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BUFFERING POLICIES FOR PREFABRICATED CONSTRUCTION SUPPLY CHAIN SUBJECT TO MATERIAL LEAD TIME AND ACTIVITY DURATION UNCERTAINTIES

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Abstract. Supply chain management plays a pivotal role in the smooth execution of prefabricated construction. One key aspect involves strategically placing and sizing buffers to handle uncertainties (e.g., stochastic material lead-times and activity durations) within the prefabricated construction supply chain (PCSC). This study examines three buffering policies based on varying combinations of time and inventory buffers to mitigate stochastic material delays and activity prolongs in PSCS, namely, pure inventory buffering policy, pure time buffering policy, and mixed inventory-time buffering policy. To enable this analysis, we characterize how stochastic material delays originating from off-site supply chains impact project schedules, and then develop mathematical procedures for sizing inventory and/or time buffers under the three buffering policies. Case application and numerical analysis are conducted to investigate the performance of these buffering policies and the impact of the project characteristics on them (e.g., due date and arrival rate). Finally, insights are extracted to assist managers in choosing appropriate policies for projects with different characteristics. In general, combining inventory and time buffers results in better performance, particularly under tight project deadlines and high arrival rates. The pure time buffering policy can also be a viable option in specific situations, allowing managers to have more choices.

Keywords: prefabricated construction, supply chain management, time buffer, inventory buffer, uncertainty.

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1. Introduction

Over the last few years, industrialized construction (IC) has been rapidly developing and evolving. IC revolutionizes the traditional construction methods by implementing off-site mass production, leading to increased safety, cleanliness, energy efficiency, and environmental conservation in the industry (Ekanayake et al., 2020; Liu et al., 2018; Wang et al., 2020). Under the trend of IC, projects are characterized by standardized processes and supply chains of prefabricated materials, e.g., prefabricated housing (Xu & Zhao, 2010). However, the success of these projects critically depends on the prefabricated construction supply chain management, which encompasses both project and supply chain operations. PCSC plays a key role in connecting construction sites and off-site factories (Wang et al., 2019).

However, PCSC still faces turbulence and disruptions due to uncertainty and fragmentation. Generally, there are various possible causes for uncertainty in PCSC, such as stochastic activity durations and material delays: 1) Stochastic activity durations usually stem from inaccurate time estimates, bad weather conditions, and other factors. They may result in changes in the starting times of subsequent activities and lead to additional costs due to required subcontractor flexibility and due to schedule nervousness (Lambrechts et al., 2011). Recent studies have investigated robust project scheduling with stochastic activity durations (Bruni et al., 2017; Chakrabortty et al., 2017; Fu et al., 2015; Ning et al., 2017). 2) Random material delays are also prevalent in PCSC due to stochastic lead times, where the processing times at the producer and fabricator are stochastic, delaying the delivery of prefabs beyond the due date. Such delays could result in significant waiting periods and affect project stability and duration. It is confirmed by an investigation of time waste in construction, which reveals that the site workforce spends a considerable amount of time waiting for approval or for materials to arrive on site (Yeo

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& Ning, 2002). Wambeke's et al. (2011) case study research shows that material delay is one of the key causes of low-frequency/high-severity variation and black swans in the construction industry. Past research has identified similar situations in Brown et al. (2004), Elfving et al. (2010), Walsh et al. (2004), and Zhai et al. (2019a, 2019b).

Buffers are regarded as the most effective method of managing uncertainties. Buffers fall into five categories: inventory, time, capacity, plan, and financial buffers (Ballard & Howell, 1995; Tommelein et al., 2009; Tommelein, 2020; Russell et al., 2013). Inventory and time buffers are the most commonly used tools for addressing potential disruptions during project execution, such as stochastic material delay and activity prolong. Research has extensively employed time buffers to enhance project stability and duration no matter the type of uncertainty. It is pretty easy to understand. Various uncertainties, including the stochastic material delays originating from the off-site supply chains, can eventually be propagated to the on-site project network. Inserting time buffers into the on-site project network can effectively accommodate them. Nonetheless, it may extend the project makespan and result in idle time and wasted resources (such as workforce and equipment) (Lu et al., 2018). In the case of stochastic material delays, implementing inventory buffers or a combination of inventory and time buffers would be a more efficient solution, as it reduces idle time in the project schedule network. However, the applicability and effectiveness of time and inventory buffers in PCSC have not been adequately assessed and evaluated to date.

Given the above background, this study investigates three buffering policies to address stochastic material delays and activity durations in PCSC: the pure inventory buffering policy, pure time buffering policy, and mixed inventory-time buffering policy. As the name suggests, under the pure inventory buffering policy, only inventory buffers will be deployed to respond to uncertainties. Similarly, the pure time buffering policy will only deploy time buffers. Whereas, the mixed inventory-time buffering policy with deploy both inventory and time buffers simultaneously. Then the following work will be carried out regarding these three buffering policies: 1) investigating the mathematical relationship between material supply delays and schedule deviations and developing models and procedures to strategically locate and size the inventory and/or time buffers under these buffering policies; 2) making inter-policy comparisons and identifying the most appropriate policies for the projects with different characteristics. This study fills the gap related to the quantitative performance evaluation and comparison between different buffering policies and provides insights for effective buffer management in PCSC.

The rest of this paper is structured as follows. The paper first offers the "Literature review" section. Then, the "Problem statement" section illustrates the practical problem of buffering decisions. The "Assumptions" and "Models and procedures for alternative buffering policies" sections introduce the assumptions, mathematical models and procedures for the three buffering policies. The "Model validation and numerical analysis" section covers performance validation and comparisons. Finally, the "Discussion" and "Conclusions" sections are presented.

2. Literature review

2.1. Uncertainties in PCSC

Han et al. (2022) conducted an overall review of PCSC and analyzed keyword co-occurrence of the related research. It showed that the total link strength and co-occurrence times of "Uncertain" are very high and rank very high among all keywords. Uncertainties in PCSC could be further divided into demand uncertainty (Zhai et al., 2018), material delivery and logistics uncertainty (Hsu et al., 2018; Liu & Lu, 2018; Xu et al., 2016), operational and productivity uncertainty (Hsu et al., 2017, 2019), due date uncertainty (Kim et al., 2020), labor force and equipment reliability and availability uncertainty, work and jobsite conditions uncertainty, etc. However, most of the previous studies that mention uncertainty mainly focus on the topics of supply chain optimization (e.g., production scheduling, logistics planning, and reverse logistics network design), rather than grasping the comprehensive impacts of all uncertainties and how to cope with them. Research towards positioning buffers to hedge against uncertainties in PCSC is limited. Zhai et al. (2018, 2019a, 2019b) investigated the buffer space hedging issue in PCSC and developed several mechanisms to enables win-win coordination between the building contractor and logistics provider towards buffer space hedging decisions. However, the series of studies only considers prefabs supply uncertainties and adopts only one type of buffers. In this research, we focus on both the uncertainties stem from the off-site factories and construction sites, i.e., material supply uncertainty and activity duration uncertainty. Meanwhile, various forms of buffer technologies will be used to deal with these uncertainties.

2.2. Time buffer

Time buffers are widely investigated in two fields, i.e., Critical Chain scheduling and Buffer Management (CC/BM) and robust project scheduling.

In the well-known CC/BM approach, time buffers are utilized as part of the time required to perform tasks (Goldratt, 1997). Time buffers within activities are then relocated to the end of the critical chain and noncritical chains to form the project buffer and feeding buffers, respectively. Notably, CC/BM has emerged as one of the most prominent project management tools. Several methods have been proposed to determine the sizes of the project buffer and feeding buffers, such as the cut and paste method (C&PM) (Goldratt, 1997), root square error method (RSEM) (Newbold, 1998), probabilistic-based method (Poshdar et al., 2016), resource reliability analysis (Zarghami et al., 2020), failure mode and effects analysis

(FMEA) (Zohrehvandi & Khalilzadeh, 2019), network decomposition method (She et al., 2021), brittle risk entropy (J. L. Peng & C. Peng, 2022), and data driven method (Li et al., 2022).

Furthermore, extensive research on time buffer sizing has been conducted in the area of robust project scheduling. Unlike CC/BM, these studies propose procedures to scatter time buffers in front of each activity (Herroelen & Leus, 2004; Leus, 2003), which are primarily employed to absorb project uncertainties that may lead to changes in the starting times of activities. The scattered time buffers guarantee the starting time of each activity and enhance schedule robustness, particularly when addressing uncertain activity durations (Bruni et al., 2017; Chakrabortty et al., 2017; Moradi & Shadrokh, 2019), resource disruptions (Chakrabortty et al., 2016; Lambrechts et al., 2011), and rework risks (Zhu et al., 2021). In the present study, this type of scattered time buffer will be used. Solving the time buffer sizing problem for robust scheduling depends on measuring the impact of uncertainty on the project schedule and assessing the project schedule's robustness. The former varies depending on the uncertainty factors considered, with a prominent method for modeling the impact of resource breakdowns on an activity's actual duration proposed by Lambrechts et al. (2011). The latter can be measured by the sum of the weighted instability costs of all activities (Herroelen & Leus, 2004; Leus, 2003) or other surrogate measures developed to improve computational efficiency, such as starting time criticality (STC) (Van de Vonder et al., 2008; Liang et al., 2020), float index (Zahid et al., 2019), or the slack utility function of each activity (Ma et al., 2019). Besides, Poshdar et al. (2018) proposed a multi-objective probabilistic-based buffer allocation method (MPBAL) to determine the optimum allocation of time buffers in the construction schedule. Zarghami and Zwikael (2023) developed a three-step method to allocate time buffers by simultaneously considering the e probability and impact of disruptions. It also incorporated a key attribute of project complexity (i.e., the interconnectedness between project activities) into the process of buffer allocation.

2.3. Inventory buffer

Besides, several researchers studied the inventory buffer issues in construction projects. Ballard and Howell (1994, 1998) investigated the impact of inventory buffers on project variability, whereas Horman and Thomas (2005) analyzed the role of inventory buffers in labor performance. Tommelein et al. (2009) summarized the various functions of inventory buffers in the construction supply chain. Under the trend of IC, with mass production and prefabricated items developed in off-site supply chains, the effect of inventory buffers on project variability and labor performance rises in prominence. However, the inventory levels are usually manually in the studies related to construction supply chain analysis and optimization, such as Pan et al. (2011) and Liu and Tao (2015). Only a few studies have investigated quantitative methods for inventory sizing issues, such as Walsh et al. (2004), who developed a strategic inventory location model to align with material demand in a capital project supply chain. Similarly, Lu et al. (2016) developed a procedure for determining the inventory levels of construction materials under nonstationary stochastic material demand and supply yield.

The term "inventory buffer" in the manufacturing industry is commonly referred to as safety stock, which serves as a crucial tool for hedging against uncertainties or risks arising from demand (Thevenin et al., 2021), lead time (Ben-Ammar et al., 2019), supply yield (Chaturvedi & Martínez-de-Albéniz, 2016), production disruption (Strohhecker & Größler, 2019), and so on. Currently, there are two principal methods for determining the appropriate level of safety stock: the guarantee service-time approach and the stochastic service-time approach (Schoenmeyr & Graves, 2022). The guarantee service-time approach assumes certain service or delivery times provided by a supplier to their downstream customers, while the stochastic service-time approach accounts for material availability at the supplier stage and assumes stochastic service. In this study, we will use the stochastic service-time approach because of the stochastic delay caused by stock-out and/or unpredictable processing times, making the guarantee approach impractical. However, all of these works focus on the material supply chain operations without considering the project scheduling and their interactions. Specifically, the literature focuses on establishing mathematical relationships between stochastic supply delays and customer demand service levels. When this approach is applied to dimensioning the safety stock of PCSC, additional issues need to be examined, such as the impact of stochastic supply delays on the project schedule.

2.4. Comparison of inventory and time buffers

Although both time and inventory buffers function as a safeguard against uncertainties, there are significant distinctions between the two. Horman (2000) emphasized that while the time buffer is highly responsive, it is also significantly expensive despite its utilization. Conversely, the inventory buffer is comparatively less responsive and less costly, as it can be easily repurposed if not needed. Additionally, Horman and Thomas (2005) and Lu et al. (2018) pointed out that the inventory buffer can maintain continuous operational flow, even if it encounters challenges at previous stages. On the other hand, the time buffer ensures the start time of the following stages is independent of ground conditions. Both the inventory and time buffers have their respective advantages and disadvantages, and in certain cases, they can complement each other. In some contexts, the time buffer may be more applicable, while for others, the inventory buffer may be preferable, or a combination of both may be optimal.

2.5. Research gap and motivation

Previous research has extensively examined the use of inventory and time buffers. However, according to the authors' knowledge, less research effort has been dedicated to the following issues:

1) Based on time and inventory buffers, a variety of forms of buffering policies can be formed, including the pure inventory buffering policy, pure time buffering policy, and mixed inventory-time buffering policy (see "Problem statement" section for details). However, most studies only focus on the pure time buffering policy and do not pay attention to comparative analysis between the different buffering policies. To fill the gap, mathematical models and procedures will be proposed for the three buffering policies. Further analysis will also be conducted to compare their effectiveness.
2) Current buffer evaluations and comparisons are chiefly qualitative, providing restricted information about the most suitable buffering policy. It is, therefore, crucial to differentiate between inventory and time buffers quantitatively. This analysis aims to evaluate and compare the performance of inventory and time buffers in terms of project schedule robustness and inventory holding costs. It further intends to identify the appropriate buffering policies for projects with diverse characteristics.

3. Problem statement

Figure 1 illustrates the general structure of the PCSC, including both the on-site project network and off-site supply chains. The on-site project network denotes a type of recurrent projects which are similar in schedule and resource requirements. Simultaneously, projects arrive in a probabilistic manner, and the duration of each activity is also subject to stochasticity. Furthermore, particular activities require prefabricated units that are provided by off-site supply chains. Specifically, activity i requires prefabricated units that supplied by the K_i-stage serial supply chain i. Activity i can only commence after the relevant prefabricated units arrive on-site and the immediate predecessors are completed. However, the processing time at each supply chain stage is uncertain. The stochastic material delays and activity durations frequently disturb the project schedule, e.g., deviation between the initial schedule and the realized schedule. Motivated by this observation, this study focuses on the time and inventory buffers that accommodate uncertainties of material supply and activity duration.

As illustrated in Figure 2, two crucial choices need to be made to improve the initial schedule's robustness. First, given the initial schedule, one has to decide whether to place inventory buffers in the off-site supply chains. Next, it has to decide whether to insert time buffers in front of activities. This corresponds to different buffering policies, i.e., no any buffers, pure inventory buffering policy, pure time buffering policy, and mixed inventory-time buffering policy. Among them, the pure time buffering policy is most commonly used in previous studies, while other policies are rarely mentioned. Having decided upon these policies, further analysis is required to determine how to strategically position and size the inventory and/or time buffers to improve the project schedule's robustness. This includes identifying the supply chain stages that require inventory buffers and determining the optimal quantity to hold, as well as deciding how many time units to insert before each activity. Importantly, appropriate buffering policies must be identified for projects with diverse characteristics.

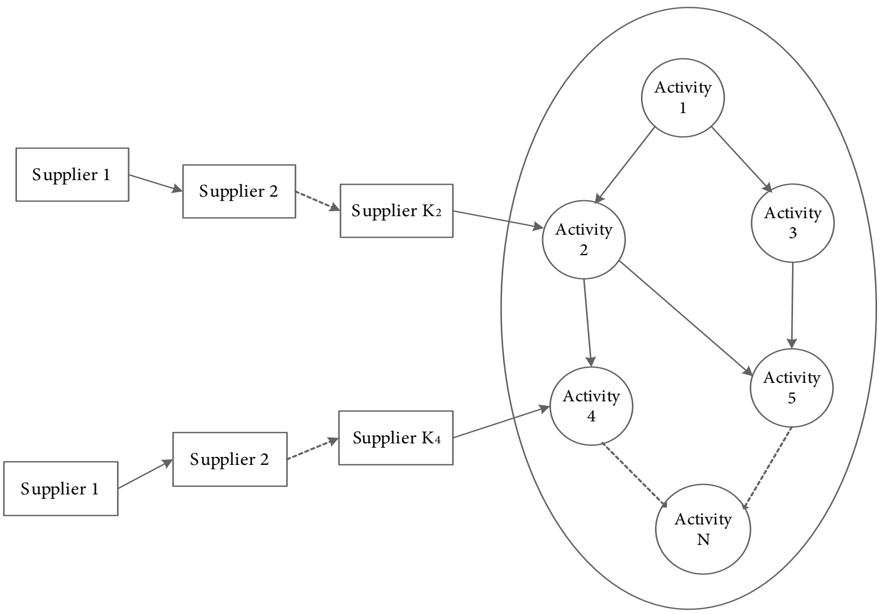

Figure 1. Prefabricated construction supply chain

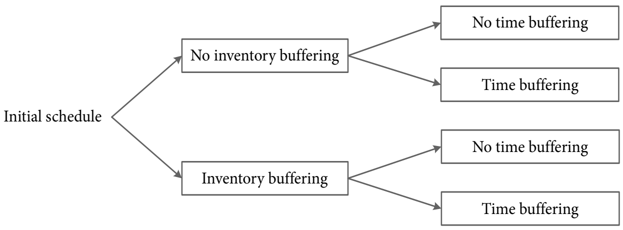

Figure 2. Buffering policies

4. Assumptions

This section makes the following assumptions on the on-site project network and off-site supply chains, as well as their interface, according to observations in practice and mathematical simplification requirements:

1) On-site project network. (i) The on-site project network is depicted using the activity-on-node representation: the digraph $G = (N, A)$ contains a set of nodes N and a set of arcs A. The nodes represent the activities constituting the project, whereas the arcs represent the finish-start, zero-lag precedence relations. $(i, j) \in A$ denotes that activity i (i = 1, ..., N) is an immediate predecessor of activity j. (ii) The arrival rate of projects follows Poisson distribution and the stochastic duration δ_i of any activity i follows logarithmic normal distribution. This distribution function is widely used to model uncertain activity duration, such as Herroelen and Leus (2001) and Tukel et al. (2006). The corresponding parameters can be obtained through historical data or expert knowledge, or a combination thereof. (iii) The project also has a planned deadline T, which is often set at the minimal project make span in the deterministic environment increased with a deadline factor α. The deadline factor is usually chosen by the project manager towards the trade-off between project stability and project duration (Van de Vonder et al., 2005).
2) Off-site supply chains. (i) All the off-site supply chains are serial-line structures. The kth (k = 1, 2, ..., K_i) stage in supply chain i is denoted as stage ik. In construction projects, the most expensive prefabs are precast concretes and steel components. Their supply chains usually consist of two or three serial-line stages. For instance, the fabricated steel structure supply chain consists of a producer (manufacture standardized shapes), service center (serve as a warehouse before fabricator), and fabricator (customize the structural steel according to engineering drawings). (ii) Each stage in the supply chains operates under a periodic review base-stock policy. The base-stock level at stage ik is represented as B_{ik}. This assumption is based on the fact that material procurement in construction projects is usually formulated as a fixed-ordering period (FOP) system, i.e., replenishing the inventory at the beginning of fixed intervals when new orders are acquired to cover the demand for the succeeding intervals (Said & El-Rayes, 2010). This is equivalent to employing the base-stock replenishment policy, and the corresponding ordering period may be one week or month, depending on the production and transportation capacity of the supplier and the granularity of material planning. (iii) The lead time L_{ik} (includes any waiting time, manufacturing time, and transportation time) at stage ik is stochastic. This assumption is true as the shortages of raw materials, machine failures, and unskilled operation occurre from time to time. Meanwhile, the probabilistic parameters of the lead time can be obtained through historical data or expert knowledge, or a combination thereof.
3) Interface between on-site project network and off-site supply chains. For any supply chain i, delivery is made as soon as inventory becomes available in all stages except the last one iK_i where no early delivery can be made to projects on-site. This assumption is based on the fact that the project sites usually have limited space. Accordingly, prefabricated units are not expected to arrive early.

5. Models and procedures for alternative buffering policies

5.1. Pure inventory buffering policy

To set correct inventory buffer sizes, it first needs to describe how stochastic material delays originating from off-site supply chains are calculated. Beforehand, the service time Δ_{ik} at each stage ik is introduced. It refers to the time elapsed between the downstream stage placing an order to the upstream stage and the upstream stage delivering the order to the downstream stage (Graves & Willems, 2003). Each stage quotes a service time to its adjacent downstream stage. Due to the stochastic lead time, the service time at each stage is also stochastic. According to the general procedure developed by Hausman et al. (1998), Zipkin (2000), and Xu et al. (2016), for the kth stage in supply chain i, when k = 1, the probability $RL_{ik\tau}$ that demand $d_i(t)$ (demand of prefabricated unit i at period t) is satisfied within τ periods can be expressed as

$$RL_{ik\tau} = \sum_{L_{ik}} \Pr\left\{B_{ik} - D_i\left(L'_{ik} + L'_{i0} - \tau + 1\right) \geq 0\right\} \Pr\left\{L_{ik} = L'_{ik}\right\} \Pr\left\{L_{i0} = L'_{i0}\right\}. \quad (1)$$

When $k \geq 2$, $RL_{ik\tau}$ can be expressed as:

$$RL_{ik\tau} = \sum_{\Delta_{ik-1}} \sum_{L_{ik}} \Pr\left\{B_{ik} - D_i\left(L'_{ik} + \Delta'_{ik-1} - \tau + 1\right) \geq 0\right\} \Pr\left\{L_{ik} = L'_{ik}\right\} \Pr\left\{\Delta_{ik-1} = \Delta'_{ik-1}\right\}. \quad (2)$$

Prefabricated unit demand is derived from activities in a randomly arrived project. Of course, $d_i(t)$ is stochastic. $D_i(\eta)$ in Eqns (1) and (2) represents the total demand of prefabricated unit i over periods from t to $t + \eta$ if $\eta \geq 0$, and $D_i(\eta) = 0$ if $\eta < 0$.

Actually, $RL_{ik\tau}$ is the probability that $\Delta_{ik} \le \tau$. Consequently, the service time Δ_{ik} at stage ik can be expressed as:

$$\Pr\left\{\Delta_{ik} = 0\right\} = RL_{ik0}; \quad (3)$$

$$\Pr\left\{\Delta_{ik} = \tau\right\} = RL_{ik\tau} - RL_{ik\tau-1},\ \tau \ge 1. \quad (4)$$

With the service time, the relationship between the project schedule and supply plan can be described. An activity can start only after three conditions are met. That is, the planned starting time has been met, immediate predecessors have been completed and required prefabricated units have been supplied to the site. Hence, the actual starting time s_i' of activity i can be expressed as:

$$s_i' = \max_{j \in P_i}\left(s_i, s_j' + \delta_j', \Delta_{iK_i}\right). \quad (5)$$

Equation (5) reveals two approaches to prevent the deviation of the planned starting time and actual starting time of activity i. The first one is inserting a time buffer before activity i to prevent the completed time of activity j exceeds the planned starting time s_i. The second is holding inventory buffers in supply chain i to prevent the service time Δ_{iKi} at K_ith stage exceeds s_i. But this, of course, may cause inventory holding costs.

For stage ik, when k = 1, the inventory level under steady state can be expressed as:

$$IH_{ik} = E\left|B_{ik} - D_i\left(L_{ik} + L_{ik-1} + 1\right)\right|^{+}. \quad (6)$$

When $2 \le k \le K_i - 1$, IH_{ik} can be expressed as:

$$IH_{ik} = E\left|B_{ik} - D_i\left(L_{ik} + \Delta_{ik-1} + 1\right)\right|^{+}. \quad (7)$$

When $k = K_i$, IH_{ik} can be expressed as:

$$IH_{ik} = E\left|B_{ik} - D_i\left(L_{ik} + \Delta_{ik-1} + 1\right)\right|^{+} + d_i \cdot \left|s_i' - \Delta_{ik}\right|^{+}. \quad (8)$$

Assume that the inventory holding cost at each stage is h_{ik} per unit per period. When deciding the sizes of inventory buffers, the corresponding inventory holding costs need to be taken into account. Although holding abundant inventory can guarantee immediate availability of all prefabricated units and improve the robustness of the project schedule, it may be very costly and not wise. To this end, further analysis is needed to learn to strategically locate and size the inventory buffers so as optimally balance the robustness of the project schedule and the inventory holding costs. The corresponding multi-objective inventory buffering model (P1) is formulated as follows:

$$\text{(P1)}\ \min \sum_{i=1}^{N} w_i \cdot E\left|s_i' - s_i\right|; \quad (9)$$

$$\min \sum_{i=1}^{N}\sum_{k=1}^{K_i} h_{ik} \cdot IH_{ik}; \quad (10)$$

s.t. Eqns (1)–(8):

$$s_i' + \delta_i' \le s_j',\ \left(i, j\right) \in A; \quad (11)$$

$$\sum_{i \in busy_t} r_{il} \le RA_l,\quad \forall l, \forall t; \quad (12)$$

$$\Pr\left(s_N' \le T\right) \ge \gamma. \quad (13)$$

Equation (9) denotes the objective of minimizing the expected weighted instability costs, in which w_i is the instability weight of activity i, s_i and s_i' denotes the planned starting times and real starting times. Generally, w_i, represents the marginal cost of the deviation of activity i. Equation (10) denotes the objective of minimizing the expected inventory holding cost. Specifically, these two objective functions are both calculated by simulation. As stated by Lambrechts et al. (2008), the analytic evaluation of the schedule instability cost objective function is very cumbersome. The easiest and most reliable way to estimate the quality of a schedule with respect to the weighted instability cost objective function is by using simulation (Lambrechts et al., 2011). Based on the Eqns (1)–(8), the parameters $RL_{ik\tau}$, Δ_{ik}, s_i', IH_{ik} can be simulated from the described probability functions and used to calculate the average inventory holding cost. Besides, Eqn (11) denotes the sequence constraints of activities, where δ_i' is the realization of the stochastic duration δ_i of activity i. Equation (12) implies that for each period t and each resource type l (l = 1, 2, ..., L) the sum of the resource requirements r_{il} of the activities that are in progress during period t ($busy_t$) cannot exceed the availability RA_l. Equation (13) is the project deadline constraint. It implies the probability that a project ends within the projected deadline T, i.e., timely project completion probability, must be greater than a given threshold γ. Minimizing expected instability without exceeding the deadline constraint is widely acknowledged.

The decision variables in this model are the base-stock levels BS_{ik}, which indicates the inventory buffers at each stage. For this multi-objective problem, the ε-constraint method is utilized to identify the trade-off solutions. It transforms the problem into a mono-objective optimization problem with additional constraints. Specifically, the objective function with high priority is reserved as the objective function, while others are transformed as constraints by using a constraint vector ε. Specifically, in model P1, Eqn (9) remains the objective, while Eqn (10) is transformed into a constraint. By changing the value of ε, the trade-off surface of P1 is obtained. To this aim, the genetic algorithm (GA) is adopted to solve the transformed inventory buffering model. The GA is an excellent choice due to its wide application in construction supply chain analysis and optimization, such as procurement and storage (Said & El-Rayes, 2010) and inventory replenishment and allocation (Lu et al., 2018).

In this study, the procedure for inventory buffering using the ε-constraint method and GA is depicted in Figure 3. A pre-defined constraint vector ε is selected, and the GA process is initiated to search for optimal base-stock levels. A penalty function approach is employed to handle inventory holding cost, project deadline, and other constraints, aiding in the fitness evaluation of each individual. Once the intermediate GA process is complete, the next value in ε is considered. If the constraint vector ε is already traversed, the procedure is terminated. The set of efficient solutions identifies the trade-off surface or Pareto front of P1.

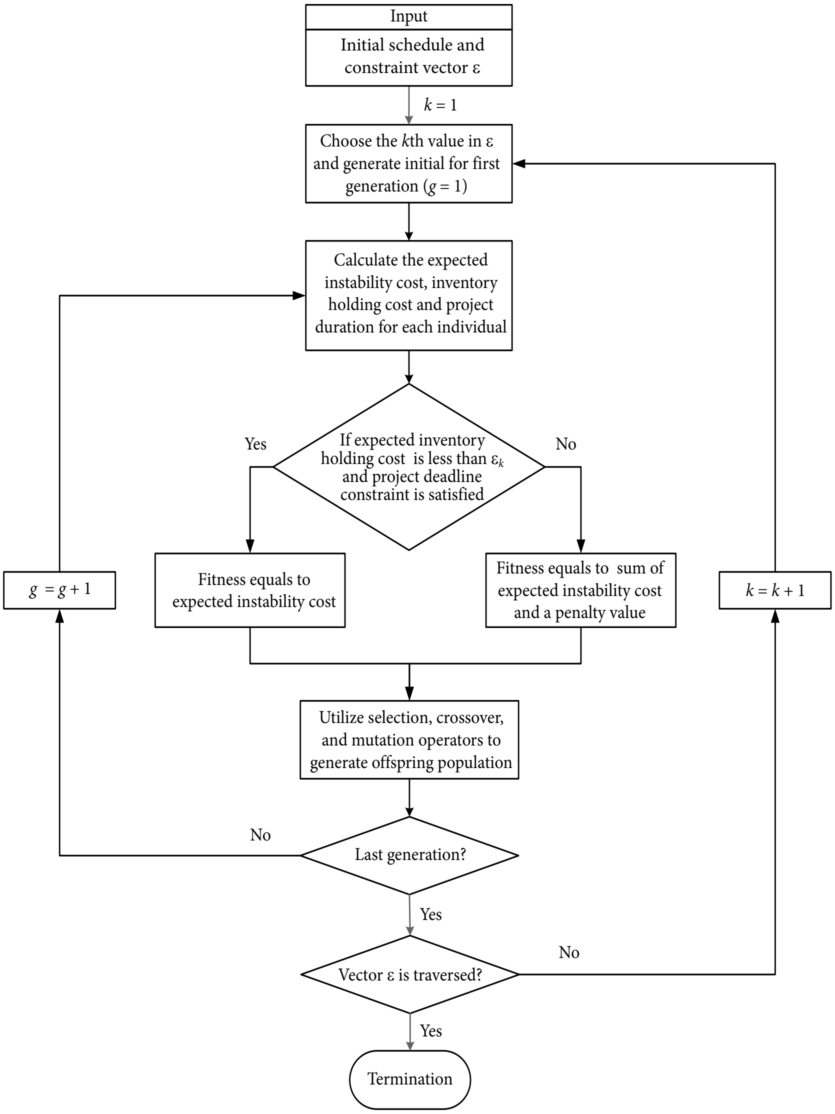

Figure 3. Inventory buffering procedure using ε-constraint method and GA

5.2. Pure time buffering policy

Although not explicitly stated, the pure time buffering policy has always been used most commonly. A great deal of research and project practices responds to uncertainties with time buffers rather than other forms of buffers. Under this policy, the objective is to strategically insert a time buffer of size TB_i in front of the starting times s_i of each activity i. The pure time buffering problem can be formulated as a single-objective optimization model, given that it only minimally affects inventory holding costs. This corresponds to a new transformation of the P1 model, in which Eqn (10) is dismissed as neither the target function nor the constraint. The decision variables are now defined as the time buffer of TB_i in front of each activity i, rather than the base-stock levels B_{ik}.

In order to set correct time buffer sizes TB_i for each activity i, it needs to have a rough idea of how critical its starting time is in the current schedule. The starting time criticality (STC) has been first introduced by Van de Vonder et al. (2008) as a metric for measuring the criticality of each activity and their requirements towards time buffers. It exploits information about the instability weights of the activities and the probability distributions of their starting time. If the predicted finish time of the considered predecessor or the service time of the last stage in supply chain i exceeds the planned starting time of activity i, it can be expected that there is a reasonable chance that activity i will be disrupted. On this basis, the starting time criticality STC_i of activity i can be approximated as:

$$STC_i = w_i \cdot \Pr\left(s_i' > s_i\right) = \sum_{j \in P_i} w_i \cdot \left[1 - \Pr\left(s_j + \delta_j + \left|\Delta_{jK_j} - s_j\right|^+ \le s_i\right)\right] \cdot \left[1 - \Pr\left(\Delta_{iK_i} \le s_i\right)\right], \quad (14)$$

where $s_j + \delta_j + |\Delta_{jKj} - s_j|^+$ approximatively denotes the finish time of the considered predecessor j. Of course, this is a simplification of reality, but taking the duration prolongs of the predecessors of activity j and their own predecessors into account would greatly complicate the results. By contrast, given a certain schedule S and base-stock level BS_{ik} in the supply chains, STC_i can be easily estimated based on Eqn (14).

The time buffers are now iteratively inserted by using the STC heuristic as shown in Figure 4. The activities are sorted into a list, based on their STC_i, in a descending order (in case of a tie, the criterion is the lowest number). The first activity in the list is shifted rightward by a single time unit, and the activities affected due to schedule precedence are adjusted accordingly. If the resulting schedule exhibits an improvement in robustness (i.e., the sum of total STC_i decreases) and succeeds in meeting the deadline constraint, it serves as the input schedule for the next iteration. If not, the next activity in the list is considered. When no such movement can be found, the procedure is terminated. Specifically, the measure of schedule robustness used in this procedure is the sum of the starting time criticality of each activity. As demonstrated by Lambrechts et al. (2011), this is a high-performing surrogate of robustness measures. It is easy to calculate and saves computation time.

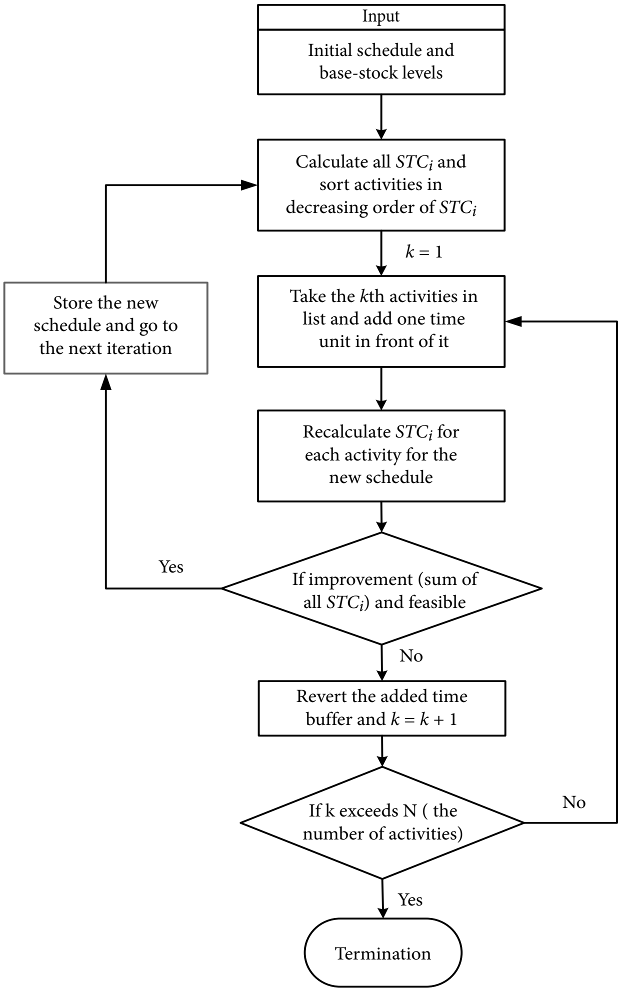

Figure 4. Time buffering procedure using STC heuristic

5.3. Mixed inventory-time buffering policy

Under this mixed policy, it needs to determine the location and size of both the inventory and time buffers to optimally balance the schedule robustness, due date, and inventory holding costs. The formulation of this problem is very similar to that of the P1 model, except for the decision variables. The decision variables of the current model are the base-stock levels BS_{ik} and the time units TB_i in front of each activity i. Meanwhile, a hybrid meta-heuristic algorithm is proposed to solve this problem. As shown in Table 1, it consists of two optimization levels: an outside search level and an inside search level. The outside search adopts the inventory buffering procedure sing ε-constraint method and GA as described in the subsection of "Pure inventory buffering policy" (also shown in Figure 3). It utilizes the ε-constraint method to transform the multi-objective problem into a mono-objective problem and then the GA to search for the best base-stock levels. When a new solution of base-stock levels is searched, the inside search is called to find its best time buffer allocation scheme based on the time buffering procedure using STC heuristic as described in the subsection of "Pure time buffering policy" (also shown in Figure 4). The arrangement of two search levels is beneficial to reduce the computation time. Because the inside search procedure needs to be called several times, the calculation time of the inside search procedure is expected to be less. Due to the population generation, crossover, mutation, and other operations, the inventory buffering procedure using ε-constraint method and GA is more computationally intensive than the time buffering procedure using STC heuristic. If the inventory

Table 1. Procedure for mixed inventory-time buffering

Population initialization (base-stock levels) at random
Call Inside search (Time buffering procedure using STC heuristic):
Search to find the best time buffer allocation scheme for the solution
Calculate the fitness of the solution and transfer it to Outside search
Call Outside search (Inventory buffering procedure using ε-constraint method and GA):
Execute steps below until the stopping condition is met:
Receive the outcome of the Inside search
Create and search for better solutions
Call Inside search

buffering procedure is placed in the inside search level and the time buffering procedure is placed in the outside search level, then the GA will be called repeatedly and time-consuming. In contrast, if the time buffering procedure is placed in the inside search level and the inventory buffering procedure is placed in the outside search level, then the GA will be called only once and the computation time will be much smaller.

6. Model validation and numerical analysis

6.1. Case background

This part aims to validate the buffering policies and models through a real-world example initially introduced by Xu et al. (2016) and Shah and Zhao (2009). A construction management company (Intercontinental Construction Management (ICM) Inc.) specializes in constructing and renovating military buildings. Their most projects have similar schedules and resource requirements. Some data (e.g., planned task duration, standard project schedule, supply chain structure) used here are directly from the public reports, while others are deduced from a broader perspective. They do not affect the applicability of the model, and in practice, users are free to determine these inputs according to their own experience and knowledge.

Specifically, the standard project schedule consists of 22 tasks. For simplicity, we set Task 5 (where the structural steel is required) as the cut-off point: all activities prior to Task 5 are group as activity 0, Task 5 and its immediate successors as activity 1, and all subsequent activities as activity 2. Accordingly, their expected durations are 6, 5, and 13 weeks, respectively. The duration deviation of these three activities is set to 0.1, and the instability weights are assumed as the number of tasks involved in each, i.e., 4, 5, and 13. The instability weight of activity 2 is much larger than the others to reflect that meeting the deadline is often more important than the planned activity starting times. Of course, these instability weights can be quantified using for example the computer-supported risk management system by Schatteman et al. (2008).

Besides, the fabricated structural steel needed by activity 2 is the most expensive material in these projects. As illustrated by Figure 5, the structural steel supply chain consists of three stages, i.e., producer (manufacture standardized shapes), service center (serve as a warehouse before fabricator), and fabricator (customize the structural steel according to engineering drawings). The lead times for each stage are 3–5 weeks, 1 week, and 1–2 weeks, respectively. Inventory buffers can only be kept at the service center in the form of standardized shapes, as holding customized steel before the project is awarded can be quite risky. The annual inventory holding cost is $ 199.2 per ton per year. Taking the project's arrival time as a reference, the planned start times of the three activities are 1st week, 7th week, and 12th week. The structural steel is slated to be delivered at the beginning of the 7th week.

Here three values for the project arrival rate are considered, which are 0.5 for a sluggish market demand, 1 for moderate market demand, and 1.5 for a booming market demand. Meanwhile, three project deadline factors are considered, which are 10% for a tight deadline setting, 15% for a moderate deadline setting, and 20% for an ample deadline setting.

6.2. Model validation

Various validation methods have been developed for models, such as trace, graphics, face validation, comparison with recognized results or realistic data, and conceptual validation methods (Browne, 2000; Huber, 2010; Sargent, 2013). This paper will focus on two specific aspects of model validation: (1) comparing the performance of the proposed buffering policies against the unbuffered case regarding schedule stability and inventory holding cost, and (2) observing the actual start times of activities when executing the proposed buffering policies by simulation-based trace.

Figure 6 illustrates the approximate trade-off surfaces of the three buffering policies and the results of the unbuffered case when given a 10% deadline factor and a 1 project arrival rate. Similar results are presented in Table 2, with the unbuffered case serving as a benchmark for the validation of the buffering policies and models. Among all instances, the unbuffered case resulted in the highest schedule instability cost of 11.01. In contrast, the three buffering policies significantly reduced the schedule instability costs. For example, the pure time buffer strategy could reduce the schedule instability cost to 7.17 while maintaining a comparable inventory holding cost of 4212.

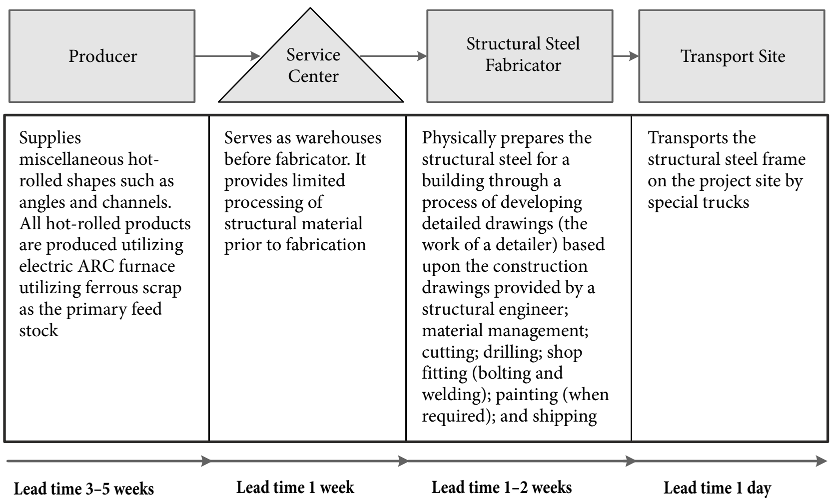

Figure 5. The structural steel supply chain (Xu et al., 2016; Shah & Zhao, 2009)

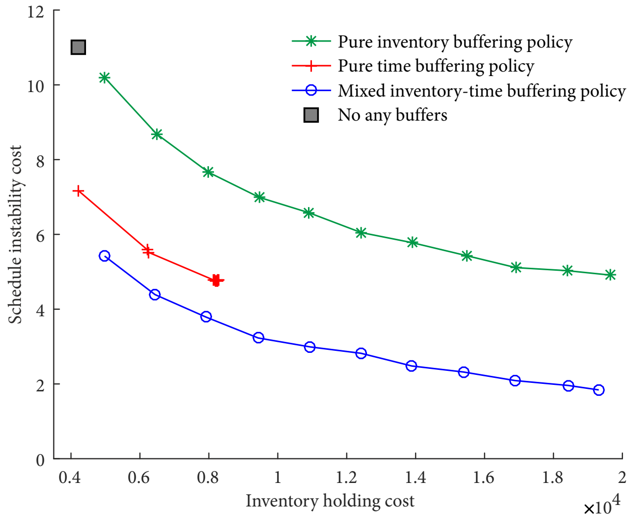

Figure 6. Approximate trade-off surfaces of the three buffering policies

The mixed inventory-time buffering policy could even lower the schedule instability cost to 1.84. These findings indicate that the three buffering policies, models, and procedures can effectively improve schedule stability. The extent to which they achieve this goal is primarily dependent on the project deadline constraint and the inventory holding cost that users are willing to bear. Enhancing schedule stability is generally advantageous for workforce and equipment planning, yielding numerous benefits for the project. The high inventory holding cost required to achieve schedule stability is a worthwhile investment.

The three buffering policies and models are further verified through a simulation trace of the actual start time of the activities, as given in Figure 7. This figure shows statistical descriptors of the actual start time of activities 1 and 2, including the time fluctuation range that represented by the width of the boxes. It can be intuitively found that the time fluctuation range of the two activities under the unbuffered case is very large. In contrast, because of the positioned time or/and inventory, the time fluctuation range of the two activities is significantly reduced. Generally, a large range of time fluctuation usually means less schedule stability, and vice versa. These results demonstrate that reasonable use of the three buffer policies can effectively make the actual start time of activities as close as possible to the planned start time, and ensure the stability of the schedule.

6.3. Interpolicy comparisons

In this subsection, to make detailed comparisons of the three buffering policies, an extensive numerical study is conducted with respect to the project parameters, such as project arrival rate and deadline factors.

Firstly, we review the results in Figure 6 and Table 2. In comparison to the pure inventory buffering policy, it is evident that the trade-off surface of the mixed inventory-time buffering policy is unequivocally shifting downwards. Under the arbitrary value of ε, the inventory holding cost of the mixed inventory-time buffering policy is almost the same as the pure inventory buffering policy; however, its schedule instability cost is remarkably inferior to the former. The trade-off surface of the pure time buffering policy lies between the other two policies with a narrower scale. In other words, its crowding distance and span are relatively minute. Several solutions bunch together at the point [8200, 4.78], and they are all dominated by other solutions. As summarized in Table 2, there are 12 non-dominated solutions, and the majority of them stem from the mixed inventory-time buffering policy, while only one emerges from the pure time buffering policy. It is without question that, in this scenario, the mixed inventory-time buffering policy possesses an outright advantage over the other two policies.

Table 2. Results of the three buffering policies

ε	No any buffers		Pure inventory buffering policy		Pure time buffering policy		Mixed inventory-time buffering policy	
	Schedule instability cost	Inventory holding cost	Schedule instability cost	Inventory holding cost	Schedule instability cost	Inventory holding cost	Schedule instability cost	Inventory holding cost
5000	11.01	4182	10.19	4981	***7.17***	***4212***	***5.42***	***4974***
6500			8.69	6478	5.58	6220	***4.39***	***6437***
8000			7.66	7993	5.52	6244	***3.79***	***7915***
9500			6.99	9466	4.77	8162	***3.23***	***9429***
11000			6.58	10901	4.77	8251	***2.99***	***10942***
12500			6.05	12418	4.78	8296	***2.82***	***12414***
14000			5.78	13894	4.76	8256	***2.48***	***13887***
15500			5.43	15482	4.79	8256	***2.32***	***15389***
17000			5.11	16912	4.75	8229	***2.09***	***16892***
18500			5.03	18393	4.76	8193	***1.96***	***18422***
20000			4.91	19656	4.78	8131	***1.84***	***19313***

Notes: The bold italics represent the non-dominated solutions; the schedule instability cost and inventory holding cost under the scenario of no any buffers are not relevant with ε.

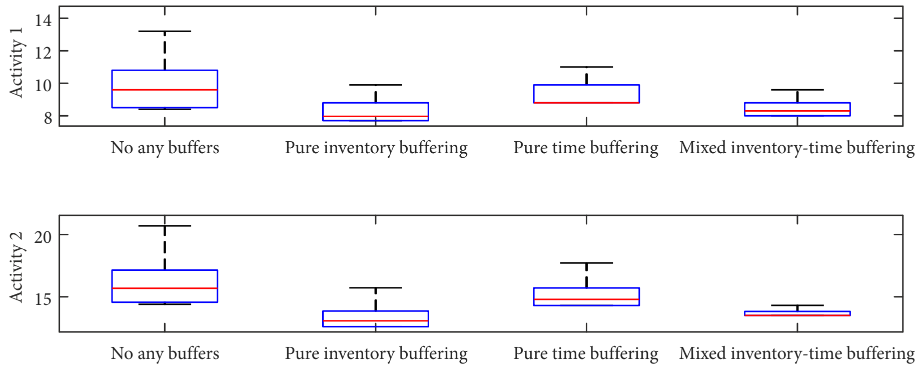

Figure 7. Actual start time of the activities

Additionally, Figure 8 displays the findings concerning the deadline factors: 0.10, 0.15, and 0.20. The results indicate that, despite the deadline factor, there is a specific gap between the trade-off surfaces of the pure inventory buffering policy and the other two policies. Relying solely on inventory buffers makes it arduous to accommodate uncertainties. The inventory buffers can only deal with the stochastic material delays and do nothing about the stochastic activity durations. However, the capability of the inventory buffers cannot be denied on this basis. As shown in Figure 8a, under the tight deadline setting, the trade-off surface of the mixed inventory-time buffering policy almost dominates the pure time buffering policy. This perfectly exemplifies the benefits emanating from inventory buffers. With a tight deadline setting, the capacity of the time buffer is severely constrained given the nominal idle time on the schedule. At this moment, if inventory buffers work to mitigate some of the unpredictability (primarily due to stochastic material delays), good performance can still materialize. However, as deadlines become more relaxed, inventory buffers become gradually negligible. As displayed in Figures 8b and 8c, the trade-off surface of the pure time buffering policy gradually approaches the mixed inventory-time buffering policy. Although the latter still provides superior performance, the discrepancy with the former is gradually declining. This is because the capability of the time buffer is fully released. It can effectively deal with uncertainties. At this time, the inventory buffer makes little influence. Under the circumstance of deadline factor = 0.20, there are 17 nondominated solutions, amongst which 11 emanate from the mixed inventory-time buffering policy and the remaining 6 arise from the pure time buffering policy.

Finally, Figure 9 depicts the results under the project arrival rates 0.5, 1.0, and 1.5. The results indicate that the pure inventory buffering policy still lags behind other buffering policies, regardless of the project arrival rate. This reasoning corresponds with our earlier elucidations. Concerning the pure time buffering policy, when the project arrival rate is low (e.g., 0.5), all of its solutions are packed tightly around the point [4100, 1.12]. They are not dominated by any solution derived from the mixed inventory-time buffering policy. However, when the project arrival rate increases (e.g., 1.5), the gap between the pure time buffering policy and the mixed inventory-time buffering policy widens once again. This outcome can be explained

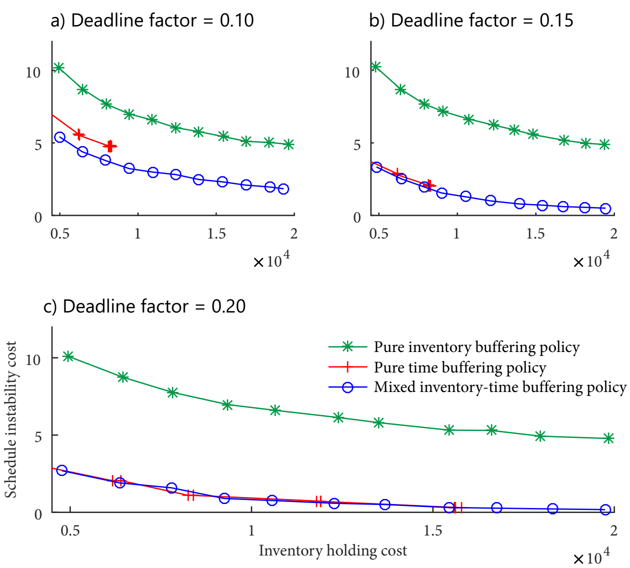

Figure 8. The results under different deadline factors

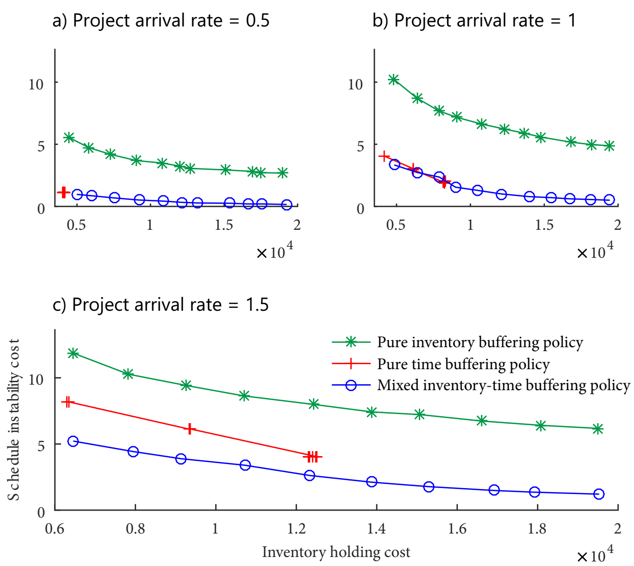

Figure 9. The results under different project arrival rates

as follows. A high project arrival rate means a frequent occurrence of future projects and a high degree of variation and uncertainty. But restricted by the deadline, the time buffers that can be added is very limited. Relying on the time buffers alone may not be enough. Only in combination with the inventory buffers can uncertainties be effectively mitigated.

7. Discussion

Despite considering a project schedule with a simplistic structure and one critical material, the case application and numerical analysis still capture the characteristics of the buffering policies for PCSC under stochastic material lead times and activity durations. Based on the analysis of the results, insights into the characterization of the responsiveness of time and inventory buffers and the applicable scenes of different buffering policies could be obtained. They are similar to the arguments of Horman and Thomas (2005) and Russell et al. (2013), but go a step further and facilitate project buffer management.

Amongst all situations, the pure inventory buffering policy noticeably underperforms when contrasted with the other two buffering policies. This shows the low responsiveness of the inventory buffers, as the uncertain factors they can deal with are relatively simple. Specifically, the inventory buffers can only deal with uncertain material delays and do not play any role in preventing uncertainties from the on-site project network. Of course, the inventory buffers are less expensive, as they only cause inventory holding costs and do not prolong the total project duration. In the language of Horman and Thomas (2005), the inventory buffers are more easily recovered (converted to other things for other benefits) if not used. In general, the pure inventory buffering policy is best suited for scenarios where stochastic material supply delay is prominent and the project deadline is tight.

The better performance of the pure time buffering policy compared with the pure inventory buffering policy also confirms an advantage of the time buffers, that is, strong responsiveness. The time buffers can simultaneously deal with uncertainties from the off-site material supply chains and the on-site project network. However, as for the pure time buffering policy, its performance is still inferior to the mixed inventory-time buffering policy, especially when the project deadline is tight. This reveals the disadvantage of the time buffers, that is, prolonging the project duration. In turn, the project deadline often limits the size of the time buffers that can be inserted, especially under a tight deadline. Because of this, the responsiveness of the time buffer is somewhat limited by the project deadline. Therefore, the ideal application scenario of the time buffer strategy is a situation where the project deadline is relatively generous.

In addition, it can be found from the above analysis that the disadvantages of the time buffers and inventory buffers serve as an advantage to each other. They exhibit significant complementarity. Typically, inventory buffers can be set up to cope with stochastic material supply delays at the expense of inventory holding cost, while time buffers can be inserted to accommodate stochastic activity durations and material supply delays that are not entirely eliminated. Combining these two methods can lead to optimal performance, especially when faced with tight project deadlines and high arrival rates. In situations where the project deadline is tight, the inventory buffers can effectively supplement the limited responsiveness of the time buffers. In cases where the project arrival rate is high, the total material demand is greater and the material supply delay problem will become more prominent. It is more necessary to set up inventory buffers to ease the burden on time buffers. In general, deploying both the inventory and time buffers is undoubtedly the best option in such situations.

Nevertheless, when the project deadline is ample or the project arrival rate is relatively low, it is preferable to consider both the pure time buffering policy and the mixed inventory-time buffering policy. This approach can yield a more extensive range of nondominated solutions for facilitating buffer size decisions for the project manager to consider. As an illustration, as noted earlier, under the scenario of a deadline factor of 0.20, the mixed inventory-time buffering policy furnishes 11 Pareto-optimal solutions, while the pure time buffering policy offers 6. In total, there are 17 solutions for the project manager to choose from, catering to the different trade-offs between project schedule robustness and inventory holding costs.

8. Conclusions

This study is motivated by the observations of buffer management in PCSC. Given the adverse impact of uncertainties and variability on performance, inventory and time buffers are essential. A total of three buffering policies are proposed in this study, revolving around inventory and time buffers, namely the pure inventory buffering policy, the pure time buffering policy, and the mixed inventory-time buffering policy. The mathematical models and procedures for the three buffering policies are presented. Under different deadline factors (i.e., 0.10, 0.15, and 0.20) and project arrival rates (i.e., 0.5, 1.0, and 1.5), computational analysis is conducted to evaluate and compare the policies. In all scenarios, a total of 86 nondominated buffer allocation schemes are obtained. Among them, 73.26% come from the mixed inventory-time buffering policy, while 26.74% come from the pure time buffering policy. The results demonstrate the outstanding performance of the mixed inventory-time buffering policy and the slightly less desirable but acceptable performance of the pure time buffering policy.

The research contributions can be summarized as follows: (1) proposing the three buffering policies and addressing the corresponding buffers positioning and sizing decisions; (2) outlining the responsiveness of the inventory buffer and time buffers, including their complementarity; (3) evaluating and comparing the three buffering policies, and extracting insights to support the project manager's decision towards choosing the appropriate buffering policy with respect to different project characteristics. Generally speaking, combining inventory and time buffers results in better performance, particularly when project deadlines are tight, and arrival rates are high. The pure time buffering policy deserves consideration in certain situations, providing decision-makers with more options, along with the mixed inventory-time buffering policy.

Besides, this study raises several relevant problems for further consideration. Specifically, the models and procedures proposed scatter time buffers in front of each activity, whereas the CC/BM approach splits time buffers into two, the project buffer and feeding buffer. A re-examination of the corresponding buffering model and procedures for this centralized form of time buffering is required, as well as comparisons with the inventory buffer. Additionally, only inventory and time buffers are considered in this study, and it would be noteworthy to investigate their combination with other buffers, such as capability buffer, plan buffer, and financial buffer, which may provide additional choices for buffering decisions. Nevertheless, the positioning and sizing decisions of such buffers can be more complicated. The development and application of corresponding buffering models and procedures remain the subject of future research in these areas.

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Author contributions

LH was responsible for Conceptualization, Data collection, Writing-Original draft preparation. LD was responsible for Methodology, Writing-Reviewing and Editing, Supervision. LJ was responsible for Resources.

Disclosure statement

The authors declare no conflict of interest.

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