which may not cause earliness/tardiness or additional environmental emission penalties. When $m = N$, the waiting time penalty is zero, while the earliness/tardiness and the additional environmental emission penalties can vary greatly since the starting time for the transportation of Ndeliveries varies with the time of the day. Thus, for a given permutation of $P(m)$, the minimum penalty is determined by the combined effects of the earliness/tardiness and additional environmental emission penalties. When applying sustainable construction, environmental factors become important in delivery practices. As is shown in Table 6, the given parameters have the relationship $\delta > \alpha = \beta > \gamma$. The following part gives one kind of solution to the scheduling problem when setting $\delta = 1.2$, $\alpha = \beta = 1.0$ and$\gamma = 0.5$. The environmental emission penalty is set to be a little more important than the earliness/tardiness penalties, but all are more important than the resource-waste penalty caused by the truckers' waiting time.

Taking Case 1 for instance, Fig. 4 presents the total optimal change in penalties with different delivery batches from 2 to 7 according to the $P(m)$ permutations.

The optimal objectives for Case 1 in each fixed delivery batch are depicted in Fig. 5(a). Similarly, the objectives in Cases 2, 3 and 4 can be calculated. Fig. 5(b), (c) and (d) illustrate the objectives changing with different delivery batches for Cases 2, 3 and 4 respectively. Tables 7–10 show the optimal starting times of delivery corresponding to the objective values in Fig. 5 for Cases 1, 2, 3 and 4 respectively.

As shown in Fig. 5(a) and (c) and 5(d), when $m \le \text{int}[N/2] + 1$ (where $\text{int}[N/2]$ means the integer part of $N/2$), the total penalty reduces as more delivery batches are partitioned, while, after $m = \text{int}[N/2]$ or $\text{int}[N/2] + 1$, the total penalty increases with m. Thus, the optimal delivery batch m is $\text{int}[N/2]$ or $\text{int}[N/2] + 1$, which obtains the least objective value. As shown in Fig. 5(b), the optimal delivery batch m is 2 for Case 2, which is not $\text{int}[N/2]$. The difference between Case 2 and the other three cases is that more complex traffic levels are adopted in Case 2. Therefore, full consideration of traffic levels can have a significant effect on the objective function. Tables 7–10 show that the starting times for deliveries between two successive batches converge with increases of m, and become very close after m reaches $\text{int}[N/2]$. Table 7 shows that the corresponding optimal $P(i)$and starting time $r$in Case 1 are $\pi = (2, 2, 2, 2)$ and $r = (4.9, 6.0, 6.5, 6.9)$, respectively. Table 8 presents the corresponding optimal $P(i)$and starting time $r$in Case 2 are $\pi = (2, 6)$ and$r = (5.0, 5.8)$, respectively. Table 9 shows the corresponding optimal $P(i)$and starting time $r$in Case 3 are $\pi = (2, 1, 2)$ and$r = (4.9, 6.0, 6.7)$, respectively. Table 10 shows the corresponding optimal $P(i)$and starting time $r$in Case 4 are $\pi = (2, 1, 2)$ and$r = (4.9, 6.1, 6.9)$, respectively. The results can provide decision makers with an intuitive guideline for actual batch delivery.

Compared to the green value, the generated sustainable performance (Δ) by the proposed method can be quantified as follows:

For Case 1:

$$\Delta_1 = \frac{z' - z_1(m = 4)}{z'} = \frac{15 - 13.2}{15} = 12\% \tag{30}$$

For Case 2:

$$\Delta_2 = \frac{z' - z_2(m = 2)}{z'} = \frac{11 - 10.04}{11} = 8.73\% \tag{31}$$

For Case 3:

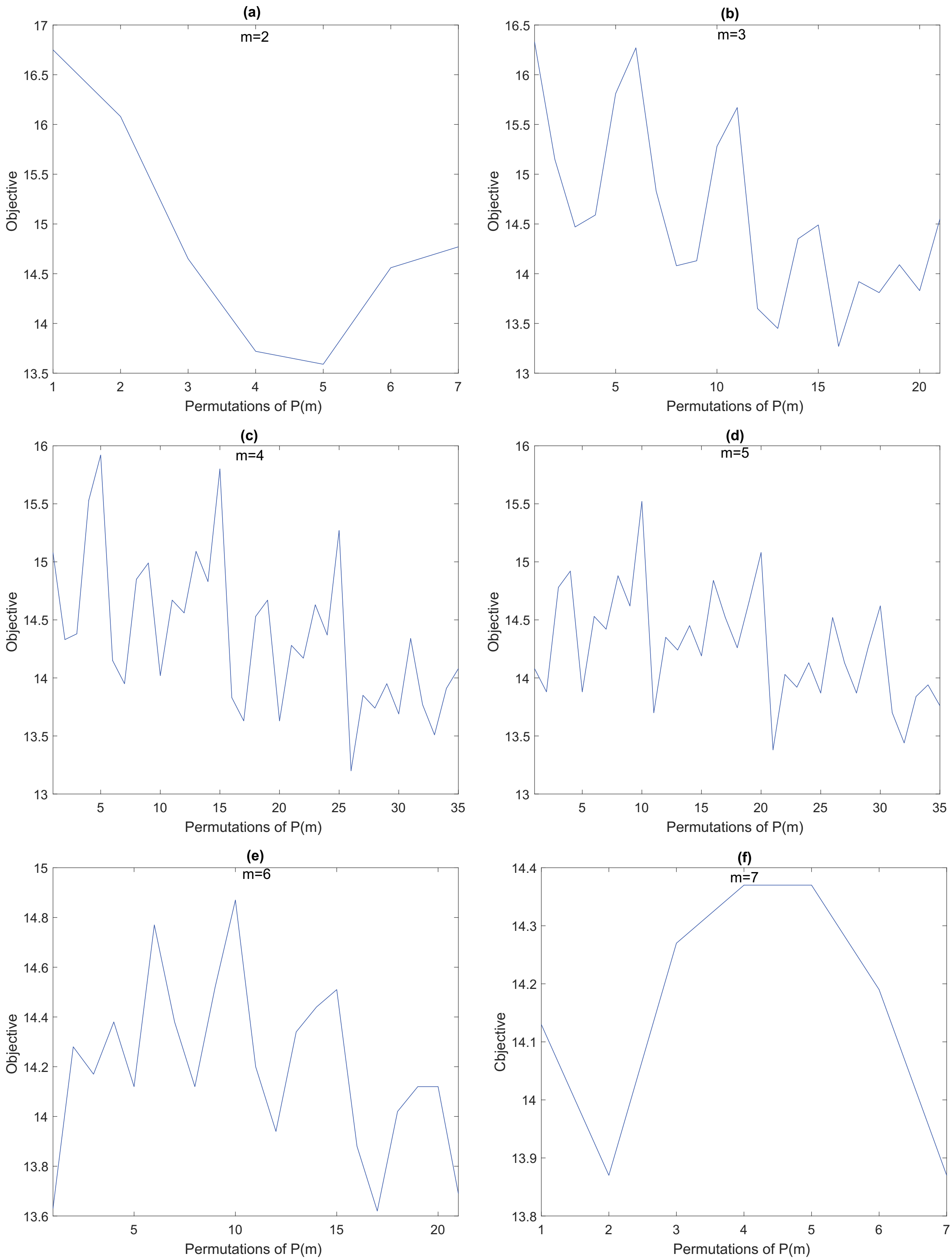

Fig. 4. Minimized penalties for different permutations when delivered m batches: (a) $m=2$; (b) $m=3$; (c) $m=4$; (d) $m=5$; (e) $m=6$ and (f) $m=7$.

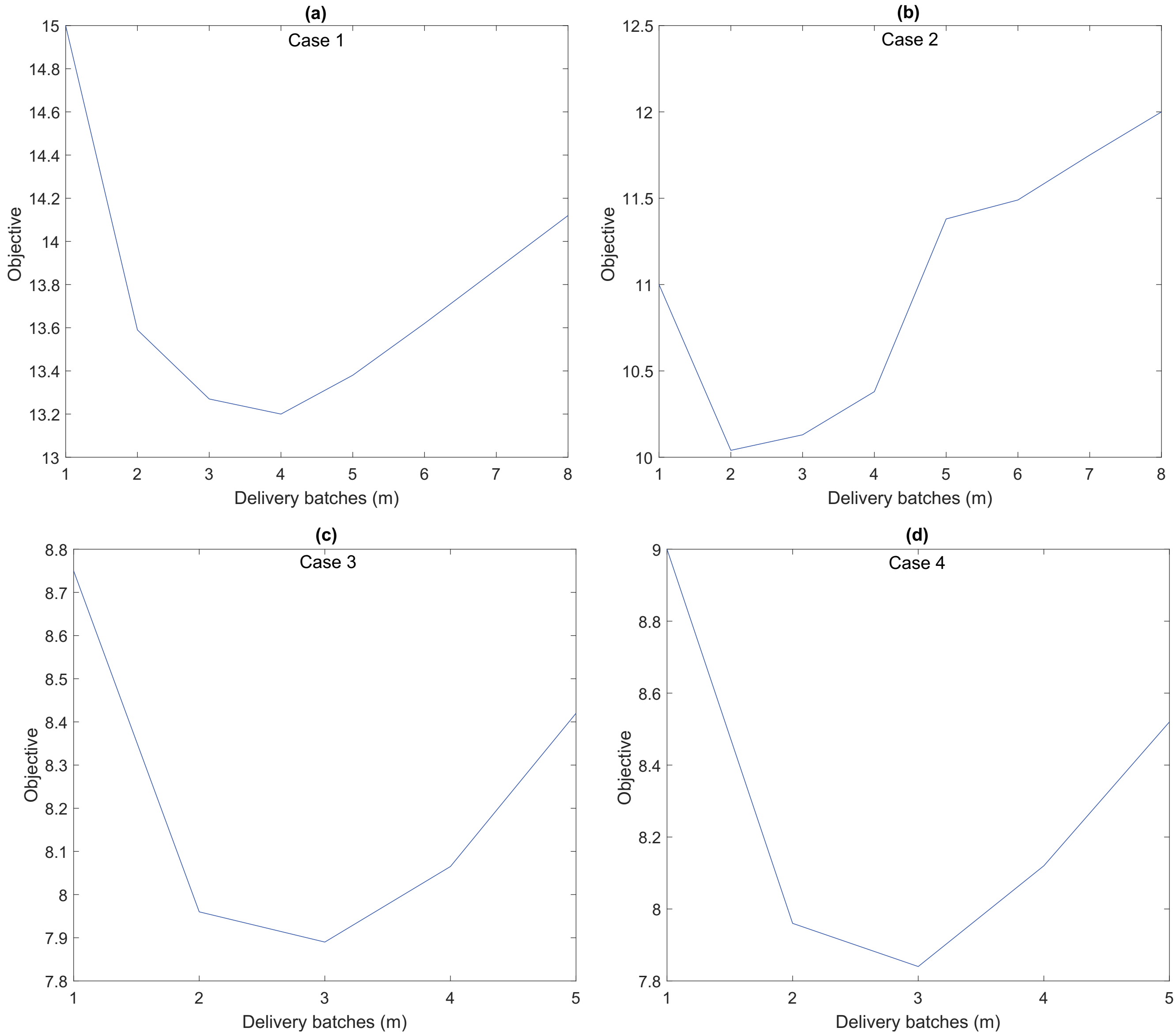

Fig. 5. Optimal batch scheduling: (a) for Case 1; (b) for Case 2; (c) for Case 3 and (d) for Case 4.

Table 7
The optimal starting time of batch delivery in different situations in Case 1.

Number of batches delivered (m)	Optimum batches number (n_i)	Optimum starting time (r_i)	Transportation time ($C(r_i)$)
1	8	4.9	2.1
2	4,4	4.9,6.9	2.1,3.5
3	2,3,3	4.9,6.5,6.9	2.1,3.5,3.5
4	2,2,2,2	4.9,6.0,6.5,6.9	2.1,3.5,3.5,3.5
5	1,1,2,2,2	4.9,5.5,6.0,6.5,6.9	2.1,2.1,3.5,3.5,3.5
6	1,1,1,1,2,2	4.9,5.5,6.0,6.5,6.9,7.3	2.1,2.1,3.5,3.5,3.5,4.2
7	1,1,1,1,1,1,2	4.8,4.9,5.5,6,6.5,6.9,7.3	2.1,2.1,3.5,3.5,3.5,3.5,4.2
8	1,1,1,1,1,1,1,1	4.8,4.9,5.5,6,6.5,6.8,6.9,7.3	2.1,2.1,3.5,3.5,3.5,3.5,3.5,4.2

$$\Delta_3 = \frac{z' - z_3(m=3)}{z'} = \frac{8.75 - 7.89}{8.75} = 9.83\% \tag{32}$$

For Case 4:

$$\Delta_4 = \frac{z' - z_4(m=3)}{z'} = \frac{9 - 7.84}{9} = 12.5\% \tag{33}$$

The results in above equations demonstrate an average 10.7% reduction of the total objective value in a one-day assembly task. For this project, there are almost 180 (30 floors * 6 days/floor) one-day assembly tasks, which will generate a great reduction in the objective value. In the long term, the construction cost of precast buildings can be reduced, which will contribute to a wider use of precast techniques. The reverse is also true: a wider use of precast

Table 8
The optimal starting time of batch delivery in different situations in Case 2.

Number of batches delivery (m)	Optimum batches number (n_i)	Optimum starting time (r_i)	Transportation time $(C(r_i))$
1	8	5.0	2.5
2	2,6	5.0, 5.8	2.5,3.2
3	1,1,6	5.0,5.4,5.8	2.5,3.2,3.2
4	1,1,1,5	5.0,5.4,5.9,6.0	2.5,3.2,3.2,3.2
5	1,1,1,1,4	5.0,5.4,5.8,5.9,6.0	2.5,3.2,3.2,3.2,3.2
6	1,1,1,1,1,3	5.0,5.4,5.7,5.8,5.9,6.0	2.5,3.2,3.2,3.2,3.2,3.2
7	1,1,1,1,1,1,2	5.0,5.4,5.6, 5.7,5.8,5.9,6.0	2.5,3.2,3.2,3.2,3.2,3.2,3.2
8	1,1,1,1,1,1,1,1	5.0,5.4, 5.6, 5.7,5.8,5.9,6.0,6.6	2.5,3.2,3.2,3.2,3.2,3.2,3.2,4.5

Table 9
The optimal starting time of batches delivery in different situations in Case 3.

Number of batches delivery (m)	Optimum batches number (n_i)	Optimum starting time (r_i)	Transportation time $(C(r_i))$
1	5	4.9	2.1
2	3,2	4.9,6.7	2.1,3.5
3	2,1,2	4.9,6.0,6.7	2.1,3.5,3.5
4	2,1,1,1	4.9,6.0,6.7,6.9	2.1,3.5,3.5,3.5
5	1,1,1,1,1	4.9,5.2,6.0,6.7,6.9	2.1,3.5,3.5,3.5,3.5

Table 10
The optimal starting time of batch delivery in different situations in Case 4.

Number of batches delivery (m)	Optimum batches number (n_i)	Optimum starting time (r_i)	Transportation time $(C(r_i))$
1	5	4.9	2.1
2	3,2	4.9,6.9	2.1,3.5
3	2,1,2	4.9,6.1,6.9	2.1,3.5,3.5
4	1,1,1,2	4.9,5.3,6.1,6.9	2.1,3.5,3.5,3.5
5	1,2,1,1,1	4.9,5.3,6.1,6.8,6.9	2.1,2.1,3.5,3.5,3.5

techniques can contribute to a decreasing cost of precast construction; thus, it is a virtuous cycle in sustainable construction.

5.2. Economic effects

The economic effect of implementing of JIT management in the precast construction process is an important factor. The precast components are delivered to the job site JIT for assembly with no inventory, which avoids a second handling so that on-site resources (e.g., temporary holding areas, expensive cranes and manpower) can be saved. The corresponding economic performance generated was not quantified in the current research, but the economic performance generated by the reduction of earliness/tardiness penalties and resource-waste penalty was analyzed quantitatively as shown in Figs. 6 and 7 respectively. The earliness/tardiness penalties of different batches within the optimal solution for different cases are presented in Fig. 6, which shows that, when the minimum earliness/tardiness penalties were obtained, the delivery batches *m* for Cases 1 to 4 are 6, 3, 5 and 4, respectively. The resource-waste penalties of different delivery batches within the optimal solution for different cases are presented in Fig. 7, which illustrates that the resource-waste penalty was decreasing monotonically with increases in delivery batch *m*. The JIT strategy promotes more frequent delivery batches *m*with a smaller number of precast components in each batch. As the results show, when delivery batches *m* reached the maximum value for each case, resource-waste penalties obtained the minimum value of zero, which suggests that JIT strategy contributes to eliminating waste caused by overproduction and waiting. The total generated economic performance is maximum when the minimum objective value of earliness/tardiness penalties and resource-waste penalty is obtained, where the delivery batches *m* are also 6, 3, 5 and 4 for Cases 1 to 4, respectively. This implies the earliness/tardiness penalties are more sensitive to the generated economic performance than the resource-waste penalty. The results indicate that time-dependent transportation time could be an influential factor in determining the economic performance.

5.3. Environmental effects

In addition to the economic effects, adopting JIT management also has a positive environmental effect. The JIT philosophy has a potential role in eliminating waste caused by over-production, waiting time, transportation, processing, inventory and movement. In this paper, the environmental issue related to transportation time was considered by optimal time-dependent transportation time. When the transportation distance between two locations is determined, different traffic levels can cause different transportation times. To reduce the transportation time is to reduce carbon emissions. Thus, the generated environmental performance can be quantified using the additional transportation time obtained by the real transportation time subtracting the transportation time during the light traffic level. Fig. 8 illustrates the additional environmental emission penalties changing with different delivery batches (m) within the optimal solution, showing that the penalty is increasing with *m*. The minimum penalty is zero for all cases when the delivery batch *m* is 1. This can happen when all precast components are delivered as one batch during the light traffic level, so that no additional transportation time occurs. The results provide important managerial implications in actual transportation, as they indicate that carbon emissions can be greatly reduced by delivering precast components in normal traffic or light traffic levels.

However, the delivery all precast components by one batch will reduce the economic performance and waste on-site resources - decreasing hidden environmental performance by a second

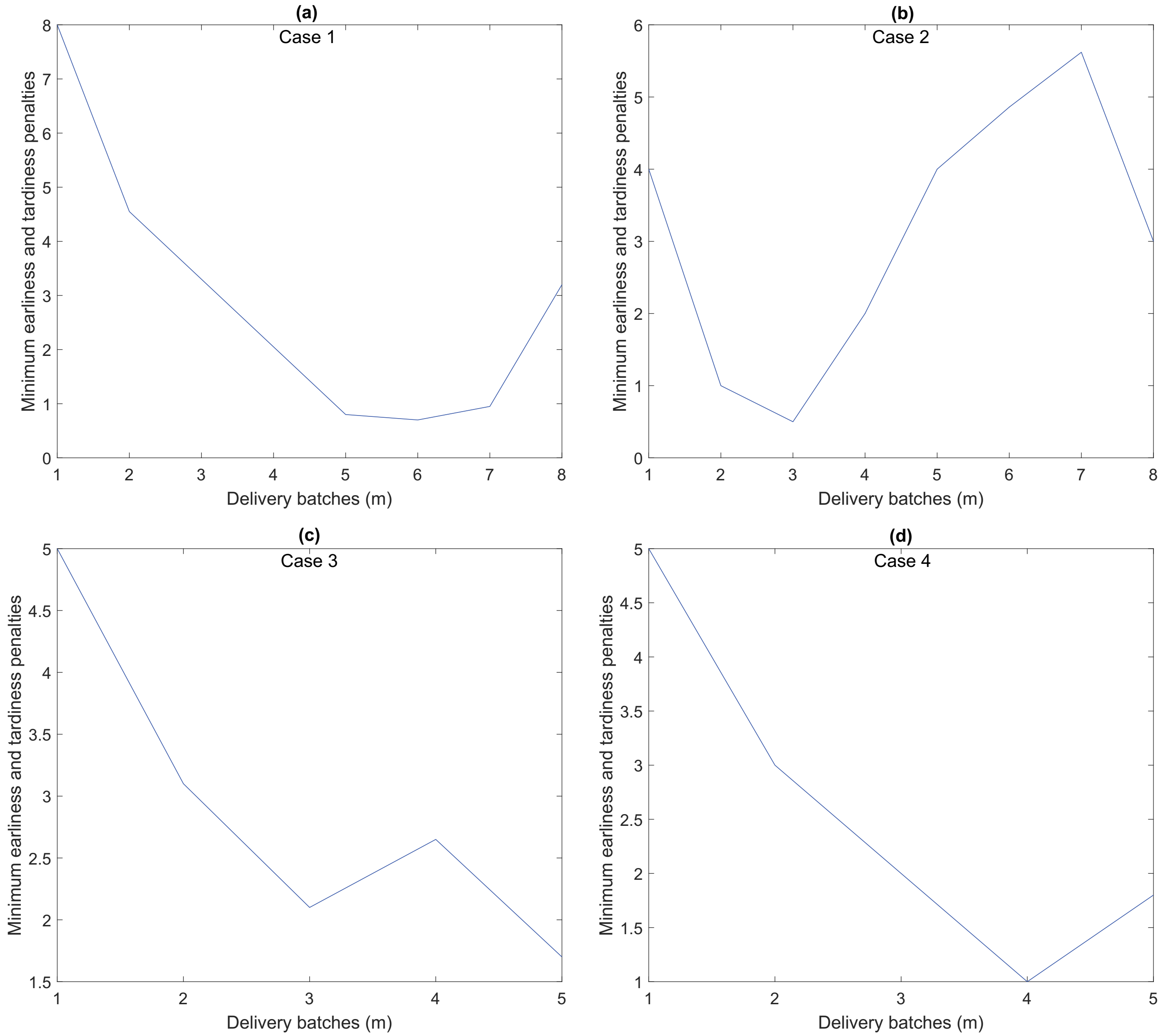

Fig. 6. Minimum earliness/tardiness penalties: (a) for Case 1; (b) for Case 2; (c) for Case 3 and (d) for Case 4.

handling of the delivered components. The results show the optimal m by considering generated environmental performance conflicts with that considering the generated economic performance. The optimal solution to the total objective function may not be the best solution when only environmental performance is considered, because the environmental performance depends on the time-dependent transportation time, where more delivery batches will increase the probability of delivery during traffic jams. It is expected that the proposed method can improve environmental performance without affecting commercial sustainability. Therefore, both economic and environmental performance were incorporated into our research objective, where the best situation is to fully consider all the relevant factors affecting the objective value.

5.4. Impact of different penalty coefficients

This section discusses the impact of the different penalty coefficient parameters on the scheduling results. The results from Figs. 6–8 show that the objective of minimizing earliness/tardiness and time loss penalties conflict with that of minimizing the additional environmental emissions penalty. As illustrated previously, different penalty coefficients denote different the weights of each individual objective. The special cases given above analyze only one kind of solution to the scheduling problem, by setting $\delta = 1.2 > \alpha = \beta = 1 > \gamma = 0.5$, where the penalty parts by additional environmental emissions per unit (δ), earliness/tardiness per unit (α/β) and resource loss per unit (γ) are the most important, middle important and least important, respectively. By setting δ, α, β and γ with different values, a variety of scheduling solutions can be obtained. Nowadays, managers are increasingly forced to deal with environmental issues to gain such competitive advantages as a positive corporate image, increased efficiency and innovation leadership (Laari et al., 2017). Thus, the following results demonstrate the distribution of the optimal scheduling solutions for Case 1 when more importance is assigned to the environmental effects.

Due to the generated environmental performance conflicting with the generated economic performance, we keep the penalty

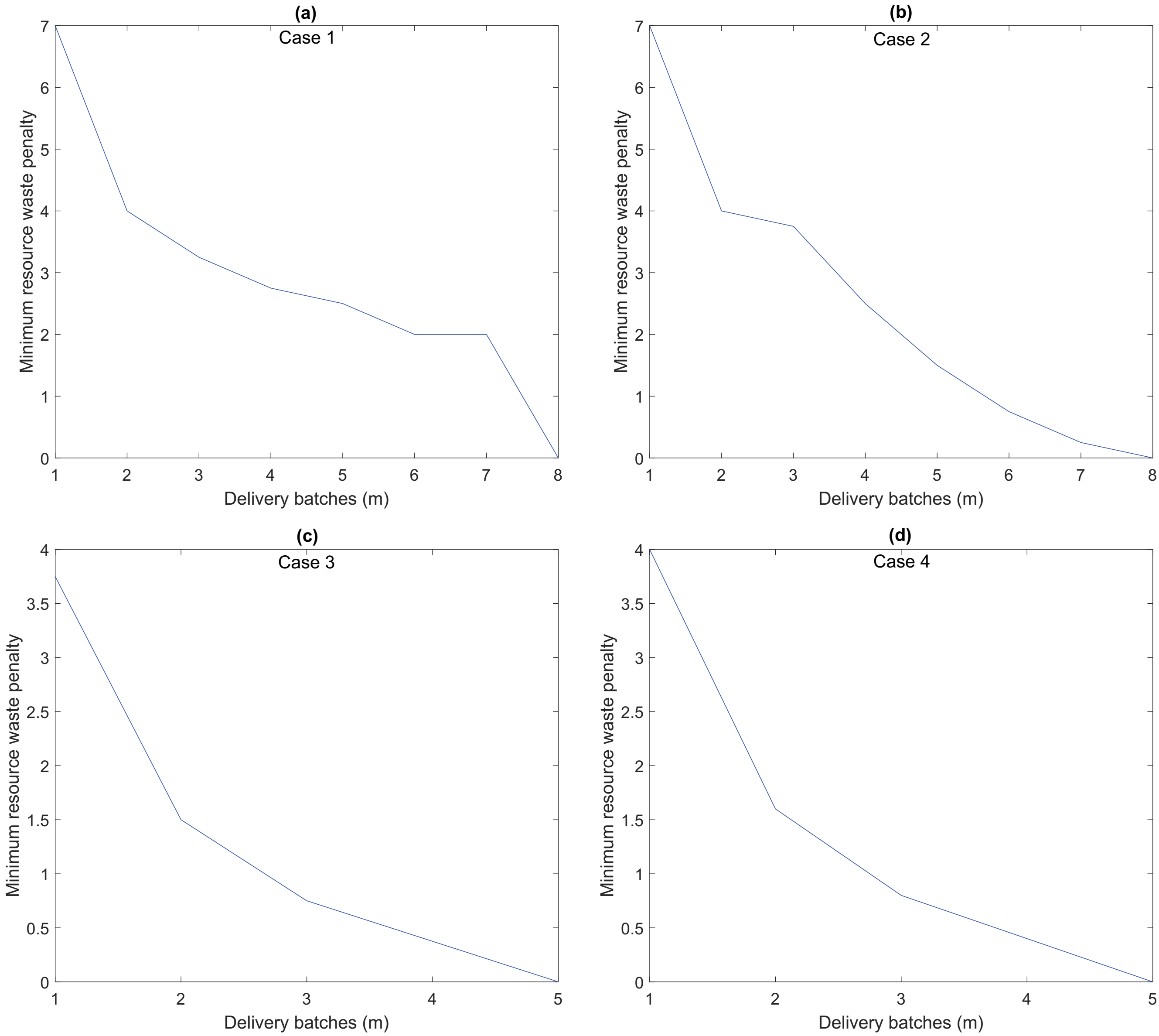

Fig. 7. Minimum resource-waste penalty: (a) for Case 1; (b) for Case 2; (c) for Case 3 and (d) for Case 4.

coefficients $\alpha = \beta = 1.0$ and $\gamma = 0.5$ constant but increase δ from 1.2 to 2.5 ($\alpha + \beta + \gamma = 2.5$). Fig. 9 depicts the results for the total objective and three individual objectives, when $\delta = 1.2$, $\delta = 1.5$, $\delta = 2.0$ and $\delta = 2.5$ respectively. As Fig. 9(a) shows, the objective value varies from 13.2 units to 22 units with δ increasing from 1.2 to 2.5. When $\delta \geq 2.0$, the minimum objective is obtained when all precast components are delivered in one batch (shown in Fig. 9(a)), where the environmental emission penalty is zero (Fig. 9(b)). The earliness/tardiness penalties and the resource waste penalty become larger as δ increases (illustrated in Fig. 9(c) and (d)). However, it is worth noting that the environmental emission penalty decreases sharply to zero when δ reaches 2.5 (shown in Fig. 9(b)). In this case, the weight of the environmental emission penalty is so high that all the precast components are delivered in one batch during light traffic with least transportation times, and the objective value is 15 units (shown in Fig. 9(c) and (d)). Although the suppliers achieved green value for environmental protection, the minimum objective value increased, which denotes an increased construction cost. Compared with conventional construction, therefore, precast construction generates less construction waste and less environmental emissions but consumes more construction cost. Thus, for the development of precast construction, a decrease in construction cost may sometimes become more important. Additionally, the contractors prefer implementing the JIT strategy with a smaller number of precast components delivered more frequently. Thus, for a sustainable business, suppliers should also consider customer service - JIT delivery. In this sense, full consideration should be given to both the economic and environmental impacts.

6. Discussion and limitations

The aim of this article was to apply the JIT strategy in the supply chain management of precast construction by considering the time-dependent transportation time and wasted time of the truck drivers waiting for on-site assembly. By JIT delivery, on-site resources related to a second handling of precast components (e.g., temporary storage areas, expensive cranes and workers) can be

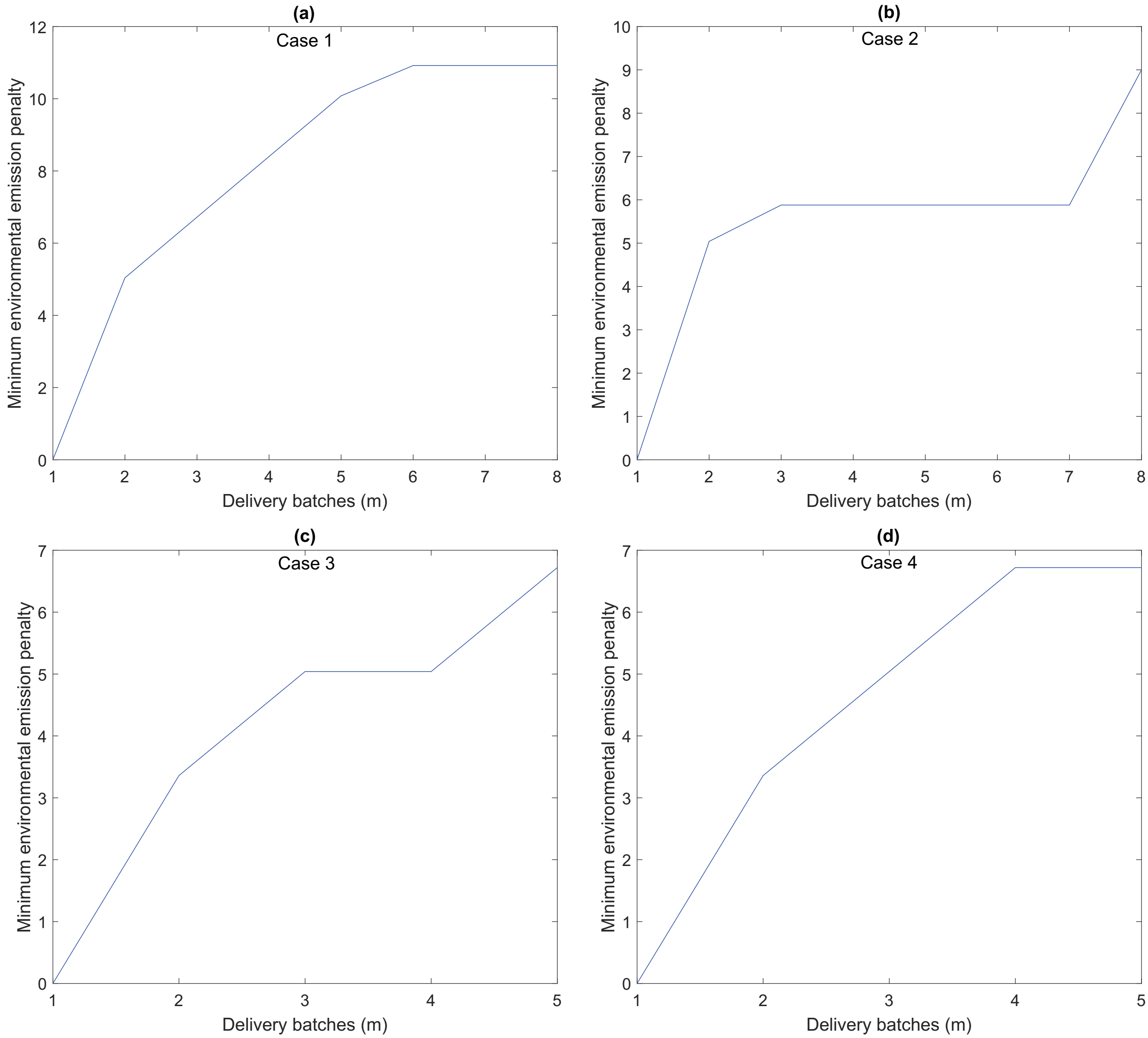

Fig. 8. Environmental emissions of each batch within the optimal solution: (a) for Case 1; (b) for Case 2; (c) for Case 3 and (d) for Case 4.

saved and thus environmental emissions can be reduced by corresponding energy saving. The application of JIT delivery seemingly benefits the contractors more than the precast manufacturers, but our results show the objective value can be reduced more than 10%, which denotes the equal economic and environmental performance generated by the precast manufacturers. Considering time-dependent batch-delivery scheduling, can to some extent reduce the environmental emissions caused by ignoring the changing environment. The on-site waiting time for assembly is considered as a variable to help enhance the efficiency of delivery for the first time. Meanwhile, less on-site deliveries waiting for assembly reduce site congestion so that on-site productivity can be improved.

The proposed multi-objective problem is transformed into a single objective by assigning different weights for each objective. This characteristic is mainly constrained by the time-dependent transportation times, assembly time and number of precast components (or number of trucks). The optimal results show that the objectives to minimize the earliness/tardiness penalty and time-loss penalty, conflict with the objective to minimize the environmental emissions penalty. It is therefore necessary to determine how these parameters jointly affect the scheduling results. If one of the penalty coefficients weighs much more than the others, the optimal delivery scheduling is almost determined by the individual objective with the largest penalty coefficient. When the penalty coefficients of each individual objective are comparable (e.g. $\delta = 1.2 > \alpha = \beta = 1 > \gamma = 0.5$), the optimal delivery batch (m) when considering the three traffic levels is half of total deliveries ($m = [N/2]$or $m = [N/2] + 1$) with an equal number of trucks in each batch. However, different optimal solutions can be obtained to the objective function when more complex traffic levels are considered. The optimal result of Case 2 considering four traffic levels is to deliver eight trucks in two batches. These research results provide important managerial implications in actual transportation, which indicates that carbon emissions can be greatly reduced by delivering precast components in normal traffic or light traffic levels.

However, some important limitations of the model need to be

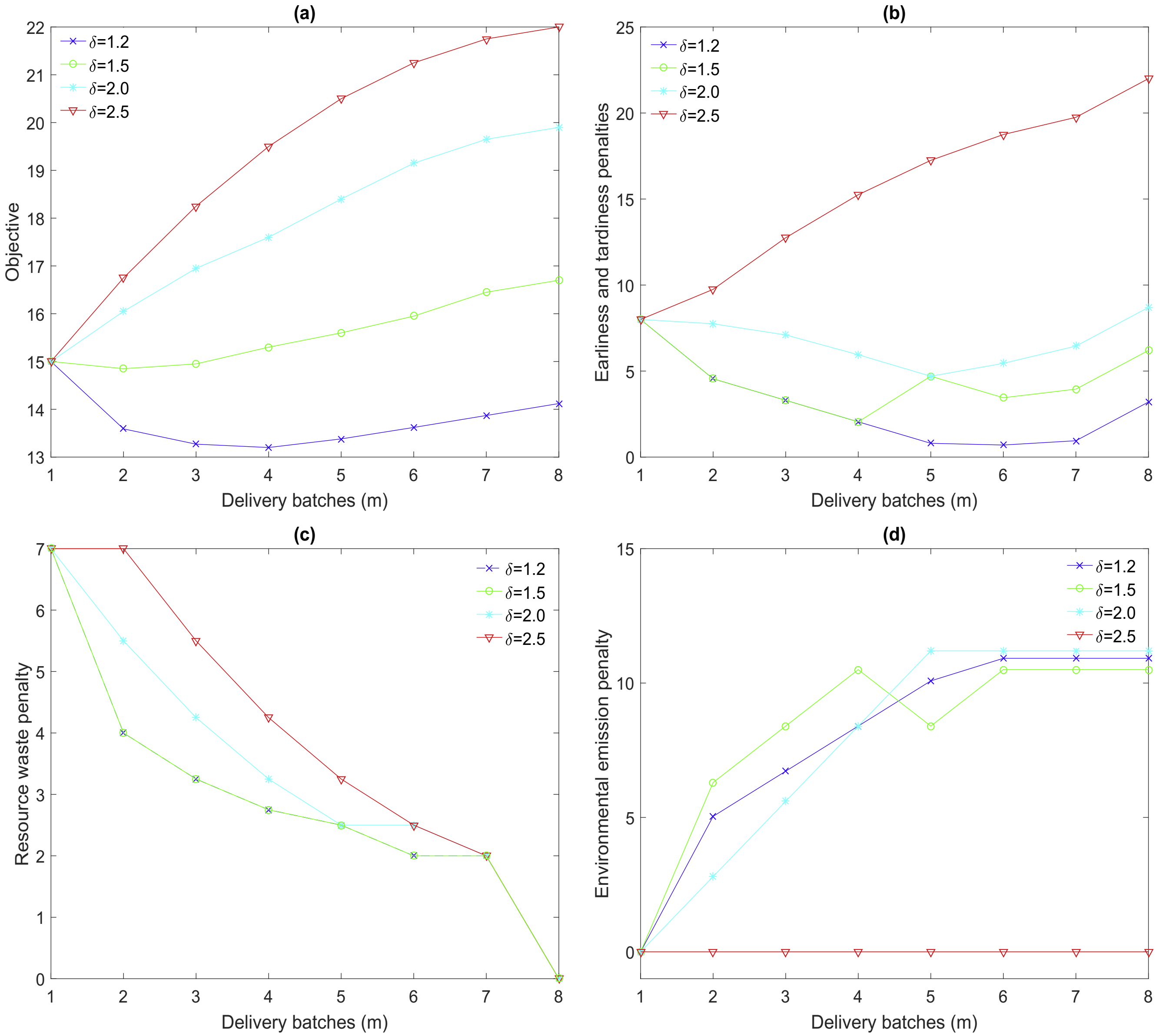

Fig. 9. Scheduling solutions for Case 1: (a) minimized total objective; (b) minimized earliness/tardiness penalties; (c) minimized resource waste penalty; (d) minimized environmental emission penalty.

borne in mind when considering the implications of the results. Firstly, in the precast construction project analyzed in this study, the delivery time was defined as a step function of starting time with limited traffic levels. If more accuracy of the planning tasks is required, more function values of transportation time are needed (e.g. a continuous function with a starting time). When delivery time is a continuous function of the starting time (considering different transport vehicles), this will greatly increase the size of the optimization problem, and more sophisticated algorithms need to be developed to solve the problem. Secondly, batch delivery optimization considers only one type of precast component for one daily assembly task. When more than one type of non-preemptive precast component is required for the same construction task, the assembly sequence of different types of precast components should be optimized. Thus, different assembly times for non-preemptive precast components are added to make the objective function more complex, which requires such practical metaheuristics as tabu search to be applied to prioritize the assembly sequence based on the earliest due dates in the construction schedules.

7. Conclusion

This study investigates for the first time the operational decision-making problem of optimal batch delivery scheduling considering the combined effect of time-dependent transportation and on-site assembly time; focusing on the minimization of earliness/tardiness, resource waste and carbon dioxide emission penalties with time constraints. This is addressed by modeling the situation as a multi-objective optimization problem, which expands the current batch-scheduling model of minimizing earliness/tardiness penalties by incorporating environmental impact in considering the time-dependent transportation time and economic impact of resources wasted by waiting for on-site assembly. Both economic and environmental performance with different weights are incorporated into the objective function, which transforms the multi-objective problem into a single objective one. Then, a polynomial time optimization algorithm is presented to locate the solution. The case study analysis shows that significant resource savings can be made in a one-day assembly task when six days are the assembly cycle for one floor, which would make a major difference to the whole construction project. However, the additional environmental emissions increase with the increase of delivery batches, which conflicts with the generated economic performance, since precast construction schedules need to be both responsive to onsite assembly and feasible for transportation. Therefore, weighting these different aspects is necessary to avoid such conflicting outcomes when optimizing sustainable performance, and parameter analysis of the coefficient penalties suggests the need for some consensus on this. The JIT philosophy is one of the management techniques contributing to eliminating waste caused by overproduction, waiting, transportation, stocks and producing defective products. By incorporating JIT philosophy into the proposed batch delivery scheduling strategy, significant improved sustainable performance can be obtained, which generates positive effects for both the suppliers and contractors. The work contributes to batch delivery theory by expanding the insight into time-dependent delivery to considering both economic and environmental performance. The method developed will be of practical value for precast building projects in ensuring the implementation of JIT strategies.

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