RAIRO-Oper. Res. 58 (2024) 5029–5049
https://doi.org/10.1051/ro/2024209

RAIRO Operations Research
www.rairo-ro.org

OPTIMAL FORWARD CONTRACT DESIGN IN A SUPPLY CHAIN WITH ASYMMETRIC COST INFORMATION

Yuanyuan Luo*

Abstract. In a buyer-led supply chain, the buyer utilizes a forward contract to effectively cope with the risk brought about by uncertainty in demand and raw material prices. However, the production cost, as private information of the supplier, will inevitably affect the formulation of a forward contract. This study constructs a procurement system consisting of a buyer, a supplier, and an imperfect spot market to explore how the buyer designs the forward contract under asymmetric cost information. By applying the principal-agent theory, this study allows the buyer to maximize profits while disclosing the supplier's cost information. The results obtained indicate that in order to screen the cost type, the forward order quantity from the high-cost supplier is downward distorted. Asymmetric cost information reduces the buyer's profits, but brings additional information rent to the supplier. Interestingly, it is also observed that asymmetric material cost information can discourage the buyer from engaging in speculative activities in the spot market. While the existence of a well-developed raw material spot market with a reduced price provides the buyer with an alternative means of procurement, which mitigates the negative impacts of his cost information disadvantages.

Mathematics Subject Classification. 91A80.

Received November 29, 2023. Accepted October 25, 2024.

1. Introduction

Enterprises are currently facing the dual uncertainties of demand and price with the increasingly fierce market competition and the volatile product demand. Particularly, when they engage in the trade of commodities with lengthy lead times such as semiconductors, agricultural products, commodity metals, and chemical items, which are characterized by unpredictable trends [20]. Thus, finding ways to make the supply of products match the demand as much as possible is a prevalent challenge encountered by those enterprises.

Taking into account the unpredictable demand, it is advisable to make preparations for procurement well ahead of the selling season. With the development and popularization of internet technology, the utilization of B2B spot markets is considered an efficient approach for mitigating the risks associated with supply-demand imbalances in the supply chain. In China, B2B spot markets have been witnessed to make great progress in the past few years. According to related data analysis, the total value of trade in China's commodity electronic trading market amounted to RMB15 600 billion by the end of 2020. As the end of 2019, the electronic trading market had attracted over 1 million investors and included more than 5000 member units. The market's par-

Keywords. Forward contract, principal-agent theory, asymmetric cost information, imperfect B2B spot markets.

College of Management and Economics, Tianjin University, 300072, P.R. China.
*Corresponding author: yuanyuanluo@tju.edu.cn

ticipation has been steadily increasing[1]. Obviously, the boom and burst of spot markets not only broadens the channels for enterprises' transactions, but also disrupts the traditional practice where supply chain members rely solely on specific contracts to establish long-term cooperation relationships. This shift promotes a more rational distribution of market resources and enhances transaction efficiency. However, the spot market with essentially negligible lead time naturally in a higher and more volatile price for extra flexibility [19]. In addition, factors such as economic conditions, government policies and the misalignment of industry cycles lead to an illiquid transaction environment in the spot market, making transactions more difficult [27]. Hence, the spot market is flawed with the unpredictable changes in the transaction. For instance, Indonesia, a country abundant in natural resources, has been reported by Financial Times that due to the government's implementation of a ban on palm oil exports on April 28, 2022, Indonesian palm oil producers suffered from a sell-off, with Triputra Agro Persada, a company listed in Jakarta, experiencing a decline of almost 7%, while its competitor Astra Agro Lestari saw a decline of over 4%[2].

Concerned about fluctuating spot market prices and the uncertain supply of raw materials affected by market liquidity, the benefits of the spot market are limited. As a result, downstream firms may face difficulties procuring necessary products at the appropriate price and within the required timeframe in an imperfect spot market. Conversely, to secure components at a specified future time for a specific price, a forward contract can legally grant the buyer the obligation and right to execute the forward to complete a transaction in the event that a specific "state of nature" occurs [22]. The buyer typically employs such a long-term contract to ensure that her procurement is less affected by fluctuations in the spot market. As for suppliers, they may face the risk of exorbitant prices and being unable to find counter parties. These risks also drive the supplier to pick a forward contract to lock in his own earnings. To some extent, the forward contract has been widely applied across sectors since it provides guarantees for the stable development of the supply chain members. Empirical evidence demonstrates that incorporating forward contracts in the pre-sale of real estate provides participants with stability [23], which indeed helps secure funds for builders and reducing the likelihood of defaults. Moreover, smallholders in developing nations experience significant poverty due to their exposure to frequent spot price changes and natural calamities. Thus, the prevalent utilization of forward contracts can help the buyers form a long-term, stable supply chain partnership with vulnerable farmers [10].

Long term contract transactions and spot transactions are mutually beneficial and interdependent. Although forward contract transactions can guarantee the acquisition of a specific quantity of commodities at a predetermined price, their rigidity limits the ability to make strategic modifications within a company. Compared with the former transactions, spot transactions with short lead time bring downstream companies unparalleled flexibility, enabling them to negotiate supply contracts with greater autonomy. Actually, the purchaser has the opportunity to promptly acquire or dispose of goods in B2B spot markets when her stock levels are either insufficient or excessive relative to current demand [27]. Consequently, a buyer is willing to acquire goods in advance through a contract and then adjust her inventory levels through spot trading once demand is detected. Taking Hewlett Packard (HP) as an example, HP enters into the contractual agreements to fulfill 85% of its purchasing requirements, while reserving the remaining 15% for the spot market. This strategic approach enables HP to effectively implement a portfolio strategy in its sourcing decisions, contributing to its status as a prominent firm [2]. Naturally, to better improve decision-making flexibility and reduce uncertain risks in price and demand, it is common for enterprises to combine these two transaction methods in supply chains across various industries such as fashion apparels [30], energy [7] and electronics [3].

Despite the extensive applicability of the two transactions, there are still some questions that need to be settled. Essentially, the forward contract signed between upstream and downstream parties in a supply chain forms a contractual relationship. Supply chain members who sign the contract are always inconsistent in their goals, which will cause certain conflicts. In particular, with the aim of maximizing their own financial gains, some supply chain members usually conceal their own information to diminish the earnings of others [11,16,17].

[1] See https://baijiahao.baidu.com/s?id=1800400432176004429&wfr=spider&for=pc.

[2] See https://www.ft.com/content/38b6df62-e863-4ba1-8274-138ccb2b061b.

Production cost, as private information held by the supplier, inevitably causes the optimal decision-making of an enterprise to deviate from the level under symmetric information, which in turn restricts firms' sustainable development [14]. Thus, the purpose of this paper is to examine how to formulate forward incentive mechanisms to compel the supplier to disclose true production cost information, sequentially mitigating the potential risk of price and demand fluctuations. Furthermore, the influences of an imperfect spot market on the procurement strategy of a downstream buyer who lacks cost information is also worthy of being explored.

To address the above questions, this work establishes a model by principal-agent theory to capture the role of asymmetric cost information and an imperfect spot market on the forward contract. It is assumed that the downstream buyer has two ways for its procurement: entering into a forward contract with the supplier, and purchasing directly from the spot market once the demand is determined. To incentivize the supplier to disclose accurate cost information, the buyer, as the leader in the supply chain, offers a menu of contracts based on her judgment of the supplier and spot market. Meanwhile, the supplier, who possesses private cost information organizes his production according to the terms of the contract. This study presents novel viewpoints on mixed procurement in the presence of asymmetric cost information. Specifically, it generates analytical outcomes that outline the best practices for the buyer to acquire procurement through a forward contract and the imperfect spot market. It also designs appropriate incentive mechanisms to disclose cost information. Moreover, several intriguing conclusions are obtained from the comparison of procurement strategies in various information states and market conditions. For thorough views, please see Section 7.

The subsequent sections of this work are structured as follows. Section 2 conducts a comprehensive review of the literature related to this study. Section 3 provides the model and assumptions. Optimal forward incentive contract under symmetric information is presented in Section 4. Optimal forward incentive contract under asymmetric information is given in Section 5. Numerical study is arranged in Section 6. Section 7 summarizes the conclusions.

2. Literature review

There exists a substantial collection of supply chain literature that specifically examines different facets of the matching supply with demand. To the best of my knowledge, there are two primary branches of literature that are pertinent to this research: one is procurement through long-term contracts and/or spot markets, and the other is information asymmetry.

The presence of the spot market allows participants to utilize its platform by selling surplus inventory or purchasing products to meet excess market demand, hence accelerating the rate of resource circulation. Nevertheless, in the face of a relatively imperfect spot market, it is necessary for supply chain participants to enter into a contractual agreement in order to guarantee the stable supply and sales of goods. Forward, as a type of financial derivative, can be introduced into the supply chain to mitigate the impact of market volatility. Accordingly, there has been a significant increase in research due to the strong growth of spot markets and the widespread use of forward contracts in recent years. Cachon and Lariviere [3] study the formulation of forward and option contracts. In their study, the manufacturer with superior market information is recognized as the primary participant. The contracts are provided to assist the supplier in identifying the reliability of the market information through a signal transmission. Dong and Liu [5] characterize the behavior of two risk-averse firms involved in a forward contract by constructing a Nash game. They derive an analytical solution for the contract parameters and discover that the participants in the supply chain can benefit from risk avoidance through a forward contract. This finding explains why forward contracts continue to be present in the spot market with good liquidity and no trade delays. Li *et al.* [15] analyze the decision-making process of the buyer who chooses between periodically purchasing products from the spot market or signing a long-term contract when facing a dynamic market. They derive that the buyer will opt for signing the long-term contract when the price volatility increases, while they will choose to purchase products in the more flexible spot market when there is an increase in demand volatility. Goel and Gutierrez [9] formulate procurement and distribution strategies that integrate the observed spot and futures prices from commodity markets, demonstrating how this price knowledge can

be leveraged to improve the effectiveness of a supply chain. Xing *et al.* [25] introduce market liquidity and explore the decisions regarding the reseller's forward order volume and product sales price in an imperfect spot market. Xu *et al.* [27] integrate the spot market with two distinct forms of long-term agreements, namely forward contracts and option contracts. Taking into account the buyer's risk attitude and the effects of multiple purchases, they examine the impact of the spot market on decision-making. In the context of unpredictable supply and demand, Merzifonluoglu [18] addresses the research gap through an analysis of risk-averse sourcing decisions involving forward contracts, option contracts, and spot markets. Zhao *et al.* [30] develop a two-stage model that incorporates demand information updating to assess the influence of supply competition between the spot market and the option contract market. Consider a two-echelon supply chain with suppliers' competition, Xing *et al.* [26] analyze the designs of procurement contracts and the equilibrium contract structures which specify the trade-off between index-based contracts and fixed-price contracts. When confronted with a supplier who has cost advantage or a more consistent supply, Ai and Xu [1] investigate the sourcing strategies of a monopolistic retailer in a spot market where the price is determined by the trading quantity. Fan *et al.* [6] consider the factors that affect the decision of a downstream buyer to execute a forward contract in a B2B procurement platform. It has been observed that the willingness of chain members to sign the forward contract is greater when there are substantial fluctuations in the spot market. Xu *et al.* [28] explore the impact of an imperfect spot market on supply chain coordination and decision-making. The results show that after signing the forward contract, the spot market can benefit the manufacturer, but the supplier's profits may be negatively impacted in some circumstances. Supply chain coordination can be achieved through the implementation of revenue-sharing contracts.

Another stream of research related to this paper is the study of the role of asymmetric information. The transparency of information plays an important role in the supply chain. Typically, the party who has private information will conceal it and leverage it as a bargaining chip against his counterparty, undermining the precision of the opposing party's decisions. Hence, how to reveal the true information of the disguised party is an urgent problem that needs to be jointly solved by the theoretical and industrial communities. To facilitate the sharing of reliable forecast demand information possessed by the manufacturer, Özer and Wei [21] estimate the formulation of contracts (a nonlinear capacity reservation contract and an advance purchase contract) by modeling screening and signaling games, respectively. Cao *et al.* [4] explore the optimal wholesale contract formulation problem for a dual-channel supply chain where the seller's sales cost is private information. Kegui *et al.* [13] apply incentive mechanism theory to derive the optimal contracts for the government to stimulate emission reduction in a scenario where there is asymmetric information regarding technology and investment. Zhao *et al.* [31] examine the manufacturer's approach in creating a non-linear contract that exposes the third parties' private recycling efficiency information. The study conducted by Huang *et al.* [12] reveals that in a dual-channel supply chain, the asymmetric information regarding producer sales cost leads to the distortion of chain members' respective sales volume in the opposite direction. Therefore, the asymmetry of cost information will not necessarily affect the channel efficiency. Lu and Meng [16] establish a principal-agent model to analyze how the government formulates the BOT contract to maximize social welfare when enterprises have access to investment cost information. Gao *et al.* [8] are engaged in the dynamic contract design of procurement for the buyer, and they deeply investigate the interaction of the supplier's private cost information and cost learning ability on the performance of the chain members. In the context of asymmetric information, channel intrusion has also received some scholars' attention. Zhang *et al.* [29] establish a signaling game with manufacturer intrusion under asymmetric demand information. They explore the impact of demand information structure on manufacturer intrusion and product quality. Hou *et al.* [11] examine the decision of a retailer to share demand information when faced with encroachment by a supplier. Zheng *et al.* [32] consider the information-sharing decision of a better-informed online retailer in the context of the platform economy. They find that the online retailer will share demand information when the commission rate given to the retailer is high and market competition is not fierce. Matsui [17] suggests that the downstream buyer with demand advantages chooses to disclose information to obtain more profits when the upstream supplier is threatened by competition.

TABLE 1. Contribution of this work (✓: covered).

Authors	Forward contract	Asymmetric cost information	Impact of an imperfect spot market
Goel and Gutierrez [9]	✓		A one-way purchase spot market
Xu *et al.* [27]	✓		✓
Merzifonluoglu [18]	✓		
Zhao *et al.* [30]	✓		A perfect spot market
Ai and Xu [1]	✓		
Fan *et al.* [6]	✓		A perfect spot market
Xu *et al.* [28]	✓		A perfect spot market
Kegui *et al.* [13]		✓	
Zhao *et al.* [31]		✓	
Huang *et al.* [12]		✓	
This work	✓	✓	✓

In contrast to previous research, this study focuses on the buyer's approach to developing a forward contract to identify the true cost types of the supplier in an imperfect spot market. Specifically, it examines how to formulate the forward contract incentive mechanism to force the supplier to reveal true production cost information, and mainly explores the combined impact of asymmetric information and an imperfect spot market on the procurement behavior of the less-informed downstream buyer. The results of this study enrich the existing research on the forward contract and cost information asymmetry. Table 1 summarizes the major differences from the previous studies.

3. Model and assumptions

Consider a two-tier supply chain consisting of a single supplier (he) and a single buyer (she) with an imperfect spot market, where the buyer, who has a relatively stronger bargaining power (a buyer's market), acts as a contract leader. The supplier is responsible for the production and delivery of raw materials, and the buyer carries out minimal processing on these raw materials to manufacture final products and then manages her sales. Due to the short sales season and a lengthy lead time for related commodities, the supplier is unable to conduct secondary replenishment within a short period. However, prior to the start of a new season, the buyer can secure a specific quantity of reserved goods at a predetermined unit reservation price by entering into a forward contract with the supplier. Under this contractual relationship, as the main participant in production, the supplier holds private knowledge regarding the production cost C_i, $i \in \{L, H\}$, $0 \leq C_L \leq C_H$, where L and H represent low production cost and high production cost. While the buyer is only aware of the distribution of this cost information. *i.e.*, $P_r(C_H) = \beta$, $P_r(C_L) = 1 - \beta$ $(0 < \beta < 1)$; β is the probability of the high-cost state.

The development sequence of the entire transaction is as follows: At time T_0 (the contract phase), the buyer predicts the spot price P and the market demand D for the final product at time T_1. After that, the buyer offers a menu of forward contracts that includes the total payment and reservation quantity (T_i,q_i) $i \in \{H, L\}$. Accordingly, to ensure that his expected profits are greater than reservation utility, the supplier, depending on his own type i chooses to accept or reject the corresponding contract. Once the supplier accepts the contract, production begins immediately. At time T_1 (the spot market phase), the final product market demand and the spot market price of the material are realized. The supplier delivers the materials, and the buyer pays and decides whether to interact in the spot market to meet demand or sell excess materials based on the realized demand. It is worth noting that with the concerns about the imperfect spot market, the buyer may not be

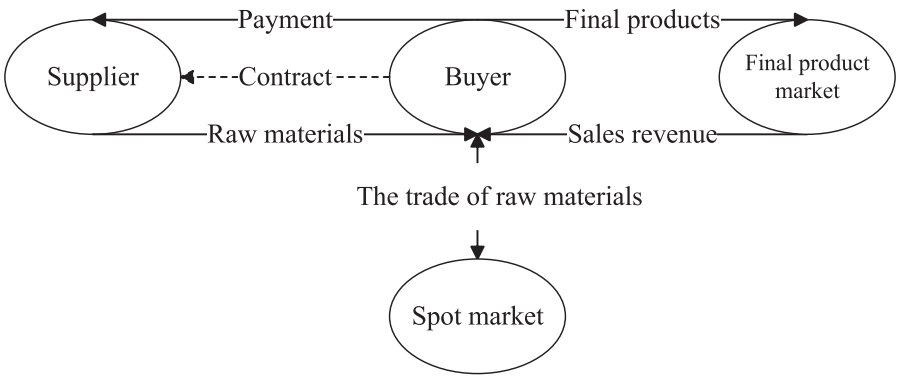


FIGURE 1. Process for signing the forward contract and the transaction.

TABLE 2. Notation.

Symbol	Description
(T_i,q_i), $i \in \{H, L\}$	The forward contract provided by the buyer includes the total payment T_i and the reservation quantity q_i;
D	The random demand for the final product, $D \in [0, \infty)$ has a mean of μ_D and a variance of σ_D^2; $G(x)$, $g(x)$ are the distribution function and probability density function, respectively; $G(x)$ is monotonically increasing and differentiable in the interval $D \in [0, \infty)$, and $\overline{G}(x) = 1 - G(x)$;
P	Spot market price, $P \in [\underline{P}, \overline{P}]$ has a mean of μ_P and a variance of σ_P^2;
C_i, $i \in \{H, L\}$	Supplier's unit material production cost;
r	Unit retail price of the final product, an exogenous variable;
m	Market liquidity;
l	Unit out-of-stock penalty for the buyer;
v	Unit salvage value of the material unsold by the buyer;
π_S	Supplier's profits;
π_B	Buyer's profits.

able to successfully trade raw materials in the spot market. Following Xing *et al.* [25] and Xu *et al.* [27], it is assumed that whether the spot transactions can be completed within a certain period of time is subject to market liquidity m. That is, the buyer can find the counterparty to complete the transaction with a probability of m $(0 \leq m \leq 1)$, but only obtain the residual value v with a deal collapse probability of $1 - m$. After the rational procurement, the buyer conducts a process with negligible costs to produce final products. At time T_2, the buyer engages in sales activities, obtaining profits at a unit price r. If the additional demand for the final product is not met, the buyer will suffer a shortage penalty l. A more intuitive transaction description is depicted in Figure 1.

The corresponding symbol definitions are listed in Table 2.

Assumption 1. *The spot market cannot be manipulated due to its enormous number of participants. Consequently, the raw material's spot price P is an exogenous stochastic variable (see, e.g., [5, 24, 30]).*

Assumption 2. *It is set that $C_L \geq m\mu_P + (1 - m)v$ to ensure that the supplier participates in signing the forward contract.*

Assumption 3. *To preserve consumer goodwill and establish a stable cooperative relationship with customers, the sale price r is assumed to be an exogenous variable and high enough to give the buyer an incentive to accept the risk of spot market price volatility and erratic demand in exchange for a decent profit margin ($v \leq P \leq r$) (see, e.g., [25]).*

The supply chain members' profits are closely related to contract formulation and market volatility. Based on a menu of forward contracts provided by the buyer, the supplier sets the production schedule for raw materials, and delivers materials for compensation once production is completed.

Therefore, the profit function of supplier type i ($i \in \{H, L\}$) is expressed as follows:

$$\pi_{S_i} = T_i - C_i q_i,\ i \in \{H, L\}. \tag{1}$$

From the supplier's profit function, it can be seen that the supplier can obtain a stable total payment T_i from the buyer, which helps he form a long-term relationship with the downstream buyer. $C_i q_i$ represents the supplier's production cost, determined by his own efficiency in production.

Given the uncertainty of the demand for the final product, the buyer encounters two distinct market scenarios: (1) If $D \geq q$, the buyer's current inventory of raw materials is inadequate to meet the subsequent demand for processing and sales. In this case, the buyer needs to obtain additional materials from the spot market. However, due to the imperfections of the spot market, there is a risk that resources may not be available in a timely manner, leading to potential penalties for the buyer due to the shortfall; (2) If $D \leq q$, the buyer possesses excess materials. If the transaction in the spot market is successful, the buyer can sell the surplus materials to gain additional profits. Otherwise, the buyer will only receive the remaining value of the unsold materials.

Thus, the profit function of the buyer after trading with the supplier type i is as follows:

$$\pi_{B_i} = r \min\{D, q_i\} + [m(r-P) - (1-m)l]\,(D - q_i)^+ + [mP + (1-m)v]\,(q_i - D)^+ - T_i,\ i \in \{H, L\}. \tag{2}$$

Here, $t^+ = \max\{0, t\}$.

In the buyer's profit function, the first term represents the profits obtained from transforming the forward contract materials into end products to fulfill the need of the market; the second term indicates the profits gained from effectively procuring raw materials in the spot market for processing and sales, as well as the penalty due to stock shortages; the third term is the profits derived from selling surplus raw materials to the market and the residual value obtained; the last term represents the remuneration disbursed by the buyer to the supplier.

4. Optimal forward incentive contract under symmetric information

This section examines the scenario where cost information is symmetric. The superscript "E" denotes the forward contract in the context of symmetric information. With the aim of maximizing her own profits in an imperfect spot market, the challenge encountered by the buyer is to ascertain the terms of the contract: (T_i^E, q_i^E), $i \in \{H, L\}$, ensuring that the supplier's profits are always greater or equal to her reservation revenue. Without loss of generality, set reservation revenue of the supplier to 0.

The forward contract model under symmetric information is given as follows:

$$\begin{cases} \max\limits_{T_H^E, T_L^E, q_H^E, q_L^E} \pi_B^E = \beta E\left[\pi_{B_H}^E\left(T_H^E, q_H^E\right)\right] + (1-\beta)\, E\left[\pi_{B_L}^E\left(T_L^E, q_L^E\right)\right] \\ \text{subject to:} \\ \quad \pi_{S_H}^E\left(T_H^E, q_H^E\right) \geq 0, \qquad \text{(IR-1)} \\ \quad \pi_{S_L}^E\left(T_L^E, q_L^E\right) \geq 0. \qquad \text{(IR-2)} \end{cases} \tag{3}$$

The following theorem can be obtained through solving the above optimization problem. For convenience, all the proofs are given in the Appendix A.

Theorem 1. *Under symmetric cost information, the optimal forward contracts provided by the buyer to the high-cost supplier and the low-cost supplier are:*

(1) *For the high-cost supplier,*

$$\begin{cases} q_H^{E*} = G^{-1}\left[\frac{(1-m)(r+l)+m\mu_P-C_H}{(1-m)(r+l-v)}\right], \\ T_H^{E*} = C_H G^{-1}\left[\frac{(1-m)(r+l)+m\mu_P-C_H}{(1-m)(r+l-v)}\right]. \end{cases} \tag{4}$$

(2) *For the low-cost supplier,*

$$\begin{cases} q_L^{E*} = G^{-1}\left[\frac{(1-m)(r+l)+m\mu_P-C_L}{(1-m)(r+l-v)}\right], \\ T_L^{E*} = C_L G^{-1}\left[\frac{(1-m)(r+l)+m\mu_P-C_L}{(1-m)(r+l-v)}\right]. \end{cases} \tag{5}$$

Theorem 1 provides the analytical expression of the optimal forward contracts under symmetric information. Since the buyer fully knows the supplier's cost type, the supplier can only obtain reservation utility. Namely, the supplier's marginal revenue equals its marginal cost. All revenue is captured by the buyer.

Next, the impacts of important parameters on the forward contract are explored. It is easy to see from Theorem 1 that the monotonicity of the total payment and the pre-determined quantity for the buyer is consistent except for the cost parameter.

Corollary 1. *Under symmetric information, the optimal pre-order quantity of the buyer decreases as the supplier's cost increases, but increases as the expected price of the spot market and shortage penalty increase. As for the impact of market liquidity, it varies depending on the expected price of the material spot market: when $\mu_P > C_i$, the buyer will increase the quantity as the liquidity increases; otherwise, the buyer will reduce the order quantity.*

From Corollary 1, when the supplier's production cost is relatively expensive, the buyer prefers to purchase raw materials from the spot market to reduce the amount purchased from the supplier. Nevertheless, if the buyer anticipates a high spot market price for the material, she will augment the quantity requested from the supplier. On the one hand, she can lock in her own procurement costs in advance. On the other hand, if the amount purchased exceeds the demand, the excess may also be successfully sold at a better price, which results in a certain surplus in the buyer's order quantity. Regarding the impact of stock-out penalties on the buyer, when the penalty imposed is relatively severe, she will increase the order quantity of raw materials to ensure a stable supply of final products and avoid incurring serious penalties. Finally, when the expected price of materials exceeds the supplier's production cost, with the increasing market liquidity, if the order quantity exceeds market demand, it can be promptly sold in the spot market. Therefore, the buyer perceives that raising the order quantity of raw materials from the supplier can fulfill her speculative desires, and the flexibility of the buyer's order will further increase, especially when the market is highly liquid.

5. Optimal forward incentive contract under asymmetric information

The value of information can be viewed as the difference between the revenue resulting from its utilization and the expenses incurred in acquiring the information for managerial decision-making purposes. Since the cost of obtaining information for the party with an information advantage can be negligible, he will be motivated to exploit this superior information to increase his own profits. Specifically, he will deliberately deceive other chain members by providing false information about himself, leading to the distortion of the decisions made by other members compared with the actual situation. Hence, this section demonstrates how a buyer with poor information formulates a menu of forward contracts to induce the suppliers to disclose their true production cost information. To address this issue, the principle of revelation needs to be applied. Based on this approach, the buyer designs an incentive compatibility mechanism to attract the supplier to choose the most beneficial forward contract based on his own production cost type.

The superscript "F" is used to indicate the forward contract in the presence of asymmetric cost information. At the beginning, the buyer can develop two types of forward contracts $((T_H^F, q_H^F), (T_L^F, q_L^F))$ for suppliers to choose from. If the high-cost supplier chooses (T_H^F, q_H^F) and the low-cost supplier chooses (T_L^F, q_L^F), the buyer can accurately identify the true production cost of the suppliers' through their choice of the contract.

The forward contract model under asymmetric information is given as follows:

$$\begin{cases} \max\limits_{T_H^F, T_L^F, q_H^F, q_L^F} \pi_B^F = \beta E\left[\pi_{B_H}^F\left(T_H^F, q_H^F\right)\right] + (1-\beta) E\left[\pi_{B_L}^F\left(T_L^F, q_L^F\right)\right] \\ \text{subject to:} \\ \quad \pi_{S_H}^F\left(T_H^F, q_H^F\right) \geq 0, & \text{(IR-1)} \\ \quad \pi_{S_L}^F\left(T_L^F, q_L^F\right) \geq 0, & \text{(IR-2)} \\ \quad \pi_{S_H}^F\left(T_H^F, q_H^F\right) \geq \pi_{S_H}^F\left(T_L^F, q_L^F\right), & \text{(IC-1)} \\ \quad \pi_{S_L}^F\left(T_L^F, q_L^F\right) \geq \pi_{S_L}^F\left(T_H^F, q_H^F\right). & \text{(IC-2)} \end{cases} \tag{6}$$

Here, constraint conditions (IR-1) and (IR-2) represent the individual rationality constraints of the suppliers, which ensure that the suppliers receive revenue that is not less than their reservation utility, thereby incentivizing them to accept the contracts. Constraint conditions (IC-1) and (IC-2) are the incentive compatibility constraints of the suppliers, indicating that the supplier's disguised revenue is not greater than its real revenue, which deters the supplier from lying about the true cost type. Accordingly, the supplier refrains from providing misleading information and chooses the contract based on her true cost type. Solving the optimization problem (6) yields the following theorem.

Theorem 2. *Under asymmetric information, the optimal forward contracts provided by the buyer to high-cost and low-cost suppliers are respectively given as:*

(1) *For the high-cost supplier,*

$$\begin{cases} q_H^{F^*} = G^{-1}\left[1 - \frac{C_H - (1-\beta)C_L - (1-m)\beta v - \beta m \mu_P}{\beta(1-m)(r+l-v)}\right], \\ T_H^{F^*} = C_H G^{-1}\left[1 - \frac{C_H - (1-\beta)C_L - (1-m)\beta v - \beta m \mu_P}{\beta(1-m)(r+l-v)}\right]. \end{cases} \tag{7}$$

(2) *For the low-cost supplier,*

$$\begin{cases} q_L^{F^*} = G^{-1}\left[1 - \frac{C_L - (1-m)v - m\mu_P}{(1-m)(r+l-v)}\right], \\ T_L^{F^*} = C_L q_L^{F^*} + (C_H - C_L) q_H^{F^*}. \end{cases} \tag{8}$$

From Theorem 2, one can further obtain Corollaries 2 and 3.

Corollary 2. *Comparing the optimal forward contract under symmetric and asymmetric information, it can be seen that the optimal order quantity obtained by the low-cost supplier remains unchanged, while the optimal order quantity obtained by the high-cost supplier is distorted downward due to asymmetric information.*

Corollary 3. *Comparing the optimal forward contract under symmetric and asymmetric information, it can be observed that the high-cost supplier receives only reservation utility, while the low-cost supplier receives not only retained utility but also additional rent Z^F. Z^F exhibits an upward trend as $q_H^{F^*}$ increases. Here, $Z^F = (C_H - C_L) q_H^{F^*} = (C_H - C_L) G^{-1}\left[1 - \frac{C_H - (1-\beta)C_L - (1-m)\beta v - \beta m \mu_P}{\beta(1-m)(r+l-v)}\right]$.*

From Corollaries 2 and 3, it is evident that the low-cost supplier aims to maximize his gains by disguising himself as the high-cost one. Consequently, the buyer will reduce the forward order quantity from the high-cost supplier and diminish the information rent of the low-cost supplier.

Corollary 4. *The buyer's forward order quantity from the high-cost supplier will decrease as the production cost of the supplier increases, but increase as the proportion of high-cost suppliers in the market, the expected price in the spot market and the shortage penalty increase. When the expected price in the spot market* $\mu_P > \frac{C_H - C_L + \beta C_L}{\beta}$, *the buyer's forward booking quantity from the high-cost supplier will increase with respect to market liquidity.*

As is shown in Corollary 4, when the market has a higher proportion of high-cost suppliers, the difficulty for the buyer to screen both types of suppliers will decrease. Accordingly, the downward distortion in the ordering volume received by the high-cost supplier will be mitigated. Namely, his ordering volume will increase as β increases.

Comparing Corollary 4 with Corollary 1, regardless of the buyer's knowledge of the supplier's cost type, it is evident that the changes of buyer's forward order quantity from the high-cost supplier exhibit the same trend in production cost, expected price, out-of-stock penalty and liquidity. However, the degree of variation will be affected by the asymmetry of cost information. Namely, the rate of change will be different.

Specifically, as the cost expenses incurred by the high-cost supplier rise and the penalties for being out of stock decrease, the advantages obtained by the low-cost supplier's deceptive behavior will grow. Consequently, the buyer will decrease her purchases from the high-cost supplier even more to avoid being tricked by the low-cost one. Overall, when the production cost rises and out-of-stock penalty diminishes, the presence of asymmetric cost information leads to a higher rate of change in the amount of orders with the supplier who has higher cost.

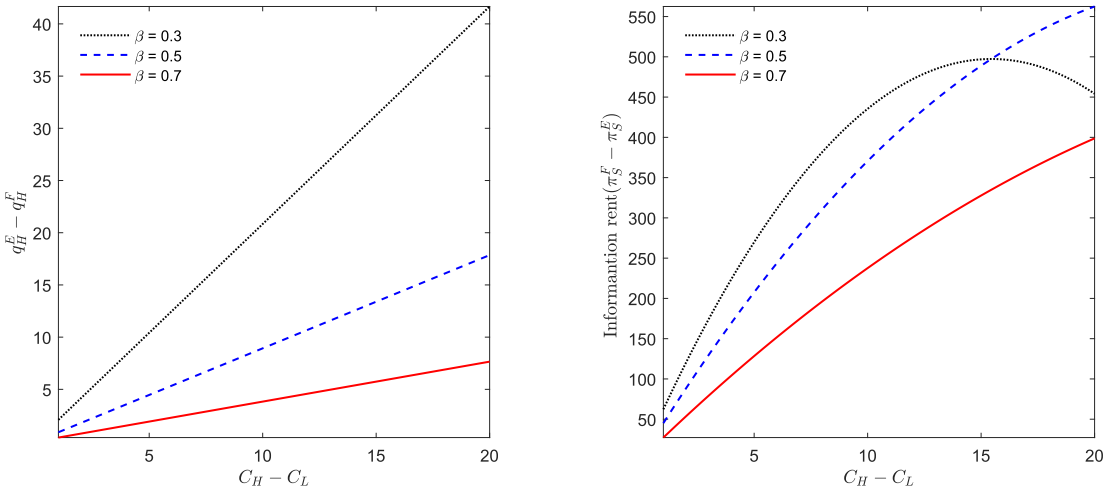
Compared with symmetric information, the buyer is more cautious under asymmetric cost information regarding the market liquidity. In a highly liquid market, it is only when the expected price of the spot material market is higher that the buyer will consider it profitable to reserve sufficient quantity of raw materials in advance from the high-cost supplier. The rationale for this can be elucidated as follows, the buyer who engages in speculative activities must endure the adverse effects of asymmetric information. Hence, only when the expected spot price is sufficiently high and the spot market has an increase in liquidity, the buyer is motivated to participate in speculative transactions by purchasing larger order quantities through the forward contract.

To better demonstrate the impact of several crucial factors on the extent of distortion in the forward order volume from the high-cost supplier, consider a simple case where the market demand D follows uniform distribution $U[0, K]$. The subsequent corollary provides the effects of crucial parameters on the distortion of the forward booking volume.

Corollary 5. *Under asymmetric cost information with a prior uniform distribution of the demand, the degree of distortion in forward bookings obtained by the high-cost supplier will increase as the cost and liquidity of the spot market increase. However, this distortion will be reduced as the fraction of high-cost suppliers in the market increases, and it is unrelated to the expected price in the spot market.*

According to Corollaries 1, 4 and 5, under asymmetric information, the reservation volume of the high-cost supplier will be distorted downward, and the degree of distortion is related to the proportion of the high-cost suppliers in the buyer's predictive perspective. As the ratio increases, it will decrease the level of misjudgment of the low-cost supplier, hence reducing the level of distortion in the order volume for the high-cost supplier. However, when the production cost is high and out-of-stock penalty is less severe, the low-cost supplier will experience a rise in profits from disguises, while the buyer will attempt to decrease forward orders from the high-cost supplier in order to decrease procurement expenses and avoid deceptive practices by the low-cost suppliers, which leads to a greater downward distortion.

Regarding the spot market, the expected price in the spot market will not change the degree of distortion of the reservation volume of the high-cost supplier, but the degree of distortion of the reservation volume will be affected by spot market liquidity. As the level of market liquidity rises, the extent of distortion will also grow. This can be illustrated by two spot market situations. When the expected spot price is high, an efficient spot market will encourage the buyer to engage in speculative activities. That is, the buyer will augment her purchases from the supplier to fulfill demand, while simultaneously sell surplus materials on the spot market for a profit. This will enhance the motivation for the low-cost supplier to conceal his true identity. The buyer



(a) (b)

FIGURE 2. The impact of the cost information on the order and information rent. (a) The impact on the distortion of order quantity. (b) The impact on the information rent.

can only exacerbate the degree of downward distortions in the amount of orders to cease this act of deceit. If the expected spot price is relatively low and the market liquidity is strong, the buyer and supplier will not be constrained by the transactions between them. It is more convenient to find trading partners in a spot market. As a result, to reduce expenditures, the buyer will be more inclined to purchase in the spot market or from the low-cost supplier, and the buyer can further reduce the quantity of reservations from the high-cost supplier and pay a small amount of rent to complete the screening.

6. NUMERICAL STUDY

Due to the complexity of the optimal decisions and associated profit functions, this section turns to numerical analysis to obtain further managerial insights. Throughout this section, this work primarily presents three aspects that influence the strategies and performance of the chain members, including cost information, an imperfect spot market and the final product market with uncertain demand. For the consistency in analysis, it is set that the sales price of the final product is $r = 270$, the shortage penalty is $l = 25$, the residual value of raw materials is $v = 15$, and the cost of the low-cost supplier is $C_L = 45$.

6.1. The impact of cost information

To ensure that the basic assumptions of the model hold, the market price of raw material P and the market demand D are assumed to follow the uniform distribution $U[40, 60]$ and $U[0, 100]$, respectively.

Figure 2 illustrates how the cost information affects the distortion of order quantity from the high-cost supplier and the information rent of low-cost supplier. It is shown that under asymmetric information, the distortion of the buyer's requested quantity from the high-cost supplier increases as the cost difference grows, but the likelihood of encountering a high-cost supplier decreases. Typically, to identify the type of a supplier, the buyer pays information rent to the low-cost supplier. However, when the cost difference is too large, the low-cost supplier is able to generate significant profits by disguising himself as a high-cost supplier. In order to avoid this situation, the buyer will intentionally reduce the order volume from the high-cost supplier and reduce the rent payment to the low-cost supplier. It is worth noting that when the probability of encountering a

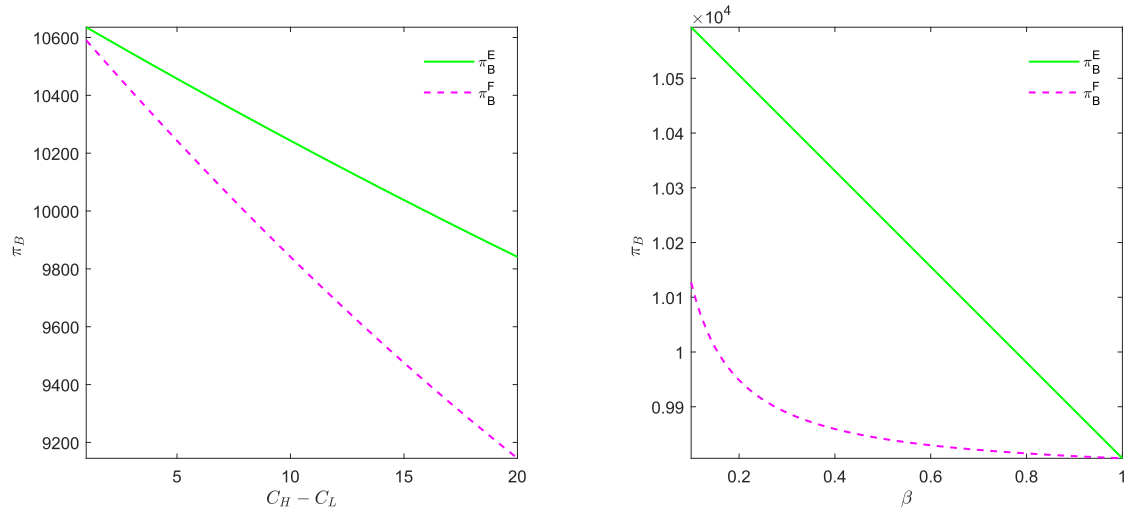


FIGURE 3. The impact of cost information on the buyer's profits. (a) The impact of cost difference on the buyer's profits. (b) The impact of β on the buyer's profits.

high-cost supplier is low, the buyer will pay higher rent to identify the type of supplier, but as the cost difference increases, the rent received by the low-cost supplier will fall. The rationale behind this is that when the cost difference increases, the buyer becomes increasingly reluctant to pay exorbitant fees to identify high proportion of low-cost suppliers. Furthermore, the presence of the spot market as an additional source of supply enhances this incentive.

In the following, to explore the impact of cost information on the buyer's profits, I set $\beta = 0.5$ and $C_H = 55$ in subfigure of Figure 3 respectively. Obviously, it can be seen that under the two information states, the buyer's profits decrease as the cost difference and the proportion of high-cost suppliers increase, with profits under asymmetric information being worse than those under symmetric information. As already stated, the buyer's procurement cost and the rent paid to the supplier will rise with respect to the disparity in production cost caused by significant variations in technological efficiency. Consequently, the buyer's profits will diminish as the cost difference increases. The greater the cost difference is, the greater the downward distortion of the buyer's profits are.

When there exists cost asymmetry, the effect of the proportion of the high-cost suppliers on the distortion of the buyer's profits is not monotonous. Specifically, if the proportion increases, the likelihood of the buyer engaging with the high-cost supplier increases, reducing her tendency to misjudge the low-cost supplier. Therefore, it can be clearly observed from the figure that as the proportion increases, the degree of the buyer's profits distortion caused by asymmetric information will be weakened. Whereas, if the proportion of the high-cost suppliers in the market is low, the buyer must incur a certain expenses to identify them, because the challenge of identification will escalate at this time. Accordingly, in this particular scenario, the extent of distortion in the buyer's profits will increase as the value of β increases.

6.2. The impact of an imperfect spot market

The spot market is measured by two elements: the market liquidity and the expected price of the spot market. To better analyze the impacts of these two factors, this paper fixes the production cost for the high-cost supplier $C_H = 50$ and the probability of encountering the high-cost supplier $\beta = 0.6$. Additionally, these examples focus on analyzing three scenarios with different levels of liquidity: low liquidity with $m = 0.3$, medium liquidity with

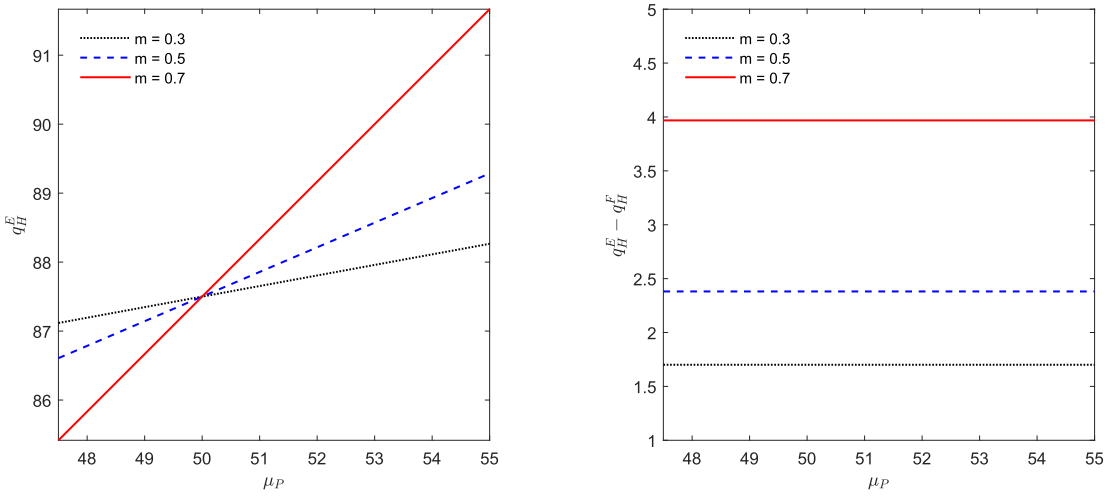


FIGURE 4. The impact of an imperfect spot market on the order quantity. (a) The impact on q_H. (b) The impact on the distortion of the order quantity.

$m = 0.5$, and high liquidity with $m = 0.7$. They are also set to compute the optimal decisions and the expected profits for μ_P from 47.5 to 55 as shown in Figures 4 and 5 to keep the expected spot price in a reasonable range.

Figure 4 examines the implications of an imperfect spot market for the buyer's rational procurement strategy. It is observed that the order quantity from the high-cost supplier is strongly affected by the mixed effect of the expected spot price and the market liquidity. There are two situations are explored here. (1) If the expected spot market price exceeds the cost of a high-cost supplier, the buyer will be more inclined to sign a forward contract with the supplier to lock in the cost. Especially, with a strong liquidity spot market, the buyer can more easily unload excess reservations at a better price, and the buyer's incentive of the speculation will be increased. Therefore, the buyer will further raise her reservations. However, due to asymmetry information, signing a contract requires a certain rent for screening purposes. Accordingly, as the spot market liquidity becomes greater, the buyer will become more dependent on the supplier, and she will be more easily affected by asymmetric cost information, which intensifies the distortion of the order quantity from the high-cost supplier. (2) When the expected spot market price is less than the cost of a high-cost supplier, the buyer will tend to purchase in the spot market to avoid high procurement costs and information rent, and this willingness will become more eager with a strong liquidity spot market, prompting the buyer to sharply reduce reservation. From the Figure 4b, it is also found that even the expected spot price is low, the distortion of order quantity from the high-cost supplier will be aggravated as the liquidity increases. The reason behind this is different from the previous scenario, such downward distortion is from a more reliable spot supply, which reduces the expense associated with the information rent, thus enabling further reduction in order volume from the high-cost supplier.

In sum, under the asymmetric cost information, the expected spot price does not affect the impact of spot market liquidity on the distortion of the order quantity from the high-cost supplier, but it does affect the buyer's reliance on the forward contract.

Here, a further investigation is conducted on how an imperfect spot market affects the performance of the chain members. The parameters are set the same as those in Figure 4. As depicted in Figures 5 and 6, since a spot market with increased liquidity may more effectively support the buyer's transactions in the spot market, irrespective of the buyer's knowledge of cost information, the presence of the spot market offers exceptional

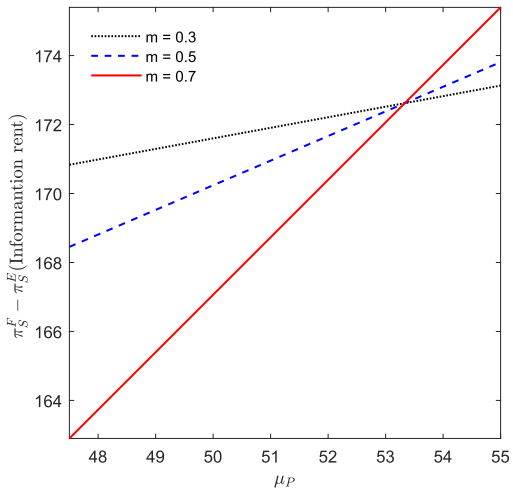


FIGURE 5. The impact of an imperfect spot market on the supplier's profits.

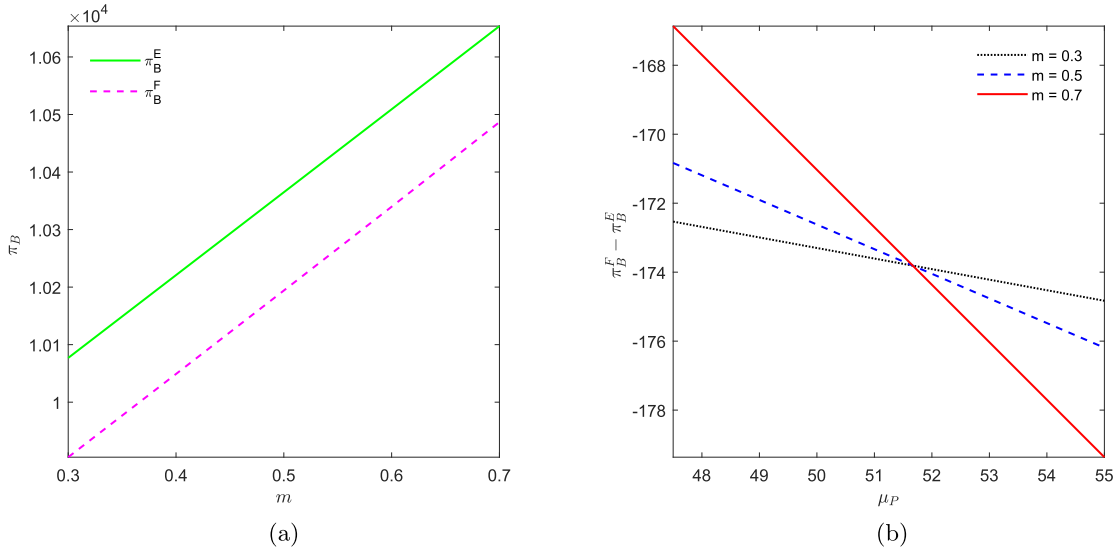


FIGURE 6. The impact of an imperfect spot market on the buyer's profits. (a) The impact on the buyer's profits. (b) The impact on the distortion of the buyer's profits.

convenience, leading to increased profits for her as liquidity in the spot market improves. However, only when the supplier possess a cost advantage can the liquidity directly affect his earnings. In the presence of asymmetric information, the influence of market liquidity on the profits of participants in the supply chain will be subjected to expected spot price.

Obviously, the expected price in the spot market will serve as the reference point for buyers' behavioral decisions. When the expected price is high, the buyer's speculative incentive will be reinforced, leading to an increase in the acquisition of raw materials through the forward contract. Thus, the buyer becomes more susceptible to asymmetric information, which allows the supplier to increase his information rent, further escalating the decrease in the buyer's earnings. But, when the expected spot price is low, it becomes more cost-effective

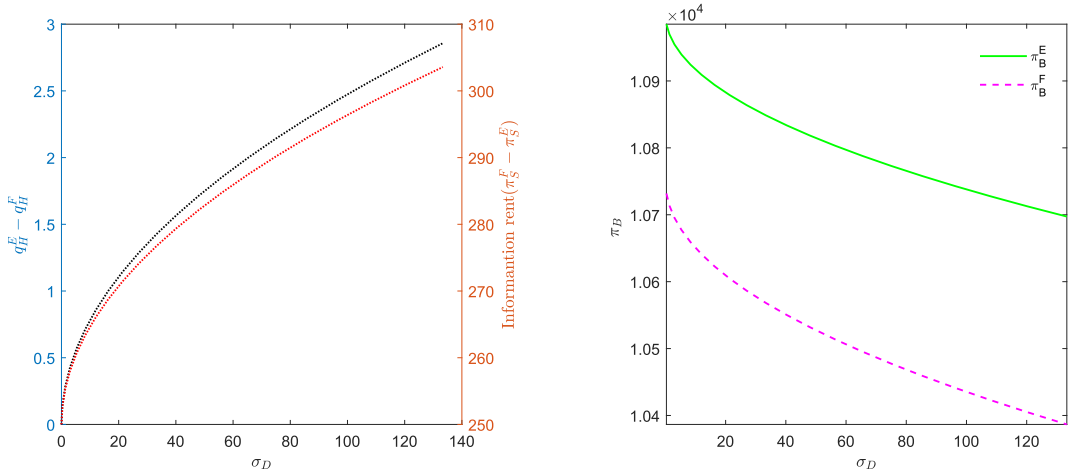


FIGURE 7. The impact of the final product market on the buyer's profits. (a) The impact on the order quantity and rent. (b) The impact on the buyer's profits.

for the buyer to meet her demand through spot sourcing. Consequently, a further decrease in the buyer's order quantity from the supplier results in a diminished impact from the asymmetric information. The buyer just needs to invest a minimal amount of information rent to identify the type of the supplier.

6.3. The impact of the final product market

Figure 7 reports the impact of the final product market when $C_H = 55$, $\beta = 0.5$ and $m = 0.5$. It is shown that as the volatility of the final product market demand increases, the forward contract is more attractive to the buyer, resulting in a greater impact from information asymmetry. Specifically, when the demand uncertainty σ_D grows larger, the degree of distortion in the reservation volume of the high-cost supplier and the information rent will increase accordingly, resulting in a decrease in the buyer's profits but a increase in the supplier's earnings.

7. CONCLUSION

With the development of economic globalization and technological progress, the individualized demand of consumers has become a scarce resource. It is no longer a seller's market where supply is in short, but a buyer's market dominated by the downstream firm who grasps the demand of the terminal market. In order to better cope with the risks associated with variable demand and price fluctuations, the integration of the spot market, financial innovation tools and the supply chain has garnered increasing attention. In practice, the extensive utilization of financial contracts, such as the forward contract, has enabled the buyer to obtain considerable benefits in the practical fields of rapidly evolving product categories, such as fashion and electronics. Nevertheless, this contract is unable to adequately mitigate the adverse consequences resulting from the supplier's private cost information. The main goal of this study is to explore how the buyer might effectively combine an imperfect spot market to develop screening forward contracts.

To better explore the management insights, this study has accomplished the following work. Firstly, the principal-agent theory is applied to formulate the buyers strategic forward contracting and spot market trading under asymmetric cost information. Subsequently, based on the revelation principle, this paper obtains the optimal contracts under different information states. Moreover, by conducting a thorough analysis of contract

specifications and numerical examples, this work examines the impacts of asymmetric cost information and imperfect spot market conditions on the strategic forward contracting and the performance of chain members.

According to the results, the forward quantity from the high-cost supplier is distorted downward to screen the cost type under asymmetric cost information. Specifically, the greater the difference in production cost and the lower the probability of encountering the high-cost supplier are, the greater the forward quantity from the high-cost supplier will be distorted. The existence of asymmetric information will reduce the buyer's own revenue, while the low-cost supplier can obtain additional information rent under asymmetric information. In addition, I discover that a spot market with higher liquidity does consistently enhance a buyer's profitability. However, in the presence of asymmetric information, the influence of market liquidity on the profits of participants in the supply chain will be subjected to expected spot price. With a highly liquid spot market, asymmetric cost information can dampen the speculation of a buyer. In turn, when the expected price in the spot market is low, the spot market with high liquidity can serve as a buyer's additional procurement channel, allowing her to decrease reliance on the supplier, which mitigates the adverse impact of asymmetric information. In the last, although the forward contract is viewed as an important tool to resist fluctuations in markets, the role of a forward contract will be affected by information asymmetry. Obviously, having suffered from a large fluctuation in market demand, the buyer is more likely to stabilize the supply of raw materials through a forward contract. However, implementing this strategy will inevitably amplify negative repercussions for the buyer due to her information disadvantage.

This framework serves as a first approach to analyze the design of a forward contract with an imperfect spot market in the presence of asymmetric cost information. To summarize, this study presents the following contributions. First, given the asymmetric cost information, this work derives a menu of forward contracts to help the buyer screen the supplier, which can not only exclude suppliers with inferior production technology, but also prevent the low-cost supplier from disguising. Second, to mitigate the risks associated with fluctuations in the market, this study provides valuable insights for managers, assisting them in rational procurement selection between the forward contract and an imperfect spot market. Lastly, this paper further investigated the interaction of the supplier's private cost information and the buyer's trading in imperfect spot market. Interestingly, it is found that asymmetric material cost information can discourage the buyer from engaging in speculative activities in the spot market. While the existence of a well-developed raw material spot market with a relatively lower price can offer the buyer alternative ways to make procurement and mitigate the negative impacts of his cost information disadvantages.

Inevitably, there is a cross-cutting relationship between supply chain management and finance. Introducing the forward contract into the supply chain can effectively control the uncertainty caused by market fluctuations. This study provides insights into how the buyer should modify her forward contracting strategies with the supplier who has private cost information to synchronize with the thriving business generated by the rise of B2B spot markets. Despite some important results are already obtained in the paper, it is promising to do further investigations to address some limitations in this work. In the future, this research can be extended in the following aspects. This study operates under the assumption that both the supplier and buyer possess rationality, without taking into account their individual risk preferences. The game model can be enhanced by incorporating risk attitudes. An another intriguing avenue for the research is the integration of forward and option contracts, as well as other complementary contracts in the presence of asymmetric information.

Appendix A.

Proof of Theorem 1. Under symmetric information, if the constraints in the problem (3) are not tight, the buyer can still obtain higher returns by reducing payments to the supplier. Therefore, when the forward contract is optimal, there must be $\pi_{S_i}^E\left(T_i^E, q_i^E\right) = 0$, $T_i^E = C_i q_i^E$.

$$\begin{cases} \max\limits_{T_H^E, T_L^E, q_H^E, q_L^E} \pi_B^E = \beta \pi_{B_H}^E \left(T_H^E, q_H^E\right) + (1-\beta)\, \pi_{B_L}^E \left(T_L^E, q_L^E\right) \\ \text{subject to:} \\ \quad \pi_{S_H}^E \left(T_H^E, q_H^E\right) = 0, & \text{(IR-1)} \\ \quad \pi_{S_L}^E \left(T_L^E, q_L^E\right) = 0. & \text{(IR-2)} \end{cases} \tag{A.1}$$

To determine if there is a maximum point for the buyer's profits in the optimization problem (A.1), the constraint conditions need to be incorporated into the objective function, and calculate the negative definite verification of the Hessian matrix of π_B^E with respect to q_H^E and q_L^E.

The expected profits of the buyer are:

$$\begin{aligned} \pi_B^E = \beta \Bigg[& r q_H^E \int_{q_H^E}^{\infty} g(x)\,\mathrm{d}x + r \int_0^{q_H^E} x g(x)\,\mathrm{d}x + \left[m\left(r-\mu_P\right) - (1-m)\, l\right] \int_{q_H^E}^{\infty} \left(x - q_H^E\right) g(x)\,\mathrm{d}x \\ & + \left[m\mu_P + (1-m)v\right] \int_0^{q_H^E} \left(q_H^E - x\right) g(x)\,\mathrm{d}x - C_H q_H^E \Bigg] + (1-\beta) \Bigg[r q_L^E \int_{q_L^E}^{\infty} g(x)\,\mathrm{d}x \\ & + r \int_0^{q_L^E} x g(x)\,\mathrm{d}x + \left[m\left(r-\mu_P\right) - (1-m) l\right] \int_{q_L^E}^{\infty} \left(x - q_L^E\right) g(x)\,\mathrm{d}x \\ & + \left[m\mu_P + (1-m)v\right] \int_0^{q_L^E} \left(q_L^E - x\right) g(x)\,\mathrm{d}x - C_L q_L^E \Bigg]. \end{aligned}$$

Calculating the second partial derivatives and mixed second partial derivatives of π_B^E with respect to q_H^E and q_L^E yields:

$$\begin{aligned} \frac{\partial^2 \pi_B^E}{\partial (q_H^E)^2} &= (m-1)(r+l-v) g(q_H^E) < 0, \\ \frac{\partial^2 \pi_B^E}{\partial (q_L^E)^2} &= (m-1)(r+l-v) g(q_L^E) < 0, \\ \frac{\partial^2 \pi_B^E}{\partial q_H^E \partial q_L^E} &= 0. \end{aligned}$$

From the above formula, it is obtained $\frac{\partial^2 \pi_B^E}{\partial (q_L^E)^2} \frac{\partial^2 \pi_B^E}{\partial (q_H^E)^2} - \frac{\partial^2 \pi_B^E}{\partial q_L^E \partial q_H^E} > 0$, so the Hessian matrix composed of the second-order partial derivatives and mixed partial derivatives of the buyer's profit with respect to q_L^E and q_H^E is negative definite. The buyer's profit function is jointly concave with respect to q_L^E and q_H^E. The stationary point is the maximum point, and the optimal reservation quantity of each type can be obtained by making its first-order derivative with respect to q_L^E and q_H^E equal to 0.

$$\begin{aligned} \frac{\partial \pi_B^E}{\partial q_H^E} &= r\overline{G}\left(q_H^E\right) + \left[(1-m)l - m\left(r-\mu_P\right)\right] \overline{G}\left(q_H^E\right) + \left[m\mu_P + (1-m)v\right] G\left(q_H^E\right) - C_H = 0, \\ \frac{\partial \pi_B^E}{\partial q_L^E} &= r\overline{G}\left(q_L^E\right) + \left[(1-m)l - m\left(r-\mu_P\right)\right] \overline{G}\left(q_L^E\right) + \left[m\mu_P + (1-m)v\right] G\left(q_L^E\right) - C_L = 0. \end{aligned}$$

The optimal forward reservation quantity is:

$$\begin{cases} q_H^{E*} = G^{-1}\left[\frac{(1-m)(r+l)+m\mu_P - C_H}{(1-m)(r+l-v)}\right], \\ q_L^{E*} = G^{-1}\left[\frac{(1-m)(r+l)+m\mu_P - C_L}{(1-m)(r+l-v)}\right]. \end{cases} \tag{A.2}$$

It is easy to find $q_H^{E^*} < q_L^{E^*}$. This solution can satisfy the constraint condition (IC-1), thus it is the optimal solution of the problem. Substituting the optimal predetermined quantity obtained into (A.1), the optimal total payment can be obtained. Theorem 1 is proved. □

Proof of Corollary 1. Recall that $q_i^{E^*} = G^{-1}\left[\frac{(1-m)(r+l)+m\mu_P-C_i}{(1-m)(r+l-v)}\right]$. Denote $J = \frac{(1-m)(r+l)+m\mu_P-C_i}{(1-m)(r+l-v)}$. Note that G^{-1} is monotonically increasing. So the monotonicity of $q_i^E(\cdot)$ is consistent with that of $J(\cdot)$. It is calculated that

$$\begin{aligned}
\frac{\partial J}{\partial C_i} &= -\frac{1}{(1-m)(r+l-v)} < 0, \frac{\partial q_i^{E^*}}{\partial C_i} < 0,\\
\frac{\partial J}{\partial \mu_P} &= \frac{m}{(1-m)(r+l-v)} > 0, \frac{\partial q_i^{E^*}}{\partial \mu_P} > 0,\\
\frac{\partial J}{\partial l} &= \frac{C_i - v + mv - m\mu_P}{(1-m)(r+l-v)^2} > 0, \frac{\partial q_i^{E^*}}{\partial l} > 0,\\
\frac{\partial J}{\partial m} &= \frac{\mu_P - C_i}{(1-m)^2(r+l-v)}.
\end{aligned}$$

when $\mu_P > C_i$, $\frac{\partial J}{\partial m} > 0$, $\frac{\partial q_i^{E^*}}{\partial m} > 0$.

Corollary 1 is proved. □

Proof of Theorem 2. Under asymmetric information, the supplier's production cost C_i is the supplier's private information. Solving the optimization problem (6) requires simplifying and relaxing the constraints. Given that $C_H \geq C_L$, as long as constraints (IR-1) and (IC-2) are met, constraint (IR-2) is automatically satisfied, so constraint (IR-2) can be ignored. In addition, constraints (IR-1) and (IC-2) must be tight, otherwise, it can always increase the amount of T_H^F and T_L^F by an equal amount of δ units to satisfy all constraints, which will reduce the buyer's objective function value. By tightening constraints (IR-1) and (IC-2), one can obtain:

$$T_H^F = C_H q_H^F, \tag{A.3}$$

$$T_L^F = C_H q_H^F - C_L q_H^F + C_L q_L^F. \tag{A.4}$$

Substituting the above equations into the buyer's objective function yields:

$$\begin{aligned}
\pi_B^F = \beta \Bigg[& r q_H^F \int_{q_H^F}^{\infty} g(x)\,\mathrm{d}x + r\int_0^{q_H^F} x g(x)\,\mathrm{d}x + [m(r-\mu_P) - (1-m)l]\int_{q_H^F}^{\infty} \left(x - q_H^F\right) g(x)\,\mathrm{d}x\\
& + [m\mu_P + (1-m)v]\int_0^{q_H^F} \left(q_H^F - x\right) g(x)\,\mathrm{d}x - C_H q_H^F \Bigg] + (1-\beta)\Bigg[r q_L^F \int_{q_L^F}^{\infty} g(x)\mathrm{d}x\\
& + r\int_0^{q_L^F} x g(x)\,\mathrm{d}x + [m(r-\mu_P) - (1-m)l]\int_{q_L^F}^{\infty} \left(x - q_L^F\right) g(x)\,\mathrm{d}x\\
& + [m\mu_P + (1-m)v]\int_0^{q_L^F} \left(q_L^F - x\right) g(x)\mathrm{d}x - C_H q_H^F + C_L q_H^F - C_L q_L^F \Bigg].
\end{aligned}$$

To determine whether π_B^F has a maximum point with respect to q_L^F and q_H^F, one can calculate the second-order partial derivatives of π_B^F with respect to q_L^F and q_H^F, and the second-order mixed partial derivatives:

$$\frac{\partial^2 \pi_B^F}{\partial \left(q_L^F\right)^2} = (m-1)(r+l-v)g\left(q_L^F\right) < 0,$$
$$\frac{\partial^2 \pi_B^F}{\partial \left(q_H^F\right)^2} = \beta(m-1)(r+l-v)g\left(q_H^F\right) < 0,$$
$$\frac{\partial^2 \pi_B^F}{\partial q_L^F \partial q_H^F} = 0.$$

The above expressions show that $\frac{\partial^2 \pi_B^F}{\partial (q_L^F)^2}\frac{\partial^2 \pi_B^F}{\partial (q_H^F)^2} - \frac{\partial^2 \pi_B^F}{\partial q_L^F \partial q_H^F} > 0$, which indicates the Hessian matrix is negative. Thus, the buyer's profit function is a joint concave function with respect to q_L^F and q_H^F. The stationary point is the maximum point, and the optimal number of reservations for each type can be obtained by making its first-order derivatives of q_L^F and q_H^F equal to zero.

$$\frac{\partial \pi_B^F}{\partial q_L^F} = r\overline{G}(q_L^F) + \left[(1-m)l - m\left(r-\mu_P\right)\right]\overline{G}\left(q_L^F\right) + \left[m\mu_P + (1-m)v\right]G\left(q_L^F\right) - C_L = 0,$$
$$\frac{\partial \pi_B^F}{\partial q_H^F} = \beta\left[r\overline{G}\left(q_H^F\right) + \left[(1-m)l - m\left(r-\mu_P\right)\right]\overline{G}\left(q_H^F\right) + \left[m\mu_P + (1-m)v\right]G\left(q_H^F\right)\right] - C_H + (1-\beta)C_L = 0.$$

The optimal pre-order quantity is given as

$$\begin{cases} q_H^{F^*} = G^{-1}\left[1 - \frac{C_H - (1-\beta)C_L - (1-m)\beta v - \beta m\mu_P}{\beta(1-m)(r+l-v)}\right], \\ q_L^{F^*} = G^{-1}\left[1 - \frac{C_L - (1-m)v - m\mu_P}{(1-m)(r+l-v)}\right]. \end{cases} \tag{A.5}$$

It is easy to verify that $q_H^{F^*} < q_L^{F^*}$. This solution can satisfy the constraint condition (IC-1). Therefore, it is a globally optimal solution. By substituting the optimal predetermined quantity into (A.3) and (A.4), one can obtain the optimal total payment.

Theorem 2 is proved. □

Proof of Corollary 4. Recall that $q_H^{F^*} = G^{-1}\left[1 - \frac{C_H - (1-\beta)C_L - (1-m)\beta v - \beta m\mu_P}{\beta(1-m)(r+l-v)}\right]$. Let $J = 1 - \frac{C_H - (1-\beta)C_L - (1-m)\beta v - \beta m\mu_P}{\beta(1-m)(r+l-v)}$. Note that the monotonicity of q_H^F is consistent with that of $J(\cdot)$. It is calculated that:

$$\frac{\partial J}{\partial C_H} = -\frac{1}{\beta(1-m)(r+l-v)} < 0, \frac{\partial q_H^{F^*}}{\partial C_H} < 0,$$
$$\frac{\partial J}{\partial \beta} = \frac{C_H - C_L}{\beta^2(m-1)(v-r-l)} > 0, \frac{\partial q_H^{F^*}}{\partial \beta} > 0,$$
$$\frac{\partial J}{\partial \mu_P} = \frac{m}{(1-m)(r+l-v)} > 0, \frac{\partial q_H^{F^*}}{\partial \mu_P} > 0,$$
$$\frac{\partial J}{\partial l} = \frac{C_H - (1-\beta)C_L - \beta v(1-m) - \beta m\mu_P}{\beta(1-m)(r+l-v)^2} > 0, \frac{\partial q_H^{F^*}}{\partial l} > 0,$$
$$\frac{\partial J}{\partial m} = \frac{\beta(\mu_P - C_L) - C_H + C_L}{\beta(1-m)^2(r+l-v)},$$

when $\mu_P > \frac{C_H - C_L + \beta C_L}{\beta}$, $\frac{\partial q_H^{F^*}}{\partial m} > 0$.

Corollary 4 is proved. □

Proof of Corollary 5. Substituting the specific distribution $U[0,K]$ of D into the Theorems 1 and 2, one has $q_H^{E*} = K\frac{(1-m)(r+l)+m\mu_P-C_H}{(1-m)(r+l-v)}$, $q_H^{F*} = K\left(1-\frac{C_H-(1-\beta)C_L-(1-m)\beta v-\beta m\mu_P}{\beta(1-m)(r+l-v)}\right)$.

Let $L = q_H^{e\,*} - q_H^{F*} = \frac{K(1-\beta)(C_H-C_L)}{\beta(1-m)(r+l-v)}$, which represents the degree of distortion of the buyer's reservations of the high-cost supplier in forward contract under asymmetric information.

$$\begin{aligned}
\frac{\partial L}{\partial \beta} &= \frac{K(C_H-C_L)}{\beta^2(m-1)(r+l-v)} < 0,\\
\frac{\partial L}{\partial \mu_P} &= 0,\\
\frac{\partial L}{\partial C_H} &= \frac{K(1-\beta)}{\beta(1-m)(r+l-v)} > 0,\\
\frac{\partial L}{\partial l} &= \frac{K(\beta-1)(C_H-C_L)}{\beta(1-m)(r+l-v)^2} < 0,\\
\frac{\partial L}{\partial m} &= \frac{K(1-\beta)(C_H-C_L)}{\beta(1-m)^2(r+l-v)} > 0.
\end{aligned}$$

Corollary 5 is proved. □

References

[1] Y. Ai and Y. Xu, Strategic sourcing in forward and spot markets with reliable and unreliable suppliers. *Int. J. Prod. Res.* **59** (2021) 926–941.

[2] C. Billington, B. Johnson and A. Triantis, A real options perspective on supply chain management in high technology 1. *J. Appl. Corporate Finan.* **15** (2002) 32–43.

[3] G.P. Cachon and M.A. Lariviere, Contracting to assure supply: How to share demand forecasts in a supply chain. *Manage. Sci.* **47** (2001) 629–646.

[4] E. Cao, Y. Ma, C. Wan and M. Lai, Contracting with asymmetric cost information in a dual-channel supply chain. *Oper. Res. Lett.* **41** (2013) 410–414.

[5] L. Dong and H. Liu, Equilibrium forward contracts on nonstorable commodities in the presence of market power. *Oper. Res.* **55** (2007) 128–145.

[6] M. Fan, W. Xing and Y. Huang, Joint forward contract negotiation: the role of B2B procurement platforms. *J. Bus. Res.* **167** (2023) 114144.

[7] C.A. Gallego, Intertemporal effects of imperfect competition through forward contracts in wholesale electricity markets. *Energy Econ.* **107** (2022) 105835.

[8] L. Gao, M.E. Nikoofal and W. Zhang, The strategic role of supplier learning. *Manuf. Serv. Oper. Manage.* **26** (2024) 271–290.

[9] A. Goel and G.J. Gutierrez, Multiechelon procurement and distribution policies for traded commodities. *Manage. Sci.* **57** (2023) 2228–2244.

[10] X. Hong, Y. He, P. Zhou and J. Chen, Demand information sharing in a contract farming supply chain. *Eur. J. Oper. Res.* **309** (2023) 560–577.

[11] R. Hou, W. Li, X. Lin and Y. Zhao, Impact of quality decisions on information sharing with supplier encroachment. *RAIRO-Oper. Res.* **56** (2022) 145–164.

[12] S. Huang, Y. Wang and X. Zhang, Contracting with countervailing incentives under asymmetric cost information in a dual-channel supply chain. *Transp. Res. Part E: Logistics Transp. Rev.* **171** (2023) 103038.

[13] C. Kegui, W. Xinyu, H. Min and R. Liang, Monitoring strategies of enterprise's emission reduction with asymmetric information. *RAIRO-Oper. Res.* **55** (2021) S2455–S2470.

[14] S.H. Kim and S. Netessine, Collaborative cost reduction and component procurement under information asymmetry. *Manage. Sci.* **59** (2013) 189–206.

[15] S. Li, A. Murat and W. Huang, Selection of contract suppliers under price and demand uncertainty in a dynamic market. *Eur. J. Oper. Res.* **198** (2009) 830–847.

[16] Z. Lu and Q. Meng, Effects of asymmetric investment cost information on revenue-compensated build-operate-transfer highway contracts. *Transp. Res. Part B: Methodol.* **172** (2023) 71–92.
[17] K. Matsui, Buyer's strategic demand information sharing with an upstream echelon for entry promotion. *Int. J. Prod. Econ.* **242** (2021) 108286.
[18] Y. Merzifonluoglu, Risk averse supply portfolio selection with supply, demand and spot market volatility. *Omega* **57** (2015) 40–53.
[19] Y. Merzifonluoglu, Integrated demand and procurement portfolio management with spot market volatility and option contracts. *Eur. J. Oper. Res.* **258** (2017) 181–192.
[20] I. Nosoohi and A.S. Nookabadi, Outsource planning through option contracts with demand and cost uncertainty. *Eur. J. Oper. Res.* **250** (2016) 131–142.
[21] Ö. Özer and W. Wei, Strategic commitments for an optimal capacity decision under asymmetric forecast information. *Manage. Sci.* **52** (2006) 1238–1257.
[22] P. Sainam, S. Balasubramanian, S. Bhattacharya and L.L. Ong, Pricing under uncertainty: forward and option pricing in sports markets. *J. Bus. Res.* **167** (2023) 114151.
[23] W.K. Wang, C.C. Lin and I.C. Tsai, Long-and short-term price behaviors in presale housing markets in Taiwan. *Econ. Anal. Policy* **74** (2022) 350–364.
[24] D.J. Wu, P.R. Kleindorfer and J.E. Zhang, Optimal bidding and contracting strategies for capital-intensive goods. *Eur. J. Oper. Res.* **137** (2002) 657–676.
[25] W. Xing, S. Wang and L. Liu, Optimal ordering and pricing strategies in the presence of a B2B spot market. *Eur. J. Oper. Res.* **221** (2012) 87–98.
[26] W. Xing, Q. Zhu and X. Zhao, Supply contract design under price volatility and competition. *Int. J. Prod. Res.* **57** (2019) 7536–7551.
[27] J. Xu, G. Feng, W. Jiang and S. Wang, Optimal procurement of long-term contracts in the presence of imperfect spot market. *Omega* **52** (2015) 42–52.
[28] J. Xu, G. Feng, K.S. Chin and W. Jiang, Supply chain decisions and coordination in the presence of an imperfect spot market. *J. Manage. Sci. Eng.* **8** (2023) 32–48.
[29] J. Zhang, S. Li, S. Zhang and R. Dai, Manufacturer encroachment with quality decision under asymmetric demand information. *Eur. J. Oper. Res.* **273** (2019) 217–236.
[30] Y. Zhao, T.M. Choi, T.C.E. Cheng and S.Y. Wang, Supply option contracts with spot market and demand information updating. *Eur. J. Oper. Res.* **266** (2018) 1062–1071.
[31] S. Zhao, Z. You and Q. Zhu, Effects of asymmetric cost information on collection outsourcing of used products for remanufacturing. *Transp. Res. Part E: Logistics Transp. Rev.* **162** (2022) 102729.
[32] H. Zheng, G. Li, X. Guan, S.P. Sethi and Y. Li, Downstream information sharing and sales channel selection in a platform economy. *Transp. Res. Part E: Logistics Transp. Rev.* **156** (2021) 102512.