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Procurement competition in the presence of IoT-enabled B2B E-commerce

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ABSTRACT

The Internet of things (IoT) has accelerated the development of e-commerce and enabled business-to-business (B2B) spot markets to emerge. This study considers a supply chain composed of one supplier and two manufacturers. Two manufacturers can procure raw materials from dual sources, that is, from a supplier with a forward contract or from a B2B spot market. Two manufacturers use raw materials to produce the final product and take part in Cournot competition in the final customer market. On the basis of the procurement strategies of two manufacturers, three competition structures exist between the manufacturers: (NN) both manufacturers procure raw materials only from a B2B spot market; (FN) one manufacturer procures raw materials from dual sources, namely, a forward contract and a B2B spot market, while the other manufacturer only obtains them from a B2B spot market; and (FF) both manufacturers procure raw materials from dual sources. We investigate which procurement strategy is better for manufacturers. Our study finds that the optimal setting is for manufacturers to procure raw materials from dual sources if and only if the spot price uncertainty exceeds a threshold value. Furthermore, the optimal wholesale price in the FN subgame is less than the price in the FF subgame. The optimal order quantity in the FF subgame is less than the quantity in the FN subgame. Whole downstream manufacturers can benefit from the FN strategy if the supplier's risk aversion exceeds a threshold value. Meanwhile, the FF subgame always benefits the whole supply chain.

1. Introduction

In the last two decades, supply chain behavior has been significantly reshaped by information technology (Li et al., 2020; Zhang et al., 2020). Particularly, the Internet of things (IoT) has pulled in numerous opportunities and has extended supply chains. Moreover, e-commerce has been widely connected with IoT with the development of the Internet. One of the outcomes of the combination of e-commerce and IoT is the business-to-business (B2B) spot commodity market. A B2B spot commodity market has a significant growth not only in terms of trading volume and contract varieties but also in terms of liquidity (Dong and Liu, 2007). The emergence of B2B spot markets provides firms with a more flexible trading mode and helps these entities effectively manage their supply and demand risk (Grey and Olavson, 2005; Zhao et al., 2015). With a B2B spot market, the supply and demand can be adjusted to balance each other at a price equal to the spot price. A B2B spot market usually has a short lead time, and managers usually rely on this new procurement channel after demand information is observed. With the growing market liquidity, numerous raw materials and commodities, such as agricultural products, chemical products, metals, and plastics, are now widely transacted in B2B spot markets (Xing et al., 2012, 2014). In this study, we explore whether traditional procurement channel must still be maintained because B2B spot market procurement provide several advantages for risk-averse firms.

Different types of manufacturers use B2B spot markets in various ways. Numerous manufacturers use B2B spot markets as their second-sourcing procurement channel. They first procure their raw materials or commodities from the forward contract. When the demand and spot price are realized, they trade raw materials or commodities via a B2B spot market. For instance, Apple and Huawei both procure their DRAM card, a key component for mobile phones, from traditional forward contract and adjust their inventory in a B2B spot market (Ma et al., 2019). Canon and Nikon, two oligarchs of professional SLR cameras in Japan, usually procure normal-sized digital processing chips from a B2B spot market. They also procure these chips from an upstream supplier, NEC, in the off-season. However, several new or small manufacturers

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procure their raw materials or commodities only from B2B spot markets. They set the spot market as a unique procuring channel. For example, in the US beef industry, some beef packers procure fed cattle mainly via B2B spot markets (Boyabatli and Kleindorfer, 2011). Meanwhile, soybean-based product manufacturers in and around the major soybean growing areas of Northeast China usually trade soybean in B2B spot markets because these markets have been widespread.

B2B spot markets can effectively help firms to manage commodity inventory to control risk exposure. Several researchers have predicted that B2B spot markets will eventually replace forward contracts. However, numerous examples of the shortcomings of B2B spot markets clearly prove that signing contracts and long-term relationships with suppliers are beneficial in reality. The related literature has not adequately investigated the necessity of traditional procurement channels for risk-averse supply chain players under the presence of B2B spot markets and competition. Thus, our motivation for this study stems from our interest in addressing the following questions. Given dual sources, namely, the traditional forward contract and the B2B spot market, should manufacturers give up the traditional procurement source? Which procurement strategy is better for the upstream supplier and the downstream manufacturers under competitive circumstances? What is the impact of spot price volatility, demand volatility, capacity, correlation coefficient, and supply chain players' risk aversion on their decisions and utilities?

To answer the above questions, this study considers a supply chain that consists of one risk-averse suppler and two risk-averse manufacturers. Two manufacturers use raw materials to produce the final product and take part in Cournot competition in the final customer market. These manufacturers have dual sources to procure raw materials. They can procure raw materials from the supplier with a traditional forward contract or from a B2B spot market. On the basis of the two manufacturers' procurement sources, three competition structures exist between the manufacturers: (NN) both manufacturers procure raw materials only from a B2B spot market, (FN) one manufacturer procures raw materials from dual sources, that is, a forward contract and a B2B spot market, while another only obtains materials from a B2B spot market, and (FF) both manufacturers procure raw materials from the dual sources. We separately analyze three competition structures and obtain the optimal wholesale price for suppliers, the optimal procurement quantity for manufacturers, and the corresponding utility of three supply chain players. By comparing the results of the three structures, we gain the optimal procurement strategy for independent manufacturers, for the whole downstream manufacturers and for the whole supply chain.

This study provides a better understanding of the strategic procurement selection between the forward contract and the business-to-business (B2B) spot market in a two-stage supply chain under a competition scenario. Risk-averse manufacturers select the optimal procurement strategy based on spot price variance, which measures the uncertainty of the spot market. The two manufacturers are suggested to procure raw materials from dual sources if the spot price volatility is high, but otherwise forego the forward contract and only procure raw materials from the B2B spot market. The FN strategy can benefit all the downstream manufacturers if the supplier's risk aversion exceeds a threshold value, while the FF strategy always benefits the supply chain. Thus, two manufacturers can cooperate to sign an ex-ante agreement, which stipulates that one manufacturer procures from dual sources while the other procures only from the spot market. One manufacturer should provide the other manufacturer with a monetary incentive to compensate for the profit loss brought by the unchanged strategy. Thus, this study provides suggestions for decision makers to set the wholesale price and procurement strategy according to important factors, such as spot price, demand variances, and the supply chain player's attitude toward risks.

The remainder of this paper is organized as follows. We present the related literature in Section 2. In Section 3, we consider the basic problem. Then, in Section 4, we analyze the optimal wholesale price for the supplier, procurement, and production strategies for manufacturers under the NN, FN, and FF subgames, respectively. Next, we determine which strategy is better for supply chain players by comparing the optimal results in the three subgames in Section 5. We summarize the conclusions and practical implications and provide some opportunities for future research in Section 6.

2. Literature review

This study is related to two streams of literature: (1) procurement decisions of the B2B spot market; and (2) risk management of supply chain.

2.1. Spot market procurement

In recent years, the supply chain problem regarding B2B spot markets has attracted substantial attention.

Some researchers have considered both dual channels: the B2B spot market and the forward contract. Seifert and Thonemann (2004) analyzed optimal procurement strategies and described some advantages of adopting a spot market from the perspective of the supply chain. They found that companies using the spot market can provide better services for downstream companies but will suffer greater profit volatility. Dong and Liu (2007) observed that the supplier and the manufacturer determine the forward contract price and order quantity by Nash negotiation considering the spot market. Boyabath et al. (2011) examined the beef supply chain in the United States. In this supply chain, meat packers can obtain raw materials through forward contracts and spot markets to produce two kinds of beef products. They found that higher variables can benefit firms but reduce their dependence on the contract market. Xu et al. (2015) considered a risk-neutral buyer who could set forward and option contracts early and transact in an incomplete spot market in which demand and spot price information could be obtained randomly. Braganca and Daglish (2016) analyzed the relationship between the spot prices and the state variables that affect an enterprise's profit by developing an electricity market model. Meanwhile, Xu et al. (2019) studied the procurement strategy of an e-retailer who sells products online under different logistics distribution systems on the basis of a game theory model. In two separate studies, Ma et al. (2019, 2015) investigated whether enterprises should provide pre-order strategies and the impact of raw material spot market on their decision-making and performance. Moreover, enterprises have certain market forces to influence spot price.

Some studies have only set the B2B spot market as the sole procuring channel and have not considered traditional procuring channels. Muermann and Shore (2005) considered a player who only trades goods from a spot market. The player has some market power and can influence spot prices to go up and down to obtain more profits from the spot market. Mendelson and Tunca (2007) investigated the impact of spot markets on the supply chain considering a closed spot market with limited participants and endogenous spot price. Hong and Lee (2013) proposed a novel strategy support framework to characterize the procurement risk and developed a purchasing plan considering a spot market. In addition, Vincent et al. (2017) presented a novel organizational buyer decision-making process in B2B e-commerce. Meanwhile, some studies have only set the traditional forward contract as the sole procuring channel. Chang et al. (2021) examined two online competing retailers who procure products from a single supplier and their decision to provide a calculated or free shipping policy.

Some works in the literature have researched B2B spot markets in the presence of competitive circumstances (e.g., Mendelson and Tunca, 2007; Gümüs et al., 2012). Cruise and Flatley (2018) studied the impact of storage Cournot competition on energy spot markets. Moreover, Ando (2018) forecasted and analyzed the competitive market environment and used business analysis to support the strategy formulation of the online group buying market. In another study, Li et al. (2019) studied the impact of drop-shipping on an e-tailer's procurement strategy; this e-tailer procures products through two competing manufacturers.

Existing literature mainly focuses on the procurement strategy and does not consider risk attitude for supply chain players. By contrast, the present study complements the research gaps by considering the procurement decisions through forward contract and spot market for risk-averse manufacturers under a competition scenario.

2.2. Risk management

Some studies have considered risk-averse supply chain players. Kazaz and Webster (2011) observed that a food producer facing yield uncertainty sells some of its raw materials in the spot market without converting them into terminal products. Xing et al. (2012) analyzed the influence of the B2B spot market on the procurement behavior and utility of a risk-averse reseller who prepares products via dual channels: the forward contract and the B2B spot market. Xing et al. (2014) studied a risk-averse supply chain player's strategy on channel selection, pricing, and procurement in the presence of a B2B spot market. Zhao et al. (2015) studied the impact of information updating on supply chain players considering risk management. Anderson and Monjardino (2019) considered yield risk in the context of a three-level supply chain, and studied the impact of contract structure on buyer's purchasing behavior. Oliveira and Ruiz (2021) explored the procurement strategy between risk-averse and oligopolistic generators and retailers in the electricity supply chain. Gümüs et al. (2012) considered a supply chain composed of one buyer and two suppliers that compete for the buyers' orders and suffer risks in supply disruption. The buyer can procure goods from two suppliers or the spot market. In their model, the trading capacity of two suppliers can influence the spot market price. In the present study, we consider a supply chain composed of one supplier and two manufacturers who suffer risks in the demand market. The two manufacturers can procure goods from one supplier or the spot market, and in our model, their trading behavior cannot influence spot price.

Our work supplements those of Xing et al. (2014) and Dong and Liu (2007), which examined risk-averse supply chain strategies on channel selection, pricing, and procurement in B2B spot markets. Although the selling/procurement strategy of dual channels and risk-averse behavior of supply chain players are examined, such problems may exist in different scenarios. First, Xing et al. (2014) assessed the selling strategy of dual channels for an upstream supplier, while Dong and Liu (2007) explored the optimal forward contract through Nash bargaining under a non-competition scenario. By contrast, we investigate the procurement channel strategy of two manufacturers who engage in Cournot competition in the final customer market. Second, Xing et al. (2014) and Dong and Liu (2007) set the forward contract as the necessary sales channel for upstream suppliers, whereas we use the spot market as the necessary procurement channel and set the forward contract as the optional channel for two competitive manufacturers. Table 1 summarizes the distinction of our study and indicates its research contributions.

3. The model

We consider a supply chain composed of one suppler (she) and two manufacturers (A and B) with a fully liquid B2B spot market. Two manufacturers can procure raw materials through dual sources, through a supplier with a forward contract with price w, or through a B2B spot market with price s. Two manufacturers use raw materials to produce the final product and take part in Cournot competition in the final customer market. Specifically, given two manufacturers' production quantities $q_i \sim (i = A,B)$, the price of the final product is $p = a - q_A - q_B$, where a is a random variable that represents the price potential of final product (demand intercept). For maintain simplicity and to not affect the analytical results, we do not consider the production cost of the final product. Literature has this common characteristic, such as in (Xing et al., 2014; Zhao et al., 2015; Xu et al., 2015 and Ma et al., 2019), that the production cost is neglected.

Assuming that the three players are risk-averse, they need to limit their suffering risk while seeking maximum profit. We merge their risk tolerances into the following models. We assume that two manufacturers have the same risk attitudes to prevent any distorted effect from asymmetric parameters. We use k_s and k_m to measure the supplier and manufacturers' risk aversion, respectively. Then, $k_s > 0, k_m > 0$. The supplier and manufacturers' profits are π_S and $\pi_i (i = A,B)$, and their utilities are $U_S, U_i (i = A,B)$, respectively. That is, $U_S(\pi_i) = E[\pi_S] - k_s V[\pi_S]$ and $U_i(\pi_i) = E[\pi_i] - k_m V[\pi_i], i = A,B$, where $E[\cdot]$ and $V[\cdot]$ are the expectation and variance, respectively. The supply chain players attempt to maximize their mean–variance utilities. Using mean–variance utility function to measure risk attitude is very common in supply chain management literature in the presence of a spot market (e.g., Xing et al., 2012; Xing et al., 2014; Zhao et al., 2015).

The decision sequence of events is presented in Fig. 1. Two manufacturers simultaneously select the procurement strategy (i.e., dual-sources or only the spot market) at time T_0. Immediately afterward (at time T_1), the supplier decides the raw material price w of a forward contract on the basis of the manufacturer's procurement strategy. At time T_2, the manufacturer(s) with the forward contract decides order quantities Q_i $(i = A,B)$ of the raw material, simultaneously. At time T_3, the random spot price and demand are realized, and the contracted quantity is shipped to the manufacturer(s). Then, two manufacturers decide their final production quantities q_i $(i = A,B)$, simultaneously. In the meantime, the manufacturers can trade raw materials through the B2B spot market on the basis of the realized spot price and demand. The supplier can also trade in the B2B spot market for the raw materials. To maximize his profit, the manufacturer should always satisfy all market demands before disposing the excess inventory of raw materials through the B2B spot market (Ma et al., 2015).

Generally, demand intercept a can reflect the whole market trend. If the demand intercept is high, spot price s will rise, and vice versa. Therefore, a positive correlation exists between the demand intercept and the spot price (Seifert and Thonemann, 2004). For model tractability, we assume that demand intercept a and spot price s satisfy a normal distribution, i.e., $(a,s) \sim BN[\mu_a, \mu_s, \sigma_a^2, \sigma_s^2, \rho]$ and $0 \leqslant \rho < 1$. The

Table 1
Difference between this research and related literature

Literature	Channels		Risk		Competition	
	Sole channel	Dual Channel	Risk-aversion	Risk-neutral	Without competition	With competition
(Xu et al., 2015; Braganca and Daglish, 2016; Ma et al., 2019, 2015)		✓		✓	✓	
(Muermann and Shore, 2005; Mendelson and Tunca, 2007; Hong and Lee, 2013)	✓					
(Gümüs et al., 2012)		✓	✓			✓
(Cruise and Flatley, 2018; Ando, 2018)						✓
(Dong and Liu, 2007; Xing et al., 2012, 2014; Zhao et al., 2015)		✓	✓		✓	
This paper		✓	✓			✓

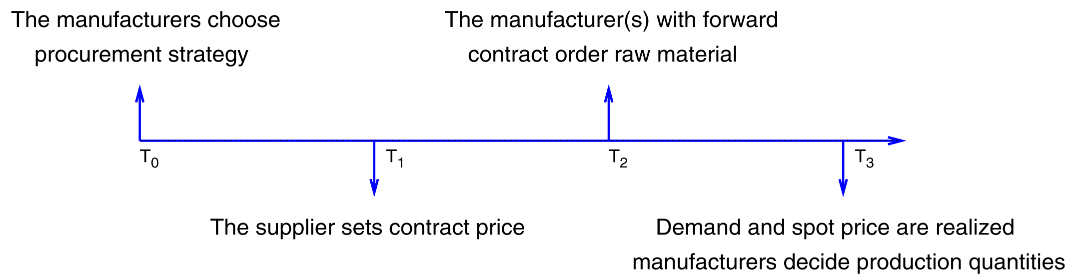

Fig. 1. Events Decision Sequence.

normal-distribution assumption is reasonable for commodity and is common in recent literature (Aviv, 2001; Zhao et al., 2015; Ma et al., 2019). We assume that $\mu_a > \mu_s$ to ensure a positive production in the final market.

The supplier's profit comprises three parts, the first of which comes from the forward contract while the second and third parts come from the spot market.

$$\pi_S = w(Q_A + Q_B) + s(C - Q_A - Q_B)^+ - s(Q_A + Q_B - C)^+, \tag{1}$$

where $(x)^+ = \max\{x, 0\}$ and C represents the supplier's capacity, $s(C - Q_A - Q_B)^+$ shows that the supplier intends to sell extra raw materials in the spot market, and $s(Q_A + Q_B - C)^+$ means that the supplier procures the shortfall from the spot market. Thus, the profit function can be simplified as $\pi_S = w(Q_A + Q_B) + s(C - Q_A - Q_B)$. The supplier decides the wholesale price w to maximize her mean–variance utility, that is $\max_w U_S(\pi_S)$. Furthermore, the forward contract order quantities are no less than zero, i.e., $Q_i \geqslant 0 (i = A, B)$.

Before we analyze the equilibrium strategies, we need to first solve the equilibrium contract price, procurement, and production quantities using backward induction given each possible combination of the procurement strategy. NN, FN, and FF denote the three possible equilibrium subgames of the strategies. For instance, U_A^{FN} denotes the utility of manufacturer A under the FN subgame in which manufacturer A adopts the forward contract while manufacturer B only trades in the spot market.

4. Equilibrium Analysis

In Section 4, we analyze the optimal wholesale price of the supplier, procurement, and production strategies of the manufacturers under the NN, FN and FF subgames, respectively. Under each of the subgame, we formulate a multi-stage game. Then, we solve each of the decision stage and characterize its equilibrium, starting at time T_3 and going backwards.

4.1. NN Subgame

We consider the NN subgame in which neither manufacturers adopt a forward contract. In this case, the manufacturers can only procure raw materials through the B2B spot market. At time T_3, spot price s and demand intercept a are realized. Manufacturers A and B determine their production quantities q_A and q_B. Then, they procure that quantity from the B2B spot market simultaneously. The manufacturers' decision problems can be expressed as follows.

$$\max_{q_i} \pi_i = (a - q_A - q_B)q_i - sq_i, \qquad i = A, B. \tag{2}$$

Manufacturer i's profit includes two parts. The first part is the profit obtained via the end customer market. The second part is the cost of raw materials when purchasing through the B2B spot market.

Lemma 1. *Under the NN subgame, the manufacturers' optimal production quantities and profits at time T_3 are given by*

$$q_i^{NN} = \frac{a - s}{3}, \ \pi_i^{NN} = \frac{(a - s)^2}{9}. i = A, B. \tag{3}$$

Given that manufacturers only procure raw materials through the spot market, the supplier can only dispose her inventory through this market. On the basis of the optimal production quantities, we can obtain the manufacturers' and supplier's equilibrium utilities as follows.

Theorem 1. *Under the NN subgame, the supplier and manufacturers' equilibrium utilities are as follows.*

$$U_S^{NN} = \mu_s C - k_s \sigma_s^2 C^2, \tag{4}$$

$$U_M^{NN} = \frac{E[(a - s)^2]}{9} - k_m \frac{V[(a - s)^2]}{81}. \tag{5}$$

Theorem 1 shows that the supplier's utility is composed of two terms. First is the expected profit brought by trading in the spot market and the second comprises the supplier losses caused by volatility of spot price. Manufacturer's utility is also composed of two terms. First is the expected profit from the final customer market and the second comprises the losses brought by uncertainties of demand and spot price.

4.2. FN subgame

We consider the FN subgame where only manufacturer A sets a contract with the supplier. Then, manufacturer A procures the raw material from the dual sources: the forward contract and the spot market. At time T_3, manufacturer A's decision problem is given by

$$\max_{q_A} \pi_A = (a - q_A - q_B)q_A + s(Q_A - q_A)^+ - s(q_A - Q_A)^+ - wQ_A. \tag{6}$$

As manufacturer B only procures from the spot market, his profit function is $\pi_B = (a - q_A - q_B)q_B - sq_B$. By maximizing the manufacturers' profit function, we can obtain the optimal production quantity, which is identical to the results in the NN subgame, i.e., $q_i^{FN} = q_i^{NN}, i = A, B$. One manufacturer's contract order quantity does not affect two manufacturers' competition in the final customer market.

At time T_2, manufacturer A orders raw materials from the supplier according to the wholesale price.

Lemma 2. *Under the FN subgame, given wholesale price w at time T_2, manufacturer A's optimal order quantity is*

$$Q_A^{FN} = \frac{\mu_s - w}{2k_m\sigma_s^2} + \frac{2(1 - \rho\sigma_a/\sigma_s)(\mu_a - \mu_s)}{9}. \tag{7}$$

From Lemma 2, we can observe that manufacturer A adjusts his contract order quantity on the basis of two parts. The first part is the strategic quantity, which represents two aspects. When the mean of spot price is higher than the wholesale price, i.e., $\mu_s > w$, manufacturer A will intentionally increase the contract order quantity to deal with the excess quantity through the spot market and obtain additional profits. When the mean of spot price is lower than the wholesale price, i.e., $\mu_s < w$, manufacturer A will intentionally reduce the contract order quantity to purchase the insufficient quantity through the spot market. As manufacturer A becomes more risk averse, this strategic quantity decreases. If the spot market is more volatile, then the strategy quantity will also decrease. Without the effect of strategic quantity, i.e., $w = \mu_s$, the expected production quantity is still larger than the optimal order quantity, i.e., $E[q_i^{FN}] > Q_A^{FN}$. Manufacturer A will intentionally underorder the raw materials from the forward contract in hopes of procuring them from the spot market. The second part refers to the risk-reduced expected demand, which is dependent on the correlation coefficient because of manufacturer A's contract from the upstream supplier. The risk-reduced factor $(1-\rho\sigma_a/\sigma_s)$ decreases in the volatility of the final market demand and increases in the volatility of the spot price. Then, it disappears if $\rho = 0$. In this scenario, manufacturer A adjusts the order quantity of the forward contract to avoid the demand risk partially. The demand of the final product is correlated with the spot price.

Under the FN subgame, the supplier's profit comes from two channels: the forward contract and the spot market, i.e., $\pi_S = wQ_A + s(C-Q_A)^+ - s(Q_A - C)^+$. At time T_1, the supplier sets the optimal wholesale price to maximize her utility function.

As we mainly study the impact of spot trading on the procurement strategy of the manufacturer, we set a threshold on the spot price

$$\sigma_s^* = \frac{2k_m\rho\sigma_a(\mu_a-\mu_s)}{9k_sC + 2k_m(\mu_a-\mu_s)}. \tag{8}$$

Theorem 2. *Under the FN subgame, manufacturer A will give up the forward contract if $\sigma_s \leqslant \sigma_s^*$, i.e., $Q_A^{FN} = 0$. Otherwise, manufacturer A will adopt the forward contract, i.e., $Q_A^{FN} > 0$ and supplier sets optimal wholesale price w^{FN},*

$$w^{FN} = \mu_s - \frac{2k_mk_s\sigma_s^2C}{2k_m+k_s} + \frac{4k_m\sigma_s^2(k_m+k_s)(1-\rho\sigma_a/\sigma_s)(\mu_a-\mu_s)}{9(2k_m+k_s)}. \tag{9}$$

The optimal order quantity of the manufacturer A is given by

$$Q_A^{FN} = \frac{k_sC}{2k_m+k_s} + \frac{2k_m(1-\rho\sigma_a/\sigma_s)(\mu_a-\mu_s)}{9(2k_m+k_s)}. \tag{10}$$

The supplier and manufacturers' utilities are present, respectively, as follows,

$$U_B^{FN} = U_M^{NN}, \tag{11}$$

$$U_S^{FN} = U_S^{NN} + (2k_m+k_s)\sigma_s^2(Q_A^{FN})^2, \tag{12}$$

$$U_A^{FN} = U_M^{NN} + k_m\sigma_s^2(Q_A^{FN})^2. \tag{13}$$

Theorem 2 represents the equilibrium results for the FN subgame. When the uncertainty of the spot price is lower, manufacturer A will give up the forward contract. Given that manufacturer A will gain more profit via the spot market with little volatility loss, he will only procure through the spot market. However, when the uncertainty of the spot price is higher, manufacturer A will suffer large volatility loss. Thus, he will transact with the supplier via a forward contract to decrease the loss brought by the fluctuating spot market. The supplier sets the wholesale price using μ_s as the starting point and takes into account the capacity and downstream members' risk aversion. Then, the supplier will decrease the wholesale price to drive the manufacturer to procure more raw materials from the forward contract when the supplier's capacity increases. When the capacity is larger, i.e., $C > 2(k_m + k_s)(1-\rho\sigma_a/\sigma_s)(\mu_a-\mu_s)/(9k_s)$, then the optimal wholesale price is lower than the mean of spot price, i.e., $w^{FN} < \mu_s$. The supplier will set a lower price to attract the manufacturer to procure more from the forward contract. In doing so, the manufacturer can reduce his inventory and avoid the risk caused by the spot trading. If the supplier becomes risk-neutral, i.e., $k_s \to 0^+$, the supplier will set the wholesale price to be larger than μ_s, i.e., $w^{FN} > \mu_s$. The supplier is not afraid of the risk caused by the spot price volatility. Hence, she sets a higher price to maximize her expected profit. If the manufacturer becomes risk-neutral, i.e., $k_m \to 0^+$, then the supplier will set the optimal wholesale price equal to μ_s, i.e., $w^{FN} = \mu_s$. Moreover, the manufacturer's strategic procurement quantity will become zero. Then, manufacturer A's order quantity via a forward contract is equal to the capacity of the supplier. In this scenario, manufacturer A wants to procure more materials via the contract and speculate in the spot market. We also observe from this theorem that the forward contract can always benefit the supplier and manufacturer A when the spot price fluctuates greatly. Further, the supplier obtains more benefits from the forward contract than manufacturer A, i.e., $(U_S^{FN} - U_S^{NN})/(U_A^{FN} - U_M^{NN}) = 2 + k_s/k_m$.

4.3. FF Subgame

We consider the FF subgame, where both manufacturers opt to procure raw materials via a forward contract prior to the selling season. Then, at time T_3, the two manufacturers' problem is given by

$$\max_{q_i} \pi_i = (a - q_A - q_B)q_i + s(Q_i - q_i)^+ - s(q_i - Q_i)^+ - wQ_i, \qquad i = A, B. \tag{14}$$

By maximizing the manufacturers' profit functions and utilities, the optimal production quantity q_i^{FF} and order quantity Q_i^{FF} can be obtained (given a wholesale price w), respectively, which are consistent with the strategy of manufacturer A in the FN subgame.

Theorem 3. *Under the FF subgame, the supply chain players follow the same threshold policy as the FN subgame. The manufacturers do not procure the raw materials from the forward contract if the spot price uncertainty is less than a certain threshold, i.e., $\sigma_s \leqslant \sigma_s^*$. However, if the uncertainty is larger than the threshold, i.e., $\sigma_s > \sigma_s^*$, then the manufacturers adopt the forward contract. In this case, we obtain the optimal wholesale price w^{FF},*

$$w^{FF} = \mu_s - \frac{k_mk_s\sigma_s^2C}{k_m+k_s} + \frac{2k_m(k_m+2k_s)\sigma_s^2(1-\rho\sigma_a/\sigma_s)(\mu_a-\mu_s)}{9(k_m+k_s)}. \tag{15}$$

The optimal order quantity of the manufacturer is given by

$$Q_i^{FF} = \frac{k_sC}{2(k_m+k_s)} + \frac{k_m(1-\rho\sigma_a/\sigma_s)(\mu_a-\mu_s)}{9(k_m+k_s)}, \quad i = A, B. \tag{16}$$

Then, the supplier and manufacturers' utilities are as follows, respectively,

$$U_S^{FF} = U_S^{NN} + 4(k_m+k_s)\sigma_s^2(Q_i^{FF})^2, \tag{17}$$

$$U_M^{FF} = U_M^{NN} + k_m\sigma_s^2(Q_i^{FF})^2. \tag{18}$$

From Theorem 3, we can observe that their structures are similar to those in Theorem 2. Thus, they have analogous interpretations. When the uncertainty of the spot price is relatively large, the two manufacturers will transact with the supplier to avoid the volatility risk. In such case, the supplier sets the mean of spot price as the starting item while taking into account the risk attitudes of both players and capacity. If the supplier's capacity is higher, i.e., $C > 2(k_m + 2k_s)(1-\rho\sigma_a/\sigma_s)(\mu_a-\mu_s)/(9k_s)$, then the optimal wholesale price will be lower than the expected spot price, i.e., $w^{FF} < \mu_s$. Comparing this capacity threshold with that in Theorem 2, we gather that the capacity threshold in the FF subgame is larger than that in the FN subgame, as both manufacturers transacting with the supplier via forward contract brings some advantage to the supplier. If the manufacturers become risk-neutral, i.e., $k_m \to 0^+$, then the manufacturers' order quantity via the forward contract is half of the supplier's capacity. The supplier also reaps more benefits from the forward contract than the manufacturers, i.

e., $(U_S^{FF} - U_S^{NN})/(U_M^{FF} - U_M^{NN}) = 4(1 + k_s/k_m)$.

5. Dual-sourcing or not? Comparisons and sensitivity analysis

In the above section, we have obtained the optimal solutions under the three different subgames in closed forms. Understanding which strategy is better for the supply chain players would provide useful guidelines for managers to manage risk in practice better. Furthermore, we also research the impact of the spot price uncertainty, demand uncertainty, and correlation coefficient on the optimal wholesale price, optimal order quantity, and supply chain members' utilities under the three subgames.

5.1. Comparisons for the three subgames

Proposition 1. *If $\sigma_s > \sigma_s^*$, (1) the optimal wholesale price satisfies $w^{FN} < w^{FF}$, (2) the optimal order quantity satisfies $Q_A^{FN} > Q_A^{FF}$, and (3) the optimal utility for the three players satisfies $U_A^{FN} > U_M^{FF} > U_B^{FN} = U_M^{NN}$, $U_S^{FN} < U_S^{FF}$. Then, the FF subgame is the Nash equilibrium strategy for the two manufacturers.*

Proposition 1 represents the comparison results for the three different subgames. As observed from Proposition 1, we can see that if the spot price uncertainty is relatively high, i.e., $\sigma_s > \sigma_s^*$, then the optimal wholesale price in the FN subgame is less than the optimal wholesale price in the FF subgame. Both manufacturers transacting with the supplier in the FF subgame bring more advantages to the supplier in setting the wholesale price. Meanwhile, a lower wholesale price in the FN subgame attracts manufacturer A to order more quantities than in the FF subgame. With the comparison on the manufacturers' utilities under different subgames, we can find that the FF subgame is the pure equilibrium competition strategy. We suppose that both manufacturers initially procure raw materials only from the spot market. If one of them transacts with the supplier via a forward contract, then he can get more benefit from this strategy. Hence, they both opt to transact with the supplier to improve their equilibrium utilities. In addition, the transaction with the two manufacturers can further improve the supplier's utility. Thus, the supplier prefers that the downstream manufacturers select the FF subgame. If the spot price uncertainty is lower, i.e., $\sigma_s \leqslant \sigma_s^*$, the two manufacturers will give up the forward contract and only procure raw materials from the spot market. Furthermore, if the supplier is risk-neutral, i.e., $k_s = 0$, then $w^{FF} = w^{FN}, Q_A^{FN} = Q_A^{FF}, U_A^{FN} = U_M^{FF}$, and $U_S^{FF} > U_S^{FN}$, it means the procurement strategy of two manufacturers does not influence the supplier's wholesale price strategy while it can actually improve supplier's utility.

Proposition 2. *We suppose that $\sigma_s > \sigma_s^*$. (1) For downstream manufacturers, $U_A^{FN} + U_B^{FN} > U_A^{FF} + U_B^{FF}$ if and only if $k_s > \sqrt{2}k_m$. (2) For the whole supply chain, $U_S^{FN} + U_A^{FN} + U_B^{FN} < U_S^{FF} + U_A^{FF} + U_B^{FF}$.*

If the supplier's risk attitude is larger than a threshold, i.e., $k_s > \sqrt{2}k_m$, the FN subgame can benefit all downstream manufacturers compared with the FF subgame. If the two manufacturers cooperate, they should select the FN subgame. The FN subgame always hurts the whole supply chain compared with the FF subgame. Thus, Proposition 2 provides useful guidelines for the supply chain players.

Proposition 3. *If $k_s > \sqrt{2}k_m$, manufacturer A can provide subsidy, which is no less than $U_A^{FF} - U_M^{NN}$ for manufacturer B. Then, the FN subgame is the best strategy for the two downstream manufacturers.*

When the supplier's risk attitude is relatively high, i.e., $k_s > \sqrt{2}k_m$, manufacturer *A* can provide some subsidy for manufacturer *B*, which is no less than $U_A^{FF} - U_M^{NN}$, and sign a contract to entice manufacturer *B* to adopt N strategy. Hence, the FN subgame is the best strategy for the two downstream manufacturers (set two manufacturers as a whole).

5.2. Sensitivity analysis on strategies and performances

Proposition 4. *We suppose that $\sigma_s > \sigma_s^*$. In the FN and FF subgames, the optimal wholesale price, optimal order quantity, and utilities for supplier and manufacturers decrease in the demand uncertainty.*

Proposition 4 has the following implications. With the increase of demand uncertainty, the manufacturer will suffer more risks in the final customer market. To avoid the risk of demand uncertainty, the manufacturer will deliberately decrease the forward contract quantity, hoping to obtain the shortfall from the spot market. Further, to increase the order quantity of the forward contract, the supplier will decrease her wholesale price. A lower wholesale price allows the supplier to obtain a lower marginal profit. Thus, a higher demand uncertainty always hurts the supplier and manufacturers for the FN and FF subgames.

Proposition 5. *We suppose that $\sigma_s > \sigma_s^*$. (1) In the FN subgame, the optimal wholesale price decreases in the spot price uncertainty if and only if $C > (k_m + k_s)(2 - \rho\sigma_a/\sigma_s)(\mu_a - \mu_s)/(9k_s)$. In the FF subgame, the optimal wholesale price decreases in the spot price uncertainty if and only if $C > (k_m + 2k_s)(2 - \rho\sigma_a/\sigma_s)(\mu_a - \mu_s)/(9k_s)$. (2) In the FN and FF subgames, the equilibrium order quantity always increases in the spot price uncertainty.*

Proposition 5 suggests that if such uncertainty increases, trading in the spot market is more risky for the supplier in the FN and FF subgames. Then, the supplier should set a small wholesale price if the capacity is relatively large. A smaller wholesale price can stimulate a higher contract order quantity so that the supplier can dispose her high capacity inventory. Proposition 5 also shows that if the spot price uncertainty increases, trading in the spot market becomes riskier. Thus, the manufacturer will deliberately procure more quantities from the forward contract.

Proposition 6. *We suppose that $\sigma_s > \sigma_s^*$. In the FN and FF subgames, the optimal wholesale price, the optimal order quantity, and the utilities for the supplier and manufacturers decrease in the correlation coefficient ρ.*

Proposition 6 has the following implication. If the demand and spot price become more relevant, the manufacturers can control their risk exposure better via the spot market. Hence, they will decrease their forward contract quantities and trade more via the spot market to fulfill the demand of the final customer market. Knowing this trend, the supplier will decrease her wholesale price. The supplier's utility can be further reduced because of the decreasing order quantity and wholesale price.

6. Conclusions

We consider a supply chain that consists of one risk-averse suppler and two risk-averse manufacturers. Manufacturers can procure raw materials from dual sources, that is, from a supplier with a forward contract or from a B2B spot market. In the final customer market, the two manufacturers engage in Cournot competition. On the basis of the manufacturers' procurement strategies, three competition subgames exist: (NN) both manufacturers procure raw materials only from the B2B spot market; (FN) one manufacturer procures raw materials from dual sources, that is, the forward contract and the B2B spot market, while the other only obtains resources from the B2B spot market; and (FF) both manufacturers procure raw materials from dual sources. We analyze and compare the supplier's optimal wholesale price, the manufacturers' procurement, and the production strategies under three different subgames, respectively.

This study's key contribution is to show a better understanding of the strategic procurement selection among the forward contract and the B2B spot market in a simple supply chain under a competition scenario. Our study finds that the risk-averse manufacturer selects the optimal procurement strategy on the basis of spot price variance because this variance measures the uncertainty of the B2B spot market. If the spot price uncertainty is higher, the two manufacturers should procure raw materials from the dual sources. If the spot price uncertainty is lower, the two manufacturers should give up the forward contract and only procure raw materials from the B2B spot market. Further, the optimal wholesale price in the FF subgame is larger than the price in the FN subgame. In the FF subgame, the optimal order quantity is less than the quantity in the FN subgame. The FN strategy can benefit the whole downstream manufacturers if and only if the supplier's risk aversion exceeds a threshold value. However, the FN strategy always hurts the whole supply chain. Our results also show that if the demand uncertainty increases, then the optimal wholesale price, optimal order quantity, and utilities for the supplier and manufacturers will decrease. If the spot price uncertainty increases, then the optimal order quantity will increase. The optimal wholesale price decreases under spot price uncertainty if and only if the supplier's capacity is relatively high. The optimal wholesale price, optimal order quantity, and utilities for the supplier and manufacturers decrease if the demand and spot price become more relevant.

Our results shed light on several practical implications. First, we reveal that the manufacturers can adjust their procurement strategies based on the uncertainty of spot price. If this uncertainty is relatively high, then the dual-source strategy completely dominates only the spot market procurement. The reason is that the forward contract always complements spot market procurement to obtain additional profit for the two manufacturers by protecting their trading against the uncertainty of spot price. Thus, rationally, the two manufacturers both choose dual-source procurement if the uncertainty of spot price is relatively high. Second, whether the forward contract option benefits the downstream manufacturers or not depends on the supplier's risk aversion. If the supplier is less averse to risk, then the two manufacturers procuring from dual sources can bring greater benefits for all the downstream manufacturers; otherwise, then the scenario in which one manufacturer procures from dual sources and the other procures only from the spot market can bring the greater benefits. Thus, two manufacturers can cooperate to sign an ex-ante agreement, which stipulates that one manufacturer procures from dual sources while the other procures only from the B2B spot market. One manufacturer should provide the other manufacturer with a monetary incentive to compensate for the profit loss brought by the unchanged strategy. Then, the entire downstream chain can acquire maximum profit. Furthermore, two manufacturers procuring from dual sources can benefit the supply chain. In the FF subgame, the supplier should set a higher wholesale price and the manufacturers can set a smaller contract quantity compared with those in the FN subgame. In addition, the results provide suggestions for decision makers to set the wholesale price and procurement strategy according to important factors, such as the spot price, demand variances, and the supply chain player's attitude toward risks.

This study provides several avenues for future research. In our work, we suppose that the two manufacturers are symmetric. However, under some situations, different players might process private knowledge of demand and spot price. Thus, an interesting topic for future research is to discuss the problem with asymmetric members.

Credit authorship contribution statement

Shanshan Ma: Conceptualization, Methodology, Writing - original draft, Formal analysis. **Guo Li:** Conceptualization, Writing - original draft, Supervision. **Mengqi Liu:** Formal analysis, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Proof of Lemma 1. Under NN Subgame, manufacturers' profits are given by $\pi_i = (a - q_A - q_B)q_i - sq_i$. We have $\frac{d\pi_i}{dq_i} = a - 2q_i - q_j - s,\ i,j = A,B$ and $\frac{d^2\pi_i}{dq_i^2} = -2 < 0$. Therefore, the equilibrium production quantities are given by $q_i^{NN} = \frac{a-s}{3}$ and profits at time T_3 are given by $\pi_i^{NN} = \frac{(a-s)^2}{9}$. □

Proof of Theorem 1. Similar to Lemma 1, we can get manufacturer's equilibrium utility as shown in Theorem 1. Under NN Subgame, the supplier's profit is given by $\pi_S = sC$, so we can easily get supplier's equilibrium utility as shown in Theorem 1. □

Proof of Lemma 2. Under FN Subgame, the manufacturer A's profit at time T_2 is given by $\pi_A = (a - q_A - q_B)q_A + s(Q_A - q_A) - wQ_A = \frac{(a-s)^2}{9} - (s - w)Q_A$, thus its utility is $U_A^{FN} = \frac{E[(a-s)^2]}{9} + (\mu_s - w)Q_A - k_m(\frac{V[(a-s)^2]}{81} + \sigma_s^2 Q_A^2 + \frac{2Q_A cov((a-s)^2,s)}{9}) = U_M^{NN} + (\mu_s - w)Q_A - k_m\sigma_s^2 Q_A^2 - \frac{2k_m Q_A cov((a-s)^2,s)}{9}$ (the computation of $cov((a-s)^2, s)$ can be find in Appendix B). We have $\frac{dU_A^{FN}}{dQ_A} = \mu_s - w - 2k_m\sigma_s^2 Q_A - \frac{2k_m cov((a-s)^2,s)}{9}$ and $\frac{d^2U_A^{FN}}{dQ_A^2} = -2k_m\sigma_s^2 < 0$. Therefore, given a contract price, we get the optimal order quantity based on the first-order condition as shown in Lemma 2. □

Proof of Theorem 2. Under FN Subgame, at time T_1, the supplier's profit is $\pi_s = wQ_A + s(C - Q_A)$ and its utility is $U_S^{FN} = wQ_A + \mu_s(C - Q_A) - k_s(C - Q_A)^2\sigma_s^2$. We have $\frac{dU_S^{FN}}{dw} = Q_A + (w - \mu_s)\frac{dQ_A}{dw} + 2k_s(C - Q_A)\sigma_s^2\frac{dQ_A}{dw}, \frac{dQ_A}{dw} = -\frac{1}{2k_m\sigma_s^2}$ and $\frac{d^2U_S^{FN}}{dw^2} = -\frac{2k_m+k_s}{2k_m^2\sigma_s^2} < 0$. If $Q_A \leqslant 0$, which is equal to $\sigma_s \leqslant \sigma_s^* = \frac{2k_m\rho\sigma_a(\mu_a-\mu_s)}{9k_sC+2k_m(\mu_a-\mu_s)}$, thereby meaning that the manufacturer A do not adopt contract procurement. If $Q_A > 0$, then the manufacturer A adopts contract procurement. Based on the first-order condition, we can get the optimal contract price which is shown by (9). By substituting (9) into (7), we obtain the optimal contract quantity as (10). By substituting (9) and (10) into the manufacturers' and supplier's profit, we get manufactures' and supplier's equilibrium utility, which are given by (11), (12), (13). □

Proof of Theorem 3. Under FF Subgame, at time T_1, the supplier's profit is $\pi_s = w(Q_A + Q_B) + s(C - Q_A - Q_B)$ and its utility is $U_S^{FF} = w(Q_A + Q_B) + \mu_s(C - Q_A - Q_B) - k_s(C - Q_A - Q_B)^2\sigma_s^2$. We have $\frac{dU_S^{FF}}{dw} = Q_A + Q_B + 2(w - \mu_s)\frac{dQ_A}{dw} + 4k_s(C - Q_A - Q_B)\sigma_s^2\frac{dQ_A}{dw}, \frac{dQ_A}{dw} = -\frac{1}{2k_m\sigma_s^2}$ and $\frac{d^2U_S^{FF}}{dw^2} = -\frac{2k_m+k_s}{k_m^2\sigma_s^2} < 0$. If $Q_i \leqslant 0$, which is equal to $\sigma_s \leqslant \sigma_s^* = \frac{2k_m\rho\sigma_a(\mu_a-\mu_s)}{9k_sC+2k_m(\mu_a-\mu_s)}$, thereby meaning that the two manufacturers do not adopt contract procurement. If $Q_i > 0$, then the two manufacturers adopt contract procurement. Based on the first-order condition, the optimal contract price exists and is shown by (15). By substituting (15) into (7), we obtain the optimal contract quantity in (16). By substituting (15) and (16) into the manufacturers and the supplier's profits, we get the manufactures' and supplier's equilibrium utility, which are given by (17) and (18). □

Proof of Proposition 1. If $\sigma_s > \sigma_s^*$, we can obtain that $w^{FF} - w^{FN} = \frac{9k_m k_s^2 \sigma_s^2 C + 2k_m^2 k_s \sigma_s^2 (1-\rho\sigma_a/\sigma_s)(\mu_a-\mu_s)}{9(2k_m+k_s)(k_m+k_s)} > 0$, $Q_A^{FN} - Q_A^{FF} = \frac{k_s}{(k_s+2k_m)(k_s+k_m)}[\frac{k_s C}{2} + \frac{k_m(1-\rho\sigma_a/\sigma_s)(\mu_a-\mu_s)}{9}] > 0$, $U_A^{FN} - U_M^{FF} = k_m\sigma_s^2 (Q_A^{FN})^2 - k_m\sigma_s^2 (Q_A^{FF})^2 > 0$, $U_M^{FF} - U_B^{FN} = k_m\sigma_s^2 (Q_A^{FF})^2 > 0$, $U_S^{FN} - U_S^{FF} = (k_s + 2k_m)\sigma_s^2 (Q_A^{FN})^2 - 4(k_m + k_s)\sigma_s^2 (Q_A^{FF})^2 = \frac{-4k_m\sigma_s^2}{(k_s+2k_m)(k_m+k_s)}[\frac{k_s C}{2} + \frac{k_m(1-\rho\sigma_a/\sigma_s)(\mu_a-\mu_s)}{9}]^2 < 0$. □

Proof of Proposition 2. If $\sigma_s > \sigma_s^*$, we can obtain that (1) $U_A^{FN} + U_B^{FN} - U_A^{FF} - U_B^{FF} = k_m\sigma_s^2((Q_A^{FN})^2 - 2(Q_A^{FF})^2) = \frac{2k_m\sigma_s^2(k_s^2-2k_m^2)}{(k_s+2k_m)^2(k_m+k_s)^2}[\frac{k_s C}{2} + \frac{k_m(1-\rho\sigma_a/\sigma_s)(\mu_a-\mu_s)}{9}]^2$. Thus $U_A^{FN} + U_B^{FN} > U_A^{FF} + U_B^{FF}$ if $k_s > \sqrt{2}k_m$. (2) $U_S^{FN} + U_A^{FN} + U_B^{FN} - U_S^{FF} - U_A^{FF} - U_B^{FF} = (3k_m + k_s)\sigma_s^2 (Q_A^{FN})^2 - (6k_m + 4k_s)\sigma_s^2 (Q_A^{FF})^2 = \frac{-2k_m\sigma_s^2(6k_m^2+6k_m k_s+k_s^2)}{(k_s+2k_m)^2(k_m+k_s)^2}[\frac{k_s C}{2} + \frac{k_m(1-\rho\sigma_a/\sigma_s)(\mu_a-\mu_s)}{9}]^2$. Thus $U_S^{FN} + U_A^{FN} + U_B^{FN} < U_S^{FF} + U_A^{FF} + U_B^{FF}$. □

Proof of Proposition 3. Because $U_A^{FN} + U_B^{FN} > U_A^{FF} + U_B^{FF}$ if $k_s > \sqrt{2}k_m$, then $U_A^{FN} - U_A^{FF} > U_B^{FF} - U_B^{FN} > 0$, we easily obtain the result in Proposition 3.

Proof of Proposition 4. If $\sigma_s > \sigma_s^*$, we obtain that $\frac{\partial w^{FN}}{\partial\sigma_a} = -\frac{4k_m(k_m+k_s)\sigma_s^2\rho(\mu_a-\mu_s)}{9(2k_m+k_s)\sigma_s} < 0$, $\frac{\partial w^{FF}}{\partial\sigma_a} = -\frac{2k_m(k_m+2k_s)\sigma_s^2\rho(\mu_a-\mu_s)}{9(k_m+k_s)\sigma_s} < 0$, $\frac{\partial Q_A^{FN}}{\partial\sigma_a} = -\frac{2k_m\rho(\mu_a-\mu_s)}{9(2k_m+k_s)\sigma_s} < 0$, $\frac{\partial Q_i^{FF}}{\partial\sigma_a} = -\frac{k_m\rho(\mu_a-\mu_s)}{9(k_m+k_s)\sigma_s} < 0$, $\frac{\partial U_S^{FN}}{\partial\sigma_a} = 2(2k_m + k_s)\sigma_s^2 Q_A^{FN}\frac{\partial Q_A^{FN}}{\partial\sigma_a} < 0$, $\frac{\partial U_A^{FN}}{\partial\sigma_a} = 2k_m\sigma_s^2 Q_A^{FN}\frac{\partial Q_A^{FN}}{\partial\sigma_a} < 0$, $\frac{\partial U_S^{FF}}{\partial\sigma_a} = 8(k_m + k_s)\sigma_s^2 Q_i^{FF}\frac{\partial Q_i^{FF}}{\partial\sigma_a} < 0$, $\frac{\partial U_i^{FF}}{\partial\sigma_a} = 2k_m\sigma_s^2 Q_i^{FF}\frac{\partial Q_i^{FF}}{\partial\sigma_a} < 0$. □

Proof of Proposition 5. (1) In FN subgame, we obtain $\frac{\partial w^{FN}}{\partial\sigma_s} = \frac{4k_m\sigma_s[-9k_s C+(k_m+k_s)(\mu_a-\mu_s)(2-\rho\sigma_a/\sigma_s)]}{9(2k_m+k_s)}$, $\frac{\partial w^{FN}}{\partial\sigma_s} < 0$ if and only if $C > \frac{(k_m+k_s)(2-\rho\sigma_a/\sigma_s)(\mu_a-\mu_s)}{9k_s}$. In FF subgame, we obtain that $\frac{\partial w^{FF}}{\partial\sigma_s} = \frac{2k_m\sigma_s[(k_m+2k_s)(\mu_a-\mu_s)(2-\rho\sigma_a/\sigma_s)-9k_s C]}{9(k_m+k_s)}$, $\frac{\partial w^{FF}}{\partial\sigma_s} < 0$ if and only if $C > \frac{(k_m+2k_s)(2-\rho\sigma_a/\sigma_s)(\mu_a-\mu_s)}{9k_s}$. (2) According to the equilibrium order quantity in FN and FF subgames, we obtain that $\frac{\partial Q_A^{FN}}{\partial\sigma_s} = \frac{2k_m\rho\sigma_a(\mu_a-\mu_s)}{9(2k_m+k_s)\sigma_s^2} > 0$, $\frac{\partial Q_A^{FF}}{\partial\sigma_s} = \frac{k_m\rho\sigma_a(\mu_a-\mu_s)}{9(k_m+k_s)\sigma_s^2} > 0$. □

Proof of Proposition 6. If $\sigma_s > \sigma_s^*$, we obtain $\frac{\partial w^{FN}}{\partial\rho} = -\frac{4k_m(k_m+k_s)\sigma_a\sigma_s/(\mu_a-\mu_s)}{9(2k_m+k_s)} < 0$, $\frac{\partial w^{FF}}{\partial\rho} = -\frac{2k_m(k_m+2k_s)\sigma_a\sigma_s(\mu_a-\mu_s)}{9(k_m+k_s)} < 0$, $\frac{\partial Q_A^{FN}}{\partial\rho} = -\frac{2k_m\sigma_a(\mu_a-\mu_s)}{9(2k_m+k_s)\sigma_s} < 0$, $\frac{\partial Q_A^{FF}}{\partial\rho} = -\frac{k_m\sigma_a(\mu_a-\mu_s)}{9(k_m+k_s)\sigma_s} < 0$, $\frac{\partial U_S^{FN}}{\partial\rho} = 2(2k_m + k_s)\sigma_s^2 Q_A^{FN}\frac{\partial Q_A^{FN}}{\partial\rho} < 0$, $\frac{\partial U_A^{FN}}{\partial\rho} = 2k_m\sigma_s^2 Q_A^{FN}\frac{\partial Q_A^{FN}}{\partial\rho} < 0$, $\frac{\partial U_S^{FF}}{\partial\rho} = 8(k_m + k_s)\sigma_s^2 Q_i^{FF}\frac{\partial Q_i^{FF}}{\partial\rho} < 0$, $\frac{\partial U_i^{FF}}{\partial\rho} = 2k_m\sigma_s^2 Q_i^{FF}\frac{\partial Q_i^{FF}}{\partial\rho} < 0$.

This completes the proof. □

Appendix B

To get the covariance $Cov[(a-s)^2, s]$, we first compute $Cov(a^2, s)$, $Cov(as, s)$, and $Cov(s^2, s)$.

$Cov(a^2, s) = \frac{V(a^2+s)-V(s)-V(a^2)}{2}$, where $V(a^2 + s) = E[V[(a^2 + s)|a]] + V[E[(a^2 + s)|a]] = E[V(s|a)] + V[E(s|a) + a^2] = (1-\rho^2)\sigma_s^2 + V[E(s|a)] + V(a^2) + 2Cov(a^2, E(s|a)) = (1-\rho^2)\sigma_s^2 + V(\mu_a + \frac{\rho\sigma_s(a-\mu_a)}{\sigma_a}) + V(a^2) + 2Cov(a^2, E(s|a)) = (1-\rho^2)\sigma_s^2 + \rho^2\sigma_s^2 + V(a^2) + 2Cov(a^2, E(s|a)) = \sigma_s^2 + V(a^2) + 2Cov(a^2, E(s|a))$, then $Cov(a^2, s) = Cov(a^2, E(s|a)) = Cov(a^2, \mu_s + \frac{\rho\sigma_s(a-\mu_a)}{\sigma_a}) = 2\rho\sigma_a\sigma_s\mu_a$,

$Cov(as, s) = \frac{V(as+s)-V(as)-V(s)}{2}$, where $V(as+s) = E[V[(as+s)|s]] + V[E[(as+s)|s]] = E[s^2V(a|s)] + V[s + sE(a|s)]$ and $V(as) = E[V[(as)|s]] + V[E[(as|s)]] = E[s^2V(a|s)] + V[sE(a|s)]$, then $Cov(as, s) = \frac{V(s)+V[sE(a|s)]+2Cov(s,sE(a|s))-V(s)-V[sE(a|s)]}{2} = Cov(s, sE(a|s)) = Cov(s, s(\mu_a + \frac{\rho\sigma_a(s-\mu_s)}{\sigma_s})) = \mu_a\sigma_s^2 + \rho\mu_s\sigma_a\sigma_s$.

$Cov(s^2, s) = E(s^3) - E(s)E(s^2) = \mu_s^3 + 3\mu_s\sigma_s^2 - \mu_s(\mu_s^2 + \sigma_s^2) = 2\mu_s\sigma_s^2$.

Therefore, $Cov[(a-s)^2, s] = Cov(a^2, s) - 2Cov(as, s) + Cov(s^2, s) = 2\sigma_s(\rho\sigma_a - \sigma_s)(\mu_a - \mu_s)$.

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