Journal of Civil Engineering and Management
ISSN 1392-3730 / eISSN 1822-3605
2021 Volume 27 Issue 1: 45–59
https://doi.org/10.3846/jcem.2021.14114

RESILIENCE-COST TRADEOFF SUPPLY CHAIN PLANNING FOR THE PREFABRICATED CONSTRUCTION PROJECT

Hong ZHANG, Lu YU*

Institute of Construction Management, College of Civil Engineering and Architecture, Zhejiang University, 310058, Hangzhou, PR China

Received 6 June 2020; accepted 13 November 2020

Abstract. Delivery of the prefabricated components may be disrupted by low productivity and various of traffic restrictions, thus delaying the prefabricated construction project. However, planning of the prefabricated component supply chain (PCSC) under disruptions has seldom been studied. This paper studies the construction schedule-dependent resilience for the PCSC plan by considering transportation costs and proposes a multi-objective optimization model. First, the PCSC planning problem regarding schedule-dependent resilience and resultant transportation cost is analyzed. Second, a quantification scheme of the schedule-dependent resilience of the PCSC plan is proposed. Third, formulation of the resilience-cost tradeoff optimization model for the PCSC planning is developed. Fourth, the multi-objective particle swarm optimization (MOPSO)-based method for solving the resilience-cost tradeoff model is presented. Finally, a case study is presented to demonstrate and justify the developed method. This study contributes to the knowledge and methodologies for PCSC management by addressing resilience at the planning stage.

Keywords: prefabricated construction, prefabricated component supply chain (PCSC), disruption, schedule-dependent resilience, resilience quantification, resilience-cost tradeoff, multi-objective particle swarm optimization (MOPSO).

Introduction

Prefabricated construction involves producing the components in an off-site factory, transporting them to the construction site and installing them according to design (Li et al., 2014). Compared to the traditional construction mode, the prefabricated construction has the advantages of productivity improvement, project duration reduction, safety and environment enhancement (Li et al., 2014; Polat, 2010; Wang et al., 2018). The prefabricated component supply chain (PCSC) from the production site to the construction site is crucial to achieving the advantages of the prefabricated construction. Supply chain management plays an important role in reducing the costs and improving the performance of the construction projects (Davis, 2008). Modern supply chain management focuses on a wide variety of uncertainties or risks such as delays, disruptions or interruptions along the entire chain (Meng, 2013; Taillandier et al., 2015). Hence, effective management of the PCSC by addressing uncertainties or risks is indispensable to installation progress according to the construction schedule.

Disruptions can occur at any time along the PCSC due to both internal and external risks. In most cases, the transportation conditions are inevitable sources of external risks, such as climate change and weather impacts (Aloini et al., 2012). The low productivity or resource limits may lead to unavailable provision of the prefabricated components (Kim et al., 2020). In addition, the transit operations may be unfeasible due to bad weather. Moreover, some traffic routes are unfeasible for some period of time due to traffic jam, uncertain restrictions. These uncertainties or risks lead to disruptions or interruptions on the PCSC and delay delivery of the components to the construction site (Luo et al., 2019; Wang et al., 2017a). On the other hand, the heavy, big and bulky natures of the prefabricated components may trigger transportation restrictions such as heavy limit, size or height limit, and passing time limit, thus aggravating the disruptions on the PCSC. Moreover, the contractor generally selects one supplier of the components by addressing the price and timely delivery, so the disruptions on the supply chain may lead

*Corresponding author. E-mail: *510813951@qq.com*

to delivery delay and additional cost that are responsible by the supplier, thus often causing legal dispute.

Managing disruptions or risks are indeed challenges and issues for planning transportation or supply chain (Chen et al., 2016). Management on disruptions or risks is a complex and dynamic problem that involves the design of transportation network and the selection of component supplier as well as transportation means and routes. Although the concept of supply chain risk management was rooted and have been utilized in the manufacturing industry (Ellram et al., 2004), it is still not a mature subject within the construction industry (Shojaei & Haeri, 2019; Taroun, 2014). With development of industrialized buildings by utilizing the advantages of the manufacturing industry, some researches have been devoted to the supply chain management in the prefabricated construction industry. Li et al. (2016) investigated the underlying network of stakeholder risks in prefabricated construction projects and identified key risks and their interactions. Luo et al. (2019) identified and prioritized the supply chain risks in prefabricated construction projects by considering related stakeholders together with dynamic risk interactions. Nevertheless, management on disruptions or risks over the PCSC has not been studied enough, most of the existing studies focused on identification and qualitative evaluation rather than real-time treatment of the risks or disruptions. Kim et al. (2020) proposed a dynamic model for prefabricated component production scheduling by addressing real-time respondence to due date changes and associated uncertainties. Arashpour et al. (2017) also proposed a robust supply decision making model for the advanced manufacturing of prefabricated products under uncertainties. However, these studies mainly focused on the component production stage rather than the delivery or transportation stage from the supplier to the construction site. It is indispensable to explore how to conduct quantitative evaluation and real-time treatment of the disruptions or risks in the delivery of the prefabricated components when planning the PCSC.

The resilience concept has been proposed and applied for supply chain management by addressing uncertainties, risks and disruptions (Aloini et al., 2012; Colicchia et al., 2010; Kumar & Viswanadham, 2007). Resilience was first defined as the persistence of relationships within a system and a measure of the system's ability to persist and absorb changes of state variables, driving variables, and parameters (Holling, 1973). Since then, the resilience concept has been investigated and applied in various research fields (Ta et al., 2009). The idea of building supply chain resilience to deal with disruptions has recently gained considerable academic support (Brandon-Jones et al., 2014; Geng et al., 2014; Murino et al., 2011). Resilience of a supply chain was defined as the ability to return to its original state or an even better state through preparing, adjusting or recovering strategies in face of uncertainties, risks or disruptions (Geng et al., 2014; Torabi et al., 2015). Murray-tuite (2006) proposed ten dimensions of the supply chain resilience such as redundancy, diversity, efficiency, autonomous components, strength, collaboration, adaptability, mobility, safety, and the ability to recover quickly. In addition, quantitative measures have been advocated to enhance the supply chain resilience through changes in demand (Ip & Wang, 2011; Morlok & Chang, 2004), travel time (Murray-tuite & Mahmassani, 2004) and traffic assignment (Murray-tuite, 2006). Moreover, some operational research methods and information technologies have been applied to evaluate and optimize supply chain resilience, such as Meta-Heuristic techniques (Torabi et al., 2015; Hackl et al., 2018), linear programming (Ratick et al., 2008), simulation (Colicchia et al., 2010; Francis & Bekera, 2014) and building information modeling (BIM) (Wang et al., 2017a).

Nevertheless, most of these studies considered the resilience concept in the unimodal transportation network with risk of link failures (Peeta et al., 2010) and node failures (Peng et al., 2011; Snyder & Daskin, 2005), but rarely considered intermodal transportation network with alternative routes and traffic means between two nodes. In addition, supply shortage of the goods such as the components at the production site due to low productivity or resource limits was not addressed. Further, different delivery times and schedules corresponding to different batches that may trigger weight or size-related traffic restrictions were neglected (Chen & Miller-Hooks, 2012; Miller-Hooks et al., 2012). Recently, the resilience concept has been considered for supplier selection in the construction supply chain from the perspective of the contractor (Wang et al., 2017b). Nevertheless, few of studies on quantitative evaluation of the resilience and resultant cost for the PCSC plan have been noticed.

This study focuses on solving the resilience-based PCSC planning problem in consideration of additional cost for adjusting or recovering strategies. Based on analyses on the construction schedule-dependent resilience for the PCSC as well as the adjusting or recovering strategies and resultant costs for achieving such a resilience, the quantification scheme for the resilience of the PCSC is proposed. The mathematical formulation of the resilience-cost tradeoff model for the PCSC planning is developed, and then the MOPSO algorithm is applied to solve the resilience-cost tradeoff optimization problem. An application study is presented to demonstrate and justify the proposed method in solving the resilience-cost tradeoff PCSC planning problem.

1. Background of resilience-based PCSC planning

The prefabricated component supply chain (PCSC) is a network of multiple organizations and relationships, which includes the flow of information, the flow of the prefabricated components and services or products. The prefabricated construction is a multi-stage process that includes component production, logistics transportation and field installation. The transportation systems of the prefabricated components complete supply chains while providing strong linkages between the production site, transit places for changing transportation means, and the construction site through efficient movement and timely supply of the prefabricated components. The transportation network can be represented by a directed graph composed of nodes and edges. The nodes may represent the original production site, alternative outsourcing sites of the supplier, intermediate transit places and construction site. The edges denote traffic sections with certain transportation means and routes between two nodes. There may exist various transportation means between any two connected nodes, such as highway, railway and waterway.

Appropriate transportation or logistics of the prefabricated components from the original production site of the suppler to the construction site is crucial to the performance of the PCSC. The prefabricated construction requires strict coordination among multiple stages including production, transportation and installation. Generally, the late or early delivery of prefabricated components is the main hindrance that limits the productivity of the PCSC. Early delivery of the components may result in need of layout, storage space congestion or higher crane-handling cost on site, while late delivery of the prefabricated components to the construction site may delay the installation activities and prolong the project duration when certain lead times and total floats are consumed. The late delivery of the prefabricated components may be caused by late or unfeasible provision of the components by the supplier due to disruptions on the production process, disruptions on the transit nodes due to bad weather, and disruptions on the traffic routes due to traffic jam, uncertain restrictions on pass times or lanes. In addition, the characteristics of the prefabricated components such as heavy, big and bulky may face transportation restrictions such as heavy limit for bridges or highways, size or height limit for tunnels, and time limit for routes or lanes (see Figure 1), increasing disruptions along the PCSC and complexities of the feasible combinations of transportation routes and means. These disruptions on the PCSC may result in incoordination among the transportation linkages or adjacent traffic sections and late delivery of the components on the construction site, disturbing the construction process and leading to project delay (Ip & Wang, 2011).

A great number of researches have been conducted to enhance the performance of the transportation network when facing disruptions or interruptions, such as reliability, capacity flexibility and vulnerability (Berdica, 2002). Transportation vulnerability reflects the maximum impact that the supply chain can resist under network interruption, which also means the maximum deviation from the normal performance after an interruption occurs (Geng et al., 2014). Transportation flexibility is a concept that focuses on the capability to adapt to the external changes, while transportation robustness is the ability to maintain operational function when the system is subject to uncertain interference from the internal operations and external events. The concept of transportation resilience can be regarded as a comprehensive integration of vulnerability resistance, flexibility and robustness. Compared with transportation flexibility strategy and robustness strategy, transportation resilience puts more emphasis on recovery capability to achieve the delivery objective through adjusting or recovering strategies with minimal delay (Geng et al., 2014).

Resilience for the PCSC is to achieve the objective of the supplier for delivering the prefabricated components to the construction site with minimal delay with regards to the construction schedule through adjusting or recovering strategies. Late or unfeasible provision of the components by the supplier can be solved by considering alternative outsourcing producers or site of the supplier with additional costs dependent on the type and number of the components. Unfeasible transit nodes can be solved by using other feasible transit nodes corresponding to different transportation routes or means. Unfeasible traffic routes can be dealt with by adjusting to different transportation routes or means in the existing transportation network. In general, the above strategies for achieving resilience of the PCSC are based on the conclusion that the redundant connections among the nodes would increase the survivability of a network (Ip & Wang, 2011). Therefore, one or two alternative outsourcing producers, more transit nodes with alternative traffic routes and means are required to achieve

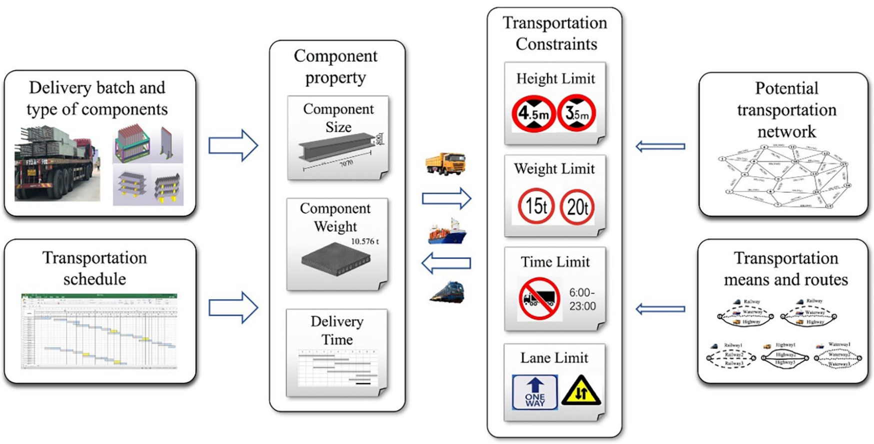

Figure 1. Disruptions on the PCSC due to various transportation constraints

resilience of the PCSC by constructing more combinations of the transportation network. Meanwhile, consideration of alternative outsourcing sites, more transit nodes and more transportation means and routes may lead to more costs. Such costs include the fixed cost building transit stations as well as the variable cost for obtaining components from outsourcing producers without lead times and the variable cost relying on the length and toll rates of alternative transportation routes and means for all batches. The goal of this study is to make tradeoff between resilience and cost of the PCSC plan.

2. Scheme for quantifying resilience of the PCSC plan

So far, there have been no standard methods for quantifying resilience (Huang et al., 2011). For the PCSC, the most vital objective is to guarantee the timely supply of the prefabricated components that need to be installed on construction site according to the construction schedule. Hence, quantification of prefabricated component transportation resilience performance should consider the schedule coordination, i.e., construction schedule and transportation schedule. Figure 2 illustrates the framework for quantitatively evaluating the resilience performance of each delivery batch of the prefabricated components. The changed transportation time under disruptions needs to be compared with the transportation time based on the initial transportation schedule and the total buffer time including the lead time of the required components and total floats of the involved installation activities.

The initial transportation schedule can be determined by the supplier based on the construction schedule. The transportation means and routes regarding each traffic section between two nodes or stations as well as the initial transportation time TT are optimally determined. Normally, a buffer of time, i.e., the lead time LT, ahead of the required installation time t_{es} is required to ensure construction progress by absorbing uncertainties in transportation and site handling. Based on the construction schedule and the Critical Path Method (CPM), the earliest installation time t_{es}, the latest installation time t_{ls}, and the total float time FT of the installation activity requiring a type of the prefabricated components can be determined. In addition, a lead time for delivering a batch of components of a certain type is determined in consideration of various uncertainties. Therefore, the lead time plus the total float of the installation activity requiring a type of prefabricated components is generally used to absorb the disruptions or uncertainties along the PCSC. When disruptions occur along the PCSC, the resilience is implemented in terms of adjusting or recovering strategies for the transportation plan so as to deliver the prefabricated components to the construction site according to the construction schedule as far as possible. The adjusting or recovering strategies in face of scenarios of disruptions (denoted as Φ) along the PCSC lead to varied transportation time denoted as $TT(\Phi)$ for each delivery batch of the prefabricated components.

Therefore, the index for quantitatively measuring the PCSC resilience should reflect the impact of the changed transportation time on the project duration by considering the lead times of the required components and the total floats of the involved installation activities. With assumption that each batch carries one type of components, the resilience for each delivery batch is measured by dividing the change of the transportation time by the total buffer time including the total float of the involved installation activity and the lead time of this batch of components that is assumed larger than zero. The resilience of the PCSC for the prefabricated construction project can be measured

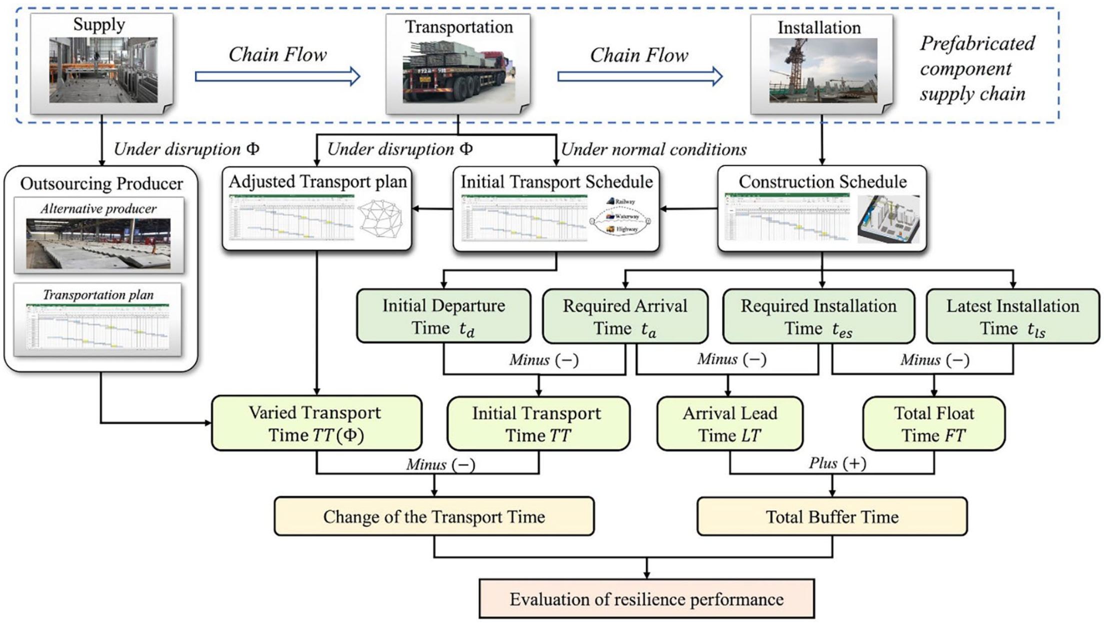

Figure 2. Framework for quantitatively evaluating the resilience performance of each delivery batch

by weighting the resilience performances of all delivery batches of the prefabricated components. The resilience weights for the batches of components required by the critical activities are assigned larger values than those for the batches of components required by the non-critical activities.

3. The resilience-cost tradeoff based PCSC planning model

Based on the analyses on the resilience issue and quantification scheme for the resilience, the goal is to achieve resilience of the PCSC in consideration of cost. The resilience-cost tradeoff optimization model for PCSC planning is formulated.

3.1. Assumptions

Prior to developing the resilience-cost tradeoff based PCSC planning model, some assumptions are made as follows:

(1) The disruption and resultant supply shortage on each node or edge in the transportation network of the PCSC are independent to each other;

(2) Each type of prefabricated components needs to be transported to the construction site with several delivery batches according to the construction schedule, and each batch carries only one type of prefabricated components;

(3) The transportation time of each delivery batch is dependent on transit nodes, transportation means and routes.

3.2. Formulation of the resilience-cost tradeoff optimization model

While the resilience of the PCSC plan for all delivery batches of components is maximized, the resultant total costs including the fixed cost for building transit stations as well as the variable costs for obtaining components from outsourcing producers and the variable cost relying on the alternative transportation routes and means need to be minimized. The resilience-cost tradeoff planning for the PCSC is a multiple-objective optimization problem.

In order to clearly describe the model, the decision variables and the parameter variables used in the formulation are explained as follows.

The decision variables:

$x_{e(lk)}^{m,s}(\theta)$ = 1 if the transportation means for batch k of component type m is transferred from means m to means s at transit node e under scenario θ, otherwise $x_{e(lk)}^{m,s}(\theta)$= 0;

$y_{ij(lk)}^{m,r}(\theta)$ = 1 if the batch k of component type l is delivered from point i to j with transportation means m and route r under scenario θ, otherwise $y_{ij(lk)}^{m,r}(\theta)$ = 0;

$z_{a(lk)}(\theta)$ = 1 if the batch k of component type l is delivered from outsourcing producer a, under scenario θ, otherwise $z_{a(lk)}(\theta)$ = 0.

The parameter variables:

L – sets of the prefabricated component types;
K_l – sets of the delivery batches of component type l;
N – sets of all the nodes in the transportation network;
A – sets of the outsourcing producers, $A \subset N$;
E – sets of the transit nodes, $E \subset N$;
M – sets of the transportation means;
R_m – sets of the transportation routes of transportation means m;
X – the vector including all decision variables x_e, denoting whether the transit node e is opened;
Φ – sets of the disruption scenarios;
w_{lk} – resilience weight of delivery batch k of prefabricated component type l;
c_e – fixed cost for building a transit at node e;
p_θ – disruption weight of scenario θ;
LT_{lk} – lead time of delivering batch k of component type l;
FT_{lk} – total float time of the installation activity that requires delivery batch k of component type l;
TT_{lk} – transportation time of delivery batch k of component type l under normal conditions;
$TT_{lk}(\Phi)$ – transportation time of delivery batch k of component type l under disruption scenarios Φ;
$t_{ij(lk)}^{m,r}$ – transportation time from point i to j under transportation means m and route r for batch k of component type l;
$t_{n(lk)}^{m,s}$ – transit time from transportation means m to s at transit node n for batch k of component type l;
$c_{e(lk)}^{m,s}$ – transit cost from transportation means m to s at transit node n for batch k of component type l;
$c_{ij(lk)}^{m,r}$ – unit transportation cost under transportation means m and route r from node i to j for batch k of component type l;
$c_{a(lk)}$ – unit variable cost for obtaining component batch k of type l from outsourcing producer a;
q_{lk} – transportation quantity of batch k of component type l;
$w_{ij}^{m,r}$ – transportation capacity of transportation means m and route r from node i to j.

The model is expressed as follows:

$$\begin{cases} \text{maximize}\, R = \sum_{l=1}^{L}\sum_{k=1}^{K_l} w_{lk} r_{lk}(X,\Phi) \\ \text{minimize}\; TC = \sum_{e=1}^{E} x_e c_e + C(X,\,\Phi) \end{cases} \quad (1)$$

subject to:

$$\begin{cases} x_e, x_{ij(lk)}^{m,r}(\theta), y_e^{m,s}(\theta), z_a(\theta) \in \{0,1\} \\ x_{ie(lk)}^{m,r}(\theta) \le y_{e(lk)}^{m,s}(\theta) \\ x_{ej(lk)}^{m,r}(\theta) \le y_{e(lk)}^{m,s}(\theta) \\ x_{aj(lk)}^{m,r}(\theta) \le z_a(\theta) \\ q_{lk} x_{ij(lk)}^{m,r}(\theta) \le w_{ij}^{m,r} \\ \sum_{m}^{M} \sum_{r}^{R_m} x_{ij(lk)}^{m,r}(\theta) = 1 \\ \sum_{m=1}^{M} \sum_{s=1}^{M} y_{e(lk)}^{m,s}(\theta) = 1 \\ \sum_{a=1}^{A} z_{a(lk)}(\theta) = 0 \; or 1 \\ \sum_{\theta=1}^{\ddot{O}} p_\theta = 1; \end{cases} ; \quad (2)$$

$$r_{lk}(Y,\Phi) = \begin{cases} \dfrac{\left((TT_{lk} + LT_{lk} + FT_{lk}) - TT_{lk}(\Phi) \right)}{(LT_{lk} + FT_{lk})}, & TT_{lk} < TT_{lk}(\Phi); \\ 1, & TT_{lk} \ge TT_{lk}(\Phi) \end{cases} \quad (3)$$

$$TT_{lk}(\Phi) = \sum_{\theta=1}^{\Phi} p_\theta \left(\begin{array}{c} \sum_{e=1}^{E} \sum_{m=1}^{M} \sum_{s=1}^{M} x_{e(lk)}^{m,s}(\theta) t_{n(lk)}^{m,s} \\ + \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{m=1}^{M} \sum_{r=1}^{R_m} y_{ij(lk)}^{m,r}(\theta) t_{ij(lk)}^{m,r} \end{array} \right); \quad (4)$$

$$C(X, \Phi) = \text{minimize} \sum_{\theta=1}^{\Phi} p_\theta \left\{ \begin{array}{c} \sum_{l=1}^{L} \sum_{k=1}^{K_l} q_{lk} \\ \left(\begin{array}{c} \sum_{e=1}^{E} \sum_{m=1}^{M} \sum_{s=1}^{M} x_{e(lk)}^{m,s}(\theta) c_{e(lk)}^{m,s} \\ + \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{m=1}^{M} \sum_{r=1}^{R_m} y_{ij(lk)}^{m,r}(\theta) c_{ij(lk)}^{m,r} \\ + \sum_{a=1}^{A} z_{a(lk)}(\theta) c_{a(lk)} \end{array} \right) \end{array} \right\}. \quad (5)$$

The upper part of Eqn (1) models the objective function of maximizing the resilience of the PCSC plan that requires to transport L types of the components to the construction site by K_l batches for each type of the components through the transportation network under disruptions of scenarios Φ. w_{lk} represents the resilience weight for the delivery of batch k and the components of type l. In order to ensure supply of the components required on site, a larger value of the resilience weight will be assigned to the delivery batch of the prefabricated components required by the critical activities.

As formulated in Eqns (3) and (4), the transportation schedule and the construction schedule are incorporated into the resilience $r_{lk}(X,\Phi)$. The lead time LT_{lk} and total float time FT_{lk} of the prefabricated component of type l and the corresponding delivery batch k are determined based on the construction schedule. The transportation time TT_{lk} is normally determined based on the construction schedule and the initial transportation schedule, which may arise a dynamic component site layout planning problem that had been addressed by another study of ours (Zhang & Yu, 2020). The value of resilience $r_{lk}(X,\Phi)$ ranges from 0 to 1. Note that the lead time LT_{lk} is supposed to be larger than 0.

The below part of Eqn (1) models the objective function for minimizing the total costs consisting of fixed cost associated with transit stations or nodes e_n as well as the total variable costs $C(X,\Phi)$. Such total variable costs include the variable cost for obtaining components from outsourcing producers z_a without lead times and the transportation variable cost on the length and tolls of the selected transportation means and routes when facing disruption of scenarios Φ, as formulated in Eqn (5).

4. Solving methodologies based on MOPSO

The solutions to the multiple-objective optimization model for the resilience-cost tradeoff planning problem can be searched out by means of the multi-objective particle swarm optimization (MOPSO) algorithm.

4.1. Multi-objective particle swarm optimization (MOPSO) algorithm

The particle swarm optimization (PSO) algorithm is an optimization algorithm inspired by the natural foraging behavior of birds to find an optimal solution (Kennedy & Eberhart, 1995). A particle is treated as a point in a multidimensional space and the status of the particle is characterized by its position and velocity. The position of a particle can be used to represent a candidate solution for the problem at hand. The general trajectory-updating (or particle-updating) mechanism of a particle is formulated as follows:

$$v_{t+1}^d = w v_t^d + c_1 r_1 \left(p_t^d - x_t^d \right) + c_2 r_2 \left(p_t^g - x_t^g \right); \quad (6)$$

$$x_{t+1}^d = v_t^d + x_t^d, \quad (7)$$

x_t^d denotes the dth dimension position for each particle in the t th iteration, whereas v_t^d denotes the dth dimension velocity for the particle in the tth iteration; p_t^d represents the local best, whereas p_t^g represents the global best; c_1 and c_2 are positive constants namely learning factors, and r_1 and r_2 are random numbers between 0 and 1; w is the inertia weight used to control the impact of the previous velocities on the current one, influencing the tradeoff between the global and local experiences.

The multi-objective PSO (MOPSO) algorithm uses the concept of Pareto dominance to determine the flight direction of a particle and maintains the previously found non-dominated vectors in a global repository that is later used by other particles to guide their own flight. This study searches for the resilience-cost tradeoff solution to the PCSC planning problem through the MOPSO algorithm. The Pareto Archived Evolution Strategy (PAES) is adopted to update the best position during searching for the non-dominated solution in the proposed MOPSO algorithm. The PAES uses the leader selection technique based on Pareto dominance.

4.2. Representation of the solutions to the PCSC planning problem through particles

The solution to the resilience-cost tradeoff PCSC planning problem includes optimal arrangement of transit stations for building along the existing transportation network connecting the supplier and the construction site, selection of alternative outsourcing producers, transit stations and transportation means and routes under disruptions. In order to utilize the MOPSO algorithm to solve the resilience-cost tradeoff PCSC planning problem, the potential solutions need to be encoded or represented through the particles. Binary encoding scheme and priority-based encoding scheme are comprehensively adopted to represent the solution to the resilience-cost tradeoff PCSC planning problem.

$$s\left(v_{t+1}^{d}\right) = \frac{1}{\left(1+\exp\left(-v_{t+1}^{d}\right)\right)}. \quad (8)$$

Arrangement of the transit stations along the existing transportation network is represented a particle position composed of a set of binary variables. Meanwhile, the particle velocity corresponding to each binary variable is transformed into the change of probability reflecting the chance that the binary variable is to be 1 based on the sigmoid function as formulated in Eqn (8). The dimension of the particle is equal to the total number of transit nodes in the transportation network. And the solution is encoded by single dimensional arrays of binary variables, which represents the arrangement of the corresponding transit stations. For example, the representation of a solution is illustrated in Figure 3a, where $x_e \in \{0,1\}$ denotes the position of a particle. Note that arrangement of the transit stations along the existing transportation network results in fixed cost for building the transit stations.

The solution to the optimal arrangement of transit stations for building along the existing transportation network represented by a particle should be transformed to a feasible plan, i.e., the to-be-built transit stations or nodes. According to the sigmoid function, the particle velocities are transformed to the sigmoid values representing the probabilities of selecting the corresponding transit stations. If the probability is larger than 0.5, the binary variable of the particle position representing the corresponding transit stations is assigned 1 otherwise it is assigned 0.

Selection of outsourcing producers, transit stations and transportation means and routes in the existing transportation network is encoded through a set of priority values based on the priority-based encoding scheme. The dimension of the particle is equal to the total number of transportation section between two adjacent transit stations or nodes in the existing transportation network. Each transportation section is encoded by single dimensional arrays of binary variables in terms of feasible combination of means and route, such as highway denoted by *H*, railway denoted by *R*, and waterway denoted by *W* and their priorities of selections encoded by p_{ij}, as shown in Figure 3b. For all the transportation sections connected with a node, the transportation means and route with the highest priority value is intended to be selected for delivering the components out of the node. This encoding method can ensure that the outsourcing producer and the transit nodes are determined inherently when the transportation section is selected with certain means and route.

4.3. Transformation of the particle-represented solutions

The particle-represented solution should be transformed to the PCSC plan. The procedure to transform the particle representation to a PCSC plan is presented as:

Step 1: Regarding the particle-updating mechanism formulated as Eqn (6) and Eqn (7), the priority values from 0 to 100 are assigned to the particle positions.

Step 2: With respect to the transportation constraints such as height limit and weight limit on the transportation lines, each combination of means and route will be checked if feasible for delivering the prefabricated component of type *l* for batch *k*.

Transit node	A	B	C	D	E	F	G	H	I	J
Binary value	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}

Figure 3a. Particle-represented arrangement of transit stations in the existing transportation network

Transport section	1			2				3		
Means (Route)	H(1)	H(2)	R(1)	H(1)	H(2)	R(1)	W(1)	H(1)	H(2)	R(1)
Priority value	p_{11}	p_{12}	p_{13}	p_{21}	p_{22}	p_{23}	p_{24}	p_{31}	p_{32}	p_{33}

Figure 3b. Particle-represented selection of outsourcing producers, transit stations and transportation means and routes under disruptions

Step 3: The disruption or supply shortage of the prefabricated components of type l for batch k at the production site needs to be identified. Once this disruption occurs, an outsourcing producer will be selected as the start node of the next traffic section for delivering the corresponding components of type l for batch k.

Step 4: At the start node, the connected transportation line with the highest priority value among the feasible ones will be selected as the transportation means and route for delivering the components of type l for batch k out of the start node.

Step 5: If the start node of the next traffic section is the original production site or a transit station, the connected transportation line with the highest priority among the feasible ones will be selected as the transportation means and route for delivering the batch of components out of this start node. Otherwise, if the start node of the next traffic section is not one of the transit stations, the transportation means for the next traffic section cannot be changed, while the transportation route with the highest priority among the feasible ones will be selected.

Step 6: If the end node of the current traffic section is not the destination of construction site, go to step 4. Otherwise, obtain a potential PCSC plan.

Figure 4 illustrates transformation of the particle-represented solution to the PCSC plan. Figure 4a shows the particle positions representing the values of priorities to be selected. In traffic section 1, among all the transportation means and routes, route 1 of highway with the highest priority value of 83 is selected. Similarly, the route 1 of railway with the priority value of 78 and route 2 of railway with the priority value of 82 are determined for traffic sections 2 and 3 respectively. While, in consideration of the transportation constraints such as weight limit, route 1 of highway for traffic section 1 is unfeasible for delivering the corresponding batch of components, hence the route 2 of highway with the second-highest priority value is then selected. As the transit station is not built at node B, route 2 of highway is finally selected for the next traffic section 2 since the transportation means cannot be changed at the node B.

4.4. Simulation of the disruptions

Three kinds of disruptions on the PCSC with respect to availability of the components at the original production site, feasibility of the transit operations at nodes, and feasibility of the alternative transportation means and routes occur stochastically, affecting the delivery times of the required components and delaying the project duration. Adjusting or recovering strategies for considering alternative outsourcing producers, selection of feasible transit stations and adjusting of feasible transportation means and routes along the existing transportation network are adopted to achieve resilience of the PCSC plan, arising additional costs. In order to obtain the optimum PCSC plan with resilience-cost tradeoff problem, the disruptions are modeled by probabilities and simulated through the Monte Carlo simulation technique, which is incorporated into the MOPSO-based method.

The occurring times the three kinds of disruptions are generally modeled by certain probabilistic distributions such as Poisson distribution $X \sim P(\lambda)$ and Normal distribution $Y \sim N(\mu, \sigma^2)$, respectively. The probabilistic distributions and relevant parameters need to be determined based on the historical data, empirical data and knowledge of the experts.

At each iteration of the MOPSO execution searching for a potential solution to the PCSC plan, a number of sam-

a)

Transport Section	1			2				3		
Means (Route)	H(1)	H(2)	R(1)	H(1)	H(2)	R(1)	W(1)	H(1)	H(2)	R(1)
Position Value	83	67	13	39	56	78	14	31	82	21

Transformation

b)

Transport Section	1			2				3		
Means (Route)	H(1)	H(2)	R(1)	H(1)	H(2)	R(1)	W(1)	H(1)	H(2)	R(1)
Solution Value	1	0	0	0	0	1	0	0	1	0

Transportation Constraints

c)

Transport Section	1			2				3		
Means (Route)	H(1)	H(2)	R(1)	H(1)	H(2)	R(1)	W(1)	H(1)	H(2)	R(1)
Solution Value	0	1	0	0	0	1	0	0	1	0

Transit node limitation

d)

Transport Section	1			2				3		
Means (Route)	H(1)	H(2)	R(1)	H(1)	H(2)	R(1)	W(1)	H(1)	H(2)	R(1)
Solution Value	0	1	0	0	1	0	0	0	1	0

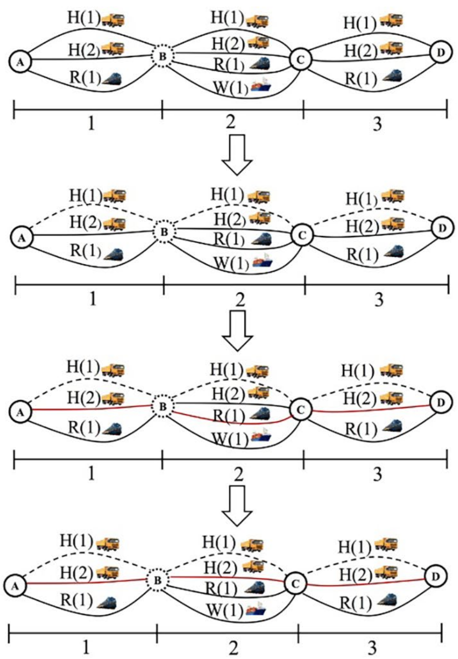

Figure 4. Transformation of the particle-represented solution to the PCSC plan

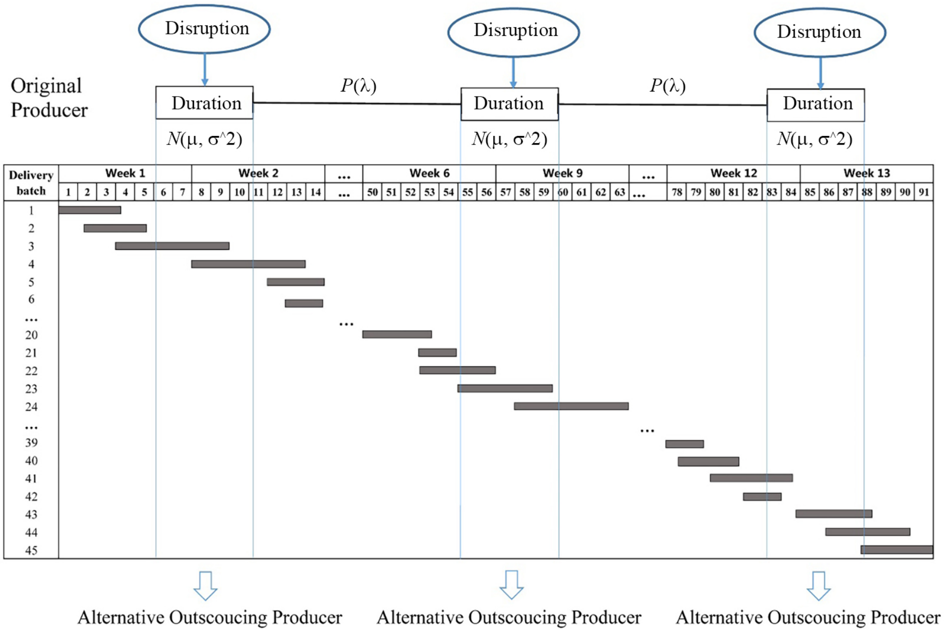

Figure 5. Disruptions on supply of the components at the production site

pling cycles will be performed based on the probabilistic disruptions to produce the occurring times and durations of the three kinds of disruptions. Note that the disruptions are identified through comparing with the initial transportation schedule. For instance, as shown in Figure 5, for the disruption on availability of the components at production site, an alternative outsourcing producer along the existing transportation network with transit stations needs to selected with the objective of resilience-cost tradeoff. After certain cycles of simulation, the average value of the results will be returned as the fitness value of the particle in the MOPSO algorithm for solving the near-optimal particle-represented solution to the PCSC plan.

4.5. Framework of the MOPSO-based methodologies

The integrated framework for solving the resilience-cost tradeoff PCSC planning problem based on the MOPSO algorithm is developed, as shown in Figure 6. Two-stage of the MOPSO is adopted to carried out searching for the near-optimal solution to the PCSC plan under disruptions. The first stage is to optimize the arrangement of transit stations, then the second stage is to search for the near-optimal transportation plan with the objective of resilience-cost tradeoff when considering disruptions. At each iteration of MOPSO execution in searching for the near-optimal transportation plan, the Pareto-optimal solution with the minimum cost and the resilience satisfying with required level will be used to calculate the fitness of the particle-represented solution. Monte Carlo sampling technique is adopted to model scenarios of disruptions through a number of sampling cycles based on the probabilistic distributions.

The particle-updating mechanism represented by Eqn (6) and Eqn (7) is used to update the velocities of the particles until finding the near-optimal solution. The initial or updated solutions are evaluated by calculating the fitness according to the multi-objective functions (1), based on which the local best of each particle and the global best in the swarm are identified through Pareto Archived Evolution Strategy (PAES). In the particle transformation process, the transportation constraints need to be identified based on the input information. The MOPSO execution should be terminated if the t iteration number gets to the maximum number of iterations. Then the global best solution is the near-optimal solution to the resilience-cost tradeoff PCSC planning problem.

According to the proposed framework for solving the formulated resilience-cost tradeoff model of the PCSC planning, the MOPSO-based method incorporated with the Monte Carlo simulation technique is implemented in Python programming language.

5. Case study

The proposed method for resilience-cost tradeoff planning of the PCSC is illustrated through a prefabricated construction project located in Shanghai of China. The sensitivity analyses with different demands on the batches of prefabricated components are conducted to demonstrate the effectiveness of the proposed method.

5.1. Description of the case project

Four types of the prefabricated components including prefabricated columns, prefabricated beams, prefabricated floors and prefabricated stairs are required by a prefabricated construction project. These components need to be transported from the original production site or alternative outsourcing sites of the supplier to the construction site in 36 delivery batches according to the construction schedule.

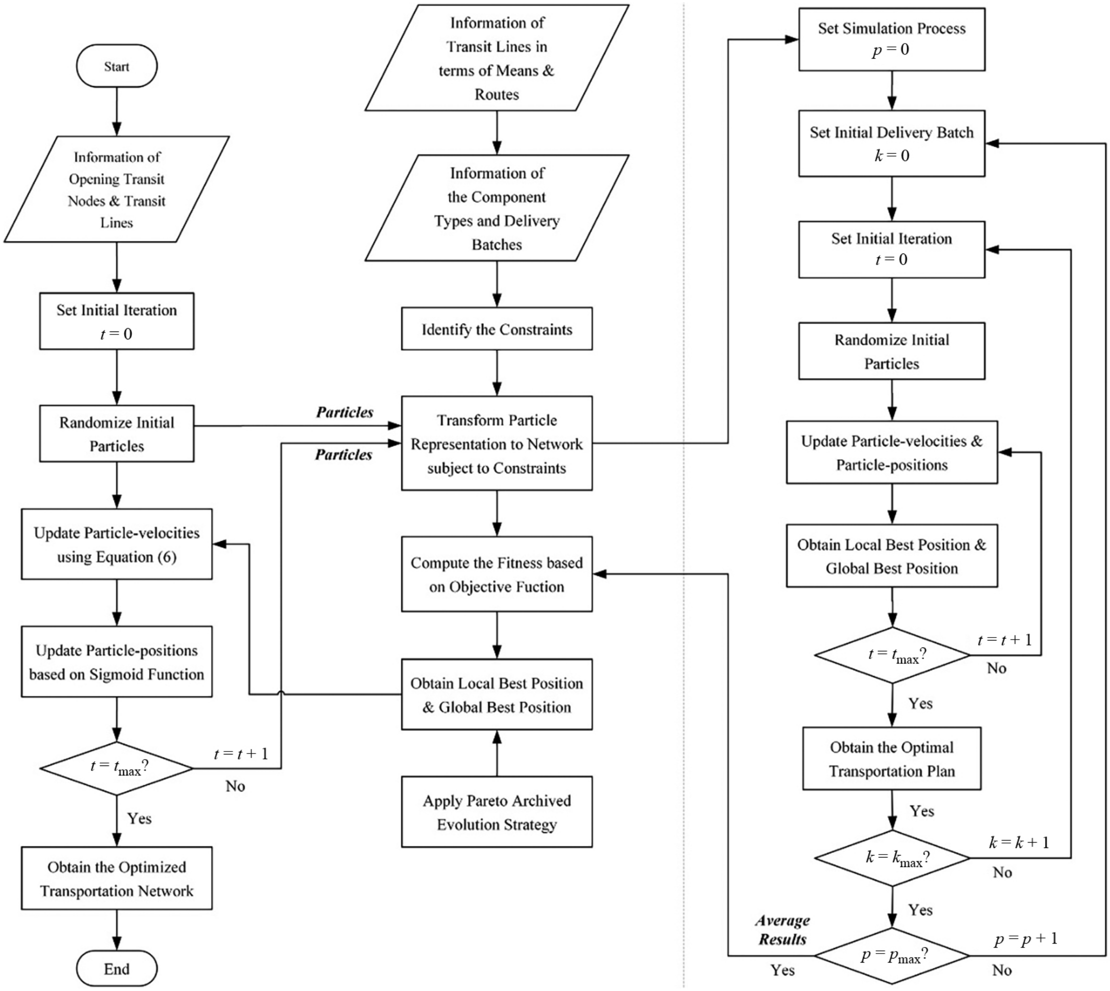

Figure 6. Framework for solving the resilience-cost tradeoff problem by using MOPSO algorithm

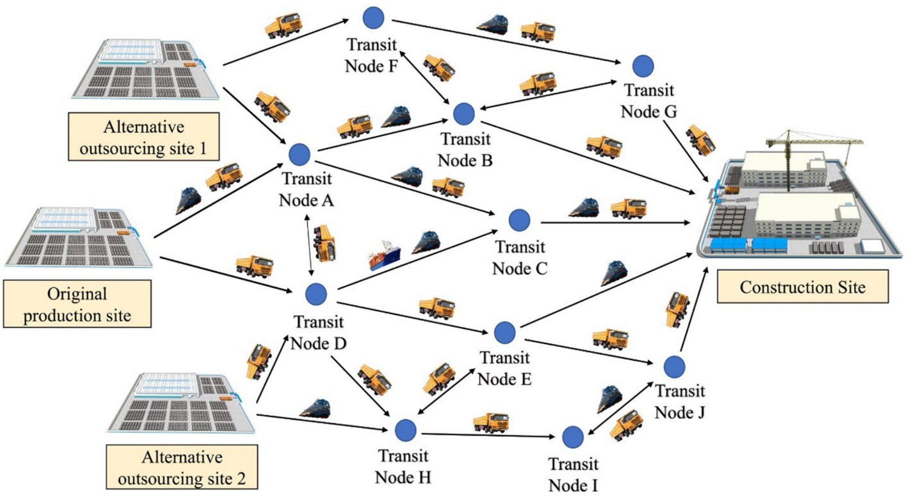

Figure 7. Potential transportation network of the PCSC for the precast construction project

As shown in Figure 7, the potential transportation network for the PCSC of the case project consists of 1 original production site, 2 alternative outsourcing sites, 10 potential nodes (e.g., transit places or crossroads) and 71 potential line edges corresponding to different combinations of transportation means and routes. The detailed information concerning transit time and costs of each transit node, transportation time and cost of each transportation route and means, delivery batches including component type, size, amount and unit weight are determined based on the transportation network, relevant regulations, contract for component delivery, BIM and construction schedule. The probabilities of the disruptions occurring at the original production site, transportation lines and transit nodes are determined based on the historical data and experience of the experts. Table 1 lists the parameters of the disruptions (i.e., the Poisson distribution $X \sim P(\lambda)$ for occurring times and Normal distribution $Y \sim N(\mu,\sigma^2)$ for corresponding durations, respectively) on supply of the components at the production site and on operation of transit at nodes. Table 2 shows the parameters of the disruptions on ten transportation lines.

The feasible transportation plan in terms of combinations of means and routes for different prefabricated component types and delivery batches can be then identified based on the transportation constraints such as height limits for tunnels, weight limits for bridges and regular or random traffic restrictions for urban roads. Table 3 shows the data concerning ten delivery batches of components corresponding to component-type, quantity, size, weight and available number of the transportation lines.

Table 1. Disruption parameters regarding $P(\lambda)$ and $N(\mu, \sigma^2)$ for the original producer and transit nodes

Node	Disruption interval λ (day)	Mean value of the duration μ (day)	Variance of the mean value σ^2
Original Producer	732	31	0.1
Transit Node A	168	20	1.5
Transit Node B	334	26	0.3
Transit Node C	712	25	0.8
Transit Node D	900	37	0.3
Transit Node E	777	15	0.1
Transit Node F	1359	20	0.2
Transit Node G	1429	26	0.7
Transit Node H	168	20	1.0
Transit Node I	334	26	0.4
Transit Node J	312	25	0.4

Table 2. Disruption parameters regarding $P(\lambda)$ and $N(\mu, \sigma^2)$ for the 10 transportation lines

Starting Node	Terminal Node	Transport Means	Transport Route	Disruption interval λ (day)	Mean value of the duration μ (day)	Variance of the mean value σ^2
A	B	Railway	1	420	25	0.2
A	B	Railway	2	300	5	0.5
A	B	Highway	1	167	15	0.8
A	B	Highway	2	135	7	0.2
A	B	Highway	3	73	11	0.4
A	C	Railway	1	927	3	0.1
A	C	Highway	1	238	14	0.3
C	A	Highway	1	433	25	1.5
D	C	Railway	1	420	12	0.4
D	C	Highway	1	253	3	0.6

Table 3. Available transportation lines for the 10 delivery batches

Delivery batch	Component type	Quantity	Size (mm)	Unit weight (t)	Total number of available lines
1	Columns Columns	20 12	800×900×6500 700×700×6500	10.576 7.177	56
2	Columns Columns	20 12	800×900×6500 700×700×6500	10.576 7.177	56
3	Beams Beams Beams	4 8 20	7020×400×800 7070×400×800 7320×400×800	4.791 4.825 5.064	59
4	Beams Beams Beams Beams	4 12 8 6	6270×500×900 6370×500×900 6620×500×900 6820×500×900	6.172 6.270 6.516 6.713	59
5	Floors Floors	22 36	3420×2430×70 3370×2430×70	1.471 1.449	63
6	Stairs	3	4640×1610×200	5.116	63
7	Floors Floors	8 34	4470×2170×70 3810×2910×70	1.738 1.834	62
8	Columns Columns	20 12	500×650×4500 500×500×4500	3.140 2.415	61
9	Stairs	3	4640×1610×200	5.116	63
10	Columns Columns	20 12	500×650×4500 500×500×4500	3.140 2.415	61

Note that all the nodes can be planned to be the transit places to transfer the prefabricated components when achieving resilience-cost tradeoff transportation plan for the PCSC.

5.2. MOPSO-based solution to the resilience-cost tradeoff PCSC plan

For the two-stage execution of the proposed MOPSO algorithm based on PAES, some parameters need to be specified. A series of sensitivity analyses of the MOPSO model have been carried out with different combinations of the relevant parameters to determine appropriate values of the parameters. The sensitivity analysis showed that different values of the learning factors c_1 and c_2 do not have much influence on the final result, with almost the same conclusion as that of Trelea (2003). So c_1 and c_2 are given the value of 1.0 in the case study. The analysis on the inertial weight w with the values of 0.6, 0.7, 0.75, 0.8, 0.85, 0.9 and 1.0 indicated that the value of 0.85 results in best performance in terms of searching number of iterations and solution convergence. The sensitivity analysis on the number of iterations varying from 1 to 100 showed that the maximum number of iterations since last updating of the non-dominated solutions is nearly 50 for the resilience-cost tradeoff problem, hence the maximum number of iterations is given as 50. Based on the suggestion of Trelea (2003), the population sizes of 50, 75, 100, 125, 150 have been respectively tested in the sensitivity analysis, which indicated that the population sizes of 100 and 125 have almost the same performance in terms of searching time, and the population size of 150 has a little bit impact on the searching time. Therefore, the population size is set to be 100. Meanwhile, the sensitivity analysis on the Archive set sizes of 200, 250, 300, 350 and 400 showed that it is chosen to be 300. With regards to the Monte Carlo simulation technique adopted to model the disruptions, the number of sampling is set to be 50. At each iteration of MOPSO execution in the second stage, the required resilience level is set to be 0.7.

The solution to the resilience-cost tradeoff PCSC planning problem for the first iteration and the 50-th iteration of searching is shown in Figure 8. The Pareto frontier clearly demonstrates the tradeoff between the schedule-dependent resilience and the total transportation cost of the PCSC plan, which demonstrates that a higher resilience level of the PCSC plan may lead to more cost. The decision makers can choose their preferred plan from these Pareto-optimal solutions. For example, they could consider a lower level of resilience if they are more concerned with the transportation cost than the resilience, thus choosing the far-left solution among the Pareto-optimal solutions shown in Figure 8. Figure 9 illustrates the PCSC plan with resilience-cost tradeoff, where the transit stations C and D are arranged along the existing transportation network, the alternative outsourcing site 1 and 30 transportation lines of certain means and routes are selected. This resilience-cost tradeoff PCSC plan is also presented in details in Table 4.

5.3. Sensitivity analysis and discussion

Based on the supply business of the prefabricated components, the sensitivity analyses with different demands on the number of delivery batches (i.e., 36, 27, 18 and 9) have been conducted by applying the proposed method. The results of the sensitivity analyses are listed in Table 5, including the minimum, maximum and gap values of the resilience as well as the minimum, maximum and gap values of the transportation costs among the Pareto-optimal solutions of the PCSC plans for each delivery batch demand.

As tabulated in Table 5, for various values of the delivery batches, the resilience levels change a little under different delivery batch demands. However, when the delivery batch demand decreases, the gap value for the transportation cost increases while the gap value for the resilience changes a little. It means that a larger number of demands on the prefabricated components will be of greater benefit to the supplier in investing more in improving resilience of the PCSC plan.

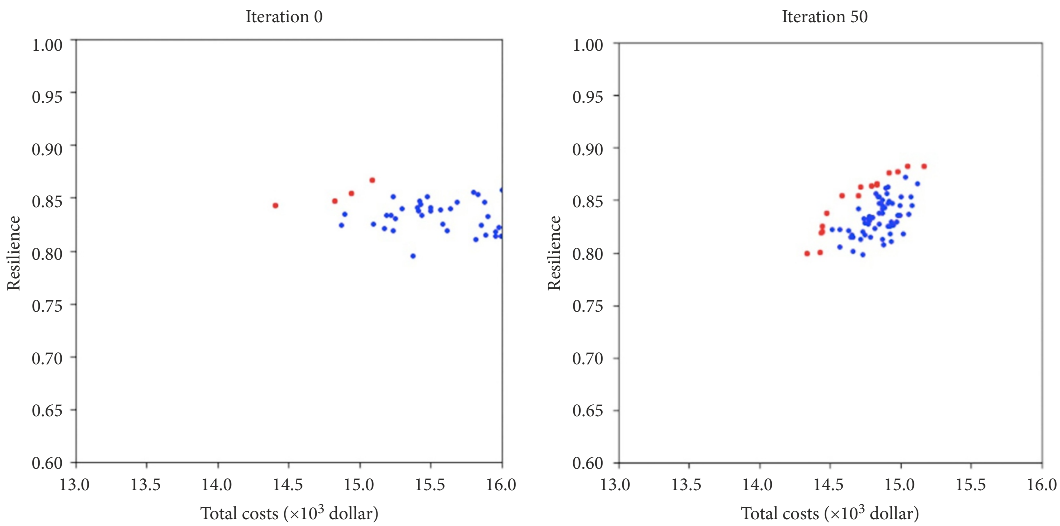

Figure 8. Pareto-optimal solutions of the PCSC planning for the case study

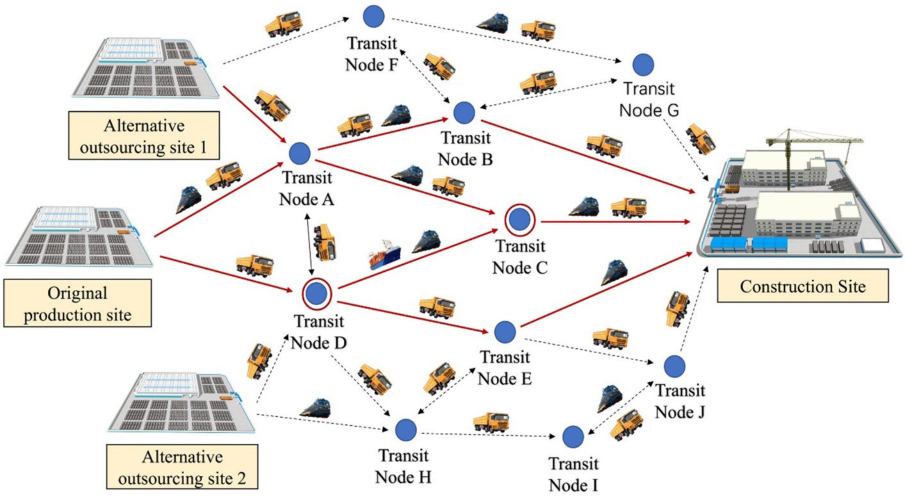

Figure 9. A resilience-cost tradeoff PCSC plan for the precast construction project

Table 4. Detailed description of the resilience-cost tradeoff PCSC plan

Start Node	Terminal Node	Transport Means	Transport Route
Original Producer	Transit Node A	Railway	1
Original Producer	Transit Node A	Railway	2
Original Producer	Transit Node A	Highway	1
Original Producer	Transit Node A	Highway	2
Original Producer	Transit Node A	Highway	3
Original Producer	Transit Node D	Highway	1
Original Producer	Transit Node D	Highway	2
Original Producer	Transit Node D	Highway	3
Outsourcing Producer 1	Transit Node A	Highway	1
Outsourcing Producer 1	Transit Node A	Highway	2
Transit Node A	Transit Node B	Railway	1
Transit Node A	Transit Node B	Railway	2
Transit Node A	Transit Node B	Highway	3
Transit Node A	Transit Node B	Highway	4
Transit Node A	Transit Node B	Highway	5
Transit Node A	Transit Node C	Railway	1
Transit Node A	Transit Node C	Highway	2
Transit Node D	Transit Node C	Highway	1
Transit Node D	Transit Node C	Railway	2
Transit Node D	Transit Node C	Railway	3
Transit Node D	Transit Node C	Waterway	4
Transit Node D	Transit Node E	Highway	1
Transit Node D	Transit Node E	Highway	2
Transit Node B	Construction Site	Highway	1
Transit Node B	Construction Site	Highway	2
Transit Node C	Construction Site	Highway	1
Transit Node C	Construction Site	Highway	2
Transit Node C	Construction Site	Railway	3
Transit Node E	Construction Site	Railway	1
Transit Node E	Construction Site	Railway	2

Once the resilience-cost tradeoff PCSC plan shown in Figure 9 and Table 4 have been determined by the decision makers, the stakeholders such as drivers are able to adjust transportation strategies to deliver the components to the construction site according to the contracted schedules in face of disruptions. Incorporation of the resilience concept enables to enhance dynamic management of the PCSC under disruptions with regards to timely requirement of the components and coordination among involved installation activities, thus fully utilizing the advantages of the prefabricated construction. The stakeholders of the suppliers can also consider balance between the resilience and the cost based on their preferences when selecting the potential PCSC plan. In addition, the suppliers that are developed well and have potential to obtain large orders of the prefabricated components should pay more importance on the PCSC resilience by contracting alternative outsourcing producers and building transit nodes or stations.

Conclusions

With regards to disruptions on the supply chain due to risks or uncertainties, this study attempts to incorporate resilience into the PCSC plan while controlling the induced costs. A quantification scheme for the resilience of a PCSC plan is proposed, then the resilience-cost tradeoff optimization model for the PCSC planning is developed and formulated. A framework for solving the resilience-cost tradeoff optimization model by applying the MOPSO algorithm is proposed. The proposed approach for developing the PCSC plan with resilience-cost tradeoff optimization is applied to a prefabricated construction project to illustrate its effectiveness. The study contributes to the domain knowledge of the PCSC management from the perspective of resilience enhancement and minimization of resultant transportation costs. The study also contributes to the domain knowledge of the MOPSO-based methodology for solving the resilience-cost tradeoff planning problem for the PCSC. The proposed method enables to achieve disruption management of the PCSC, improve the effectiveness of the supplier, enhance coordination and reduce dispute between the contractor and the supplier, thus fully achieving the advantages of the prefabricated construction.

However, further studies should be conducted to address following issues. For instance, more reasonable approaches for modeling the disruptions on the PCSC need to be considered. In addition, modern information technologies such as BIM, RFID and video monitoring need to be applied to achieve the resilience-based PCSC plan through real-time monitoring and intelligent decision-making.

Funding

This work was supported by the National Natural Science Foundation of China under Grant (number 71972167).

Author contributions

Hong Zhang was respnsible for the research project, the research planning, and the article editing. Lu Yu was responsible for the model development and implementation, data collection and analyses, and the article writing.

Disclosure statement

The authors in this paper have no competing financial, professional, or personal interests from other parties.

References

Aloini, D., Dulmin, R., Mininno, V., & Ponticelli, S. (2012). Supply chain management: a review of implementation risks in the construction industry. *Business Process Management Journal*, *18*(5), 735–761. https://doi.org/10.1108/14637151211270135

Arashpour, M., Bai, Y., Aranda-mena, G., Bab-Hadiashar, A., Hosseini, R., & Kalutara, P. (2017). Optimizing decisions in advanced manufacturing of prefabricated products: Theorizing supply chain configurations in off-site construction. *Automation in Construction*, *84*, 146–153. https://doi.org/10.1016/j.autcon.2017.08.032

Berdica, K. (2002). An introduction to road vulnerability: what has been done, is done and should be done. *Transport Policy*, *9*(2), 117–127. https://doi.org/10.1016/S0967-070X(02)00011-2

Brandon-Jones, E., Squire, B., Autry, C., & Petersen, K. J. (2014). A contingent resource-based perspective of supply chain resilience and robustness. *Journal of Supply Chain Management*, *50*(3), 55–73. https://doi.org/10.1111/jscm.12050

Chen, C.-C. (Frank), Tsai, Y.-H. (Natalie), & Schonfeld, P. (2016). Schedule coordination, delay propagation, and disruption resilience in intermodal logistics networks. *Transportation Research Record: Journal of the Transportation Research Board*, *2548*(1), 16–23. https://doi.org/10.3141/2548-03

Chen, L., & Miller-Hooks, E. (2012). Resilience: An indicator of recovery capability in intermodal freight transport. *Transportation Science*, *46*(1), 109–123. https://doi.org/10.1287/trsc.1110.0376

Colicchia, C., Dallari, F., & Melacini, M. (2010). Increasing supply chain resilience in a global sourcing context. *Production Planning & Control*, *21*(7), 680–694. https://doi.org/10.1080/09537280903551969

Davis, P. R. (2008). A relationship approach to construction supply chains. *Industrial Management & Data Systems*, *108*(3), 310–327. https://doi.org/10.1108/02635570810858741

Ellram, L. M., Tate, W. L., & Billington, C. (2004). Understanding and managing the services supply chain. *Journal of Supply Chain Management*, *40*(3), 17–32. https://doi.org/10.1111/j.1745-493X.2004.tb00176.x

Francis, R., & Bekera, B. (2014). A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliability Engineering & System Safety*, *121*, 90–103. https://doi.org/10.1016/j.ress.2013.07.004

Geng, L., Xiao, R., & Xu, X. (2014). Research on MAS-based supply chain resilience and its self-organized criticality. *Discrete Dynamics in Nature and Society*, Article ID 621341. https://doi.org/10.1155/2014/621341

Hackl, J., Adey, B. T., & Lethanh, N. (2018). Determination of near-optimal restoration programs for transportation networks following natural hazard events using simulated annealing. *Computer-Aided Civil and Infrastructure Engineering*, *33*, 618–637. https://doi.org/10.1111/mice.12346

Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, *4*(1), 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245

Huang, M., Li, R., & Wang, X. (2011). Network construction for fourth-party logistics based on resilience with using Particle Swarm Optimization. In *2011 Chinese Control and Decision Conference* (pp. 3924–3929). IEEE. https://doi.org/10.1109/CCDC.2011.5968907

Ip, W. H., & Wang, D. (2011). Resilience and friability of transportation networks: Evaluation, analysis and optimization. *IEEE Systems Journal*, *5*(2), 189–198. https://doi.org/10.1109/JSYST.2010.2096670

Kennedy, J., & Eberhart, R. (1995). Particle swarm optimization. In *Proceedings of ICNN'95 – International Conference on Neural Networks* (pp. 1942–1948). IEEE. https://doi.org/10.1109/ICNN.1995.488968

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

Kumar, V., & Viswanadham, N. (2007). A CBR-based decision support system framework for construction supply chain risk management. In *2007 International Conference on Automation Science and Engineering* (pp. 980–985). IEEE. https://doi.org/10.1109/COASE.2007.4341831

Li, Z., Shen, G. Q., & Xue, X. (2014). Critical review of the research on the management of prefabricated construction. *Habitat International*, *43*, 240–249. https://doi.org/10.1016/j.habitatint.2014.04.001

Li, C. Z., Hong, J., Xue, F., Shen, G. Q., Xu, X., & Mok, M. K. (2016). Schedule risks in prefabrication housing production in Hong Kong: a social network analysis. *Journal of Cleaner Production*, *134*, 482–494. https://doi.org/10.1016/j.jclepro.2016.02.123

Luo, L., Qiping Shen, G., Xu, G., Liu, Y., & Wang, Y. (2019). Stakeholder-associated supply chain risks and their interactions in a prefabricated building project in Hong Kong. *Journal of Management in Engineering*, *35*(2), 05018015. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000675

Meng, X. (2013). Change in UK construction: Moving toward supply chain collaboration. *Journal of Civil* Engineering *and Management*, *19*(3), 422–432. https://doi.org/10.3846/13923730.2012.760479

Miller-Hooks, E., Zhang, X., & Faturechi, R. (2012). Measuring and maximizing resilience of freight transportation networks. *Computers & Operations Research*, *39*(7), 1633–1643. https://doi.org/10.1016/j.cor.2011.09.017

Morlok, E. K., & Chang, D. J. (2004). Measuring capacity flexibility of a transportation system. *Transportation Research Part A: Policy and Practice*, *38*(6), 405–420. https://doi.org/10.1016/j.tra.2004.03.001

Murino, T., Romano, E., & Santillo, L. C. (2011). Supply chain performance sustainability through resilience function. In *Proceedings of the 2011 Winter Simulation Conference* (pp. 1600–1611). IEEE. https://doi.org/10.1109/WSC.2011.6147877

Murray-tuite, P., & Mahmassani, H. (2004). Methodology for determining vulnerable links in a transportation network. *Transportation Research Record: Journal of the Transportation Research Board*, *1882*, 88–96. https://doi.org/10.3141/1882-11

Murray-tuite, P. (2006). A comparison of transportation network resilience under simulated system optimum and user equilibrium conditions. *Proceedings of the 2006 Winter Simulation Conference* (pp. 1398–1405). IEEE. https://doi.org/10.1109/WSC.2006.323240

Peeta, S., Sibel Salman, F., Gunnec, D., & Viswanath, K. (2010). Pre-disaster investment decisions for strengthening a highway network. *Computers & Operations Research*, *37*(10), 1708–1719. https://doi.org/10.1016/j.cor.2009.12.006

Peng, P., Snyder, L. V., Lim, A., & Liu, Z., (2011). Reliable logistics networks design with facility disruptions. *Transportation Research Part B: Methodological*, *45*(8), 1190–1211. https://doi.org/10.1016/j.trb.2011.05.022

Polat, G. (2010). Precast concrete systems in developing vs. industrialized countries. *Journal of Civil Engineering and Management*, *16*(1), 85–94. https://doi.org/10.3846/jcem.2010.08

Ratick, S., Meacham, B., & Aoyama, Y. (2008). Locating backup facilities to enhance supply chain disaster resilience. *Growth and Change*, *39*(4), 642–666. https://doi.org/10.1111/j.1468-2257.2008.00450.x

Snyder, L. V., & Daskin, M. S. (2005). Reliability models for facility location: The expected failure cost case. *Transportation Science*, *39*(3), 400–416. https://doi.org/10.1287/trsc.1040.0107

Shojaei, P., & Haeri, S. A. S. (2019). Development of supply chain risk management approaches for construction projects: A grounded theory approach. *Computers & Industrial Engineering*, *128*, 837–850. https://doi.org/10.1016/j.cie.2018.11.045

Ta, C., Goodchild, A. V., & Pitera, K. (2009). Structuring a definition of resilience for the freight transportation system. *Transportation Research Record: Journal of the Transportation Research Board*, *2097*, 19–25. https://doi.org/10.3141/2097-03

Taillandier, F., Taillandier, P., Tepeli, E., Breysse, D., Mehdizadeh, R., & Khartabil, F. (2015). A multi-agent model to manage risks in construction project (SMACC). *Automation in Construction*, *58*, 1–18. https://doi.org/10.1016/j.autcon.2015.06.005

Taroun, A. (2014). Towards a better modelling and assessment of construction risk: Insights from a literature review. *International Journal of Project Management*, *32*(1), 101–115. https://doi.org/10.1016/j.ijproman.2013.03.004

Torabi, S. A., Baghersad, M., & Mansouri, S. A. (2015). Resilient supplier selection and order allocation under operational and disruption risks. *Transportation Research Part E: Logistics and Transportation Review*, *79*, 22–48. https://doi.org/10.1016/j.tre.2015.03.005

Trelea, I. C. (2003). The particle swarm optimization algorithm: convergence analysis and parameter selection. *Information Processing Letters*, *85*(6), 317–325. https://doi.org/10.1016/S0020-0190(02)00447-7

Wang, Z., Hu, H., & Zhou, W. (2017a). RFID enabled knowledge-based precast construction supply chain. *Computer-Aided Civil and Infrastructure Engineering*, *32*, 499–514. https://doi.org/10.1111/mice.12254

Wang, T.-K., Zhang, Q., Chong, H.-Y., & Wang, X. (2017b). Integrated supplier selection framework in a resilient construction supply chain: An approach via Analytic Hierarchy Process (AHP) and Grey Relational Analysis (GRA). *Sustainability*, *9*(2), 289. https://doi.org/10.3390/su9020289

Wang, Y., Yuan, Z., & Sun, C. (2018). Research on assembly sequence planning and optimization of precast concrete buildings. *Journal of Civil Engineering and Management*, *24*(2), 106–115. https://doi.org/10.3846/jcem.2018.458

Zhang, H., & Yu, L. (2020). Prefabricated component site layout planning subject to dynamic and interactive constraints. *Automation in Construction* (Submitted manuscript).