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Discrete-event simulation-based decision making of Just-In-Time strategies for precast concrete supply chain using batch delivery and offsite inventory level

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Precast concrete (PC) can potentially improve construction industry projects when used as a primary process in the precast concrete supply chain (PCSC). Successful inventory reduction and on-time delivery are essential in the PCSC because of critical scheduling and cost factors. To solve these challenges, this study applied Just-In-Time (JIT) strategies in the PCSC using the Discrete-Event Simulation (DES) model to help manufacturers identify the optimal decision. The factors considered were offsite inventory levels (based on days buffered) and batch delivery decisions that reduced supply penalties and improved construction performance. The model was validated based on a precast project experiment in Vietnam; the model provided a saving of 52% in manufacturer penalties and reduced construction idle work by 77%. An optimal combined decision was provided for the manufacturer, such as a 1day-4batch decision with maximum benefit and a 2day-2batch decision for safety using an uncertainty risk consideration in the PC wall panel study case. This research contributes a tool to help manufacturers in decision making and promotes the use of JIT applications/strategies in the PCSC process.

1. Introduction

In recent years, the precast concrete (PC) method has increasingly been adopted worldwide because it offers various advantages, including enhanced quality performance, short construction time, reduced supervision cost, less workload, less complicated work, and reduced environmental impacts (Kim et al., 2020; Kong et al., 2018; Leu & Hwang, 2002; Luo et al., 2020; Masood et al., 2021; Si et al., 2020; Xiong et al., 2021). The precast concrete supply chain (PCSC) is associated with many activities and processes, which concern interdependent sections, including offsite manufacturing, transportation, and onsite construction coordination (Al-Bazi & Dawood, 2012; Anvari et al., 2016; Zhang & Yu, 2020).

However, there are still major challenges in the PCSC, including reducing inventory on the manufacturing site (offsite) and on the construction site (onsite) while warranting on-time delivery and minimum performance time/cost in the PCSC process. This challenge is due to three main problems: excessive offsite and onsite inventory and relocation related to inappropriate delivery planning (Ahmadian et al., 2021; Bamana et al., 2019; Ko & Chen, 2012; Lyu et al., 2020; Modak et al., 2015; Xiong et al., 2021). The offsite and onsite inventory will create non-adding value and negatively impact the PCSC performance, such as unnecessary inventory cost and stock time, taking up space, and inviting damage risk to the offsite and onsite inventory items. Furthermore, early or late delivery (early and tardy times) cause site congestion and unproductive idle work resources from inappropriate delivery planning (Anvari et al., 2016; Baker, 2004; Kim et al., 2020; Kong et al., 2018; Li et al., 2017; Luo et al., 2020). Nevertheless, the manufacturer and contractor still keep their storage and inventory because of inventory benefits, such as preventing a shortage causing interrupted production and uncertain processing time and other disturbance factors (Chan & Wee, 2003; Kim et al., 2020; Ko, 2010, 2011; Ko & Wang, 2010; Lyu et al., 2020; Si et al., 2020; Wang & Hu, 2018; Wang et al., 2018b; Wang et al., 2021; Zhai et al., 2015). To address these problems, several papers

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have been considered using the Just-In-Time (JIT) principle to make better decisions regarding their current PC production, transportation, or construction processes (Ahmadian et al., 2021; Anandh et al., 2020; Bamana et al., 2019; Chen et al., 2016; Chen et al., 2019; Cossio & Cossio, 2012; Ko & Chen, 2012; Ko & Wang, 2010; Kong et al., 2018; Li et al., 2017; Lyu et al., 2020; Modak et al., 2015; Si et al., 2020; Xiong et al., 2021). However, only a few papers have focused on JIT application in the comprehensive PCSC process, containing manufacturing, transportation, and construction sections; furthermore, these did not determine the relationship between JIT strategies in each section and uncertain performance.

This research proposes the discrete-event simulation (DES) model for decision-making with JIT strategies under uncertain performance in the comprehensive PCSC process. The JIT strategies include the offsite inventory level on the manufacturing site and batch delivery regarding transportation, to identify the optimal decisions to improve construction performance and reduce manufacturer penalties. Therefore, this paper objectives were:

1) Use the DES tool to determine early and tardy timing, onsite idle work, offsite inventory cost, and transportation performance of the JIT strategies in the PCSC process, including the manufacturing, transportation, and construction sections.
2) Evaluate the impact between offsite inventory levels and the batch delivery decisions of the JIT strategies in the PCSC process under uncertain performance considerations.
3) Optimize offsite inventory level and batch delivery for manufacturer decision making based on construction performance improvement and the reduction of manufacturer penalties.

This paper is classified into five Sections. After this introductory Section 1 that provides the study objective, Section 2 provides the literature review, consisting of the PCSC process, JIT strategies, and relevant studies. Section 3 covers the methodology, including data collection, the DES-based JIT strategies evaluation model, and the decision-making formula. Section 4 provides a case study, including the scenario description and results. Finally, Section 5 concludes with the highlight from the results and the contribution of this study.

2. Literature review

2.1. PCSC process

The typical PCSC process consists of offsite manufacturing, transportation, and onsite construction, which are interdependent and coordinated (Luo et al., 2020; Zhang & Yu, 2020). From the literature, PCSC performance is often defined by the steps or workstations to identify a specific sequence, resources participant (raw material, work-in-progress (WIP), precast concrete components (PCs), worker team, and equipment), and performance time (Al-Bazi & Dawood, 2017; Anvari et al., 2016; Chen et al., 2020; Chen et al., 2016; Dan et al., 2021; Hu, 2011; Jiradamkerng, 2013; Ko & Wang, 2011; Kong et al., 2018; Leu & Hwang, 2002; Li et al., 2017; Liu, 1995; Wang & Hu, 2017; Wang et al., 2018b). All their PCSC process descriptions are similar step/workstation and following sequence, but the resources, performance time, and strategies application are different. Therefore, following JIT strategies in this study, we define PCSC flow-shop performance with 19 workstations as shown in Fig.1:

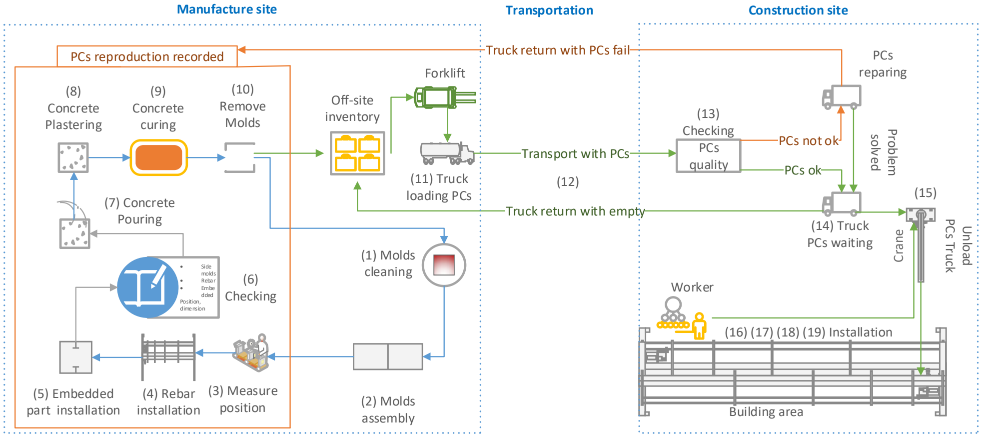


Fig. 1. Main workstations of PCSC flow-shop performance.

2.2. Just-In-Time strategies

The JIT strategies are suggestions based on the JIT principle, with the primary objective being to reduce inventory and deliver the right material, quantity, and quality at the right time following customer requirements (Akintoye, 1995; Budianto et al., 2021; Hirano, 1989; Ko & Chen, 2012; Pheng & Chuan, 2001; Pheng & Hui, 1999; Si et al., 2020; Singh & Ahuja, 2012; Terdpaopong et al., 2021; Wilujeng et al., 2022). In this study, the JIT strategies involved two variable factors:

1) Offsite inventory level: At the manufacturing site, PCs inventory could be limited by the day buffer based on contractor requirements (Bamana et al., 2019; Cossio & Cossio, 2012; Ko & Chen, 2012; Li et al., 2017; Modak et al., 2015; Wang & Hu, 2017). Therefore, the manufacturer could reduce unnecessary inventory space, risk damage, excessive inventory cost, and stock time.
2) Batch delivery: In transportation, PCs are directly delivered without onsite double handing, lifting, and inventory, according to the contractor's preference (eliminating onsite inventory and relocation). However, reducing offsite inventory and eliminating onsite inventory will create early or late delivery (earliness or tardiness, respectively) due to manufacturing shortages or inappropriate delivery planning, respectively. The earliness and tardiness will increase onsite congestion and idle resources (Jiradamkerng, 2013; Kong et al., 2018; Liu et al., 2020). Therefore, this study proposed batch delivery decisions to minimize earliness and tardiness with various batches and trucks in each batch.

2.3. Relevant studies

Previous studies of PCSC performance problems seldom considered the comprehensive JIT application in the PCSC process. The literature review gaps regarding papers relevant to this research are summarized below (Table 1):

Table 1
Gaps in literature regarding comprehensive JIT application in the PCSC process

No	Article Information		Keyword		Scope application			Type of methodology	
	Authors	Year	JIT	Uncertain perform	Production	Transportation	Construction	Optimization algorithm	Simulation
1	Ko et al	2012	√		√			√	
2	Modak et al	2015	√		√			√	
3	Li et al	2017	√		√				√
4	Kong et al	2018	√			√	√	√	
5	Wang et al	2018		√	√	√	√		√
6	Wang and Hu	2018			√			√	
7	Bamana et al	2019	√				√		√
8	Kim et al	2020		√	√		√		√
9	Zhang and Yu	2020	√			√		√	
10	Xiong et al	2021	√		√			√	
11	This study		√	√	√	√	√		√

The PCSC involves complicated activities and a strong link between each workstation; additionally, uncertainties in scheduling and performance regarding processing time and unexpected factors associated with interruptions disturbances make inventories indispensable (Abedi et al., 2016; Al-Bazi & Dawood, 2012; Anvari et al., 2016; Chan & Lu, 2005; Hu, 2011; Kim et al., 2020; Luo et al., 2020; Lyu et al., 2020; Masood et al., 2021; Wang & Hu, 2017; Wang et al., 2020; Zhang & Yu, 2020). However, Table 1 lacks a study for accurate JIT strategies to address uncertainty in PC performance. Additionally, the previous research studied JIT separately in a single section, such as production (Ko, 2010; Ko & Chen, 2012; Li et al., 2017; Modak et al., 2015), transportation (Chen et al., 2019; Kong et al., 2018; Liu et al., 2020; Zhang & Yu, 2020), or construction (Bamana et al., 2019; Chen et al., 2019; Jiradamkerng, 2013; Kong et al., 2018). Furthermore, previous studies did not consider the combined contractor and manufacturer objectives for decision making. Therefore, in the current study, the first time JIT strategies are considered in the comprehensive PCSC process involving uncertain performance based on the DES approach is to improve construction performance and reduce manufacturer penalties by optimizing decision making.

3. Research methods

In this study, the methodology was separated into three main steps and shown in Fig.2. The first step was data collection from the construction site of the project experiment (interview with the engineer and from documents/design drawings) and the literature related to the PCSC process. The second step was the DES-based JIT strategies evaluation model, which contains PCSC process performance with variables of offsite inventory levels and batch delivery decisions (JIT strategies) in each case study to conduct the DES model. After that, the impact was evaluated of the offsite inventory level and batch delivery decision for each identified result: the JIT (summary of earliness and tardiness times) objective (Dan et al., 2021; Wan & Yen, 2009; Zhou et al., 2009), onsite idle time of crane and worker, offsite inventory cost, and transportation performance (additional performance for each truck). Following construction performance improvement and minimum manufacturer penalties, the final step was the decision-making formula, which investigated the objective formula for optimal offsite inventory and batch delivery decisions (minimum performance penalty).

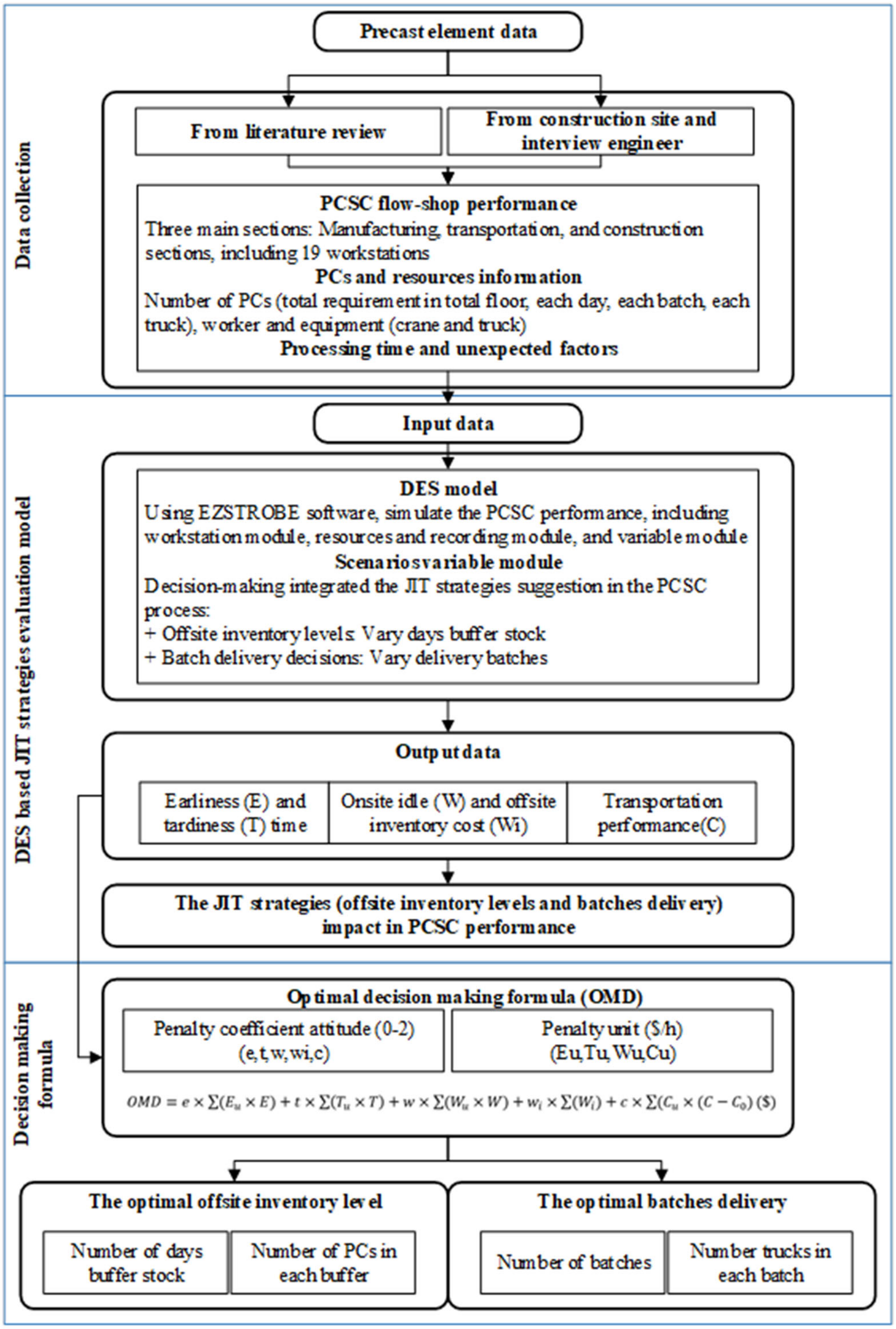


Fig. 2. Research methodology

3.1. Data collection

According to the study aims, the data were collected for input to the DES model based on three elements: (1) The number of PCs in each floor and day from the contractor demand; each buffer day, batch, and truck from manufacturer supply design; (2) The resources information (the number of cranes and worker teams in the manufacturing and construction site; the number of trucks involved in transportation); (3) The processing time and unexpected/interruption factors (activities/tasks/workstations with the specific kind of PCs in each truck, such as wall panels, beams, columns, and slabs). The data on processing time and unexpected factors data were validated with the literature related to the PCSC process (Jiradamkerng, 2013; Kong et al., 2018; Li et al., 2017; Wang et al., 2018a, 2018b). Tables 2 and 3 in Section 4 (case study) show the data on performance time and the number of PCs.

3.2. DES-based JIT strategies evaluation model

Using the data as input (first step) from the actual project experiment integrated with the literature, the DES model was adopted to simulate the JIT strategies in the PCSC process, as shown in Fig.3.

In Fig.3, the DES model according to the PCSC process is defined in five separate elements represented by different colors. These factors contribute to comprehensive PCSC performance: PCs status (blue), resources (orange), demand and information update (green), interruption problem/unexpected factors recording (red), and PCSC workstation (black). The performance time data included in the DES model with rectangular (normal or combi types) nodes represent the workstation, the cycle (queue type) nodes represent the resources and sequences, and the links represent the direction of resource flows according to the PCSC activity cycle diagram (ACD). The ACD is separated into two mainline (uninterrupted and interrupted lines). In the uninterrupted line, the PCSC started from the PCOder and PCStoring nodes in the manufacturing section and finished with the PCfinisInstall node in the construction section. The PCSC added four interruption factors after failing of checking: raw material with the ReMDeliver node, framework repairing with the FrRepairing node, PCs unsatisfactory quality with the ProblSolve node, and PCs reproduction with the Reproduction node in the interrupted line.

In this research, DES-based various offsite inventory levels and batch delivery decisions in the PCSC process are considered in the scenario variable module or scenario application. Scenario descriptions are shown in Section 4 (case study).

1) Offsite inventory levels: we modified the number of PCs produced in the manufacturing site's buffer stock to satisfy the quantity of PCs required by the project experiment each day.
2) Batch delivery decisions: we modified the number of delivery batches and the number of trucks in each batch.

The first result from the DES model was earliness time (early delivery/truck with PCs waiting time outside) and tardiness time (late delivery/available onsite space idle time), as shown in Eq. (1) and Eq. (2), respectively. Any delay in PCs delivery will prolong the construction process and increase onsite idle work, including workers and cranes, as shown in Eq. (3). Offsite inventory cost is shown in Eq. (4). Finally, transportation performance (average transportation performance per truck) is shown in Eq. (5). From these equations, the impact can be seen of batch delivery decisions and offsite inventory levels with different case studies for four main points: JIT point as a summary of earliness time (E) and tardiness time (T), onsite idle work (W), offsite inventory cost (Wi), and transportation performance (C).

The average earliness time (E) of a truck arriving before assembly time was calculated using Eq. (1):

$$E = \frac{Waiting\ time\ of\ trucks\ with\ PCs}{Number\ of\ trucks}\ (h) \tag{1}$$

The average tardiness time (T) of a truck arriving later than the assembly time was calculated using Eq. (2):

$$T = \frac{Waiting\ time\ of\ space\ available}{Number\ of\ trucks}\ (h) \tag{2}$$

The onsite idle work (W) was calculated using Eq. (3):

$$W = \frac{Waiting\ time\ of\ (crane + woker + truck)}{Number\ of\ PCs}\ (h) \tag{3}$$

The offsite inventory cost (Wi) was calculated using Eq. (4):

$$Wi = U_{buffer} \times \text{Day buffer} + U_{mantainance} \times \frac{Waiting\ time\ \text{of inventory}}{Number\ of\ PCs} \times \text{PCs (\$)} \tag{4}$$

The transportation performance (C) was calculated using Eq. (5):

$$C = \frac{TransportHighLv\ duration}{Number\ trucks\ in\ High} + \frac{TransportModeLv\ duration}{Number\ trucks\ in\ Mode} + \frac{TransportLowLv\ duration}{Number\ trucks\ in\ Low}\ (h) \tag{5}$$

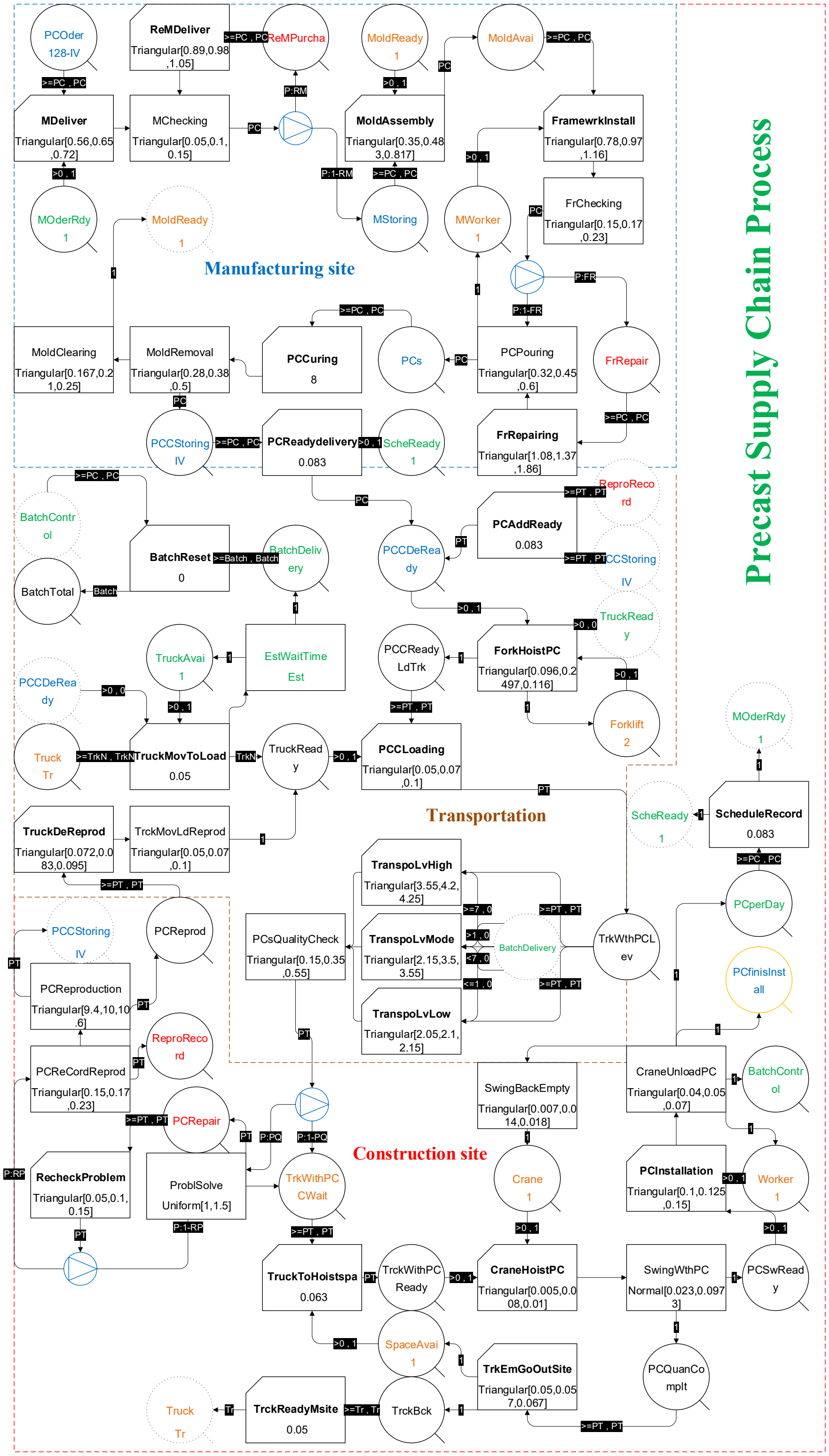


Fig. 3. DES model of PCSC process

3.3. Decision-making formula

After obtaining the parameter identification results from Eq. (1) to Eq. (5), we identified the optimal decision based on each objective. First, we separated construction performance (resource idle and earliness penalties) and manufacturing penalties (inventory cost, transportation performance, and JIT penalties). Then, a combination of penalties was suggested for both the manufacturer and contractor as a result. Finally, by using analytical technique, the effects of earliness and tardiness time, onsite idle work, offsite inventory cost, and transportation performance were converted to the cost penalty that was compared to standard amounts (Kong et al., 2018; Metham & Benjaoran, 2018), as shown in Eq.(6), Eq.(7), and Eq.(8).

Objective for decision making on construction performance improvement (OC) is presented in Eq. (6):

$$OC = e \times \sum (E_u \times E) + w \times \sum (W_u \times W)\ (\$) \tag{6}$$

Objective for decision making on manufacturer penalties reduction (OM) is presented in Eq. (7):

$$OM = e \times \sum (E_u \times E) + t \times \sum (T_u \times T) + w_i \times \sum (W_i) + c \times \sum (C_u \times (C - C_0)\ (\$) \tag{7}$$

Combination objective for decision making (OMD) is presented in Eq. (8):

$$OMD = e \times \sum (E_u \times E) + t \times \sum (T_u \times T) + w \times \sum (W_u \times W) + w_i \times \sum (W_i) + c \times \sum (C_u \times (C - C_0)\ (\$) \tag{8}$$

where *e, t, w, w_i,* and *c* are the penalty coefficients for earliness, tardiness, onsite idle work, offsite inventory, and transportation performance (0 to 2), respectively, E_u is the unit penalty of earliness time (\$/h), T_u is the unit penalty of tardiness time (\$/h), W_u is the unit penalty of onsite idle work (\$/h), and C_u is the unit penalty of transportation performance (\$/h). The objective function $(C - C_0)$ defines the additional transportation performance time caused by traffic congestion, with C_0 as the minimum transportation performance time value.

4. Case study and results

The DES model was implemented based on an application example as a project experiment (Chingluh-VH4) in Vietnam. Data collection (performance time of workstations and scenario information in the PCSC process) is shown in Table 2 and Table 3, respectively:

Table 2
Performance time of workstations in PCSC process

No	Workstation	Probability distribution function (h)			
1	Mold clearing	0.167	0.210	0.250	Triangular
2	Mold assembly	0.300	0.400	0.700	Triangular
3	Measure position	0.050	0.083	0.117	Triangular
4	Rebar installation	0.492	0.500	0.567	Triangular
5	Embedded part installation	0.288	0.470	0.593	Triangular
6	Checking	0.150	0.170	0.230	Triangular
7	Concrete Pouring	0.320	0.450	0.600	Triangular
8	Concrete Plastering	0.250	0.267	0.300	Triangular
9	Concrete curing	8.000			None
10	Remove Molds	0.280	0.380	0.500	Triangular
11	Truck loading PCs	0.096	0.116	0.250	Triangular
12	Truck transporting PCs				
	PCs transport with low traffic level	2.05	2.1	2.15	Triangular
	PCs transport with mode traffic level	2.15	3.5	3.55	Triangular
	PCs transport with high traffic level	3.55	4.2	4.25	Triangular
13	PCs quality checking	0.15	0.35	0.55	Triangular
	PCs quality problem solving	1	1.5		Uniform
	Recheck PCs problem	0.05	0.1	0.15	Triangular
	PCs reproduction recorded	0.15	0.17	0.23	Triangular
14	Truck with PCs waiting				Queue
	Truck goes to hoisting space	0.063			None
15	Crane hoist PCs	0.028	0.031	0.033	Triangular
16	Labor pick PCs	0.033333			None
17	PCs install	0.1	0.125	0.15	Triangular
18	Crane unloading	0.04	0.05	0.07	Triangular
19	Crane back	0.007	0.014	0.018	Triangular

Table 3
Scenario information

Input parameter	Type of PCs			
	Wall panel	Column	Beam	Slab
Total quantities of PCs/floor (PC)	128	118	294	2215
PCs in each truck (PC)	4	4	6	30
Batches delivery (batch)	1,2,4,8	1,2,5,10	1,2,4,8,16	1,2,4,8
Installation time/PC (h)	0.135	0.0938	0.0688	0.014
PCs/day (PC)	32	40	96	240
Trucks/day (number of trucks)	8	10	16	8

4.1. Scenario description

The case study scenario consisted of two main elements: first, the JIT strategies (various offsite inventory levels (buffer stock) and batch delivery decisions) and second, the interruption problems in PCSC with their various risk rates of occurrence (situation).

Table 4
Scenarios application

	Batch delivery decision		Transportation level			Offsite	PCSC interruption problem			
Scenario	Number of batches	Trucks/batch	Low level	Mode level	High level	Inventory level	Reproduction of PCs	Unsatisfactory quality	Framework repair	Raw material failure
1	1	8	8	0	0	1 day	0.04	0.04	0.05	0.08
2	2	4	4	4	0					
3	4	2	2	6	0					
4	8	1	2	5	1					
5	1	8	8	0	0	2 days				
6	2	4	4	4	0					
7	4	2	2	6	0					
8	8	1	2	5	1					
9	1	8	8	0	0	4 days				
10	2	4	4	4	0					
11	4	2	2	6	0					
12	8	1	2	5	1					
13	1	8	8	0	0	1 day	0.19	0.27	0.28	0.22
14	2	4	4	4	0					
15	4	2	2	6	0					
16	8	1	2	5	1					
17	1	8	8	0	0	2 days				
18	2	4	4	4	0					
19	4	2	2	6	0					
20	8	1	2	5	1					
21	1	8	8	0	0	4 days				
22	2	4	4	4	0					
23	4	2	2	6	0					
24	8	1	2	5	1					
25	1	8	8	0	0	1 day	0.19	0.27	0.05	0.08
26	2	4	4	4	0					
27	4	2	2	6	0					
28	8	1	2	5	1					
29	1	8	8	0	0	2 days				
30	2	4	4	4	0					
31	4	2	2	6	0					
32	8	1	2	5	1					
33	1	8	8	0	0	4 days				
34	2	4	4	4	0					
35	4	2	2	6	0					
36	8	1	2	5	1					
37	1	8	8	0	0	1 day	0.04	0.04	0.28	0.22
38	2	4	4	4	0					
39	4	2	2	6	0					
40	8	1	2	5	1					
41	1	8	8	0	0	2 days				
42	2	4	4	4	0					
43	4	2	2	6	0					
44	8	1	2	5	1					
45	1	8	8	0	0	4 days				
46	2	4	4	4	0					
47	4	2	2	6	0					
48	8	1	2	5	1					

Table 4 shows that the 48 scenario variables for the PC wall panels case had 128 PCs on each floor, with the schedule to install them being around 4 days requiring approximately 32 PCs/day and a fixed capacity of 4 PCs/trucks requiring 8 trucks/day. The offsite inventory levels were estimated as 1 day, 2 days, and 4 days buffer corresponding to 32 PCs, 64 PCs, and 128 PCs, respectively, that had already been produced and were stored at the manufacturing site by the due date. The various batch delivery decisions were separated into 1 batch (8 trucks/batch), 2 batches (4 truck/batch), 4 batches (2 trucks/batch), and 8 batches (1 trucks/batch). Additionally, the transportation levels related to various batches delivery were needed to design the scenario corresponding to traffic jam levels. For example, 1 batch with 8 trucks delivered PCs in the early morning with a low traffic jam level, while 2 batches with the first 4 trucks delivered PCs in the early morning (low traffic jam level), and the next 4 trucks delivering PCs during the morning (mode traffic jam level).

Every 12 scenarios represented various JIT strategies (3 offsite inventory levels × 4 various batch delivery) with interruption situations happening from the manufacturing and construction section based on four factors: reproduction of PCs, PCs unsatisfactory quality in the construction section, framework repair, and raw material failure in the manufacturing section:

1) For the first 12 scenarios (1–12), situation 1, assume the process runs smoothly without interruption (low-risk interruption factors in the whole process).
2) For the second 12 scenarios (13–24), situation 2, assume the process runs poorly (high-risk interruption factors in the whole process).
3) For the third 12 scenarios (25–36), situation 3, assume the interruption happens at the construction site (low-risk in manufacturing and high risk at construction sites).
4) For the fourth 12 scenarios (37–48), situation 4, assume the interruption happens at the manufacturing site (high risk in manufacturing and low risk at construction sites).

Through these 4 situations, we could see the impact of the interruption factors on our decision using situations 1 and 2. Furthermore, which sections (manufacturing/construction) substantially interrupted the re-make decision is shown in situations 3 and 4.

4.2. Results

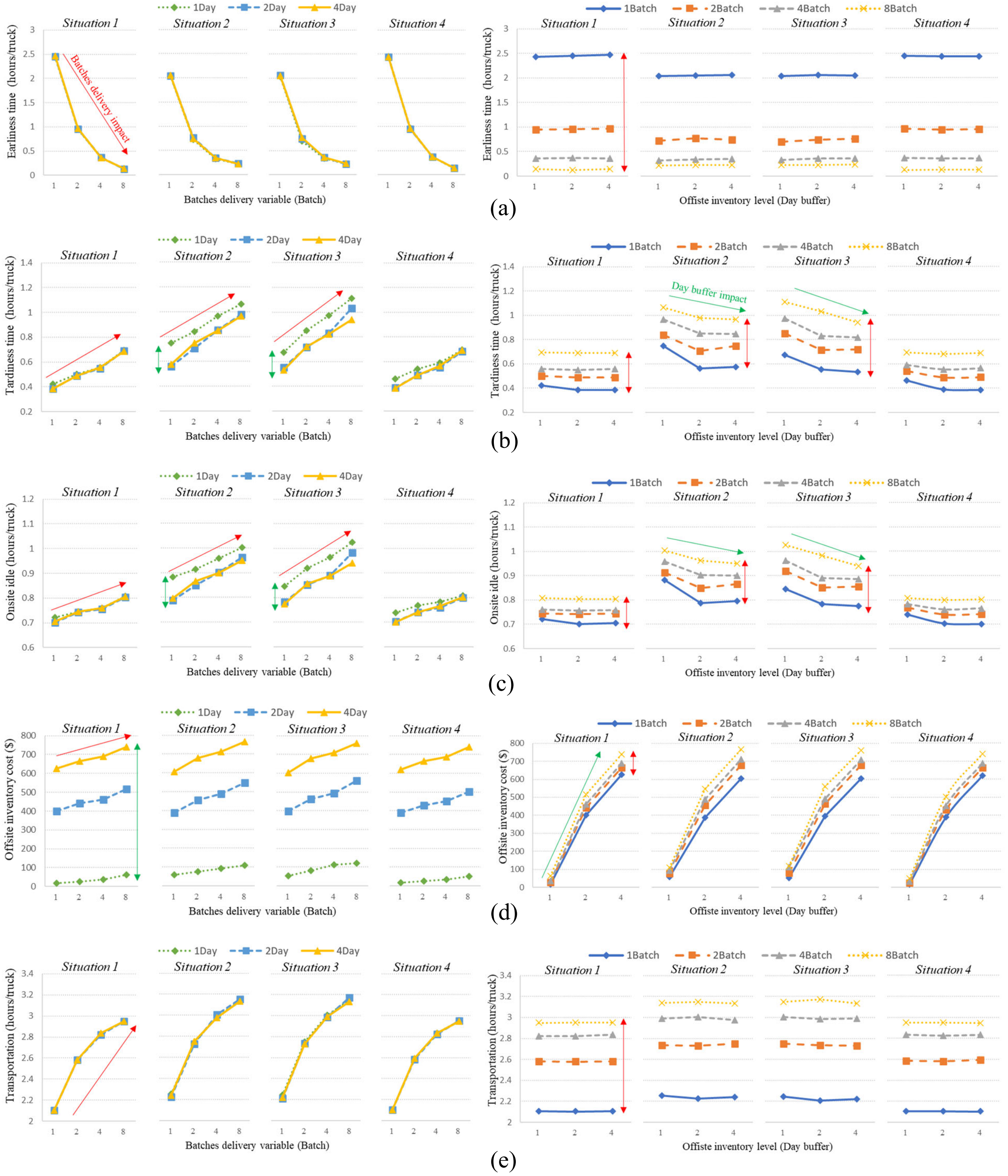
The results were obtained after running the DES model and could be viewed in the Excel analytics dashboard. First, the effect of offsite inventory levels and batch delivery decisions for each result parameter (earliness time, tardiness time, onsite idle work, offsite inventory cost, and transportation performance) are shown in Fig.4. After that, following the decision-making formula, the optimal JIT strategies/decisions were suggested by reducing manufacturer penalties and improving construction performance (Fig. 5).

In Fig.4, red and green arrows represent the impacts of batches delivery and offsite inventory levels, respectively. Increasing the batch delivery reduced the earliness time and increased the tardiness time, onsite idle work, offsite inventory cost, and transportation performance (red arrows). Furthermore, reducing the offsite inventory levels increased the tardiness time and onsite idle work and reduced offsite inventory costs (green arrows). However, the most substantial impact for each parameter was batch delivery, such as earliness (2.327 hours/truck decreasing), tardiness (0.578 hours/truck increasing), onsite idle work (0.251 hours/PCs increasing), and transportation performance (0.95 hours/truck increasing). On the other hand, offsite inventory level only had an effect when PCSC was interrupted, which substantially impacted the offsite inventory cost for every situation ($708/floor reducing) for a reduction from 4 to 1 day buffer period (Fig.4d). However, increasing batch delivery also affected the inventory costs ($156/floor increase) because this prolonged the PCs waiting time for loading the truck at the manufacturing site.

Furthermore, there were different decisions for minimal differences in the parameters. For example, in Fig.4a and 4b, the 8batch decision was the best for reducing the earliness time in every situation because each truck would arrive at the construction site following the installation time/truck previously estimated. However, with higher uncertainty of traffic jams, 8 batches also increase the highest tardiness time (average late delivery 1.11 hours/truck), while 1 batch was the best for reducing the tardiness time because all trucks could go in the early morning without a high traffic jam level and arrive at the construction site before installation time (nearly 0 late hours/truck). Similarly, for the tardiness time, onsite idle work also increased with increased batch delivery and reduced offsite inventory levels (Fig.4c). In contrast, the offsite inventory cost was reduced (minimum inventory cost of $52/floor) by reducing inventory levels and batch delivery (Fig. 4d).

The main reason for these differences was that offsite inventory levels (day buffer) are only adequate when PCSC is interrupted. For example, for almost all results for idle work, a 1day buffer is impossible because of PCs shortages appearing. However, in situation 1, 1 day still warranted the minimum idle time at the construction site as smooth PCSC performance would result in only a few PCs shortages. In addition, the earliness time and transportation performance (Fig.4e) were directly related to batch delivery and did not change even if the offsite inventory levels were varied in every situation. Because the time storing (the day buffer) in manufacturing is not relevant to traffic jams and earlier arrival, but these parameters (earliness time and additional transportation) are mainly created from batch delivery variables. In addition, the final decision requires identifying offsite inventory levels and batches delivery based on each objective; these are presented in Fig.5. In Fig.5a, The

JIT point (on-time delivery) indicates the minimum earliness and tardiness penalties (4 batches result). However, 2 batches outperformed 4 batches but not by too much when there was a high-risk interruption at the construction site in situations 2 and 3. In situation 1, offsite inventory levels did not impact the JIT point (possible to select 1 day buffer integrated in the 4batch decision). Nevertheless, when the PCSC had a high-risk interruption in situations 2, 3, and 4, The 2day buffer could reduce JIT penalties better than the 1day buffer. Therefore, the manufacturer can suggest using a combination of the 2day-4batch decision for JIT delivery (2 days buffer minimum earliness and tardiness in every situation, and 4 batches still possible for high-risk interruption).



(a)

(b)

(c)

(d)

(e)

Fig. 4. Impact of offsite inventory levels and batches delivery decisions for each identified parameter.

For reducing manufacturer penalties, Fig.5b showed that the best offsite inventory level is 1 day buffer for every situation, using 4 batches (situations 1 and 4) and 2 batches (situations 2 and 3) for minimum manufacturer penalties. A combined decision using 1day-2batch reduced manufacturer penalties. Comparing among 1, 2, and 4 batches. 2 batches simply reduced a large manufacturer penalty (saving $757 to $927 penalty/floor) and safety with the 1day buffer, even when the PCSC process had a high risk of interruption. Next, the results in Fig.5c clearly showed that 4day-4 batch was the best decision to improve construction performance for minimum onsite idle time for the crane and onsite congestion from trucks (reducing $622 to $987 idle cost/floor).

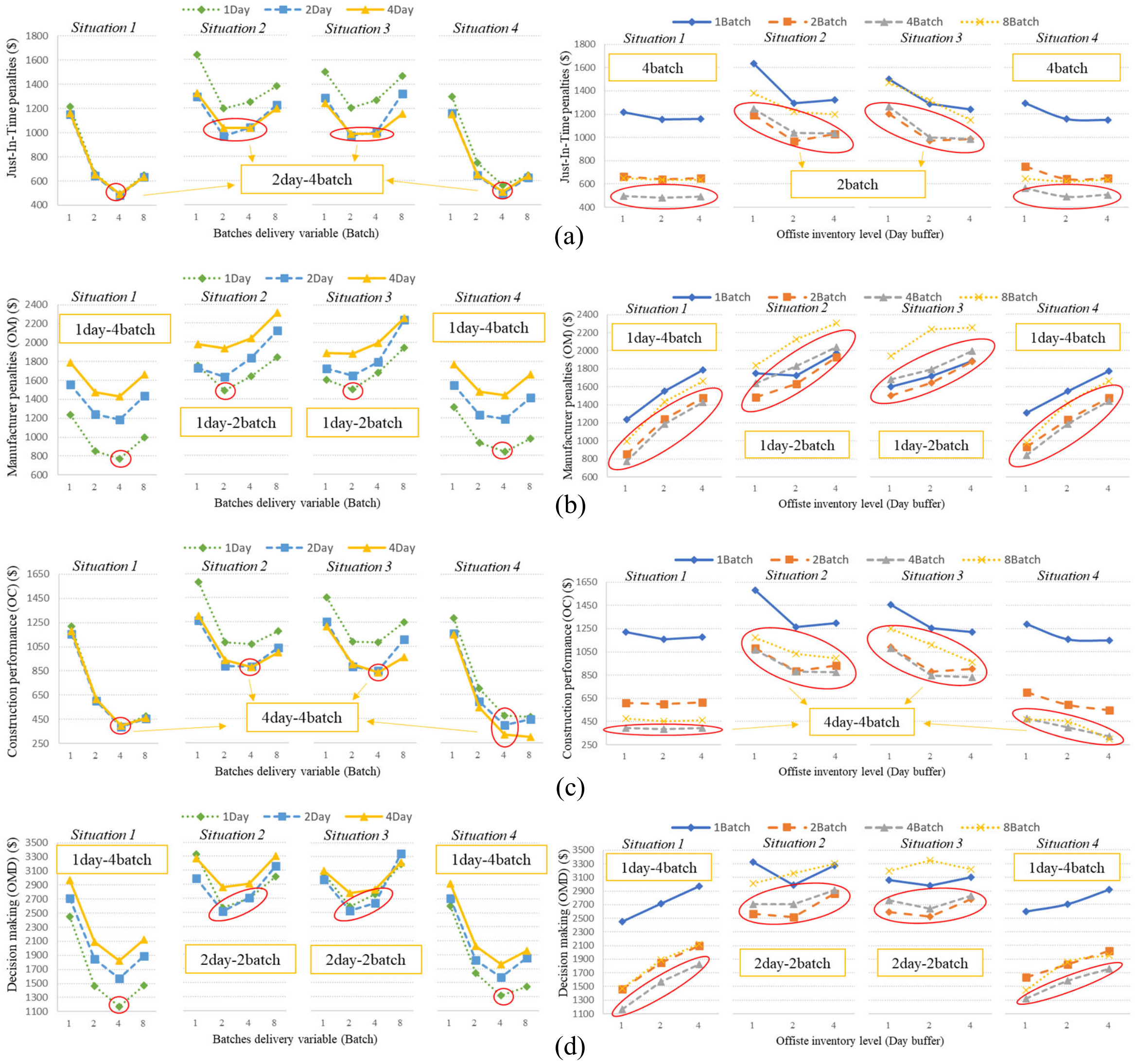


Fig. 5. Decision-making outputs for manufacturer penalties and construction performance

Finally, to determine whether the JIT strategy/decision could be acceptable regarding both manufacturer penalties reduction and construction performance improvement, the results indicated optimal using a 1 day buffer with 4 batches in situations 1 and 4, while using 2 days and 2 batches in situations 2 and 3, as shown in Fig.5d. Fig.6 shows the output selecting JIT strategies (offsite inventory levels and batch delivery) for the manufacturer with different objectives (OM, OC, and OMD). We compared the benefit of both decisions as 1day-4batch (total saving $625 to $1,797/floor) and 2day-2batch (total saving $814 to $1,334/floor) for the OMD objective. The first suggestion is to accept the uncertainty in the PCSC and select the high benefit decision as the 1day-4 batch scenario. The consequence is a maximum benefit of $1,797/floor saving and $679 higher than the 2day-2batch scenario, when the PCSC occurs smoothly. However, if the PCSC is interrupted, this decision only saves $585 and is lower than the 2day-2batch scenario (by $237). The second suggestion is to ignore any uncertainty in the PCSC process and use the 2day-2batch scenario for safety, as this decision still saves $1,334/floor when the PCSC occurs smoothly and could minimize penalties if the PCSC were interrupted.

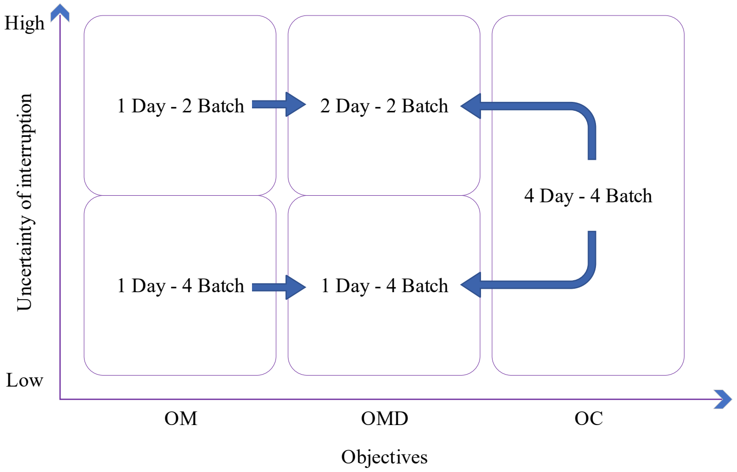


Fig. 6. Selecting JIT strategies/decisions based on OM, OC, and OMD objectives

5. Conclusion

The study results indicated that the JIT strategies could be successful with batch delivery and offsite inventory levels in reducing earliness and tardiness times (JIT point), onsite idle work, offsite inventory cost, and transportation performance. These strategies were applied in the PCSC process based on the DES model and validated based on a PC project experiment. In this case, the manufacturer could save 52% on penalties in the PCSC process, while the contractor can improve performance by reducing 77% of idle work with the optimal decision. Finally, to consider both manufacturer penalties and construction performance, we suggest using the 1day-4batch decision for maximum benefit and the 2day-2batch decision for safety.

This study analyzed the impact of different JIT strategies that included offsite inventory levels and batch delivery decisions in the PCSC process for use in decision making. Specifically: (1) The DES model was created as a tool to help manufacturers predict outcomes and select a decision based on their objectives (construction performance improvement or penalties reduction or both); (2) There was clearly a substantial interaction between offsite inventory and batch delivery in the PCSC process; (3) The approach generated more evidence and considered a range of scenarios to determine the best JIT application that should encourage manufacturers to apply JIT to improve cost benefits and performance.

Suggestion: future work could investigate using an influence diagram or decision tree to show the consequences and errors of different decisions for the manufacturer to select from.

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