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Side-payment Contracts for Prefabricated Construction Supply Chain Coordination under Just-in-Time Purchasing

Abstract

This paper considers a prefabricated construction supply chain (PCSC) consisting of a project contractor who shoulders the on-site assembly task and orders prefabs from a prefabricated factory. To mitigate the heavy double handling costs associated with early and late delivery of prefabs, the project contractor requires the right quantity and exact type of prefabs are carried to construction sites according to its assembly schedule. This is known as just-in-time purchasing (JITP). However, JITP may increase the pressure on the prefabricated factory to hold excessive inventory or to compress production time. For these reasons, the prefabricated factory may be reluctant to switch to JITP. To initiate the operation of JITP and establish a win-win outcome, side-payment contracts including a delivery-time dependent subsidy and two constant transfer terms are designed as coordinate schemes. Employing Stackelberg, we explore participants' optimal decisions. The results show that the JITP yields higher profit for PCSC, and the proposed contracts are capable of achieving a win-win coordination. In particular, the constant transfer cost term is relatively equitable to participants, while the constant cost-sharing transfer term outperforms the constant transfer cost term under a high double handling cost. Moreover, the prefabricated factory earns more profit when the double handling cost for early or late delivery is high. Some managerial implications are also obtained and help to strengthen cooperation among participants and promote the sustainable development of the PCSC.

Keywords: Prefabricated construction supply chain, Just-in-time purchasing, Double handling cost, Side-payment contract, Supply chain coordination.

Introduction

Prefabrication in construction refers to the practice of producing largely complete or semi-complete prefabs in a plant, shipping them to construction sites, and finally assembling the components to create various structures (Wu et al., 2019; Du et al., 2021). With more controlled factory-based production environments and higher levels of automation, prefabricated construction has significant advancements over conventional construction mainly including typically safer and cleaner building environments, faster construction, higher quality and lower construction waste (Tao et al., 2018; Li et al., 2018; Tavares et al., 2021). These advantages have inspired the development of prefabrication construction in many countries, such as Singapore, Australia and the UK, etc. Given the significant demand for new construction and pressures to reduce carbon emissions faced by construction industry, the Chinese government has also begun to enact policies and regulations at the national level to promote the development of prefabricated construction, and mandated a target of a 30% proportion of prefabricated buildings in all new construction by 2025 (SCC, 2016). Prefabricated construction holds promise for the sustainable transformation of construction industry in China.

Despite its advantages, however, prefabricated construction is still in its infancy in China (Hong et al., 2018). Multiple challenges, such as overproduction, early or late delivery and large inventory, exist among the manufacturing, transportation, and assembly processes (Luo et al., 2020), but one of the main bottlenecks that limit project productivity is the improper delivery of prefabs in the prefabricated construction supply chain (PCSC) (Hussein et al., 2021). Taking a real-life example of a public housing project conducted by the Shaanxi Construction Engineering New Building Materials Co., Ltd, non-value-added cost related to improper delivery of prefabs accounts for 7-12% of total prefabrication production cost. If components at a prefabricated factory (PF) are not carried to construction sites by their due dates, follow-up construction activities cannot be performed. The costly penalty for working hour loss of the workers and cranes will happen to the project contractor (PT) (Zhai et al., 2017). However, early delivery of prefabs to job sites can also be undesirable if there is insufficient storage space on-site, a problem faced by more than 80% of PTs (Kong et al., 2018). Site congestion affects the efficiency of on-site construction, and alternative buffer space has to be procured and paid for (Zhai et al., 2018). For these reasons, the heavy double handling cost due to either early or late delivery of prefabs is the main reason for projects cost overrun in Chinese construction projects (Jiang and Wu, 2021). If this predicament cannot be solved properly, the advantages from adopting prefabricated construction would easily be offset (Zhai et al., 2020). Therefore, it is extremely vital to improve the on-time delivery performance of prefabs to reduce heavy double handling costs.

The emergence of just-in-time purchasing (JITP), marked by delivering exactly the right quantity at exactly the right time, has the potential to minimize total double handling costs (Pheng and Jayawickrama, 2012; Kong et al., 2018). Since early shipments are forbidden, pre-manufactured components are stored in the PF' warehouse and then transported to the site for assembly when needed, rather than directly transported to the construction site (Grout, 1997). Thus, JITP strategy could help eliminate the costs of early delivery for the PT. Furthermore, when project schedules fluctuate and an advance of assembly schedule occurs, the PF needs to compress its production time by acquiring improved equipment or hiring extra workers to meet the changed due-date. Fig. 1 (a) and (b) show the supply chain processes of prefabricated construction under traditional purchasing mode and under JITP mode, respectively. It is easy to see that the JITP strategy benefits the PT, while it forces the PF to dedicate more resources, such as holding excessive inventory, compressing production time and information sharing, to ensure that deliveries occur on time (Grout, 1997; Chakraborty and Chatterjee, 2016). Conflict exists between the PT and PF. As independent individuals in the PCSC, they are reluctant to coordinate voluntarily unless they will benefit from cooperation (Heydari et al., 2017). A win-win coordination mechanism that ensures the smooth operation of JITP is needed.

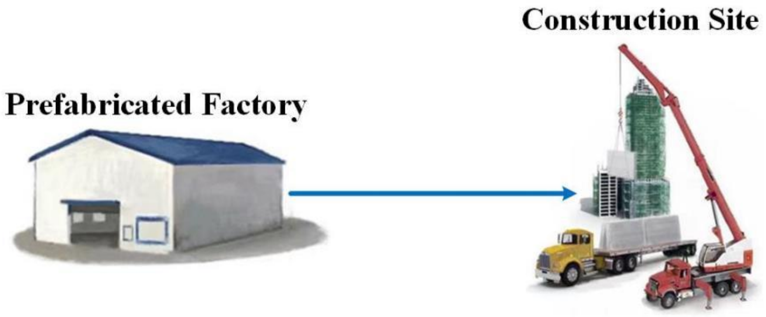


Fig. 1 (a). Supply chain processes of prefabricated construction under traditional purchasing mode.

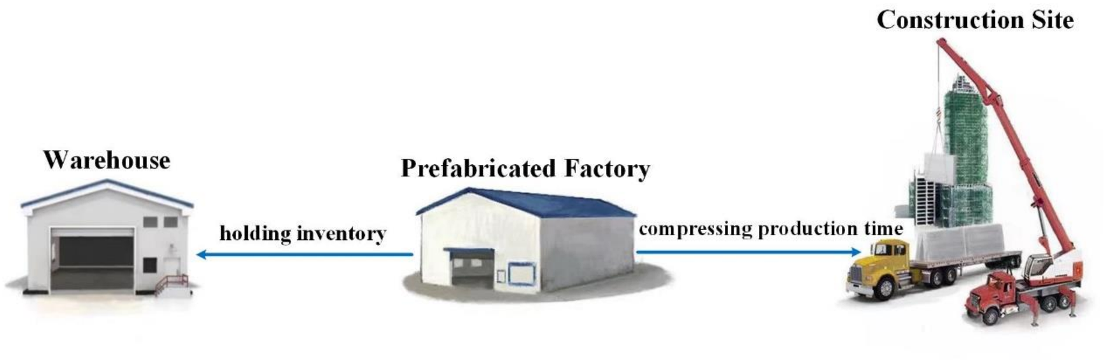


Fig. 1 (b). Supply chain processes of prefabricated construction under JITP mode.

Side-payment contracts are widely used to manage or coordinate supply chain members to achieve certain organizational objectives (Liang and Gu, 2021). This type of contract features an internal money transfer that channel members make in order to boost supply chain profit (Zhai et al., 2019a). All sorts of side-payment contracts and their combinations have been proposed to achieve Pareto improvements for various supply chains such as agriculture and manufacturing (He et al., 2021; Arbabian, 2022), and related work can also be seen in the prefabricated construction supply chain management (PCSCM) literature. For example, Zhai et al. (2017) developed a mechanism with a decision-related crash money and a cost-sharing contract to solve the lead-time hedging coordination problem, and Zhai et al. (2018) solved the buffer space hedging coordination issue by adopting a cost-sharing contract and a constant transfer term. These papers all showed that side-payment contracts can perform well in terms of supply chain coordination. However, side-payment contracts, or even other broad-level contracts, are absence to ensure the JIT delivery in PCSC (Wang et al., 2019). In an attempt to fill this gap, this paper designs side-payment contracts that include a subsidy and two constant transfer terms to solve the JITP coordination problem in the PCSCM. Generally, this research intends to answer the following research questions:

(1) Does the JITP strategy increase the profit of the PCSC?

(2) What type of side-payment contracts can be used to solve the JITP coordination issue, and what are the optimal strategies for the PT and PF respectively?

(3) How do the primary model parameters affect the profit of the PCSC, the participants' profits and their optimal decisions?

We address the first question by comparing the profit of the PCSC with and without JITP strategy. To answer the second question, a delivery-time dependent subsidy is investigated by the Stackelberg game model to release the pressure on the PF and improve on-time delivery performance. To achieve a win-win coordination, a constant cost-sharing contract is first explored and the range that can achieve Pareto optimization is derived. Then, to further provide a more convenient negotiation mechanism, a constant transfer cost contract is also analyzed. Following the basic rule of Nash arbitration scheme proposed by (Leng and Zhu, 2009), the unique value of the constant transfer cost contract is computed that fairly distributes the system-wide surplus and reaches a win-win situation. To answer the third question, we mainly employ numerical studies with sensitivity analysis to figure out how the main system parameters influence the profits of whole supply chain and of individuals.

This paper contributes to PCSCM literature in two aspects. First, the win-win coordination mechanisms are designed to resolve JITP-induced profit conflicts among independent participants in PCSC. To best of our knowledge, this paper is one of the pioneer studies that not only investigates the effects of JITP on double handling costs, but also considers how to coordinate the conflict caused by JITP in the PCSCM domain. Second, this paper employs different contract combinations to derive a range and a specific value that can achieve Pareto optimization, providing participants with various coordination schemes that can be referenced in real-life industrial practice.

The remainder of the paper is organized as follows. The literature review is given in Section 2. The problem statement and benchmark model are presented in Section 3. Section 4 develops JITP models and discusses JITP coordination issue. Numerical studies with sensitivity analysis are put forward in Section 5 and managerial implications are summarized to provide guidelines for managers. Finally, concluding remarks and directions for future research are provided in Section 6.

2. Literature Review

2.1 Prefabricated Construction Supply Chain Management (PCSCM)

Prefabricated construction is marked by the in-plant manufacturing and job-site assembly of building prefabs (Chang et al., 2018; Wang et al., 2022). More stakeholders are involved in prefabrication processes compared to conventional construction (Wang et al., 2019), and make their own decisions separately from one another. Consequently, the PCSC usually suffers from conflicts and low efficiency, leading to construction project time and cost overrun (Pero et al., 2015; Hussein et al., 2021). Supply chain management in prefabricated construction has been recognized as an effective measure to reduce costs and improve total system performance (Zhai et al., 2020; Luo et al., 2020).

Some studies have resorted to diverse modeling methods that consider multiple supply chain stages to provide frameworks for better minimizing cost. For example, Yazdani et al. (2021) developed three metaheuristic algorithms to improve precast production scheduling in the PCSC so as to reduce earliness and tardiness costs under operational uncertainty. In their model, genetic algorithm (GA), differential evolution (DE) and imperialist competitive algorithm (ICA) were investigated to optimize objective function and the results showed that DE performs better. Wang et al. (2018) developed a two-hierarchy simulation-GA hybrid model for the prefab supply chain to pursue on-time delivery and the minimum possible production costs, and Wang and Hu (2017) modified a prior precast production scheduling model by considering the entire supply chain for the minimization of earliness and tardiness costs. Other researchers have used information technology working in a centralized way to strengthen collaboration among PCSC's independent stakeholders (Li et al., 2022). For instance, Li et al. (2018) established an Internet of Things-enabled BIM platform (IBIMP) to improve the efficiency and effectiveness of daily operations, decision making, and collaboration of PCSC. A real-life project located in Hong Kong were deeply studied and demonstrated the efficiency of IBIMP. Wang et al. (2020) built a novel blockchain-based information management framework (BIMF) for a PCSC to address challenges such as fragmentation and lack of real-time information, and algorithms for smart contracts were adopted for the model implementation.

Most of the above literature is devoted to improve system performance by minimizing cost or strengthening stakeholders' collaboration from a centralized perspective. However, in reality independent contractors make decisions based on their own costs to maximize their own interests. Exploring coordination issues from a decentralized perspective is therefore of more practical significance (Zhai et al., 2018). Aiming to address the above challenges, few theoretical studies have been carried out towards the interrelationship of independent entities in the PCSC. Zhai et al. (2017) adopted lead-time hedging strategy to minimize the tardiness penalty and found that lead-time hedging strategy can enhance system profit and the reliability of delivery of prefabs. Later on, Zhai et al. (2018) quoted a positive buffer space to hedge the double handling costs. Different from the previous research, this paper develops a mathematical model to minimize cost in a decentralized PCSC. Specifically, we focus on the interaction between a PT and a PF to analyze the effectiveness of JITP strategy on double handling costs. Table 1 summarizes the related research in PCSCM.

Table 1
Summary of the related literature regarding PCSCM.

Representative publications	Methods	Strategy	Research focus	Central or decentralized
Yazdani et al. (2021)	GA, DE, and ICA	improved precast production scheduling	minimize total earliness and tardiness costs	central
Wang et al. (2018)	two-hierarchy simulation-GA hybrid model	improved precast production scheduling	minimize production cost	central
Wang and Hu (2017)	GA	improved precast production scheduling	minimize total earliness and tardiness costs	central
Li et al. (2018)	case study	IBIMP	strengthen collaboration	central
Wang et al. (2020)	algorithms for smart contracts	BIMF	strengthen collaboration	central
Zhai et al. (2017)	mathematical model	production lead-time	minimize tardiness cost	decentralized
Zhai et al. (2018)	mathematical model	buffer space	minimize double handling costs	decentralized
This paper	mathematical model	JITP	minimize double handling costs	decentralized

2.2 Just-in-Time Purchasing (JITP)

Another related stream of research is JITP in supply chain management. Widely prevailing over in manufacturing supply chain, JITP is regarded as a means of minimizing the total penalties for earliness and tardiness (Si et al., 2021; Ahmadian et al., 2021; Xiong et al., 2021). Handfield (1993) used resource dependence to explain how and why purchasing mode moved toward JITP. In this research, information sharing was shown to be an antecedent to JITP. Bond et al. (2020) further explored the factors that affect JITP performance and found that poor supplier support was convinced vital issues affecting the success of JITP. Chakraborty and Chatterjee (2016) adopted surcharge pricing as a supply chain coordinating mechanism and resolved the conflicts between stakeholders successfully in a JIT environment.

In the PCSC, it turns out that JITP is always the preferable inventory ordering system (Pheng and Jayawickrama, 2012; Wu et al., 2013). Specifically, Wang and Ye (2018) constructed the cost difference function between traditional purchasing and JITP and obtained the parameter conditions and component requirement range that favors JITP over traditional methods. Kong et al. (2018) studied the JIT delivery issue for PCSCM and expanded the current batch-scheduling model of minimizing penalties due to earliness or tardiness. Hussein and Zayed (2020) demonstrated that stakeholders' management is one of the critical factors for successful implementation of JIT in the PCSC.

Table 2 compares previous works on JITP in manufacturing supply with that in the PCSC and in particular highlights one of the contributions of this paper. Although researchers have shown an increasing interest in JITP in recent years, their research has been relatively silent on coordinating the conflict caused by JITP in PCSCM. In fact, the implementation of JITP may face challenges, if there is no mechanism to resolve JITP-induced profit conflicts among independent participants (Grout, 1997; Chakraborty and Chatterjee, 2016). This paper introduces coordination mechanisms into JITP research in PCSC to bridge the gap. Moreover, as a key factor affecting the smooth implementation of JITP, information exchange cost is also considered and quantified in our models.

Table 2
Comparison of the researches on JITP in manufacturing supply chain with that in the PCSC.

Comparison objects	Representative publications	Applicability	Influencing factors	Coordination mechanism
Researches on JITP in manufacturing supply chain	Handfield (1993)	√	√	
	Grout (1997)			√
	Chakraborty and Chatterjee (2016)			√
	Liu and Nishi (2020)	√		
	Bond et al. (2020)	√	√	
Researches on JITP in the PCSC	Pheng and Jayawickrama (2012)	√	√	
	Wu et al. (2013)	√		
	Hussein and Zayed (2020)	√	√	
	Kong et al. (2018)	√		

Wang and Ye (2018)	√		
This paper	√	√	√

2.3 Supply Chain Coordination Using Side-payment Contracts

Recent papers have paid much attention to investigating supply chain coordination with side-payment contracts. A side-payment contact may include, such as revenue sharing, subsidy, cost-sharing, and internal money transfer (Du et al., 2022; Bhavsar and Verma, 2021; Zang et al., 2022; Hu et al., 2011). Song and Gao (2017) established a retailer-led revenue-sharing contract game model and a bargaining revenue-sharing contract game model and showed that revenue-sharing contracts can effectively improve the overall profitability of the supply chain, and Zhang and Yousaf (2020) demonstrated that a government subsidy contract can achieve global supply chain optimization. Likewise, Dash Wu et al. (2019) adopted a cost-sharing contract to reduce the level of carbon emissions in a green supply chain and achieved Pareto improvement. Zhai et al., (2018) successfully resolved buffer space hedging coordinated issue in PCSC by using side-payment contracts. In their coordination mechanism, a cost-sharing transfer term and a constant transfer cost term were developed.

There are also a few publications that study JITP coordination problem through side-payment contracts. Relevant works focus on the manufacturing supply chain, mainly including, Grout (1997) and Yang and Li, (2006), who developed a contractual incentives to achieve on-time deliveries by adopting a decision-related subsidy to help the supplier improve on-time delivery performance, and Chakraborty and Chatterjee (2016), who designed an internal surcharge pricing transfer term as a supply chain coordinating mechanism under a JIT environment, in which the buyer offered the supplier an increase in the price to encourage the supplier to switch to the JIT. However, the existing researches on JITP coordination problem only focus on how to help suppliers switch to JITP and ignore the question of whether buyers could be profitable as well (Liu and Nishi, 2020).

Table 3 shows the difference between this paper with previous supply chain coordination research using side-payment contracts. We focus on the JITP coordination issue in the PCSC in particular and explicitly considers mutually beneficial coordination schemes between channel members. Specifically, following a coordination procedure proposed by (Leng and Zhu, 2009), we adopt a hybrid of a delivery-time dependent subsidy and two constant transfer terms in this paper. The subsidy aims to improve on-time delivery performance and relieve the PF's stress caused by JITP strategy, and the constant transfer terms which includes a cost-sharing transfer term and a constant transfer cost term serve to ensure a win–win outcome.

Table 3
Summary of the related literature on supply chain coordination using side-payment contracts.

Representative publications	Specific contract	PCSC	Coordination of JITP	Win-win Coordination
Song and Gao (2017)	revenue sharing			√
Zhang and Yousaf (2020)	subsidy			√
Dash Wu et al. (2019)	cost-sharing			√
Zhai et al., (2018)	cost-sharing transfer term and constant transfer cost term	√		√
Hu et al. (2011)	internal price transfer term			
Grout (1997)	subsidy		√	
Chakraborty and Chatterjee (2016)	internal price transfer term		√	
This paper	"subsidy and cost-sharing transfer term" and "subsidy and constant transfer cost term"	√	√	√

3. Problem Formulation and Benchmark Model

3.1. Problem Description and Assumptions

This paper focuses on the interaction between a PT and a PF in a PCSC, reflecting the~~a~~ real-life case which we conducted during 2018-2019. We investigated a public housing project located in Shaanxi, China (Du et al., 2019). This project was supervised by Vanke Group (VG), a leading construction and engineering contractor in China. VG (i.e.PT) ordered the prefab from Zhongtian Group (i.e. PF) at a constant price M and earned revenue at per unit S from assembled it. The prefab's order quantity Q is predetermined according to the needs at the construction site. After open tendering in 2017, VG made decision on delivery time according to its plan and the Zhongtian Group produced and delivered prefabs to order. However, on-time delivery of prefabs was hampered by several uncertainties, such as bad weather, unskilled workers and machine breakdown. Hence, we proposed a solution that contains the JITP strategy and the coordination mechanisms required for the implementation of JITP.

To ensure the rationality of modeling, we make the following assumptions.

Assumption 1. The PF's response time t follows an exponential distribution. Its probability density function and cumulative distribution function are expressed by $f(t)=\begin{cases}\lambda e^{-\lambda t}, t>0\\ 0, otherwise\end{cases}$（$\lambda>0$） and $F(t)=\begin{cases}1-e^{-\lambda t}, t>0\\ 0, otherwise\end{cases}$（$\lambda>0$）, respectively (Grout and Christy, 1993).

Assumption 2. The quoted delivery time T is defined as the time interval between the PT placing an order and the order's due date (Hammami et al., 2017). If the t exceeds the T, the double handling cost for late delivery occurs at Rd per unit per time. Again, if the t is less than the T, and prefabs are delivered to the site early, the double handling cost for early delivery occurs at Re per unit per time (Pheng and Jayawickrama, 2012; Zhai et al., 2018).

Assumption 3. T~~It is assumed that t~~he PF operates at its full capacity. To control the timeliness of deliveries under JITP, the PF has to change its production schedule frequently, which will add extra cost burden. Without loss of generality, we consider that the PF has two related costs: the inventory holding cost of finished prefabs due to early fulfillment of orders, and the production compression cost caused by delayed order completion. The two costs are proportional to the inventory time $T-t$ and delay time $T-t$, respectively (Yang and Li, 2006). In addition, the PF could charge subsidy to compensate itself for the costs incurred by JITP (Grout, 1997).

Assumption 4. I~~We assume that i~~nformation exchange cost depends upon the level of $|T-t|$. Information sharing, a prerequisite for implementing JITP, is inherently dynamic communication processes (Handfield, 1993; Hussein and Zayed, 2020). And the ultimate goal is to achieve on-time delivery in our paper. When the gap between T and t is larger, the more need for the PF and the PT to communicate and share information to facilitate on-time delivery. In other word, when the value of $|T-t|$ is larger, there exist more communication cost between the two parties to achieve on-time delivery (Li et al., 2018; Wang et al., 2020). While most of the relevant literature assume that information exchange cost is a constant variable (Feng and Song, 2009; Chao and Hao, 2019), which does not reflect the dynamic nature of information communication. Based on this reality, we quantify information exchange cost as a linear function of $|T-t|$ to capture the dynamic relationship and simplify the calculation. And the information exchange costs of the PT and PF can be expressed as $I_{PT}Q\int_0^{\infty}|T-t|f(t)dt$ and $I_{PF}Q\int_0^{\infty}|T-t|\,f(t)dt$, respectively.

Assumption 5. In order to avoid unnecessary complexity, this paper ignores other costs among participants that have very little to do with double handing operations (Zhai et al., 2018). In addition, we assume that there is information symmetry between channel members.

3.2. Models Formulation

This paper builds two types of models as shown in Fig 2.

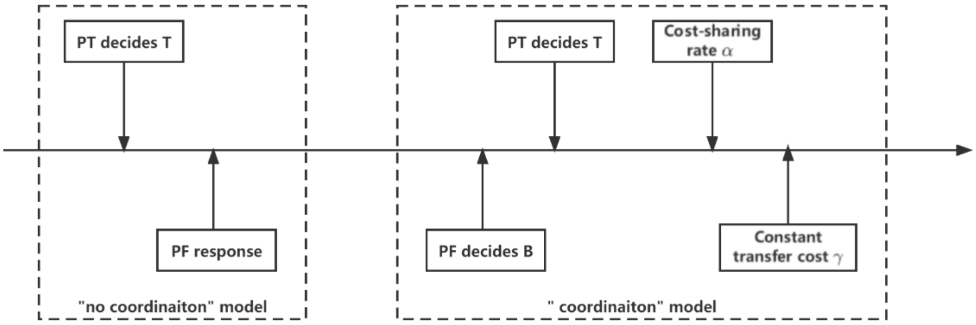


Fig. 2. Sequence of events and decision-making.

The first is “no coordination” model, which includes a traditional purchasing model and a JITP model without coordination. In both models, the PT determines T, while the PF has no decision variable (Hu et al., 2011; Zhai et al., 2017; Zhai et al., 2018). The second is the “coordination” model, where the heavy double handling costs empower the PF to charge subsidy from the PT to compensate its potential profit losses when adopts the JITP strategy. Analogous to previous studies (Zhai et al., 2017; Zhai and Cheng, 2021), we formulate a PF-led Stackelberg model. The PF decides the amount of subsidy B while taking the reaction of the PT into account. Then, given the B amount, the PT sets the T that maximize its profit. Afterwards, a constant cost-sharing rate α is explored and the range of α that can achieve Pareto optimization is derived. To further provide a more convenient negotiation mechanism, a constant transfer cost γ calculated by the Nash arbitration scheme is introduced to fairly distribute surplus generated through the cooperation. For clarity, the superscripts, parameters and decision variables related to the proposed models are listed in Table 4.

Table 4
Superscripts, parameters and decision variables related to the proposed models.

Superscripts	
PT	the project contractor (not using a PC is to avoid a confusion with PCSC)
PF	the prefab factory
TP	the traditional purchasing model
JIT	the JITP model without coordination
SF	the PF leaded Stackelberg game model
Parameters	
S	revenue per unit prefab
M	purchasing price per unit prefab
Q	order quantity
I_{PT}/I_{PF}	information exchange cost per unit per period of time for PT / PF
Rd	double handling cost for late delivery per unit per period of time
Re	double handling cost for early delivery per unit per period of time
H	inventory holding cost per unit per period of time
C	production compression cost per unit per period of time
λ	response capacity for the PF
$1/\lambda$	average response time for fulfilling the order
t	response time for fulfilling the order
$f(t)$	probability density function of the response time
$F(t)$	cumulative distribution function of the response time
Decision variables	
T	quoted delivery time
B	subsidy
α	constant cost-sharing rate
γ	constant transfer term

3.3. Benchmark Model: Traditional Purchasing Model

This section estimates the profits of the PT and the PF under the traditional purchasing model. The PT orders Q units of prefab from the PF, and the delivery time T is quoted when the order is placed by the PT. Under traditional purchasing mode, a longer T will lower the risk of tardiness cost but increase the incidence of earliness cost. The PT will choose an optimal quoted delivery time to maximize its own profit. The profit function of the PT can thus be described as:

$$\pi_{PT}^{TP}(T) = SQ - MQ - ReQ\int_0^T (T-t)f(t)dt - RdQ\int_T^{\infty}(t-T)f(t)dt \tag{1}$$

The first term SQ represents the total revenue by assembling the ordered prefabs. The second term MQ is the purchasing cost of prefabs. The third term and the last term represent the expected double handling costs for earlier and later delivery than the quoted delivery time, respectively.

The PF' profit function under the traditional purchasing model is shown below:

$$\pi_{PF}^{TP} = MQ - HQ\int_{0}^{T}(T-t)f(t)dt \tag{2}$$

Proposition 1. The profit function of the PT is a concave function of T^{TP} and the optimal T^{TP} is characterized by the following equation:

$$T^{TP} = -\frac{1}{\lambda}\ln\frac{\mathrm{Re}}{Rd + \mathrm{Re}} \tag{3}$$

Proof. Please see Appendix A.

From Proposition 1, we can see that the T^{TP} is always non-negative and determined by the double handling costs for early delivery and late delivery. This means that the PT could maximize its own profit from choosing an optimal delivery time T^{TP}.

4. Just-in-Time Purchasing (JITP) Model and Coordination Mechanism

4.1 Just-in-Time Purchasing (JITP) Model without Coordination

If the JITP strategy is adopted, the quoted delivery time determined by the PT will get rid of the double handling cost for early delivery and reduce the double handling cost for late delivery. However, the PF will be at risk of holding finished prefabs at warehouse and compressing production time in production line. The PT still determines the quoted delivery time to maximize its own profit. The new objective function of the PT is demonstrated as below:

$$\pi_{PT}^{JIT}(\mathrm{T}) = SQ - MQ - RdQ\int_{T}^{\infty}(t-T)f(t)dt - I_{PT}Q\int_{0}^{\infty}|T-t|\,f(t)dt \tag{4}$$

The SQ minus the MQ represents the profit through assembling ordered prefabs. The third component is the double handling cost for late delivery. The final term denotes information exchange cost occurring only when JITP strategy is adopted.

The profit of the PF is described as follows:

$$\pi_{PF}^{JIT} = MQ - HQ\int_{0}^{T}(T-t)f(t)dt - CQ\int_{T}^{\infty}(t-T)f(t)dt - I_{PF}Q\int_{0}^{\infty}|T-t|\,f(t)dt \tag{5}$$

The first component denotes the revenue from the sale of prefabs. The second component represents the inventory holding cost of the prefabs that are produced before the quoted delivery time. The third term is the production compression cost occurring when the response time is longer than the quoted delivery time. The last component is the information exchange cost.

Proposition 2. The profit function for the PT is a concave function of T^{JIT} and the optimal T^{JIT} in this model is as follow:

$$T^{JIT} = -\frac{1}{\lambda}\ln\frac{I_{PT}}{Rd+2I_{PT}} \tag{6}$$

Proof. Please see Appendix B.

Proposition 2 show that the optimal T^{JIT} is only impacted by the variable costs of the PT, but has nothing to do with the PF' costs. This implies that the JITP model without coordination can solely benefit the PT while disregarding the PF's profit.

Remark 1. According to Eqs. (2) and (5), it can be seen that the PF's profit has been damaged after adopting the JITP strategy (see Appendix C). Thus, it is necessary to design an incentive mechanism to encourage PF to adopt JITP strategy.

4.2. Incentive Model with a Delivery-time Dependent Subsidy

In this scenario, a delivery-time dependent subsidy is investigated by a PF-led Stackelberg game. This subsidy aims to compensate the PF's profit loss and thus encourage the PF to move towards JITP. For another, this subsidy related to delivery-time acts as an incentive of improving on-time delivery performance. Under the circumstances, the PF determines the amount of subsidy while taking the reaction of the PT into consideration. Next, the PT decides an optimal T^{SF} to maximize its own profit with the given subsidy. The profit functions of the PT and the PF are as follows:

$$\pi_{PT}^{SF}(\mathrm{T})=SQ-MQ-\mathrm{Rd}Q\int_T^{\infty}(t-T)f(t)dt-I_{PT}Q\int_0^{\infty}\left|T-t\right|f(t)dt-BQ\int_0^T f(t)dt \tag{7}$$

$$\pi_{PF}^{SF}(\mathrm{B})=MQ-HQ\int_0^T(T-t)f(t)dt-CQ\int_T^{\infty}(t-T)f(t)dt-I_{PF}Q\int_0^{\infty}\left|T-t\right|f(t)d+BQ\int_0^T f(t)dt \tag{8}$$

The last term $BQ\int_0^T f(t)dt$ represents the total subsidy amount charged by the PF from the PT. The rest parts of the components have the same meaning as the JITP model without coordination.

Proposition 3. Under this game model, both parties' optimal decisions are presented by the following Stackelberg equilibrium (see Appendix D):

$$T^{SF} = -\frac{1}{\lambda}\ln\frac{I_{PT}}{Rd+2I_{PT}-\lambda B^{SF}} \tag{9}$$

$$B^{SF} = \frac{2Rd + H + I_{PF} + 4I_{PT} - \sqrt{(H + I_{PF} + 4I_{PT})^2 + 4I_{PT}(Rd + C - H - 2I_{PT})}}{2\lambda} \tag{10}$$

Lemma 1. Comparing the profit of the PCSC in the incentive model with that in the traditional purchasing model, we see that the JITP strategy will be adopted only if the following condition is met:

$$\frac{Re+H}{\lambda}\ln\frac{Re}{Rd+Re}+\frac{H}{\lambda}(1-\frac{Re}{Rd+Re})<\frac{(H+I_{PT}+I_{PF})-(Rd+H+C+2I_{PT}+2I_{PF})e^{-\lambda T^{SF}}}{\lambda}-(H+I_{PT}+I_{PF})T^{SF} \tag{11}$$

Proof. Please see Appendix E.

Equation. (11) means that total profit of the PCSC under the JITP must be higher than its profit under the traditional purchasing. This condition always holds as the basis for our follow-up research.

Corollary 1. The impacts of the double handling cost for late delivery and average response time on the quoted delivery time are: $\frac{\partial T^{SF}}{\partial Rd} > 0$ and $\frac{\partial T^{SF}}{\partial {}^1\!/_\lambda} > 0$.

Corollary 1 shows that the PT will prolong the quoted delivery time when the double handling cost for late delivery is expensive or the average response time is long. If the double handling cost for late delivery is high, the PT will bear burden caused by working hour loss of the workers and equipment. To reduce the risk of late delivery, a longer delivery time will thus be required by the PT. Similarly, a longer average response time increases the possibility of tardy delivery. In this case, on-time delivery can only be achieved with a longer delivery time.

Corollary 2. The PT's quoted delivery time decreases as information exchange cost increases, i.e., $\frac{\partial T^{SF}}{\partial I_{PT}} < 0$.

A higher the cost of information exchange means that the PT invests more in monitoring the execution of production processes and delivery schedules (Wang et al., 2020). This will reduce the risk of late delivery. Combining with Corollary 1, the PT will choose to shorten the quoted delivery time.

Corollary 3. The PF's optimal subsidy increases as the double handling cost for late delivery or average response time increases, i.e., $\frac{\partial B^{SF}}{\partial Rd} > 0$ and $\frac{\partial B^{SF}}{\partial {}^1\!/_\lambda} > 0$.

Proof. Please see Appendix F.

The PF's subsidy can be seen as an incentive to reduce PT's double handling costs. Hence, the higher Rd for PT to bear, the higher subsidy that PF can ask. In other words, a higher double handling cost for late delivery implies that the PT will suffer a more serious economic loss when prefabs arrive late, and the PT will thus be more willing to invest more to decrease the likelihood of tardy delivery. This empowers the PF to charge more subsidy. Moreover, the PF with a longer average response time may invest more to increase response capacity by acquiring improved equipment or hiring extra workers etc. Thus, more subsidy will be charged to ensure on-time delivery in this scenario as well.

Corollary 4. The impacts of inventory holding cost and production compression cost on PF's optimal subsidy are: $\frac{\partial B^{SF}}{\partial H} > 0$ and $\frac{\partial B^{SF}}{\partial C} < 0$ (see Appendix F).

Intuitively, if the PF faces heavy inventory holding cost under JITP, it will charge more subsidy to compensate. Furthermore, a larger production compression cost means a larger gap between quoted delivery time and response time, which leads to a lower likelihood of on-time delivery. Therefore, the PF has to charge less subsidy.

Remark 2. Comparing the value of quoted delivery time and each party's profit under the Stackelberg game model with that under the JITP model without coordination, three results are presented as follows:

(i) the value of quoted delivery time follows $T^{JIT} > T^{SF}$ (this proof is intuitive and thus omitted);

(ii) the profit of the PF follows $\pi_{PF}^{JIT} < \pi_{PF}^{SF}$ (see Appendix G);

(iii) the profit of the PT follows $\pi_{PT}^{JIT} > \pi_{PT}^{SF}$ (see Appendix H).

The results of above comparison show that charging a delivery-time dependent subsidy shortens delivery time set by the PT, which can win more orders for a fast and efficient delivery time and thus benefit the entire supply chain (Hammami et al., 2020; Heydari et al., 2019). With the subsidy and shorter delivery time, the PF can arrange production more easily and reduce production compression cost. Under this setting, the PF's profit increases, but the PT's profit decreases, as compared to the JITP model without coordination. The concern now is how to assure that in the incentive model, both the PT and the PF' profits are higher than in the traditional purchasing model. This will be tackled in the next subsection.

4.3. Win-win Coordination Achieved by a Constant Transfer Term

4.3.1 Constant Cost-sharing Transfer Term

In this cost-sharing contract, the PT bears $\alpha[RdQ\int_T^{\infty}(t-T)f(t)dt+BQ\int_0^T f(t)dt]$, while remaining $(1-\alpha)[RdQ\int_T^{\infty}(t-T)f(t)dt+BQ\int_0^T f(t)dt]$ is shared by the PF. The cost-sharing rate is α ($0<\alpha<1$). Rewrite the profit formula (7) and (8) as follow:

$$\hat{\pi}_{PT}^{SF}=SQ-MQ-I_{PT}Q\int_0^{\infty}\left|T-t\right|f(t)dt-\alpha[RdQ\int_T^{\infty}(t-T)f(t)dt+BQ\int_0^T f(t)dt] \tag{12}$$

$$\begin{aligned}\hat{\pi}_{PF}^{SF}=&MQ-HQ\int_0^T(T-t)f(t)dt-CQ\int_T^{\infty}(t-T)f(t)dt-I_{PF}Q\int_0^{\infty}\left|T-t\right|f(t)dt+BQ\int_0^T f(t)dt\\&-(1-\alpha)[RdQ\int_T^{\infty}(t-T)f(t)dt+BQ\int_0^T f(t)dt]\end{aligned} \tag{13}$$

Though the double handling cost for late delivery should be paid directly by the PT, it is reasonable to require the PF to bear some fractions of this cost caused by such as his machine breakdowns and lack of raw materials. Since charging subsidy will shorten T and thus benefits the PCSC, potential "free-riding" may occur (He et al., 2021). As a matter of fact, it is justifiable to require the PF to share some fractions of the subsidy.

Proposition 4. To achieve win-win coordination, α should be within the following range (refer Appendix I):

$$\begin{aligned}\alpha\in[&\frac{(Rd+H+C+2I_{PF})e^{-\lambda T^{SF}}+\lambda(H+I_{PF})T^{SF}-I_{PF}+H(\frac{-Re}{Rd+Re}+\ln\frac{Re}{Rd+Re})}{Rde^{-\lambda T^{SF}}+\lambda B(1-e^{-\lambda T})},\\&\min(\frac{Re\ln\frac{Rd+Re}{\mathrm{Re}}+I_{PT}(1-2e^{-\lambda T^{SF}}-\lambda T^{SF})}{Rde^{-\lambda T^{SF}}+\lambda B(1-e^{-\lambda T^{SF}})},1)]\end{aligned} \tag{14}$$

Equation (14) provides the range of α that can achieve Pareto optimization. Within this interval, both the PT and the PF's profits can get better off than the traditional purchasing model, reaching a win-win situation. Since the PT bears the fraction $\alpha[RdQ\int_T^{\infty}(t-T)f(t)dt+BQ\int_0^T f(t)dt]$ and the rest is left to the PF, the PF benefits more from a high α, which is contrary to the PT.

4.3.2 Constant Transfer Cost Term

In reality, negotiating a deal within the above range may be time consuming. To ease this tension process, we introduce a constant transfer cost term γ that calculated by Nash arbitration scheme to fairly distribute the system-wide surplus generated by adopting the JITP strategy. A positive γ means that the money is paid by the PT to the PF and vice versa for a negative one. We now rewrite the profit functions (7) and (8) as follows:

$$\overline{\pi_{PT}^{SF}} = SQ - MQ - I_{PC}Q\int_0^\infty |T-t|\, f(t)dt - RdQ\int_T^\infty (t-T)f(t)dt - BQ\int_0^T f(t)dt - \gamma \tag{15}$$

$$\overline{\pi_{PF}^{SF}} = MQ - HQ\int_0^T (T-t)f(t)dt - PQ\int_T^\infty (t-T)f(t)dt - I_{PF}Q\int_0^\infty |T-t|\, f(t)d + BQ\int_0^T f(t)dt + \gamma \tag{16}$$

The optimal solutions of B and T in Eqs. (15) and (16) are the same as B^{SF} and T^{SF} in the incentive model. Following the basic rule of the Nash arbitration scheme, i.e. rationality, scale invariance, symmetry, and independence of irrelevant alternatives (Leng and Zhu, 2009), we have:

$$\underset{\Delta_1 \ge \Delta_1^0, \Delta_2 \ge \Delta_2^0}{Max} (\Delta_1 - \Delta_1^0)(\Delta_2 - \Delta_2^0),\ s.\,t(\Delta_1,\ \Delta_2) \in \wp \text{, where}$$

$$\Delta_1 = \overline{\pi_{PT}^{SF}} - \pi_{PT}^{TP} = \pi_{PT}^{SF} - \gamma - \pi_{PT}^{TP} = \tau_1 - \gamma\,,$$

$$\Delta_2 = \overline{\pi_{PF}^{SF}} - \pi_{PF}^{TP} = \pi_{PF}^{SF} + \gamma - \pi_{PF}^{TP} = \tau_2 + \gamma\,.$$

Here, we let $\begin{cases} \tau_1 = \pi_{PT}^{SF} - \pi_{PT}^{TP} \\ \tau_2 = \pi_{PF}^{SF} - \pi_{PF}^{TP} \\ \tau = \tau_1 + \tau_2 \end{cases}$, where τ denotes the system surplus gaining from adopting JITP strategy. Lemma 1 supports the $\tau > 0$. Δ_1 and Δ_1^0 denote the PT's allocated surplus and security level, respectively. Similarly, Δ_2 and Δ_2^0 denote the PF's allocated surplus and security level, respectively. $\wp$ is the Pareto optimal solutions' set. Any value on the set complies with the following two requirements: (i) it is Pareto-optimal; (ii) it is at or above both players' security levels (von Neumann and Morgenstern, 1944).

The security level is defined as the minimum surplus that ensures the benefits of the participants. To make both players better off, the security levels in our model should make $\Delta_1 \geq 0$, $\Delta_2 \geq 0$ true and thus are $(\Delta_1^0, \Delta_2^0) = (0,0)$. Fig. 3 shows the basic rules for obtaining γ and indicates that the middle point on the Pareto optimal set is the point of equally allocating τ.

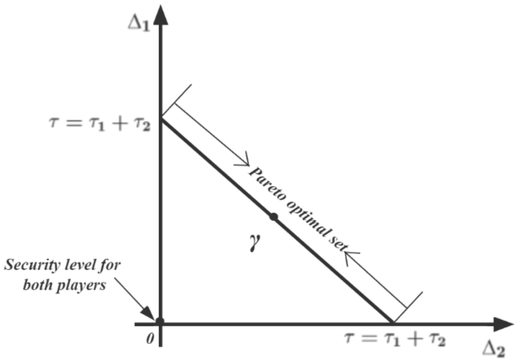


Fig. 3. Schematic diagram of calculating γ.

Then, we have: $\Delta_1=\Delta_2=\frac{\tau}{2}=\frac{\pi^{SF}-\pi^{TP}}{2}$, and the following equation can be obtained:

$$\gamma=\tau_1-\frac{\tau}{2}=\frac{\tau}{2}-\tau_2=\frac{(\pi_{PT}^{SF}-\pi_{PT}^{TP})-(\pi_{PF}^{SF}-\pi_{PF}^{TP})}{2} \tag{17}$$

Substituting Eqs. (1), (2), (3), (7) and (8) into Eq. (17), we get Proposition 5.

Proposition 5. Following the basic rule of Nash arbitration scheme, we have:

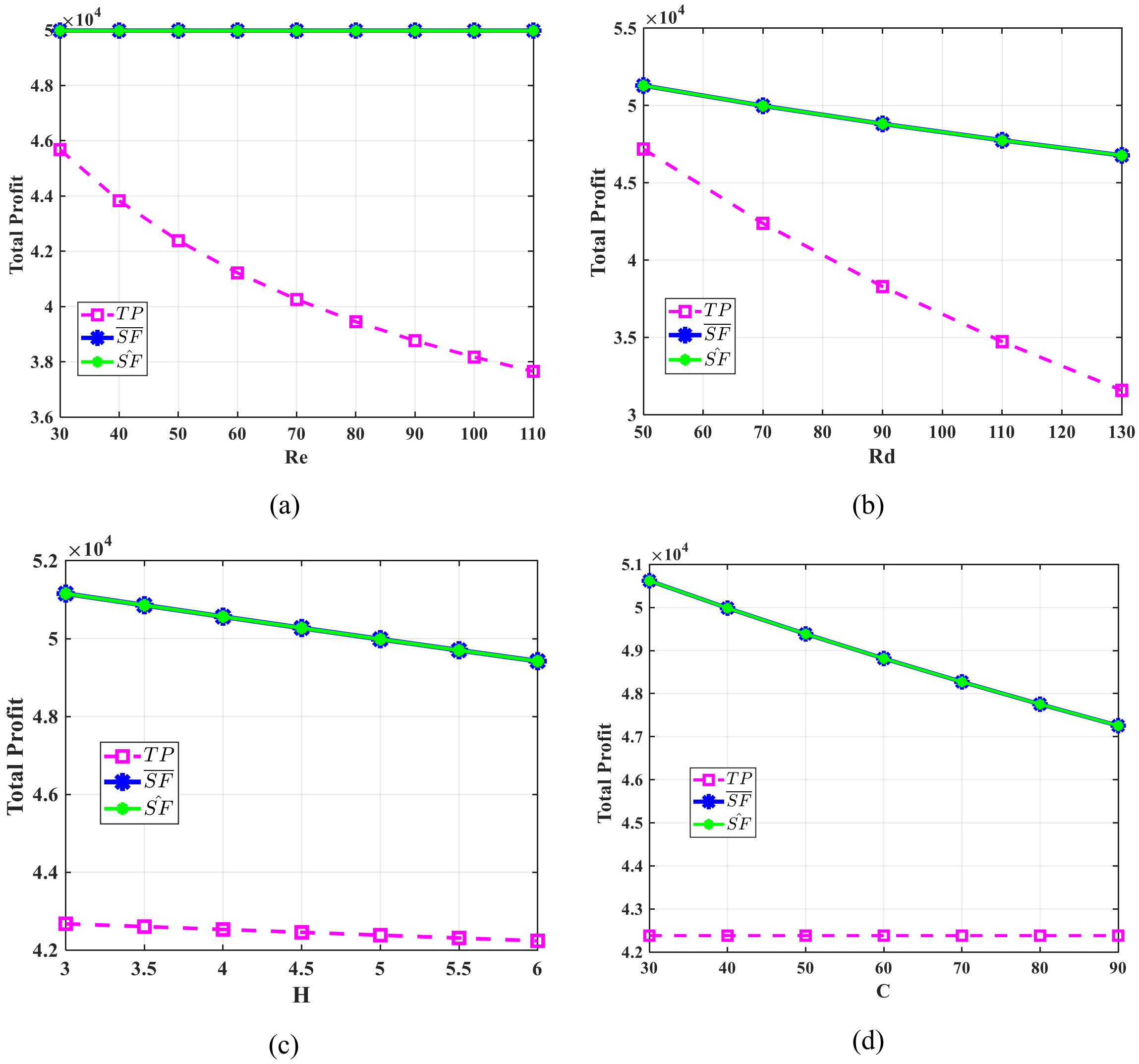
$$\gamma=\frac{(-R_d-2I_{PT}+C+H+2I_{PF})\,\mathrm{e}^{-\lambda T^{SF}}+\lambda T^{SF}(H+I_{PF}-I_{PT})+(I_{PT}-I_{PF}-\frac{HR_e}{R_e+R_d})+(H-R_e)\ln\frac{R_e}{R_e+R_d}}{2\lambda}\mathrm{Q}-BQ(1-\mathrm{e}^{-\lambda T^{SF}}) \tag{18}$$

Equation. (18) provides the unique γ value that can promote the fair distribution of the surplus between the two players. At the same time, it enables the Pareto optimization to be achieved. It is acceptable to both the PT and the PF, for the profit of each party under this coordination mechanism is higher than the traditional purchasing model, achieving a win-win outcome.

5. Numerical Studies and Managerial Implications

5.1 Numerical Studies

In this section, numerical studies are conducted to verify the efficiency of the proposed coordination mechanism and investigate the impact of major factors on the profits of the PCSC as a whole as well as each party. The numerical studies are performed based on the sensitivity analysis of four parameters: the double handling cost for early delivery Re, the double handling cost for late delivery Rd, the inventory holding cost H, and the production compression cost C. The values of these parameters are carefully set based on practical observations in the PCSCM and related literature (Pheng and Jayawickrama, 2012; Zhai et al., 2017; Zhai et al., 2018; Zhai et al., 2019b). The parameters are initially set as: $S=1300$, $M=300$, $Q=50$, $Re=50$, $Rd=70$, $H=5$, $C=40$, $I_{PT}=3$, $I_{PF}=2$, and $\lambda=0.1$. SFL denotes the lower bound of α, SFU denotes the upper bound of α, and SFN denotes the constant transfer cost term in the figs below.



(a)

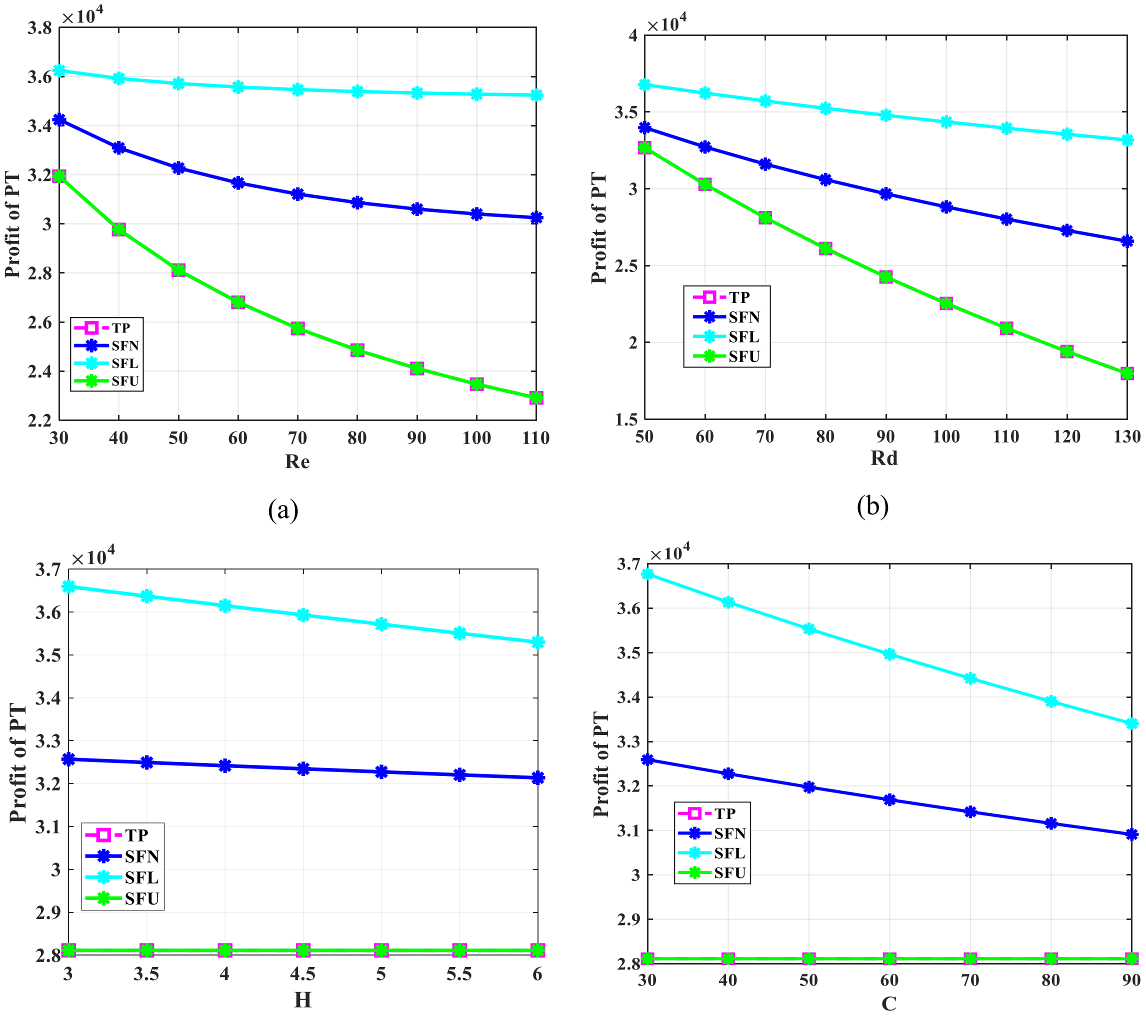
(b)

(c)

(d)

Fig. 4. The effect of Re, Rd, H and C on π.

Figs. 4 reflect the influence of Re, Rd, H and C on total supply chain profit. As we can see from Fig. 4 (a), (b), (c), and (d), the profits of the PCSC under the proposed models are higher than the traditional purchasing model. That is to confirm that adopting the JITP strategy can effectively reduce double handling costs and benefit the whole supply chain. As shown in Fig. 4 (a) and (b), the total system profit level of the traditional purchasing model decreases even more sharply with double handling costs than that of the proposed models. For example, if the double handling cost for early delivery increases 20.0% as in Table 5, the profit of the PCSC will not be affected in proposed model but will decrease 2.9% in traditional purchasing model. When the double handling for late delivery increases 20.0%, the channel suffers from 6.9% profit loss in the traditional purchasing model. In contrast, total profit only decreases by 1.7% under the proposed model. We can explain it as follows: under the proposed coordination contracts, both parties cooperate to implement JITP. The improper delivery is greatly improved after involving JITP strategy. Thus, the negative impacts of double handling costs are mitigated.



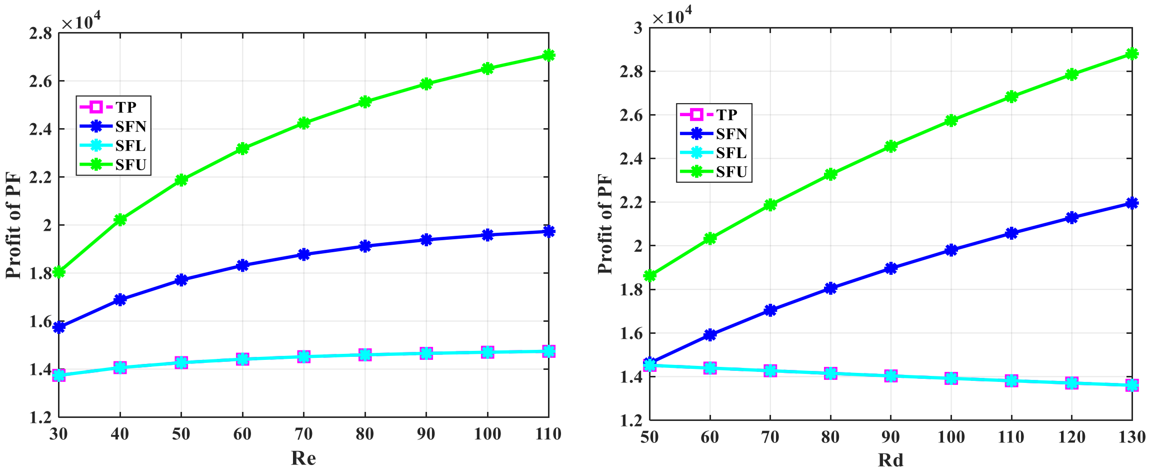
(a) (b)

(c) (d)

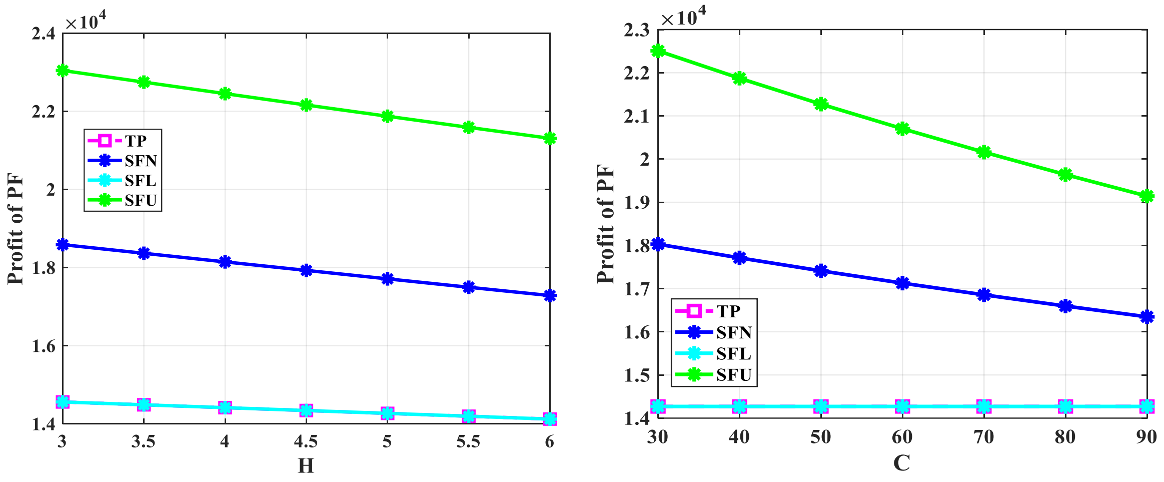
Fig. 5. The effect of Re, Rd, H and C on π_{PT}.

Fig. 5 depicts that the PT's profits under the proposed models are no less than under the traditional purchasing model. That confirms that both constant cost-sharing transfer term and constant transfer cost term can protect PT's interests in JITP. In addition, there are more parameters to cause a negative effect on the PT's profit in proposed coordination mechanism, but its profit remains higher than in the traditional purchasing model. The result seems paradoxical but can be explained: the JITP strategy makes the supply chain as a whole more profitable by effectively reducing double handling costs. Following the coordination mechanism, the system surplus is then allocated between the PT and the PF. So that the negative impacts of these parameters on the PT are offset by sharing of this larger system surplus.

As shown in Figs. 5 (a) and (b), under the traditional purchasing model, the profit of the PT is seriously affected by double handling costs both for early delivery and late delivery. For example, the PT's profit decreases by 5.9% and 9.8%, respectively, if the double handling costs for early delivery and late delivery increase by 20.0%. It only suffers from 0.0% and 1.5% profit loss, respectively under the proposed constant transfer cost term, however. A natural way to explain this is that, JITP runs smoothly under the proposed coordination contracts, reducing improper delivery. Therefore, negative impacts of the double handling costs are greatly mitigated, as compared to the traditional purchasing model. We can see from the Fig. 5 (c) that the profit of the PT is decreasing with the inventory holding cost H under the proposed coordination model. Intuitively, if the inventory holding cost is high, the PF will feel pressure to implement the JITP strategy. Therefore, the PF will charge more subsidy for a compensation. As a result, there will be a drop off in profit for the PT. In Fig. 5 (d), we can see that if the production compression cost C is sufficiently expensive, the choice to adopt the JITP strategy is trivial. The explanation for this is that a higher C means a larger cost for the PF to compress its production time. With less subsidy as described in Corollary 4, the PF loses the incentive to deliver on time which prevents the PT from benefiting from the JITP.



(a) (b)



(c) (d)

Fig. 6. The effect of Re, Rd, H and C on π_{PF}.

In Fig. 6, we can see that the PF's profits under the proposed models are also no less than under the traditional purchasing model. That is to confirm that a win–win outcome is achievable under the proposed coordination mechanisms. In particular, the PF reaps more benefit from the proposed constant transfer cost term than the PT. As shown in Table 5, the profit of the PF increases by 24.1% compared to the traditional purchasing model, while the PT's profit increases by 14.8%. It is common sense to assume that if one has more power, one will safeguard its own interests.

In Fig. 6 (a) and (b), completely opposite to the PT's situation under the coordination mechanism, it is extremely surprising to find that the PF's profit significant increases as the double handling cost for early or late delivery increases. We can explain it as follows: if the double handling cost for early or late delivery is high, the PT will bear the heavy double handling costs. Thus, the PT would rather invest more into the JITP strategy to reduce expensive double handling costs than suffer from a heavy loss. This empowers the PF to charge more subsidy when adopts the JITP strategy, leading to an increase in the PF's profit. Fig. 6 (c) shows that the PF's profits decline more in the proposed models than in traditional purchasing model. This is due to the fact that under the proposed scheme, both parties cooperate to implement JITP. The PF invariably holds more inventory under JITP, incurring higher inventory holding expenses (Gunasekaran, 1999; Wu et al., 2013). As shown in Fig. 6 (d), the PF's profits under the proposed models seriously decreases with increasing price of production compression cost C. The explanation for this is as follow: a large C indicates a larger gap between quoted delivery time and response time, which increases probability of improper delivery and thus leads to less subsidy. With a larger cost and less subsidy, therefore, the PF sees fall in its profit.

Table 5

Sensitive analysis of π, $\overline{\pi}_{PT}$, $\overline{\pi}_{PF}$ with respect to Re, Rd, H and C.

		Re			***Rd***			***H***			***C***	
Value	40	50	60	56	70	84	4	5	6	32	40	48
%	-20.0%	0.0%	20.0%	-20.0%	0.0%	20.0%	-20.0%	0.0%	20.0%	-20.0%	0.0%	20.0%
π^{TP}	43830 3.4%	42383 0.0%	41217 -2.8%	45657 7.7%	42383 0.0%	39457 -6.9%	42529 0.3%	42383 0.0%	42237 -1.5%	42383 0.0%	42383 0.0%	42383 0.0%
π^{SF}	49986 0.0%	49986 0.0%	49986 0.0%	50885 1.8%	49986 0.0%	49154 -1.7%	50564 1.2%	49986 0.0%	49420 -1.1%	50490 1.0%	49986 0.0%	49503 -1.0%
$\overline{\pi}^{TP}_{PT}$	29768 5.9%	28113 0.0%	26804 -4.7%	31215 11.0	28113 0.0%	25355 -9.8%	28113 0.0%	28113 0.0%	28113 0.0%	28113 0.0%	28113 0.0%	28113 0.0%
$\overline{\pi}^{SF}_{PT}$	33095 2.5%	32274 0.0%	31668 1.9%	34336 6.4%	32274 0.0%	30472 -5.6%	32418 0.5%	32274 0.0%	32136 -0.4%	32526 0.8%	32274 0.0%	32033 -0.8%
$\overline{\pi}^{TP}_{PF}$	14062 -1.5%	14270 0.0%	14413 1.0%	14442 1.2%	14270 0.0%	14103 1.2%	14416 1.0%	14270 0.0%	14124 1.5%	14270 0.0%	14270 0.0%	14270 0.0%
$\overline{\pi}^{SF}_{PF}$	16890 4.6%	17711 0.0%	18318 3.4%	16550 6.6%	17711 0.0%	18682 -5.5%	18146 2.5%	17711 0.0%	17284 -2.4%	17135 3.2%	17711 0.0%	16604 -6.2%

5.2 Managerial Implications

From a managerial perspective, mathematical and numerical analysis leads us to several key implications. First, as demonstrated above, the JITP strategy can effectively reduce double handling costs and achieve a more profitable system by improving on-time delivery performance. In PCSCM, it is the PT who manages project's time and cost on behalf of the client. Thus, the PT should actively promote JITP in PCSC. Moreover, the systematic profit gap between the models with and without JITP strategy continues to widen as Re or Rd increases. Thus, there is a pressing need for the PT with a high double handling cost to adopt JITP.

Second, the PT and PF would better participate in the proposed coordination mechanisms, for the "subsidy and cost-sharing term" and "subsidy and constant transfer cost term" effectively benefit the two parties. Under constant transfer cost term, the profits of both parties are located between the upper and lower bounds of cost-sharing rate. When the participants in PCSC are more concerned with fairness, constant transfer cost term is preferred for them. When double handling costs is high, the profit of the PF increases more significantly under the cost-sharing term, and the profit of the PT becomes more stable. Therefore, the cost-sharing term is recommended.

Third, a higher double handling cost for early or late delivery can be viewed as an opportunity for the PF to expand its profit under the coordination mechanisms, and the higher the double handling costs are, the greater the potential profit can be. Moreover, the PF should emphasize the importance of including the subsidy in the coordination mechanisms, which can shorten delivery time, leading to a more profitable supply chain in the long run. By charging subsidy, the losses to the PF from participating in JITP can also be compensated.

Fourth, the PT should pay more attention to production compression cost and average response time of the PF when adopts JITP. The greater production compression cost, the less benefits for both parties. In addition, a shorten average response time can reduce the subsidy paid by the PT. Therefore, the PT would better select a PF with a lower production compression cost and quick response time when implementing JITP.

6. Conclusions

Early or late delivery of prefabs in the PCSC can cause heavy double handling cost for the PT, and is the major reason for project overrun and overspend. To improve on-time delivery performance of prefabs, the PT can require the PF to implement JITP. This paper explored coordination scheme for a PT and a PF in the operation of JITP. The traditional purchasing model was studied as benchmark. Then, a delivery-time dependent subsidy was added into a Stackelberg game model to incentivize the PF on-time delivery. Employing a constant cost-sharing transfer term, we derived the interval that enables Pareto optimization. To further provide a more convenient negotiation mechanism, we following the basic rule of Nash arbitration scheme, introduced a constant transfer cost term that can fairly distribute the system-wide surplus.

The results of our mathematical and numerical analysis show that JITP can effectively reduce double handling costs and increase the total profits of the PCSC. In addition, both coordination mechanisms work well, in terms of solving the conflict caused by the JITP strategy and mutually benefiting the both players. In particular, when participants are concerned with fairness, the constant transfer cost term is preferable. When double handling costs is high, the constant cost-sharing transfer term performs better. Moreover, and perhaps counterintuitively, the PF actually earns higher profits when the double handling cost for early or late delivery is high, while the PT and the PCSC see the lower profits. Finally, a longer average response time and a prohibitively expensive production compression cost for the PF may impose challenges on adopting the JITP strategy.

There exist several future research extensions to improve this study. First, this paper considers that the PF has more power and builds a PF led Stackelberg game model to carry out coordination scheme. Other models with different power structures, i.e. PT led Stackelberg game model, Nash game model, can also be taken into consideration and thus broaden the application of our coordination mechanism. Second, following an increasing awareness of environmental protection, a valuable extension is to explore both the economic and environmental benefits of JITP in the PCSCM domain.

Acknowledgements

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Appendixes

Appendix A

Before adopting the JITP strategy, the maximum profit of PT could be obtained by optimizing T^{TP}. That is:

$$\pi_{PT}^{TP} = SQ - MQ - ReQ\int_0^T (T-t)f(t)dt - RdQ\int_T^\infty (t-T)f(t)dt .$$

The first derivative is:

$\dfrac{d\pi_{PT}^{TP}}{dT} = RdQe^{-\lambda T} + ReQe^{-\lambda T} - ReQ$, and its second derivative is:

$$\frac{d^2\pi_{PT}^{TP}}{dT^2} = -\lambda RdQe^{-\lambda T} - \lambda ReQe^{-\lambda T} \le 0 .$$

Thus, the profit of the PT is concave. The optimal T^{TP} is obtained by equating the first derivate to zero. Then we have $T^{TP} = -\dfrac{1}{\lambda}\ln\dfrac{Re}{Rd+Re}$.

Appendix B

In JITP model without coordination, the PT takes its own profit maximization into consideration ignoring the loss of PF profit. Here we get its first derivative with respect to T^{JIT}:

$$\frac{d\pi_{PT}^{JIT}(T)}{dT} = -I_{PT}Q + RdQe^{-\lambda T} + 2I_{PT}Qe^{-\lambda T} .$$

While its second derivative is:

$$\frac{d^2\pi_{PT}^{JIT}(T)}{dT^2} = -\lambda RdQe^{-\lambda T} - 2\lambda I_{PT}Qe^{-\lambda T} \leq 0 .$$

So, we find that $\pi_{PT}^{JIT}(\mathrm{T})$ is concave, for its second order derivative $\frac{d^2\pi_{PT}^{JIT}(T)}{dT^2} < 0$. From this point of view, the maximum value is obtained when the first derivative equals zero. Then we get $T^{JIT} = -\frac{1}{\lambda}\ln\frac{I_{PT}}{Rd + 2I_{PT}}$.

Appendix C

The PF's profits under the traditional purchasing model and JITP model without coordination are as follow:

$$\pi_{PF}^{TP} = MQ - HQ\int_0^{T^{TP}} (T^{TP} - t)f(t)dt ,$$

$$\pi_{PF}^{JIT} = MQ - HQ\int_0^{T^{JIT}} (T^{JIT} - t)f(t)dt - CQ\int_{T^{JIT}}^{\infty} (t - T^{JIT})f(t)dt - I_{PF}Q\int_0^{\infty} \left|T^{JIT} - t\right| f(t)dt .$$

To distinguish the cost of inventory holding cost in above models, we use T^{TP} and T^{JIT} to make a distinction. Taking the difference between π_{PF}^{TP} and π_{PF}^{JIT}, we can get:

$$\pi_{PF}^{JIT} - \pi_{PF}^{TP} = -CQ\int_{T^{JIT}}^{\infty} (t - T^{JIT})f(t)dt - I_{PF}Q\int_0^{\infty} \left|T^{JIT} - t\right| f(t)dt - HQ\int_0^{T^{JIT}} (T^{JIT} - t)f(t)dt$$
$$+HQ\int_0^{T^{TP}} (T^{TP} - t)f(t)dt.$$

Since the PF's inventory holding cost associated with JITP is higher than traditional purchasing mode (Gunasekaran, 1999; Wu et al., 2013), then we have $\pi_{PF}^{JIT} - \pi_{PF}^{TP} < 0$. Thus, adopting JITP reduces the profit of the PF.

Appendix D

The first derivation of $\pi_{PT}^{SF}(T,B)$ is:

$$\frac{\partial\pi_{PT}^{SF}(T,B)}{\partial T} = RdQe^{-\lambda T} + 2I_{PT}Qe^{-\lambda T} - I_{PT}Q - \lambda BQe^{-\lambda T} .$$

And the second derivative is:

$$\frac{\partial^2 \pi_{PT}^{SF}(T,B)}{\partial T^2} = -\lambda RdQe^{-\lambda T} - 2\lambda I_{PT}Qe^{-\lambda T} + \lambda^2 BQe^{-\lambda T}.$$

If $B > \frac{Rd+2I_{PT}}{\lambda}$, $\frac{\partial^2 \pi_{PT}^{SF}(T,B)}{\partial T} = RdQe^{-\lambda T} + 2I_{PT}Qe^{-\lambda T} - I_{PT}Q - \lambda BQe^{-\lambda T} > 0$. It means that the subsidy that PF charges from PT has exceeded the benefits that the PT can obtain through adopting JITP strategy. On this account, there is no need to implement JITP in the supply chain. Therefore, we do not consider this situation.

If $B \le \frac{Rd+2I_{PT}}{\lambda}$, $\frac{\partial^2 \pi_{PT}^{SF}(T,B)}{\partial T^2} \le 0$. So, $\pi_{PT}^{SF}(T,B)$ is a concave function. By computing its first derivation equals to 0, we have:

$$T^{SF} = -\frac{1}{\lambda}\ln\frac{I_{PT}}{Rd + 2I_{PT} - \lambda B^{SF}}.$$

Substituting the optimal T^{SF} into the PF's profit function, the function can be rewritten as:

$$\pi_{PF}^{SF}(\mathrm{B}) = MQ + \frac{(I_{PF}+H)Q}{\lambda}\ln\frac{I_{PT}}{Rd+2I_{PT}-\lambda B} - \frac{(H+C+2I_{PF})Q}{\lambda}\frac{I_{PT}}{Rd+2I_{PT}-\lambda B}$$
$$+\frac{(H+I_{PF})Q}{\lambda} + BQ(1-\frac{I_{PT}}{Rd+2I_{PT}-\lambda B}).$$

The first derivation of $\pi_{PF}^{SF}(B)$ is:

$$\frac{d\pi_{PF}^{SF}(B)}{dB} = Q[1+\frac{(I_{PF}+H)}{Rd+2I_{PT}-\lambda B} - \frac{I_{PT}(H+Rd+C+2I_{PT}+2I_{PF})}{(Rd+2I_{PT}-\lambda B)^2}].$$

Computing the first derivative $\frac{d\pi_{PF}^{SF}(B)}{dB} = 0$, we get the extreme point:

$$B_{1,2} = \frac{2Rd + H + I_{PF} + 4I_{PT} \mp \sqrt{(H+I_{PF}+4I_{PT})^2 + 4I_{PT}(Rd+C-H-2I_{PT})}}{2\lambda}.$$

Since $B < \frac{Rd+2I_{PT}}{\lambda}$, we have:

$$B^{SF} = \frac{2Rd + H + I_{PF} + 4I_{PT} - \sqrt{(H+I_{PF}+4I_{PT})^2 + 4I_{PT}(Rd+C-H-2I_{PT})}}{2\lambda}.$$

Next, we need to demonstrate $\pi_{PT}^{SF}(B)$ is quasi-concave and B is maximum value point. We let B^* satisfies:

$$1-\frac{1}{Rd+2I_{PT}-\lambda B^*}[-I_{PF}-H+\frac{I_{PT}(H+Rd+C+2I_{PT}+2I_{PF})}{Rd+2I_{PT}-\lambda B^*}]=0. \tag{D.1}$$

Case 1: when $B<B^*$, we have: $\frac{1}{Rd+2I_{PT}-\lambda B} < \frac{1}{Rd+2I_{PT}-\lambda B^*}$, and $\frac{I_{PT}(H+Rd+C+2I_{PT}+2I_{PF})}{Rd+2I_{PT}-\lambda B}<\frac{I_{PT}(H+Rd+C+2I_{PT}+2I_{PF})}{Rd+2I_{PT}-\lambda B^{*}}$.

If $-I_{PF}-H+\frac{I_{PT}(H+Rd+C+2I_{PT}+2I_{PF})}{Rd+2I_{PT}-\lambda B}>0$, then we have:

$$1-\frac{1}{Rd+2I_{PT}-\lambda B}[-I_{PF}-H+\frac{I_{PT}(H+Rd+C)}{Rd+2I_{PT}-\lambda B}]>1-\frac{I_{PC}}{Rd+2I_{PT}-\lambda B^{*}}[-I_{PF}-H+\frac{I_{PT}(H+Rd+C)}{Rd+2I_{PT}-\lambda B^{*}}].$$

If $-I_{PF}-H+\frac{I_{PT}(H+Rd+C+2I_{PT}+2I_{PF})}{Rd+2I_{PT}-\lambda B}\leq 0$, and from Eq. (D.1) we can know that $-I_{PF}-H+\frac{I_{PT}(H+Rd+C+2I_{PT}+2I_{PF})}{R_d+2I_{PT}-\lambda B^{*}}>0$. Then we have:

$$\begin{aligned}&1-\frac{1}{Rd+2I_{PT}-\lambda B}[-I_{PF}-H+\frac{I_{PT}(H+Rd+C+2I_{PT}+2I_{PF})}{Rd+2I_{PT}-\lambda B}]>1\\&-\frac{1}{Rd+2I_{PT}-\lambda B^{*}}[-I_{PF}-H+\frac{I_{PT}(H+Rd+C+2I_{PT}+2I_{PF})}{Rd+2I_{PT}-\lambda B^{*}}]=0.\end{aligned}$$

Thus, when $B<B^{*}$, we think $\pi_{PF}^{SF}(B)$ is increasing with B.

Case 2: when $B>B^{*}$, we have:

$$\frac{1}{Rd+2I_{PT}-\lambda B}>\frac{1}{Rd+2I_{PT}-\lambda B^{*}}\text{, and }\frac{I_{PT}(H+Rd+C+2I_{PT}+2I_{PF})}{Rd+2I_{PT}-\lambda B}>\frac{I_{PT}(H+Rd+C+2I_{PT}+2I_{PF})}{Rd+2I_{PT}-\lambda B^{*}}.$$

Considering $-I_{PF}-H+\frac{I_{PT}(H+Rd+C+2I_{PT}+2I_{PF})}{R_d+2I_{PT}-\lambda B^{*}}>0$, then we have:

$$\begin{aligned}&1-\frac{1}{Rd+2I_{PT}-\lambda B}[-I_{PF}-H+\frac{I_{PT}(H+Rd+C+2I_{PT}+2I_{PF})}{Rd+2I_{PT}-\lambda B}]<\\&1-\frac{1}{Rd+2I_{PT}-\lambda B^{*}}[-I_{PF}-H+\frac{I_{PT}(H+Rd+C+2I_{PT}+2I_{PF})}{Rd+2I_{PT}-\lambda B^{*}}]=0.\end{aligned}$$

Thus, when $B<B^{*}$, $\pi_{PT}^{SF}(B)$ is decreasing with B.

Therefore $\pi_{PT}^{SF}(B)$ is quasi-concave and B^{*} is maximum value point. Since $\pi_{PT}^{SF}(T,B)$ is a concave and $\pi_{PT}^{SF}(B)$ is quasi-concave, the Stackelberg equilibrium exist.

Appendix E

Using Eq. (1) plus (2) to get the whole chain profit π^{TP} , and using Eq. (7) plus (8) to get the whole chain profit π^{SF} . We have:

$$\pi^{TP}=SQ-ReQ\int_0^T(T-t)f(t)dt-RdQ\int_T^{\infty}(t-T)f(t)dt-HQ\int_0^T(T-t)f(t)dt\,, \tag{E.1}$$

$$\begin{aligned}\pi^{SF}&=SQ-RdQ\int_T^{\infty}(t-T)f(t)dt-I_{PT}Q\int_0^{\infty}|T-t|\,f(t)dt-HQ\int_0^T(T-t)f(t)dt\\&-CQ\int_T^{\infty}(t-T)f(t)dt-I_{PF}Q\int_0^{\infty}|T-t|\,f(t)dt.\end{aligned} \tag{E.2}$$

Substituting Eq. (3) into Eq. (E.1), we have:

$$\pi^{TP} = SQ+\frac{(Re+H)Q}{\lambda}\ln\frac{Rd}{Rd+Re}+\frac{H}{\lambda}Q(1-\frac{Rd}{Rd+Re})\,. \tag{E.3}$$

Letting Eq. (E.2) is greater than Eq. (E.3), we can get Lemma 1.

Appendix F

This part provides the derivation process of B with respect to $^{1}/_{\lambda}$, Re, Rd, H and C.

(1) Since $\frac{\partial B^{SF}}{\partial\, {}^{1}/_{\lambda}}>0$, $\frac{\partial B^{SF}}{\partial Re}=0$ are intuitive and thus omitted.

(2) The first derivative of $B^{SF}(Rd)$ is

$$\frac{\partial B^{SF}}{\partial Rd}=\frac{1}{\lambda}(\frac{\sqrt{4I_{PT}(C-H-2I_{PT}+Rd)+(H+4I_{PT}+I_{PF})^2}-I_{PT}}{\sqrt{4I_{PT}(C-H-2I_{PT}+Rd)+(H+4I_{PT}+I_{PF})^2}})\,.$$

Since $4I_{PT}(C-H-2I_{PT}+Rd)+(H+4I_{PT}+I_{PF})^2-I_{PT}^2=7I_{PT}^2+4I_{PT}(C-H+Rd)\frac{1}{\lambda}$ $+(H+I_{PF})^2+8I_{PT}(H+I_{PF})$, and the inventory holding cost and production compression cost is relatively lower (compared with the double handling cost for late delivery) (Pheng and Jayawickrama 2012), $C-H+Rd>0$ is usually held in a PCSC. Thus, $\sqrt{4I_{PT}(C-H-2I_{PT}+Rd)+(H+4I_{PT}+I_{PF})^2}-I_{PT}>0$. So, we have $\frac{\partial B^{SF}}{\partial Rd}>0$.

(3) The first derivative of $B^{SF}(H)$ is

$$\frac{\partial B^{SF}}{\partial H}=\frac{1}{2\lambda}(\frac{\sqrt{4I_{PT}(C-H-2I_{PT}+Rd)+(H+4I_{PT}+I_{PF})^2}-2I_{PT}+(H+4I_{PT}+I_{PF})}{\sqrt{4I_{PT}(C-H-2I_{PT}+Rd)+(H+4I_{PT}+I_{PF})^2}})\,.$$

Letting $\sqrt{4I_{PT}(C-H-2I_{PT}+Rd)+(H+4I_{PT}+I_{PF})^2}>2I_{PT}+(H+4I_{PT}+I_{PF})$, we have $4I_{PT}(I_{PF}+I_{PT}+C+Rd)>0$. Thus, we have $\frac{\partial B^{SF}}{\partial H}>0$.

(4) The first derivative of $B^{SF}(C)$ is

$$\frac{\partial B^{SF}}{\partial H}=-\frac{I_{PT}}{\lambda\sqrt{4I_{PT}(C-H-2I_{PT}+Rd)+(H+4I_{PT}+I_{PF})^2}}<0\,.$$

Appendix G

Substituting T^{JIT} and T^{SF} into Eq. (5) and (8), we have:

$$\pi_{PF}^{JIT}(\mathrm{B})=MQ+\frac{(I_{PF}+H)Q}{\lambda}\ln\frac{I_{PT}}{Rd+2I_{PT}}-\frac{(H+C+2I_{PF})Q}{\lambda}\frac{I_{PT}}{Rd+2I_{PT}}+\frac{(H+I_{PF})Q}{\lambda}\,,$$

$$\pi_{PF}^{SF}(\mathrm{B})=MQ+\frac{(I_{PF}+H)Q}{\lambda}\ln\frac{I_{PT}}{Rd+2I_{PT}-\lambda B}-\frac{(H+C+2I_{PF})Q}{\lambda}\frac{I_{PT}}{Rd+2I_{PT}-\lambda B}$$
$$+\frac{(H+I_{PF})Q}{\lambda}+BQ(1-\frac{I_{PT}}{Rd+2I_{PT}-\lambda B}).$$

Since B^{SF} leads to the maximum value for $\pi_{PF}^{SF}(B)$, which is strictly quasi-concave on B, and $B^{JIT}=0<B^{SF}$, thus, $\pi^{JIT}{}_{PF}>\pi^{SF}{}_{PF}$.

Appendix H

Substituting T^{JIT} and T^{SF} into Eqs. (4) and (7), we have:

$$\pi_{PT}^{JIT}=SQ-MQ-\frac{I_{PT}(Rd+2I_{PT})Q}{\lambda(Rd+2I_{PT})}+\frac{I_{PT}Q}{\lambda}\ln\frac{I_{PT}}{Rd+2I_{PT}}+\frac{I_{PT}Q}{\lambda},$$

$$\pi_{PT}^{SF}=SQ-MQ-\frac{I_{PT}(Rd+2I_{PT})Q}{\lambda(Rd+2I_{PT}-\lambda B)}+\frac{I_{PT}Q}{\lambda}\ln\frac{I_{PT}}{Rd+2I_{PT}-\lambda B}+\frac{I_{PT}Q}{\lambda}-BQ(1-\frac{I_{PT}}{Rd+2I_{PT}-\lambda B}).$$

Letting

$$f(B)=SQ-MQ-\frac{I_{PT}(Rd+2I_{PT})Q}{\lambda(Rd+2I_{PT}-\lambda B)}+\frac{I_{PT}Q}{\lambda}\ln\frac{I_{PT}}{Rd+2I_{PT}-\lambda B}+\frac{I_{PT}Q}{\lambda}-BQ(1-\frac{I_{PT}}{Rd+2I_{PT}-\lambda B}),$$

its first derivation is: $f^{'}(B)=\dfrac{I_{PT}(Rd+2I_{PT}-\lambda B)Q-(Rd+2I_{PT}-\lambda B)^2Q}{(Rd+2I_{PT}-\lambda B)^2}$.

Since $I_{PT}<(Rd+2I_{PT}-\lambda B)$, then, $f^{'}(B)<0$, which means $f(B)$ is decreasing with B. And, $B^{JIT}=0<B^{SF}$, thus we have $\pi_{PT}^{JIT}>\pi_{PT}^{SF}$.

Appendix I

In order to reach win–win coordination, the conditions can be set as follow:

$$\begin{cases} T=T^{SF}, \\ B=B^{SF}, \\ \overset{\wedge}{\pi}{}_{PT}^{SF}>\pi_{PT}^{TP}, \\ \overset{\wedge}{\pi}{}_{PF}^{SF}>\pi_{PF}^{TP}, \\ 0\le\alpha\le1. \end{cases}$$

From the $\overset{\wedge}{\pi}{}_{PT}^{SF}>\pi_{PT}^{TP}$, we have $\alpha<\dfrac{Re\ln\dfrac{Rd+Re}{\mathrm{Re}}+I_{PT}(1-2e^{-\lambda T^{SF}}-\lambda T^{SF})}{Rde^{-\lambda T^{SF}}+\lambda B(1-e^{-\lambda T^{SF}})}$. Similarly, with the $\overset{\wedge}{\pi}{}_{PF}^{SF}>\pi_{PF}^{TP}$, $\alpha>\dfrac{(Rd+H+C+2I_{PF})e^{-\lambda T^{SF}}+\lambda(H+I_{PF})T^{SF}-I_{PF}+H(\dfrac{-Re}{Rd+Re}+\ln\dfrac{Re}{Rd+Re})}{Rde^{-\lambda T^{SF}}+\lambda B(1-e^{-\lambda T})}$ can be obtained. If the lower bound $\dfrac{(Rd+H+C+2I_{PF})e^{-\lambda T^{SF}}+\lambda(H+I_{PF})T^{SF}-I_{PF}+H(\dfrac{-Re}{Rd+Re}+\ln\dfrac{Re}{Rd+Re})}{Rde^{-\lambda T^{SF}}+\lambda B(1-e^{-\lambda T})}>1$, it means

JITP strategy extremely costly for the PF, and even charging subsidy cannot cover these costs. In this case, adopting JITP is in vain. If the upper bound $\frac{Re\ln\frac{Rd+Re}{\mathrm{Re}}+I_{PT}(1-2e^{-\lambda T^{SF}}-\lambda T^{SF})}{Rde^{-\lambda T^{SF}}+\lambda B(1-e^{-\lambda T^{SF}})}>1$, it means that even without this cost-sharing contract, i.e. $\alpha = 1$, the PT can still benefit from JITP. In this case, the upper bound should be 1. If both $\frac{(Rd+H+C+2I_{PF})e^{-\lambda T^{SF}}+\lambda(H+I_{PF})T^{SF}-I_{PF}+H(\frac{-Re}{Rd+Re}+\ln\frac{Re}{Rd+Re})}{Rde^{-\lambda T^{SF}}+\lambda B(1-e^{-\lambda T})}$ and $\frac{Re\ln\frac{Rd+Re}{\mathrm{Re}}+I_{PT}(1-2e^{-\lambda T^{SF}}-\lambda T^{SF})}{Rde^{-\lambda T^{SF}}+\lambda B(1-e^{-\lambda T^{SF}})}$ are less than 1, from Eq. (11), we have

$$\frac{(Rd+H+C+2I_{PF})e^{-\lambda T^{SF}}+\lambda(H+I_{PF})T^{SF}-I_{PF}+H(\frac{-Re}{Rd+Re}+\ln\frac{Re}{Rd+Re})}{Rde^{-\lambda T^{SF}}+\lambda B(1-e^{-\lambda T})}<\frac{Re\ln\frac{Rd+Re}{\mathrm{Re}}+I_{PT}(1-2e^{-\lambda T^{SF}}-\lambda T^{SF})}{Rde^{-\lambda T^{SF}}+\lambda B(1-e^{-\lambda T^{SF}})}.$$

Thus, we can get the Proposition 4.

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