A Simulation-Based Optimisation for Contractors in Precast Concrete Projects

Shiwei Chen and Kailun Feng
Department of Construction Management, Harbin Institute of Technology, Harbin, China
Weizhuo Lu
Department of Civil, Environmental, and Natural Resources Engineering, Luleå University of Technology, Luleå, Sweden

Abstract

Purpose – This paper aims to provide decision support for precast concrete contractors about both precast concrete supply chain strategies and construction configurations.

Design/Methodology/Approach – This paper proposes a simulation-based optimisation for supply chain and construction (SOSC) during the planning phase of PC building projects. The discrete event simulation is used to capture the characteristics of supply chain and construction processes, and calculate construction objectives under different plans. Particle swarm optimisation is combined with simulation to find optimal supply chain strategies and construction configurations.

Findings – The efficiency of SOSC is compared with the parametric simulation approach. Over 70 per cent of time and effort used to simulate and compare alternative plans is saved owing to SOSC.

Research Limitations/Implications – Building simulation model costs a lot of time and effort. The data requirement of the proposed method is high.

Practical Implications – The proposed SOSC approach can provide decision support for PC contractors by optimising supply chain strategies and construction configurations.

Originality/Value – This paper has two contributions: one is in providing a decision support tool SOSC to optimise both supply chain strategies and construction configurations, while the other is in building a prototype of SOSC and testing it in a case study.

Keywords Precast concrete, Supply chain, Building construction, Discrete event simulation, Particle swarm optimization, Simulation-based optimization

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1. Introduction

Precast concrete (PC) construction is a construction method in which building components are produced in an off-site factory and transported to construction site to be assembled into a building. In conventional cast-*in-situ* concrete projects, contractors decide construction configurations, including the types and quantities of equipment and workers used for every construction activity, to make construction plans. Because many parts of a PC building are produced in factories rather than construction site, PC supply chain has great impact on the construction objectives (Zhai *et al.*, 2013). Thus, when making construction plans of PC projects, contractors should consider not only construction configurations, but also PC supply chain strategies, including whether and where to store PC components.

In PC projects, contractors usually decide PC supply chain strategies and construction configurations according to a rule of thumb, leading to extra costs, prolonged construction duration or worse sustainable performance (Pheng and Chuan, 2001). Previous studies analysing PC supply chain strategies are mostly conducted from the perspective of PC component suppliers and seldom combine construction and PC supply chain together (Hosseini *et al.*, 2018). There still lacks a decision-support method selecting both PC supply chain strategies and construction configurations for contractors.

When considering PC supply chain with construction, it is difficult to compare all alternative plans manually because the interactions between PC supply chain and construction are dynamic and complex (Arashpour *et al.*, 2017). Progress of construction activities decides when PC components are needed on construction site and PC component supply chain influence PC-related construction processes. In addition, there are too many combinations of PC supply chain strategies and construction configurations. Finding the optimal solutions manually takes too much time and effort, which is unacceptable in the actual construction practice (Nguyen *et al.*, 2014).

Computer-based simulation has the ability of capturing the dynamic and complex interactions among construction engineering systems (AbouRizk, 2010). However, using conventional parametric simulation approach to compare all alternative plans still costs a lot of time because it has to run all possible combinations (Nguyen *et al.*, 2014). Thus, in some studies, simulation is combined with optimisation as an integrated method, known as the simulation-based optimisation (SO), to accelerate the process of finding optimal solutions. The SO method is mainly used in building performance comparison of different designs but seldom used in PC construction area, especially not in problems considering both PC supply chain and construction.

This paper combines discrete-event simulation (DES) and particle-swarm optimisation (PSO) to propose a simulation-based optimisation of supply chain and construction (SOSC) for contractors in PC projects. The SOSC approach can provide decision support for contractors by quickly selecting optimal combinations of PC supply chain strategies and construction configurations from a great number of alternative plans. A prototype of SOSC is developed, and a case study is conducted to demonstrate the effectiveness and efficiency of the proposed method.

2. Precast concrete supply chain strategies

To choose PC supply chain strategy, the contractors should decide whether and where to store PC components after components left factories (Pheng, C. and Chuan, L. 2001). Based on the decisions, PC supply chain strategies can be categorised into three types: just-in-time (JIT) strategy (no storage), on-site storage strategy and off-site storage strategy. An interview with 14 professionals from 3 contractors and 2 suppliers in China is conducted to find out the processes of the three strategies (shown in Figure 1).

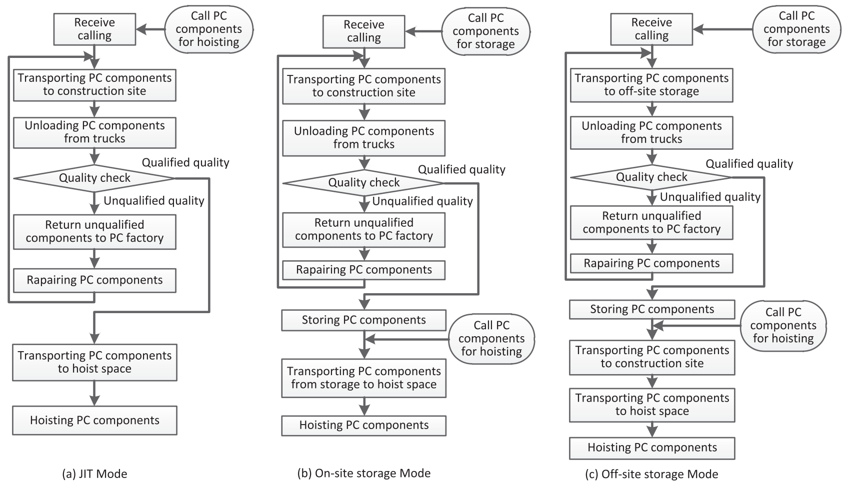

Figure 1.
Processes of Three PC Supply Chain Strategies.

In the JIT strategy, PC components are directly transported to construction site and will be unloaded, checked and hoisted as soon as they reach site. The contractor will call PC suppliers for components according to construction progress. The quality of components will be checked when they reach the site, and the components with quality flaws will be returned to the factory for repair.

In on-site storage, the contractor will use components in storage when the components are needed. The contractor will set a recalling point for the number of components and call PC supplier for components when the number of stored components is below recalling point. Owing to limited space on site, the storage usually can only store limited components.

The off-site storage strategy has the same processes as the on-site storage strategy, except the storage is located beyond construction site. Thus, there is usually no limitation for store capacity. The transportation from off-site storage to construction site is usually conducted by the contractor, not PC supplier.

3. SOSC approach

This paper proposes a simulation-based optimisation of supply chain and construction (SOSC) during the planning phase of PC building projects, to provide decision support for contractors. The framework of SOSC is shown in Figure 2.

First, some detailed data about the construction project is collected and analysed, including interactions between construction and supply chain activities, construction sequences, and PC components, equipment and labour needed for each activity.

Based on the collected data, a DES model is built. An Activity-Component-Resource-Action-Sequence (CARS) model proposed by Fischer *et al.* (1999) is used to capture the

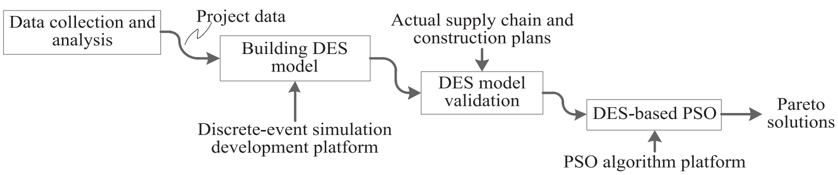

Figure 2.
Framework of SOSC.

characteristics of PC supply chain and construction processes: “Activity” is the PC supply chain and construction activities; “Component” refers to the buildings parts, including PC components and cast-*in-situ* concrete; “Resource” means construction equipment and workers; “Action” means executed work information for each activity; and “Sequence” is the logic restriction between activities of supply chain and construction. The project data is categorised and input into DES according to CARS.

After building the DES model, two tests need to be conducted. One is minimum simulation runs determination (Lee *et al.*, 2015), which tests reliability of the simulation outcomes under different simulation runs to find out the minimum simulation runs needed to obtain reliable simulation outcomes. Another test is simulation results validation (Lee *et al.*, 2015), which tests the accuracy of DES. The actual PC supply chain strategies and construction configurations are input into the built DES model. The simulation outcomes are compared with actual construction objectives to test the model accuracy. If the accuracy is acceptable, the DES model can be used in next procedure. Otherwise, the model needs modification until it can pass the tests.

Finally, a DES-based PSO (see Figure 3) is used to optimise supply chain strategies and construction configurations. The searching scope is defined to input the alternative plans to PSO, and PSO will generate particles at initial positions to represent initial random plans. Then, these plans are input into DES model to get the simulated construction objectives of

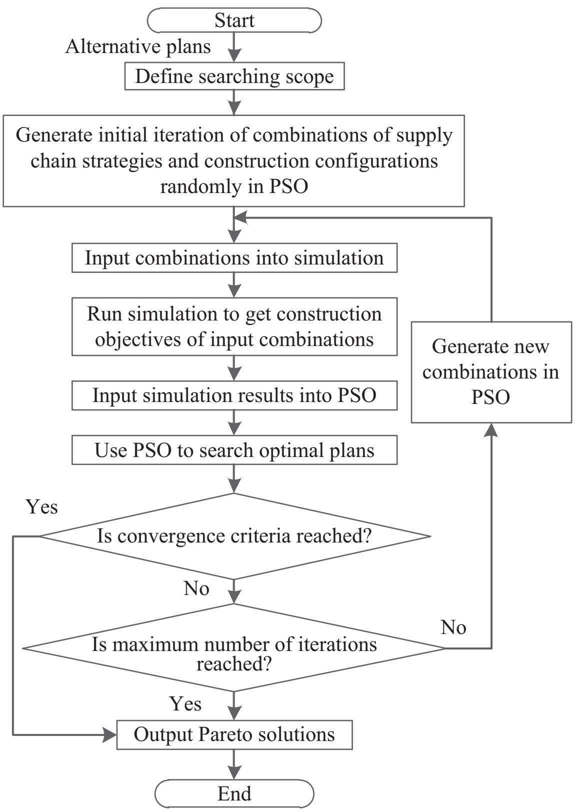

Figure 3.
Procedures of DES-Based PSO.

each plan, and the objectives will be input into PSO as the fitness value of particles. PSO will select particles with best fitness value and check the convergence criteria. If the convergence criteria or the maximum number of iterations has been reached, the optimisation will stop and combinations of supply chain strategies and construction configurations represented by the selected particles will be output as Pareto solutions. Otherwise, PSO will generate new iteration of combinations and particles will move to new positions accordingly. The particle movements in PSO are based on their own best position in the search-space and the best position found by the entire swarm. The new found improved positions will replace the former local best positions. After particle movement, the PSO will restart from calculating fitness value by simulation and repeat the whole process until the convergence criteria or the maximum number of iterations are reached.

4. Case study

4.1. Case background

A prototype of SOSC is built to demonstrate its effectiveness and efficiency. A precast concrete project in Shenzhen, China, is chosen as the study case because it has the mostly used PC structure in China, the PC shear wall structure, and a high prefabrication rate of 49.5 per cent. Data of the project is collected through reading construction records and planning documents, field survey and interview with the contractor and the supplier.

4.2. Building simulation model

To simulate the PC supply chain and construction system of the studied case, a DES model is built on the platform SIMIO. According to CARS, the construction sequences, interactions between PC supply chain and construction, PC supply chain strategies, construction configurations and performance calculation equations are input into SIMIO to build the DES model.

4.2.1. Inputting project data into DES. According to our field survey and interview with the contractor, the construction sequences and interactions between construction and PC supply chain are summarised and built in SIMIO (see Figure 4). The actual used and alternative PC supply chain strategies and construction configurations (see Table 1) are collected from our interview and document reading. These plans are set as input parameters in the built DES model. In addition, some transportation data, such as the transportation distance, speed, quality failure ratio and average delay time, are also collected through our interview and input into DES.

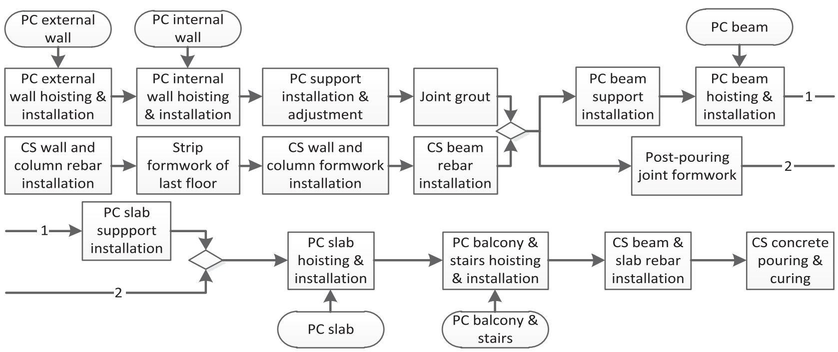

Figure 4. Construction Sequences and Interactions Between Construction and PC Supply Chain.

Tasks	Actual used plans	Alternative plans	Remarks
Components loading & unloading	3 forklifts (CPC(Q)(Y)D50)	1~3 forklifts (CPC(Q)(Y)D50) 1~3 forklifts (CPC(Q)(Y)D60) 1~3 forklifts (CPC(Q)(Y)D70)	5T 6T 7T
PC components hoisting & installation	70 PC workers 2 cranes (STT293)	65, 70, 75 or 80 PC workers 2 cranes (STT293) 2 cranes (XCP330HG7525) 1 crane (XGT8039) 1 crane (XGT500A8040)	
Concrete pouring	10 concrete workers 2 concrete pump (HBT6006A-5)	 1~3 concrete pump (HBT6006A) 1~3 concrete pump (HBT8016C) 1~3 concrete pump (HBT6013C)	 75 kW, 70 m^3/h 132kW, 85m^3/h 90kW, 65m^3/h
Material & labour transportation	3 construction elevators (SC200/200)		66 kw, 2 × 2 t
Rebar processing	40 rebar processing workers 1 rebar bending machine (GK50P) 1 rebar cutting machine (GJ7-40)	20, 30 or 40 rebar processing workers	 4kW 3kW
Rebar installation	20 rebar installation workers	20, 30 or 40 rebar installation workers	
Formwork installation	30 formwork installation workers		
Joint grout	15 joint grout workers		

Table 1. Alternative and Actual Used Construction Plans.

4.2.2. Performance calculation. To compare different plans, three comparison indicators are selected, including construction duration, construction cost and greenhouse gas (GHG) emissions. Construction duration and cost are conventional key objectives, and GHG emissions are important when measuring construction sustainability (Mao *et al.*, 2013). In SIMIO, the construction duration is automatically calculated on the basis of the quantity of work and working productivity. The construction cost in this study includes the buying price and transportation fees of PC components, cost of cast-*in-situ* materials, cost of construction crews, storage related fees and rental of construction machines. The cost data is found in construction documents. The GHG emissions in this study denotes the GHG emissions of electricity and diesel consumed by construction site operation, PC transportation trucks and construction machines, including rebar processing machines, concrete pumps, cranes, forklifts and construction lifts. The GHG emissions are calculated according to Equation (1).

$$G = E * g_e + D * g_d \tag{1}$$

where G means the total GHG emissions in construction and transportation activities; E means the electricity consumed during construction; D means the diesel consumed during PC component transportation and construction; g_e means the GHG emissions factors of electricity, which is 0.714 kg CO_2-e/kWh for this case (Provincial Greenhouse Gas Inventory Guidelines, 2011); g_d means the GHG emissions factors of diesel, which is 3.153 kg CO_2-e/kg (Mao *et al.*, 2013).

4.3. Simulation validation

To examine the reliability and accuracy of the built DES model, the minimum simulation runs determination and simulation outcome validation are conducted. According to our test, the simulated outcomes of all three construction objectives become stable after simulation runs reach 59. Therefore, every simulation in this study will be replicated for 60 times.

Then, the actual supply chain strategy (JIT) and construction configurations (see Table 1) are input to the DES model, and simulation outcomes are compared with actual construction objectives. According to our test, the difference between actual construction objectives and average simulation results are all less than 2 per cent, and all actual construction objectives are within the scope of simulation results (between maximum and minimum). This indicates that the built model has acceptable accuracy.

4.4. DES-based PSO

A multi-objective PSO is used on MATLAB to find the Pareto solutions from the alternative plans, and the detailed procedures of calling SIMIO in MATLAB is built based on the SIMIO-MATLAB framework proposed by Dehghanimohammadabadi and Keyser (2017). Table 2 shows some proper parameters for PSO dealing with construction configuration activities used in Wang *et al.* (2017). The convergence criteria used in this study is the certain number of iterations (10 in this study) with improvement below threshold.

5. Results and discussion

After SOSC, 15 plans are found as Pareto solutions (see Table 3). The construction objectives of Pareto solutions and actual construction plan are shown in Figure 5. According to

Parameter	Value
Population number of each generation (N)	30
Maximum number of iterations	500
Acceleration constant (c_1)	0.8
Acceleration constant (c_2)	0.8
Inertia weight (w)	[0.1, 1.2]

Table 2. Parameters Set in PSO.

Plan no.	Supply chain strategies	Construction configurations: Forklifts	PC workers	Cranes: Number	Cranes: Type	Concrete pumps: Number	Concrete pumps: Type	Rebar processing workers	Rebar installation workers
1	JIT	3 forklifts (CPC(Q)(Y) D50)	65	2	S	1	C	40	30
2			65	2	X	1	A	40	40
3			65	2	X	1	C	30	30
4			75	2	S	1	A	20	30
5			65	2	S	1	C	20	40
6			75	2	X	1	A	40	30
7	On-site storage		65	2	S	1	A	20	40
8			65	2	S	2	A	20	30
9			65	2	X	1	A	40	30
10			75	2	X	3	C	30	40
11			70	2	X	1	C	20	30
12			70	2	S	1	A	20	20
13			75	2	S	3	A	30	40
14			80	2	S	3	A	30	40
15			65	2	S	1	A	20	20

The type S of crane means STT293. The type X of crane means XCP330HG7525. The type A of concrete pump means HBT6006A. The type C of concrete pump means HBT6013C.

Table 3. Optimal Plans.

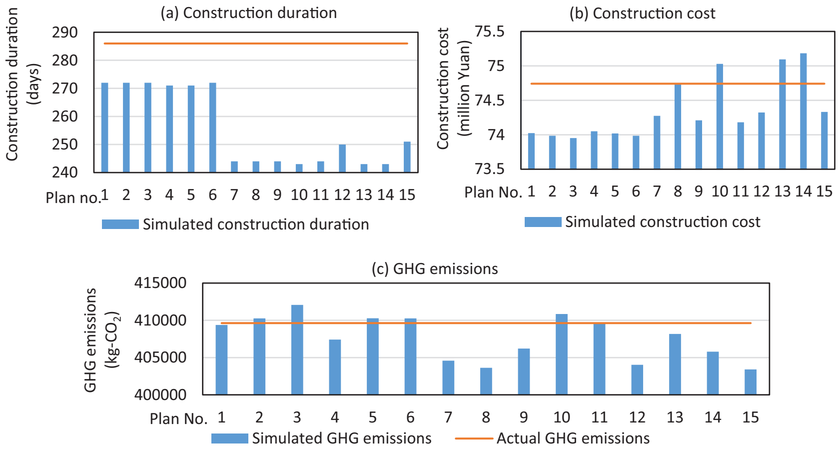

Figure 5. Construction objectives of Pareto solutions and actual plans.

Figure 5, the construction duration of all optimised plans is less than the actual construction duration. As for GHG emissions or construction cost, not all optimised plans are better than the actual plan. Plans 1, 4, 7, 8, 9, 12 and 15 have less construction duration, less cost and less GHG emissions than the actual plan, which means choosing these plans can get overall improvement. Contractors can choose one plan out of the 15 optimised plans according to their preference in different construction objectives.

Compared to conventional parametric simulation approach, which tests all alternative plans to find out the optimal plans, SOSC is a more efficient method, which saves a lot of time and effort in simulating and comparing alternative plans by reducing the alternative plans needed for simulation. In this case, the search space of all alternative plans is $(3*3*4*4*3*3*3*3)*3 = 11{,}664$ combinations of construction configurations * 3 PC supply chain strategies = 34,992 (see Table 1), and only 10,260 combinations have been generated in PSO to find out the optimal plans. According to the reduced simulation runs, $(34{,}992*60 - 10{,}260*60)/(34{,}992*60) \approx 70.68\%$ of time and effort used to simulating and comparing alternative plans has been saved due to SOSC.

6. Conclusion

This paper combines DES and PSO and proposes a simulation-based optimisation of PC supply chain and construction (SOSC) for contractors in PC projects. DES is used to capture the dynamic and complex interactions between PC supply chain and construction, and calculate the construction objectives of alternative plans. PSO is used to search for the optimal combinations of PC supply chain strategies and construction configurations for contractors based on the simulated construction objectives. A prototype of SOSC is built and tested in a case study to demonstrate its effectiveness and efficiency. The efficiency of SOSC are compared with the parametric simulation approach, and over 70 per cent of time and effort used to simulating and comparing alternative plans has been saved due to SOSC.

This paper has two contributions: one is in providing a decision support tool SOSC to optimise both supply chain strategies and construction configurations, while the other one is in building a prototype of SOSC and testing it in a case study. The proposed approach also has some limitations. Firstly, building simulation model costs a lot of time and effort. In addition, SOSC has high data requirement. How to overcome these limitations will be studied in the future research.

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