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A supply chain member should set its margin later if another member's cost is highly uncertain

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ABSTRACT

Recently, there have been several cases in which a large-scale retailer has demanded a margin for a consumer product from a supplier before the supplier has determined the margin or the wholesale price, reflecting a power shift from upstream suppliers to downstream retailers in supply chains. Given the recent change of power structures in supply chains, we investigate a practical decision-making problem of when a supply chain member should set its margin in the presence of uncertainty based on a stochastic game-theoretic supply chain model. We assume a typical two-echelon supply chain that consists of a manufacturer and a retailer, each of which determines the margin of a product based on private information of its marginal cost. Hence, the cost structure of a firm is uncertain and is known only to the firm. We construct an incomplete information game model with this setting, drawing the following clear-cut managerial implication: a supply chain member should set its margin later if the other member's cost is highly uncertain. By delaying decision-making, the late-moving member can make a more precise inference on the cost of the early-moving member by observing the margin demanded by the early-mover, thereby choosing a more desirable margin. Despite the current power shift from manufacturers to large-scale retailers in various consumer product categories, our result warns a retailer that if it assumes leadership to demand a margin from a manufacturer in an uncertain environment simply because it has power, it may cut its own throat.

1. Introduction

The structure of power in a supply chain composed of multiple separate firms who pursue individual profits has been a crucially important issue that commands attention from both researchers and practitioners. In a typical two-echelon supply chain for a general consumer product, an upstream manufacturer usually first sets the wholesale price or margin as the channel leader, and a downstream retailer then sets the retail price or margin. Recently, however, there are several cases in which a large-scale retailer has demanded a margin for a product from a manufacturer before the manufacturer has determined the margin or the wholesale price. Indeed, empirical research has examined real-life cases in which retailers demand "guaranteed profit margins" from manufacturers (e.g., Krishnan & Soni, 1997; Lee & Rhee, 2008). This change in price leadership reflects a power shift from manufacturers to retailers. Several giant retailers such as Wal-Mart, Carrefour, and Tesco often have a relatively strong competitive position and play a more dominant role than upstream channel members (Ertek & Griffin, 2002).

Given the change of power structures in supply chains, we address a practical decision-making problem of when a supply chain member should set its margin in a realistic environment under the presence of uncertainty based on a stochastic game-theoretic supply chain model. Specifically, we assume a typical two-echelon supply chain that consists of a manufacturer and a retailer, each of which determines the margin of a product for the purpose of maximization of its own expected profit based on private information of its marginal cost. Hence, the cost structure of a firm is uncertain and is known only to the firm. We construct an incomplete information game model based on this setting, deriving an equilibrium that involves sequences of decisions by the two supply chain members. By solving the model, we draw the following managerial implication: a supply chain member should set its margin later if the other member's cost is highly uncertain. As a result, our model provides the practical insight that a supply chain member must consider the cost uncertainty of another member when choosing the timing or leadership to set its margin even if the member has significant power to demand its margin in an early move in the supply chain. Despite the current power shift from manufacturers

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to large-scale retailers in various consumer product categories, our result warns a retailer that if it assumes leadership to demand a margin from a manufacturer in an uncertain environment simply because it has power, it may cut its own throat.

To reveal the mechanism behind our model that leads to the above result, it should be initially noted that previous theoretical OR/MS (operational research/management science) studies show that a supply chain member who has a leadership role and makes its decision earlier than other members generates higher profit under a wide range of circumstances (e.g., Choi, 1991; Lee & Staelin, 1997). Specifically, Gal-Or (1985) demonstrates theoretically that when the strategic variables determined by players in a noncooperative game are "strategic substitutes," a player who chooses the leader position generates a higher payoff than another player who chooses the follower position.[1] Following Gal-Or (1985), Choi (1991) demonstrates that the margins determined by firms in the same vertical supply chain are characterized by the strategic substitutes, and hence the first-mover advantage arises for a supply chain member setting its margin earlier. This advantage of leadership has been called the first-mover or, equivalently, early-mover advantage and hence an earlier decision-maker in a supply chain is often regarded as a more powerful supply chain member. Therefore, the leadership of a supply chain member in setting its margin earlier has been interpreted as its "power" in the literature. As a result, previous studies in this research stream conventionally call the leadership structure the "power structure" in a supply chain and examine how the structure affects the profitability of each supply chain member.

Given the insight gained in the literature relating to the power structure in supply chains, let us consider the situation in which the uncertainty associated with the marginal cost of the manufacturer is significantly higher than that for the retailer because a manufacturer is likely to face higher cost uncertainty in developing a product than a retailer in real business environments. Because of the early-mover advantage revealed in the literature, if the retailer sets a margin before the manufacturer sets a margin, the retailer earns a higher expected margin than otherwise in a deterministic environment. However, when the marginal cost of the manufacturer is random and unknown to the retailer as assumed in our model, the retailer who sets its margin before the manufacturer does faces the risk that the manufacturer's realized cost may subsequently prove to be far larger or smaller than the retailer expected. In such a case, realized demand and price deviate significantly from their optimal levels predicted by the retailer, thereby reducing the retailer's expected profit. To prevent this possible reduction in the expected profit, the retailer should set its margin after the manufacturer sets its margin even if the retailer can exert tremendous power over the manufacturer. This is because a delay in the decision enables the retailer to make a more precise inference on the cost to the manufacturer by observing the margin demanded by the manufacturer and hence to choose a more desirable margin. This precise inference gives rise to a late-mover advantage under cost uncertainty. To sum up, there arises not only an early-mover advantage but also a late-mover advantage in a stochastic environment, and, if the latter surpasses the former, the retailer should abandon its leadership.[2]

While we consider a situation where a supply chain member chooses its margin without knowing the other member's cost throughout this paper following previous studies relating to power structure, the empirical literature on marketing and supply chain management provides substantial real-life examples of such a situation. In the theoretical model in this paper, there are three possible leadership structures: (1) the manufacturer and the retailer simultaneously choose their respective margins, (2) the manufacturer sets its margin first and the retailer sets its margin second, and (3) the retailer sets its margin first and the manufacturer sets its margin second, which are respectively called (1) "Nash game," (2) "manufacturer Stackelberg game," and (3) "retailer Stackelberg game" in the literature (e.g., Choi, 1991; Lee & Staelin, 1997). Particularly in (3), the retailer Stackelberg game, the retailer needs to set its margin without knowing the other member's cost because the retailer sets a margin before the manufacturer does and the retailer's margin cannot thus depend on the wholesale price. As mentioned at the beginning of this paper, there is a general consensus in the empirical literature on marketing and supply chain management that guaranteed profit margins (GPM) are a real-life example of the retailer Stackelberg game, where a retailer demands a margin from an upstream manufacturer in advance and thus chooses its margin without knowing the manufacturer's cost.[3] Specifically, Lee and Rhee (2008, p. 326) explain GPM as a "guaranteed profit margin (GPM), under which a vendor guarantees the retailer's target mark-up rate even in the case of markdown sales. Large stores use their retail power and threaten to pull a vendor's products from their shelves if the vendor refuses to provide GPM (Krishnan & Soni, 1997)." Heckman (2004) documents that GPM is common in the cosmetics industry. Indeed, Lee and Rhee (2008) state that "contract that some cosmetics producers, such as L'Oreal, Estée Lauder, and Chanel, employ in business with department stores … The cosmetics producers guarantee a fixed retail mark-up rate during regular sales. Instead of guaranteeing the same mark-up rate in a discount sale as in a GPM contract, these firms keep the retail stores from markdown operations and buy back any unsold units from the stores." In addition, Bird and Bounds (1997) suggest that GPM is often used in the apparel industry. Lee and Rhee (2008) state that "GPM may help a new designer get floor space in an influential fashion retail store." Furthermore, Kuiper and Meulenberg (2004) conduct a time series analysis of an agricultural product market, finding a retailer dominance relationship, in which the manufacturers are compelled to become price takers. These real-life cases are examples of a supply chain member choosing its margin earlier without knowing the other member's cost. Our assumption that supply chain members determine respective margins as control variables is consistent with these real-life examples.

The first major contribution of this paper to the literature is the practical insight that cost uncertainty of supply chain members is a key factor that determines the equilibrium power structure in a supply chain. From a theoretical perspective, the result that a supply chain member can prefer a late decision in a stochastic

[1] Bulow, Geanakoplos, and Klemperer (1985) define "strategic substitutes" as follows. Strategic substitutes means that if a player increases the value of its strategic variable in a noncooperative game, another player decreases its strategic variable in response. Stated differently, if a player undertakes a more aggressive strategy, the other player undertakes a less aggressive strategy, implying a negative correlation between the strategic variables determined by the players. Therefore, the first-mover advantage for a player who sets its strategic variable earlier arises if the strategic variables chosen by players in a game are negatively correlated. For example, it is well known in the economics literature that quantities controlled by firms in a horizontally competitive relationship (i.e., Cournot competition) are strategic substitutes and hence a firm setting its quantity before other firms do generates higher profit.

[2] While we here assume that the cost uncertainty for the manufacturer is higher than that for the retailer, this result also applies to the case in which the relationship between the retailer and the manufacturer is reversed. That is, if the cost uncertainty for the retailer is higher than that for the manufacturer, the manufacturer should set its margin after the retailer sets its margin because the same logic elaborated above holds.

[3] Shi, Zhang, and Ru (2013, p. 1237) state "the retailer Stackelberg game closely reflects the industry practice in which some large retailers demand 'guaranteed profit margins' from manufacturers…" In addition, Wang et al. (2017, p. 465) document that "the guaranteed profit margin (or markup) required by powerful retailers is often cited as a real-world example of this retailer-Stackelberg game…"

environment is contrary to the conventional result shown in the theoretical literature examining the power structure in a deterministic environment. Additionally, from a practical perspective, given the current power shift from manufacturers to retailers, the implication that the retailer Stackelberg game, in which a retailer assumes leadership to demand its margin early, is not necessarily a beneficial choice for the retailer is highly suggestive. Furthermore, a unique feature of our model compared with previous models is the incorporation of uncertainty into the power structure in supply chains. Accordingly, we adopt the incomplete information game framework, thereby deriving a Bayesian–Nash equilibrium (BNE) and a perfect Bayesian equilibrium (PBE), but not a Nash equilibrium or subgame perfect Nash equilibrium that is normally derived in a complete information game examined in the literature. Therefore, the application of an incomplete information game with a stochastic environment to the issue of the power structure is also a contribution to the OR literature from a game-theoretic perspective.

The remainder of the paper is organized as follows. Section 2 provides a review of the literature examining power structures in supply chains and the literature exploring contracts from a game-theoretic perspective. Section 3 describes the settings of our incomplete information game model. In Section 4, we derive the equilibrium strategies and expected profits of the supply chain members in a Nash game and a Stackelberg game, respectively. By comparing the individual firm profits associated with sequential margin setting, Section 5 determines the optimal timing for a manufacturer and a retailer to set their respective margins. Section 6 shifts our focus from individual firm profit to the total profit of the supply chain, examining when each member should set its margin for the maximization of total supply chain profit. Section 7 investigates the problem in an alternative scenario in which supply chain members close a contract involving a principal–agent relationship. Section 8 provides a numerical example to illustrate the analytical model. The final section provides concluding remarks.

2. Literature review

Reflecting many real-life business cases in which a downstream supply chain member demands a margin before an upstream member, a number of OR/MS studies to date have examined the impact of price leadership or power structures in supply chains on firm profitability using game theory (e.g., Aust & Buscher, 2014; Choi, 1991; Choi & Fredj, 2013; Chung & Lee, 2017; Edirisinghe, Bichescu, & Shi, 2011; Granot & Yin, 2007; Jin, Wang, & Hu, 2015; Karray, 2013; Kumar, Basu, & Avittathur, 2018; Kumoi & Matsubayashi, 2014; Lau & Lau, 2005; Lau, Lau, & Wang, 2007a; Lau, Lau, & Zhou, 2017b; Luo et al., 2017; Ni, Li, & Tang, 2010; Pan et al., 2010; Trivedi, 1998; Wei, Zhao, & Li, 2013; Xia & Gilbert, 2007; Xiao et al., 2014; Xie & Wei, 2009; Xue, Demirag, & Niu, 2014; Yan et al., 2018; Yang, Luo, & Zhang, 2018; Yu, Cheong, & Sun, 2017; Zhao, Tang, Zhao, & Wei, 2012). Choi (1991) investigates the pricing decisions in a supply chain that consists of two manufacturers and one intermediary common retailer that sells both manufacturers' products. He considers three noncooperative games of different power structures between the manufacturers and the retailer: (1) the manufacturer Stackelberg game, in which the manufacturers are the price leaders, (2) the retailer Stackelberg game, in which the retailer is the price leader, and (3) the vertical Nash game, in which no price leader exists. His study is the seminal work that examines how the power structure influences the profits of supply chain members, and subsequent studies after Choi (1991) overall regard the price leadership of a supply chain member as its power over other members. Pan, Lai, Leung, and Xiao (2010) consider a supply chain composed of either two manufacturers and a common retailer or a single manufacturer and two competing retailers. They investigate how channel power influences the selection of two types of contracts, which are a wholesale price contract or a revenue-sharing contract. They compare equilibrium outcomes resulting from the two different contracts under different channel power structures. Edirisinghe et al. (2011) comprehensively examine the effects of channel power on supply chain stability in a setting where two asymmetric suppliers sell substitutable products through a common retailer. Specifically, they consider eight asymmetric price leadership structures in which one manufacturer acts as a Stackelberg leader and the other manufacturer as a follower. They find that power imbalances cause significant reductions in supply chain profits, and the more balanced the firms are the higher their profits. As a result, they conclude that neither the manufacturer Stackelberg nor the retailer Stackelberg supply chain is a stable structure, and hence a structure where power is equally split between firms leads to the best stability and performance. Wei et al. (2013) investigate pricing decisions for two complementary products in a supply chain with two duopolistic manufacturers and one common retailer. They construct models of three different power structures, namely, the manufacturer Stackelberg game, the retailer Stackelberg game, and the vertical Nash game. Moreover, they allow for the possibility of sequential decisions made by the two manufacturers in the two Stackelberg games and obtain closed-form solutions of optimal wholesale and retail prices. Kumoi and Matsubayashi (2014) consider a business environment where the contracting leader can be changed endogenously before and after forming a vertical integration in supply chains using a wholesale price contract. They formulate a cooperative game to analyze the stable and fair profit allocations, finding that the grand coalition's profit must be allocated more to the retailer and the members with higher costs so that vertical integration becomes stable. They further identify the conditions under which the upstream manufacturer can have strong power as in traditional supply chains. Luo, Chen, Chen, and Wang (2017) investigate a supply chain in which a retailer is supplied by two manufacturers with vertically differentiated brands, which are a good brand and an average brand. Their model involves both horizontal competition between the two manufacturers and vertical competition between the manufacturers and the retailer. They show that either of the two competing manufacturers can benefit from knowing their rival's price if that manufacturer is the second-mover to announce its price. While Luo et al. (2017) is closely related to the present paper in that they suggest the late-mover advantage in a supply chain, they consider a deterministic environment but not a stochastic environment. Differing from preceding research, this paper suggests that the late-mover advantage for a supply chain member arises in a stochastic environment by incorporating cost uncertainty into a power structure model.[4]

Moreover, we should not ignore the literature on contracts that has addressed supply chain management problems under asymmetric information substantially in a variety of uncertain environments (e.g., Alawneh & Zhang, 2018; Arcelus, Kumar, & Srinivasan, 2008; Biswas, Avittathur, & Chatterjee, 2016; Biswas, Raj, & Srivastava, 2018; Chakraborty et al., 2016; Chen, Peng, Liu, & Zhao, 2017; Chiu, Choi, Li, & Yiu, 2016; Corbett, Zhou, & Tang, 2004; Dong et al., 2018; Dong, Xu, & Evers, 2012; Fang, Ru, & Wang, 2014; Gao, 2015; Ha & Tong, 2008; Jouida et al., 2017; Kerkkamp, van den Heuvel, & Wagelmans, 2018; Lan et al., 2018; Lau, Lau, & Wang, 2008; Lee et al., 2016; Leng & Zhu, 2009; Li & Gupta, 2011; Li

[4] Several game-theoretic studies formulate an observable delay game that investigates the endogenous determination of the leadership structure (e.g., Amir & Stepanova, 2006; Hamilton & Slutsky, 1990; van Damme & Hurkens, 2004). This observable delay game has also been applied in the OR literature to determine the equilibrium sequence of decisions made by supply chain members (e.g., Chen, Chen, & Li, 2018; Chen, Yan, Ma, & Yang, 2018; Li & Chen, 2018; Matsui, 2017, 2018).

& Li, 2016; Li et al., 2009; Li, Ryan, Shao, & Sun, 2015; Löffler, Pfeiffer & Schneider, 2012; Modak & Kelle, 2019; Quigley et al., 2018; Raj, Biswas, & Srivastava, 2018; Sun & Debo, 2014; Voigt & Inderfurth, 2011; Wang & Webster, 2009; Wang et al., 2009; Wu, Crama, & Zhu, 2012; Wu, Li, & Shi, 2017; Xu, Shi, Ma, & Lai, 2010; Yan et al., 2017; Yang, Xiao, Choi, & Cheng, 2018; Yang, Zhang, & Zhu, 2017; Zissis, Saharidis, Aktas, & Ioannou, 2018).[5] Corbett et al. (2004) explore the optimal contract for the management of a supply chain consisting of a supplier and a buyer. Specifically, they use the bilateral monopoly setting to analyze general contracts both under full and incomplete information about the buyer's cost structure. They derive the supplier's optimal contracts and examine the value to a supplier of obtaining better information about a buyer's cost structure and of more general contracts, showing that the value of information is higher under two-part contracts. Xu et al. (2010) investigate a contract design problem for a manufacturer who procures major modules from a prime supplier as well as an urgent supplier. As the urgent supplier needs to put in additional effort to fulfill orders, it is difficult for the manufacturer to estimate this urgent supplier's production cost. They study two types of contingent contracts: one is the common price-only contract, and the other is a contract menu consisting of a transfer payment and a lead time quotation. They construct a Stackelberg game model, evaluating how the involvement of an urgent supplier affects the performances of the prime supplier and the manufacturer. Biswas et al. (2016) investigate the influence of the supply chain structure, market-share, and asymmetry of information on the supplier's choice of contracts, through which the supplier charges buyers. They demonstrate that a linear two-part tariff or a quantity discount contract can both coordinate the supply chain irrespective of the supply chain structure, which consists of one supplier and two buyers under complete and partial decentralization. By comparing the profit levels of supply chain agents across different supply chain structures, they show that if a buyer possesses a minimum threshold market potential, the supplier has an incentive to collude with the buyer. Kerkkamp et al. (2018) construct a contract model with asymmetric information between a supplier and a retailer, who have nonlinear cost functions consisting of ordering and holding costs. They assume that the retailer incurring private holding costs has the market power to enforce any order quantity. The supplier aims to minimize his expected costs by offering a menu of contracts with side payments as an incentive mechanism. While a common model formulation in previous studies is nonconvex, they present an equivalent convex formulation, demonstrating that their contracting model can be solved efficiently for a general number of retailer types. Raj et al. (2018) analyze the coordination of a sustainable supply chain that considers greening and corporate social responsibility (CSR) initiatives. Specifically, they consider a two-echelon supply chain consisting of a supplier who is responsible for greening and a buyer who is accountable for social responsibility. They assume that the supplier acts as the Stackelberg leader who can use five different types of contracts, which are the wholesale price, linear two-part tariff, greening-cost sharing, revenue sharing, and revenue and greening-cost sharing. They examine how the optimal greening level, CSR level, retail price, and profits of supply chain agents are affected by different contract types, demonstrating that greening and social efforts undertaken by supply chain agents are beneficial for the overall supply chain.

Note that the above two areas of the literature, i.e., the literature on power structure and the literature on contracts have thus far developed independently. The major reason why the contract framework has not traditionally been applied in the literature on the power structure is that the second-mover advantage never arises in the contract framework; that is, when one firm becomes the principal, the firm designs a contract and offers it to another firm as a take-it-or-leave-it contract, meaning that the principal is automatically fixed as the first-mover and the agent is fixed as the second-mover. Hence, the expected surplus earned by the agent (i.e., second-mover) will be extracted by the principal (i.e., first-mover) through the contract optimally designed by the principal considering the incentive compatibility and the individual rationality conditions of the agent. As a result, the second-mover-advantage completely disappears and only the first-mover advantage arises. Therefore, it becomes meaningless to examine how the leadership of a supply chain member to set its margin affects its profitability because the first-mover (principal) always generates higher profit than the second-mover (agent) in the contract framework. This is the reason why we focus mainly on a normal wholesale transaction relationship between the manufacturer and the retailer in this paper, aiming primarily to contribute to the literature on power structure. As stated earlier, the leadership problem is considered as an important managerial issue not only from the theoretical viewpoint but also from the empirical or practical viewpoint, because a powerful downstream retailer often demands a margin from an upstream manufacturer earlier nowadays. However, because the contract literature has addressed supply chain management problems under information asymmetry more extensively, we will also consider an alternative scenario where the manufacturer and the retailer use a contract in a later section to link this paper with the literature on contracts.

Even though the above overview suggests that while many previous OR/MS studies examine the issue of power structures in supply chains, no preceding research points out that cost uncertainty of another supply chain member is a key factor that determines the equilibrium power structure in a stochastic environment, as far as the author is aware.[6] Therefore, it is worth noting that the present paper is the first to demonstrate that the power structure is subject to the cost uncertainty of supply chain members based on a rigorous game-theoretic framework.

3. Model description

Initially, we present the assumptions and settings underpinning our model. Table 1 lists the variables used in the model. We consider a typical two-echelon supply chain that consists of one manufacturer and one retailer. The manufacturer produces a product at a variable cost of c_M per unit and sells the product to the retailer. The retailer incurs retailing cost c_R per unit and resells the product to end consumers, meaning that the retailer is in a monopolistic position. We assume that the marginal costs of c_M and c_R are random. Whereas the manufacturer knows the realized value of c_M as its private information, the retailer does not know this value. Similarly, the value of c_R is known only to the retailer, but not to the manufacturer. We assume that c_i $(i = M, R)$ satisfies the following properties: (i) $\mathrm{E}(c_i) = \bar{c}_i > 0$; (ii) $\mathrm{var}(c_i) = {\sigma_i}^2 > 0$; (iii) $\mathrm{cov}(c_M, c_R) = \sigma_{MR} > 0$; and (iv) $\mathrm{prob}(c_i < 0) = 0$, indicating that the correla-

[5] Shen, Choi, and Minner (2018) provide a recent comprehensive overview of the research stream on contracts between supply chain members.

[6] Apart from the supply chain management literature, the result that a player who faces rival's highly uncertain cost should not move earlier has been shown in the OR/MS literature. For example, Tyagi (2000) shows that in sequential positioning decisions on the Hotelling line, an increase in uncertainty about the late-mover's cost makes the early-mover's position far from the most attractive position in equilibrium. Theoretical studies examining the positioning strategy appear in the OR/MS literature (e.g., Ebina, Matsushima, & Shimizu, 2015; Iida & Matsubayashi, 2011; Kress & Pesch, 2012; Matsubayashi & Yamada, 2008; Matsubayashi, Ishii, Watanabe, & Yamada, 2009).

Table 1
Notations.

w	Wholesale price
p	Retail price
q	Quantity
m_M	Margin of the manufacturer ($m_M \equiv w-c_M$)
m_R	Margin of the retailer ($m_R \equiv p-w-c_R$)
M	Total margin of the supply chain ($M \equiv m_M + m_R$)
a	Intercept of the demand function
b	Slope of the demand function
c_M	Marginal production cost of the manufacturer
c_R	Marginal retailing cost of the retailer
$\bar{c}_M$	Mean of c_M
$\bar{c}_R$	Mean of c_R
${\sigma_M}^2$	Variance of c_M
${\sigma_R}^2$	Variance of c_R
σ_{MR}	Covariance of c_M and c_R
ρ	Correlation coefficient between c_M and c_R ($\rho \equiv \sigma_{MR}/(\sigma_M\sigma_R)$)
π_M	Profit of the manufacturer
π_R	Profit of the retailer
Π	Total profit of the supply chain ($\Pi \equiv \pi_M + \pi_R$)
M	Subscript denoting the manufacturer
R	Subscript denoting the retailer
i	Subscript denoting M (manufacturer) or R (retailer)
j	Subscript denoting M (manufacturer) or R (retailer), which is different from i
N	Superscript denoting the equilibrium in the Nash game
L	Superscript denoting the leader in the equilibrium in the Stackelberg game
F	Superscript denoting the follower in the equilibrium in the Stackelberg game

tion coefficient denoted by $\rho \in (0, 1)$ is: $\rho \equiv \sigma_{MR}/(\sigma_M\sigma_R)$.[7] These properties of the random variables are public and common information known to both the manufacturer and the retailer. Henceforth, let i represent either M or R, which respectively signify the manufacturer and the retailer.

Following previous major supply chain management models, we assume the following linear demand function in the retail market of the product:

$$q = a - bp, \tag{1}$$

where q is quantity, p is price, and a and b are positive constants.

Because the focus of this research is on the power structure in a supply chain, we follow previous models in the literature to assume that the manufacturer and the retailer choose their respective margins (e.g., Choi, 1991; Edirisinghe et al., 2011; Pan et al., 2010).[8] Let m_M and m_R respectively denote the manufacturer's margin and retailer's margin, which are defined as:

$$m_M \equiv w - c_M, \tag{2}$$

$$m_R \equiv p - w - c_R, \tag{3}$$

where w represents the wholesale price of the product. Eqs. (2) and (3) indicate that the following equation holds:

$$p = m_M + m_R + c_M + c_R. \tag{4}$$

Replacing the price p in Eq (1) with Eq. (4), we restate the demand function as:

$$q = a - b(m_M + m_R + c_M + c_R). \tag{5}$$

Based on Eqs. (2), (3), and (5), the profits for the manufacturer and the retailer are:

$$\begin{aligned}\pi_M &= (w - c_M)q \\ &= m_M(a - b(m_M + m_R + c_M + c_R)),\end{aligned} \tag{6}$$

$$\begin{aligned}\pi_R &= (p - w - c_R)q \\ &= m_R(a - b(m_R + m_M + c_R + c_M)).\end{aligned} \tag{7}$$

Because Eqs. (6) and (7) are symmetric with respect to the subscripts M and R, the expected profits of the two supply chain members are described as the following single equation:

$$E(\pi_i) = E(m_i(a - b(m_i + m_j + c_i + c_j)))(i, j) = (M, R), (R, M). \tag{8}$$

Hereafter, let (i, j) signify either (M, R) or (R, M) when the two variables simultaneously appear in an equation.

We assume the following linearity of the expectation of one signal conditional on the other signal, as commonly assumed in previous models relating to incomplete information games (e.g., Gal-Or, 1987; Li, 2002).[9]

$$\mathrm{E}(c_j|c_i) = \alpha + \beta c_i. \tag{9}$$

This assumption yields the following lemma, which will be used to identify equilibrium in the following section. (The Appendix includes all proofs.)

Lemma 1. $E(c_j|c_i) = \bar{c}_j + \sigma_{MR}(c_i - \bar{c}_i)/{\sigma_i}^2$ $((i, j) = (M, R), (R, M))$ holds.

4. Equilibrium of Nash and Stackelberg games

In this section, we first consider the case in which both the manufacturer and the retailer simultaneously choose their respective margins, m_M and m_R. We call this case a Nash game following the literature examining power structures (e.g., Choi, 1991).[10] Because marginal cost is random, each firm maximizes its expected profit based on private information. We employ the BNE as the equilibrium concept in this model because the Nash game is a static game. To derive the equilibrium, we follow the algorithm shown in the literature examining static incomplete information games in which players make simultaneous decisions (e.g., Li, 2002). The following lemma shows the BNE.

Lemma 2. The Bayesian Nash equilibrium (BNE) margin choice of Firm i ($i = M, R$) in the Nash game is:

$$m_i^N = \frac{a - b(\bar{c}_i + \bar{c}_j)}{3b} - \frac{\left({\sigma_{MR}}^2 - \sigma_{MR}{\sigma_j}^2 - 2{\sigma_i}^2{\sigma_j}^2\right)}{{\sigma_{MR}}^2 - 4{\sigma_i}^2{\sigma_j}^2}(c_i - \bar{c}_i)$$

$(i, j) = (M, R), (R, M)$,

resulting in expected profits of:

$$E\left(\pi_i^N\right) = \frac{(a - b(\bar{c}_i + \bar{c}_j))^2}{9b} + \frac{b{\sigma_i}^2\left({\sigma_{MR}}^2 - \sigma_{MR}{\sigma_j}^2 - 2{\sigma_i}^2{\sigma_j}^2\right)^2}{\left({\sigma_{MR}}^2 - 4{\sigma_i}^2{\sigma_j}^2\right)^2}.$$

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[7] Recent research addressing supply chain management problems under asymmetric information often assumes a correlation of costs between supply chain members to examine problems in general environments. For example, Fang, Ru, and Wang (2014) construct a contract model considering the correlation of the costs between supply chain members.

[8] The assumption that not prices but margins are control variables in a supply chain is also supported by previous empirical studies and industry practices. Cotterill and Putsis (2001) empirically show that the strategic interaction between supply chain members can be modeled as a Nash game in several product categories. Moreover, Krishnan and Soni (1997) show the industry practice in which large retailers demand guaranteed profit margins from manufacturers, which is regarded as a retailer Stackelberg game.

[9] In this paper, we apply the algorithm established by Gal-Or (1987) to derive the PBE in an incomplete information game, in which there is correlation between random signals obtained by players. Differing from this paper, the model in Gal-Or (1987) involves not cost uncertainty but demand uncertainty. In addition, the control variable determined by firms in her model is not margin or price but quantity. Nevertheless, the algorithm shown in Gal-Or (1987) is useful to our analysis for the following reason. That is, Gal-Or (1987) gives a formal proof that a linear strategy with respect to a private signal of a player constitutes a separating equilibrium, in which every player perfectly reveals its signal through the strategy. In other words, whereas a player usually has a strategic incentive to revise its strategy in an attempt to "fool" rivals in an incomplete information game, Gal-Or (1987) proves that it is not successful in its attempt at a pure strategy equilibrium.

[10] This simultaneous pricing in a supply chain is also called a vertical Nash game.

The superscript N denotes the equilibrium in the Nash game.

Next, we consider a Stackelberg game in which one supply chain member is the leader and the other is the follower. Because the two firms make sequential decisions not in a static manner but in a dynamic manner in this Stackelberg game, we employ the PBE as the equilibrium concept. To derive the PBE in the dynamic incomplete information game in which players make sequential decisions, we apply the algorithm shown in Gal-Or (1987). Henceforth, the superscripts L and F attached to the variables represent the leader and follower, respectively. Moreover, the expressions early-mover and late-mover have the same meanings as leader and follower in the Stackelberg game throughout the paper. In the following lemma, Firm i as the leader is the first to choose its margin, m_i, on the basis of its marginal cost c_i and its conjecture over the decision of the other member. Firm j as the follower observes the margin chosen by the leader, m_i, before choosing its margin, m_j. The following lemma shows a PBE.

Lemma 3. The perfect Bayesian equilibrium (PBE) margin choice in the Stackelberg game in which Firms i and j are respectively the leader and the follower is:

$$m_i^L = \frac{1}{2}\sigma_{MR}\left(\frac{a/b + \sigma_{MR}\bar{c}_i/\sigma_i^2 - \bar{c}_j}{\sigma_{MR} + \sigma_i^2} - \frac{c_i}{\sigma_i^2}\right),$$

$$m_j^F = \frac{\sigma_{MR}a + b\left(\sigma_i^2\bar{c}_j - \sigma_{MR}\bar{c}_i\right)}{2b\left(\sigma_{MR} + \sigma_i^2\right)} + m_i^L\left(\frac{\sigma_i^2}{\sigma_{MR}} - \frac{1}{2}\right) - \frac{c_j}{2},$$

$(i, j) = (M, R), (R, M),$

resulting in expected profits of:

$$E\left(\pi_i^L\right) = \frac{\sigma_{MR}\left(\sigma_{MR} + 2\sigma_i^2\right)\left(a - b\left(\bar{c}_i + \bar{c}_j\right)\right)^2}{8b\left(\sigma_{MR} + \sigma_i^2\right)^2} + \frac{b\sigma_{MR}\left(\sigma_{MR} + 2\sigma_i^2\right)}{8\sigma_i^2},$$

$$E\left(\pi_j^F\right) = \frac{\left(\sigma_{MR} + 2\sigma_i^2\right)^2\left(a - b\left(\bar{c}_i + \bar{c}_j\right)\right)^2}{16b\left(\sigma_{MR} + \sigma_i^2\right)^2} + \frac{b\left(4\sigma_i^2\left(\sigma_i^2 + \sigma_j^2\right) + 4\sigma_{MR}\sigma_i^2 - 3\sigma_{MR}^2\right)}{16\sigma_i^2}.$$

The superscripts L and F, respectively, denote the equilibrium variables of the leader and the follower in the Stackelberg game.

5. Individual profits of supply chain members

Because Lemmas 2 and 3 identify the equilibrium expected profits in the simultaneous and sequential games, comparison of the expected profits enables us to determine which position in the games brings a supply chain member higher expected profit. Initially, we present the relationship between the order of firms setting margins and their profitability in a deterministic environment as the benchmark prior to the main analysis in a stochastic environment. The next proposition summarizes the result in the absence of uncertainty.

Proposition 1. When uncertainty disappears so that $\sigma_i \to 0$ and then $\sigma_j \to 0$ ($(i, j) = (M, R), (R, M)$), the following inequalities hold.

$$E\left(\pi_i^L\right) > E\left(\pi_i^N\right) = E\left(\pi_j^N\right) > E\left(\pi_j^F\right)$$

Proposition 1 indicates that if there were no uncertainty in our model, the early-mover would generate higher expected profit than the late-mover in the Stackelberg game. Moreover, the expected profit in the Nash game would be higher than that of the follower but lower than that of the leader in the Stackelberg game. These

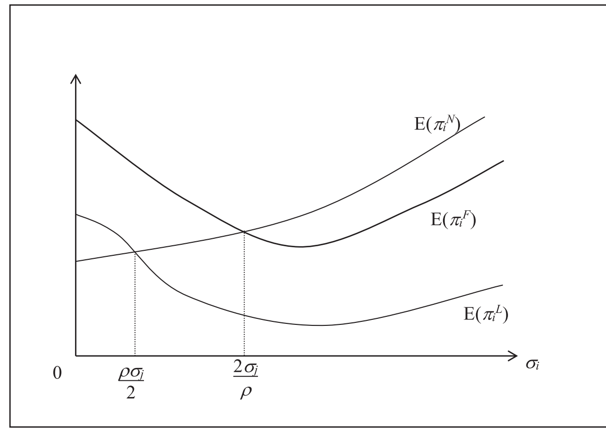

Fig. 1. Individual expected profits.

results suggest that both retailer and manufacturer have incentives to determine the margin as early as possible. Proposition 1 corresponds to the previous conventional result shown in Choi (1991, p. 287), who examined power structures in a deterministic environment. The proposition provides the rationale for why past studies examining power structure in a deterministic environment regard the supply chain member who assumes leadership to set its own margin or price as having greater power.

We next proceed to state the main result under uncertainty, which shows that the benchmark result without uncertainty in Proposition 1 can be reversed. Lemmas 2 and 3 yield the following proposition.

Proposition 2. The order of the expected profit of Firm i ($i = M, R$) is as follows, depending on the parameters associated with the uncertainty.

Case (I) $E(\pi_i^F) > E(\pi_i^L) \geq E(\pi_i^N)$ if $0 < \sigma_i \leq \rho\sigma_j/2$
Case (II) $E(\pi_i^F) \geq E(\pi_i^N) > E(\pi_i^L)$ if $\rho\sigma_j/2 < \sigma_i \leq 2\sigma_j/\rho$
Case (III) $E(\pi_i^N) > E(\pi_i^F) > E(\pi_i^L)$ if $2\sigma_j/\rho < \sigma_i$

Proposition 2 is the central finding in this paper; the proposition suggests a managerial guideline concerning under which environments a firm should choose which of the three positions of the simultaneous mover in the Nash game, the Stackelberg leader, or the Stackelberg follower. Specifically, as shown in Cases (I) and (II), if the uncertainty of the other supply chain member's cost, σ_j, is sufficiently higher than σ_i so that $\sigma_j/\sigma_i \geq \rho/2$ holds, Firm i should choose the position as the follower, because $E(\pi_i^F)$ is the highest among the three possible expected profits. Namely, a supply chain member whose cost uncertainty is relatively low should become the follower for the purpose of its profit maximization. It is also noteworthy in the proposition that the parameters a, b, $\bar{c}_M$ and $\bar{c}_R$, which are unassociated with the uncertainty, do not affect the order of profits because only ρ, σ_i, and σ_j are included in the conditions classifying the three cases. Hence, a firm can determine which position the firm should choose by comparing only σ_i, σ_j, and ρ.

To obtain a clearer picture of the result, Fig. 1 shows the expected profits in the three leadership positions against the firm's cost uncertainty.[11] Consistent with the result in Proposition 2, the figure suggests that $E(\pi_i^F)$ is highest when σ_i is smaller than

[11] The shapes, minimum points, and inflection points of the graphs of the expected profits in Fig. 1 are determined by examining the first- and second-order derivatives of the functions with respect to σ_i. The same applies to Fig. 2 shown in the next section.

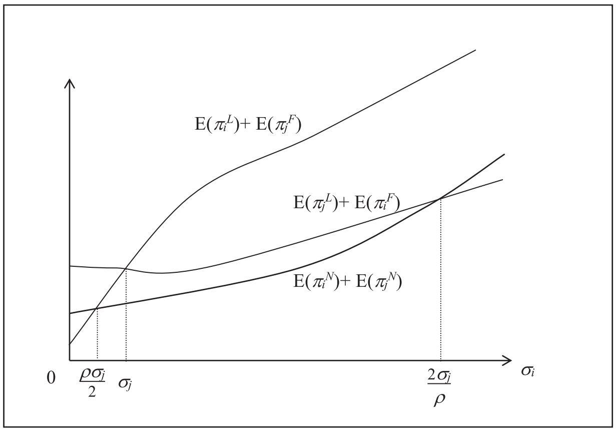

Fig. 2. Total expected profits.

$2\sigma_j/\rho$, meaning that Firm *i* should set its margin later than Firm *j* if Firm *j*'s cost uncertainty is relatively high.

6. Total profit of the supply chain

We proceed to compare total supply chain profits under different power structures, deriving the next proposition.

Proposition 3. The order of the expected total profit of the supply chain is as follows, depending on the parameters associated with the uncertainty.

Case (I) $E(\pi_j^L)+E(\pi_i^F) > E(\pi_i^N)+E(\pi_j^N) \geq E(\pi_i^L)+E(\pi_j^F)$ if $0 < \sigma_i \leq \rho\sigma_j/2$

Case (II) $E(\pi_j^L)+E(\pi_i^F) \geq E(\pi_i^L)+E(\pi_j^F) > E(\pi_i^N)+E(\pi_j^N)$ if $\rho\sigma_j/2 < \sigma_i \leq \sigma_j$

Case (III) $E(\pi_i^L)+E(\pi_j^F) > E(\pi_j^L)+E(\pi_i^F) \geq E(\pi_i^N)+E(\pi_j^N)$ if $\sigma_j < \sigma_i \leq 2\sigma_j/\rho$

Case (IV) $E(\pi_i^L)+E(\pi_j^F) > E(\pi_i^N)+E(\pi_j^N) > E(\pi_j^L)+E(\pi_i^F)$ if $\sigma_i > 2\sigma_j/\rho$

Proposition 3 deserves attention in that it indicates that, in the Stackelberg game, the total expected supply chain profit is higher when a member with higher cost uncertainty becomes the leader and the other member with lower cost uncertainty is the follower than when otherwise. More specifically, when $\sigma_i \leq \sigma_j$ as shown in Cases (I) and (II), $E(\pi_j^L) + E(\pi_i^F)$ is the highest total expected profit of the supply chain, meaning that Firms *i* and *j* should be the follower and the leader for the purpose of total profit maximization, respectively, because the cost uncertainty of Firm *j* is higher than that of Firm *i*. In addition, note that the region of $\sigma_i < \sigma_j$ is completely included in the region of $\sigma_i < 2\sigma_j/\rho$ in Proposition 2, which is the condition that Firm *i* chooses the follower position for the purpose of its individual profit maximization. Namely, $\sigma_i < 2\sigma_j/\rho$ is automatically satisfied if $\sigma_i < \sigma_j$, meaning that if the firm with lower cost uncertainty chooses the position of the second-mover, the choice of the position increases not only its own profit but also the total profit of the supply chain. Consequently, Proposition 3 demonstrates that the title of this paper holds not only from the individual profit viewpoint but also from the perspective of total supply chain profit and channel efficiency, reinforcing the main message of the paper.

Fig. 2 shows $E(\pi_i^N)+E(\pi_j^N)$, $E(\pi_i^L)+E(\pi_j^F)$, and $E(\pi_j^L)+E(\pi_i^F)$ against Firm *i*'s cost uncertainty, σ_i. It shows that if σ_i is less than σ_j, the total expected profit of the supply chain is the highest when Firms *i* and *j* choose the follower position and the leader position, respectively. In contrast, if σ_i is greater than σ_j, these leadership roles should be exchanged for the supply chain to attain the highest expected profit. Therefore, the figure suggests that it is reasonable from the perspective of total supply chain profit that the firm whose cost uncertainty is lower should be the follower, consistent with the result in Proposition 3.

7. Contract between supply chain members

As overviewed in Section 2, many previous studies in the contract literature examine supply chain management problems under asymmetric information. Given the literature, we consider an alternative scenario in which the supply chain members close a contract involving a principal–agent relationship.[12] Conventional wisdom suggests that the use of an efficient contract yields higher total supply chain profit by preventing the double-marginalization problem.[13] The following lemma presents the outcome when Firm *i* becomes the agent and chooses the total margin of the supply chain.

Lemma 4. When Firm *i* becomes the agent who sets the total margin of the supply chain, the optimal margin denoted by M_i ($i = M, R$) is:

$$M_i = \frac{a\sigma_i^2 + b\left(\sigma_{MR}\bar{c}_i - \sigma_i^2\bar{c}_j\right)}{2b\sigma_i^2} - \frac{\sigma_{MR} + \sigma_i^2}{2\sigma_i^2}c_i.$$

The expected value of the total equilibrium profit of the supply chain denoted by Π_i with the margin, M_i, is:

$$E(\Pi_i) = \frac{\sigma_i^2\left(a - b(\bar{c}_M + \bar{c}_R)\right)^2 + b^2\left(\sigma_{MR} + \sigma_i^2\right)^2}{4b\sigma_i^2}.$$

Lemma 4 yields the following proposition.

Proposition 4. The following relationship holds.

$E(\Pi_i) \gtreqless E(\Pi_j) \quad \text{if} \ \sigma_i \gtreqless \sigma_j.$

Observe that the condition of $\sigma_i \gtreqless \sigma_j$ determining the order of the expected profits of $E(\Pi_i)$ and $E(\Pi_j)$ under the implementation of the contract in Proposition 4 is identical to that in Proposition 3 determining the order of total expected supply chain profit without the contract. That is, Proposition 3 suggests that if $\sigma_i > \sigma_j$, Firm *i* should set its margin earlier for the purpose of total profit maximization in the supply chain because then $E(\pi_i^L)+E(\pi_j^F) > E(\pi_j^L)+E(\pi_i^F)$ holds. Similarly, Proposition 4 indicates that when supply chain members close a specific contract involving a principal–agent relationship, the member whose cost uncertainty is higher should simply become the agent and determine the total margin of the supply chain. By assigning a supply chain member with higher cost uncertainty as the agent, the supply chain can reduce its total risk, thereby achieving a higher total expected profit of the supply chain.

While Proposition 4 provides a clear-cut result on which supply chain member should become the agent, the allocation of the total profit is another problem that is solved independently from the problem of determining the optimal margin described by Lemma 4.

[12] While Corbett, Zhou, and Tang (2004) assume that the upstream supplier is the principal and the downstream buyer is the agent, recent contract studies often consider the opposite relationship, that the downstream firm is the principal and the upstream firm is the agent, reflecting a recent power shift from upstream suppliers to downstream retailers (e.g., Chen & Lee, 2017; Lei, Li, & Liu, 2012).

[13] Spengler (1950) initially points out that the double marginalization can be avoided if one supply chain member determines the total margin of the supply chain and the resulting profit is subsequently allocated to each supply chain member. Corbett et al. (2004, p. 550) document the following in the first paragraph of their paper: "The classic double-marginalization problem occurs: If both parties charge a markup, final retail price will be higher and total demand will be lower than in the vertically integrated case. It is well known that two-part contracts, under which the supplier sells the product at its marginal cost and charges a fixed side payment, can coordinate the channel."

Table 2
Numerical results.

Panel A: Expected profits when σ_i varies $(\rho, a-b(\bar{c}_M+\bar{c}_R), b) = (1/2, 10, 1)$						
Low uncertainty ($\sigma_j = 0.1$)				High uncertainty ($\sigma_j = 5$)		
σ_i	$E(\pi_i^N)$	$E(\pi_i^L)$	$E(\pi_i^F)$	$E(\pi_i^N)$	$E(\pi_i^L)$	$E(\pi_i^F)$
0.5	**11.17**	2.18	10.39	11.92	13.25	**30.44**
0.7	**11.23**	1.62	9.45	12.10	13.12	**30.18**
1	**11.34**	1.17	8.73	12.40	12.89	**29.86**
2	**12.01**	0.63	8.28	13.67	12.06	**29.32**
4	**14.65**	0.36	10.16	17.53	11.05	**30.37**
Panel B: Expected profits when ρ varies $(\sigma_i, a-b(\bar{c}_M+\bar{c}_R), b) = (1, 10, 1)$						
Low uncertainty ($\sigma_j = 0.1$)				High uncertainty ($\sigma_j = 5$)		
ρ	$E(\pi_i^N)$	$E(\pi_i^L)$	$E(\pi_i^F)$	$E(\pi_i^N)$	$E(\pi_i^L)$	$E(\pi_i^F)$
0.1	11.36	0.25	**14.32**	11.50	7.10	**31.14**
0.3	**11.36**	0.73	10.01	11.87	11.16	**30.46**
0.5	**11.34**	1.17	8.73	12.40	12.89	**29.86**
0.7	**11.31**	1.60	8.09	13.15	14.29	**29.31**
0.9	**11.27**	2.00	7.69	14.29	15.74	**28.81**
Panel C: Expected profits when $a-b(\bar{c}_M+\bar{c}_R)$ varies $(\sigma_i, \rho, b) = (1, 1/2, 1)$						
Low uncertainty ($\sigma_j = 0.1$)				High uncertainty ($\sigma_j = 5$)		
$a-b(\bar{c}_M+\bar{c}_R)$	$E(\pi_i^N)$	$E(\pi_i^L)$	$E(\pi_i^F)$	$E(\pi_i^N)$	$E(\pi_i^L)$	$E(\pi_i^F)$
1	**0.34**	0.02	0.30	1.40	1.52	**7.31**
5	**3.01**	0.30	2.34	4.06	4.28	**12.77**
10	**11.34**	1.17	8.73	12.40	12.89	**29.86**
20	**44.67**	4.66	34.25	45.73	47.32	**98.19**
50	**278.01**	29.07	212.89	279.06	288.40	**576.55**

That is, if the principal has greater power than the agent, the former is likely to extract more surplus earned by the latter by implementing an efficient contract. For example, while Corbett et al. (2004) consider three contracts, namely a wholesale price contract, a two-part tariff contract, and a nonlinear two-part tariff contract, the two-part tariff contract enables the principal to extract the surplus earned by the agent. Nonetheless, note that no matter which type of contract is used and how the resulting profit is allocated, the result that the firm with greater uncertainty should become the agent who sets the total margin to avoid the double marginalization remains to hold in our model because the equation of M_i in Lemma 4 always holds as the incentive compatibility (IC) condition of the agent, which is the necessary condition to solve the agency problem.[14] Because Lemma 4 holds irrespective of the type of the contract implemented, it follows that Proposition 4, which builds on the lemma, also holds.

8. Numerical illustration

To illustrate the results derived from the analytical model presented above, we provide a numerical example that will quantitatively show how a supply chain member improves its profit by enforcing a margin later under high cost uncertainty of the other member's cost. Specifically, we compare two extreme uncertainty situations and their bearing on the profitability of the supply chain members.

First, by substituting $\sigma_{MR} = \rho\sigma_M\sigma_R$ into $E(\pi_i^N)$, $E(\pi_i^L)$, and $E(\pi_i^F)$ in Lemmas 2 and 3, we find that the three equilibrium expected profits are determined by the parameters $a-b(\bar{c}_M+\bar{c}_R)$, σ_i, σ_j, ρ, and b.[15] Among them, $a-b(\bar{c}_M+\bar{c}_R)$, (σ_i, σ_j), and ρ are important parameters because they respectively represent market potential, cost uncertainty of the two firms, and the correlation coefficient of the costs. Therefore, we calculate the three equilibrium expected profits when each of $a-b(\bar{c}_M+\bar{c}_R)$, σ_i, and ρ varies. For the uncertainty of the other firm's cost, σ_j, we consider two cases, i.e., the case where Firm i faces low cost uncertainty ($\sigma_j = 0.1$), and the other extreme case where Firm i faces high cost uncertainty ($\sigma_j = 5$). The benchmark parameters values are set as: $(\sigma_i, \rho, a-b(\bar{c}_M+\bar{c}_R), b) = (1, 1/2, 10, 1)$.

Table 2 shows the results. Panels A–C report the results in the two scenarios of high uncertainty and low uncertainty when σ_i, ρ, or $a-b(\bar{c}_M+\bar{c}_R)$ varies, respectively. In each of the panels, if one expected profit under a specific environment is the highest of the three leadership structures, the value is presented in boldface. Because we are particularly interested in the environment in which a supply chain member achieves the highest profit by setting its margin later as the follower, we compare $E(\pi_i^F)$ to $E(\pi_i^N)$ and $E(\pi_i^L)$. First, Panel A shows that while $E(\pi_i^F)$ is not the highest in the scenario of low uncertainty ($\sigma_j = 0.1$), $E(\pi_i^F)$ is always the highest in the scenario of high uncertainty ($\sigma_j = 5$), which is consistent with the analytical result in Proposition 2. Second, $E(\pi_i^F)$ is the highest in all cases under high uncertainty in Panel B. Meanwhile, $E(\pi_i^F)$ is not the highest under low uncertainty, except for the case when $\rho = 0.1$. This result is in line with Proposition 2 suggesting that the order of the equilibrium expected profits depends not only on σ_i and σ_j, but also on ρ. Hence, $E(\pi_i^F)$ can be the highest when ρ is extremely low. Finally, Panel C suggests that when $a-b(\bar{c}_M+\bar{c}_R)$ varies, $E(\pi_i^F)$ is the highest under high uncertainty while it is not the highest under low uncertainty in all cases. This result is also consistent with Proposition 2, which suggests that the parameters a, b, $\bar{c}_M$, and $\bar{c}_R$ do not affect the order of expected profits. Namely, Panel C shows that the order of $E(\pi_i^N)$, $E(\pi_i^L)$, and $E(\pi_i^F)$ never changes in response to the value of $a-b(\bar{c}_M+\bar{c}_R)$.

[14] The equation for M_i in Lemma 4 corresponds to the IC condition presented as Eq. (2) in Corbett et al. (2004, p. 552). While the individual rationality (IR) condition of the agent should be satisfied in addition to the IC condition to solve the agency problem, the IR condition is automatically satisfied in our model because neither supply chain member has an outside option.

[15] While $a-b(\bar{c}_M+\bar{c}_R)$ includes four parameters, this expression appears in $E(\pi_i^N)$, $E(\pi_i^L)$, and $E(\pi_i^F)$ as shown in Lemmas 2 and 3. Hence, we need not to substitute specific values into a, $\bar{c}_M$, and $\bar{c}_R$ but only need to substitute a specific value into $a-b(\bar{c}_M+\bar{c}_R)$.

9. Conclusion

Given the recent change in the power structures in supply chains, this paper investigates the practical decision-making problem of when a supply chain member should set its margin in a realistic environment in the presence of uncertainty. To address the problem, we assume a simple two-echelon supply chain that consists of a manufacturer and a retailer, each of which knows its marginal cost as private information and determines the margin of a product for the purpose of maximization of its own expected profit. We construct an incomplete information game model based on this setting, deriving the equilibrium that determines a sequence of decisions by the two supply chain members. The solution of the model provides the managerial implication that a supply chain member should set its margin later if the other member's cost is highly uncertain. The follower can use the margin chosen by the leader to draw inferences about private information on the marginal cost of the leader in the Stackelberg game. In this respect, a supply chain member becoming the late-mover has an information advantage. Consequently, our model provides the practical insight that a supply chain member must consider the cost uncertainty of another member when choosing the timing or leadership to set its margin even if the member has significant power to demand its margin in an early move in the supply chain.

It should be noted that this implication applies to a general relationship between two firms that vertically constitute a supply chain. For example, this implication applies not only to the relationship between a manufacturer and a retailer, which has been assumed in the paper, but also to the relationship between an upstream supplier and a downstream manufacturer. For example, a large-scale manufacturer such as an automobile manufacturer often wields its power over an upstream supplier by taking the leadership to close an advantageous contract of purchasing parts for automobiles because an automaker is usually larger in size than a supplier. However, if the cost uncertainty for the supplier is very high, which is a realistic situation, the manufacturer should set its margin later to avoid the risk of possible reduction in its own realized profit from an inaccurate prediction of the true cost to the supplier. This implication provides a useful insight into how a general firm constituting a supply chain can cope with the uncertainty surrounding other members, which is an essential and practical problem in contemporary supply chain management.

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Appendix

Proof of Lemma 1. Given Eq. (9) and the properties of the cost variables, we have the next two equations by using the law of iterated expectations.

$$E\left(c_i c_j\right) = E\left(E\left(c_i c_j | c_i\right)\right) = E\left(c_i E\left(c_j | c_i\right)\right) = \alpha\bar{c}_i + \beta E\left({c_i}^2\right) = \alpha\bar{c}_i + \beta\left({\sigma_i}^2 + \bar{c}_i^2\right) \tag{A1}$$

$$E\left(c_j\right) = E\left(E\left(c_j | c_i\right)\right) = \alpha + \beta\bar{c}_i \tag{A2}$$

After substituting $E(c_j) = \bar{c}_j$ and $E(c_i c_j) = \sigma_{MR} + \bar{c}_i\bar{c}_j$ into Eqs. (A1) and (A2), we solve the equations for α and β to obtain $\alpha = \bar{c}_j - \sigma_{MR}\bar{c}_i/{\sigma_i}^2$ and $\beta = \sigma_{MR}/{\sigma_i}^2$. Replacing α and β in Eq. (9) with these values gives the equation shown in this lemma. □

Proof of Lemma 2. We follow a standard process for the derivation of Bayesian equilibrium in a product market in the presence of cost uncertainty, which has been shown in previous research constructing incomplete information game models (e.g., Li, 2002).

We first derive the BNE strategies adopted by the two firms. Firm i chooses m_i to maximize its expected profit represented by Eq. (8) conditional on available information, c_i. The first-order condition with respect to m_i yields the following reaction function:

$$m_i = (a/b - (c_i + E(m_j + c_j | c_i)))/2. \tag{A3}$$

Using this reaction function under uncertainty, we conjecture that margin choices are linear in the information variables; that is, $m_i = A_i + B_i c_i$ $(i = M, R)$. Replacing the left-hand side of Eq. (A3) with this linear conjecture gives:

$$A_i + B_i c_i = \left(a/b - \left(c_i + E\left(m_j + c_j | c_i\right)\right)\right)/2. \tag{A4}$$

Substituting $E(c_j | c_i) = \bar{c}_j + \sigma_{MR}(c_i - \bar{c}_i)/{\sigma_i}^2$ and $E(m_j | c_i) = E(A_j + B_j c_j | c_i) = A_j + B_j(\bar{c}_j + \sigma_{MR}(c_i - \bar{c}_i)/{\sigma_i}^2)$ into Eq. (A4) yields:

$$A_i + B_i c_i = \left(a/b - A_j - B_j\bar{c}_j - \bar{c}_j + \left(1 + B_j\right)\sigma_{MR}\bar{c}_i/{\sigma_i}^2\right)/2 - \left(\left(1 + B_j\right)\sigma_{MR} + {\sigma_i}^2\right)c_i/\left(2{\sigma_i}^2\right). \tag{A5}$$

Because this equation holds irrespective of the value of c_i, the following two equations must be satisfied.

$$A_i = \left(a/b - A_j - B_j\bar{c}_j - \bar{c}_j + \left(1 + B_j\right)\sigma_{MR}\bar{c}_i/{\sigma_i}^2\right)/2, \tag{A6}$$

$$B_i = -\left(\left(1 + B_j\right)\sigma_{MR} + {\sigma_i}^2\right)/\left(2{\sigma_i}^2\right). \tag{A7}$$

Because Eqs. (A6) and (A7) hold for $(i, j) = (M, R)$ and (R, M), we solve the equations for (A_i, B_i), deriving:

$$A_i = \left(a - b\left(\bar{c}_i + \bar{c}_j\right)\right)/(3b) + \left({\sigma_{MR}}^2 - \sigma_{MR}{\sigma_j}^2 - 2{\sigma_i}^2{\sigma_j}^2\right)\bar{c}_i/\left({\sigma_{MR}}^2 - 4{\sigma_i}^2{\sigma_j}^2\right) \tag{A8}$$

$$B_i = -\left({\sigma_{MR}}^2 - \sigma_{MR}{\sigma_j}^2 - 2{\sigma_i}^2{\sigma_j}^2\right)/\left({\sigma_{MR}}^2 - 4{\sigma_i}^2{\sigma_j}^2\right). \tag{A9}$$

Substituting Eqs. (A8) and (A9) into $m_i = A_i + B_i c_i$ yields:

$$m_i = a - b\left(\bar{c}_i + \bar{c}_j\right)/(3b) - \left({\sigma_{MR}}^2 - \sigma_{MR}{\sigma_j}^2 - 2{\sigma_i}^2{\sigma_j}^2\right)(c_i - \bar{c}_i)/\left({\sigma_{MR}}^2 - 4{\sigma_i}^2{\sigma_j}^2\right), \tag{A10}$$

which is the equilibrium strategy ${m_i}^N$ shown in this lemma.

Finally, we substitute Eq. (A10), $E(c_i) = \bar{c}_i$, $\mathrm{var}(c_i) = {\sigma_i}^2$, and $\mathrm{cov}(c_M, c_R) = \sigma_{MR}$ into Eq. (8), yielding:

$$E(\pi_i) = \frac{\left(a - b\left(\bar{c}_i + \bar{c}_j\right)\right)^2}{9b} + \frac{b{\sigma_i}^2\left({\sigma_{MR}}^2 - \sigma_{MR}{\sigma_j}^2 - 2{\sigma_i}^2{\sigma_j}^2\right)^2}{\left({\sigma_{MR}}^2 - 4{\sigma_i}^2{\sigma_j}^2\right)^2}, \tag{A11}$$

which is the unconditional expected profit of $E({\pi_i}^N)$ shown in this lemma. □

Proof of Lemma 3. In this proof, we follow the algorithm shown by Gal-Or (1987) to derive the PBE in a dynamic incomplete information game. Throughout this proof, subscripts L and F attached to variables respectively represent those of the leader and the follower. For example, if the manufacturer and the retailer are respectively the leader and the manufacturer, then $(L, F) = (M, R)$. Using Eq. (8), we state the expected profit conditional on available information for the follower as follows:

$$E(\pi_F | c_F) = (a - b(m_F + c_F + E(m_L + c_L | c_F)))m_F. \tag{A12}$$

The follower chooses m_F to maximize Eq. (A12). The first-order condition with respect to m_F yields the following reaction function:

$$m_F = (a/b - (c_F + E(m_L + c_L|c_F)))/2. \tag{A13}$$

Note here that because m_L is observable to the follower, $E(m_L|c_F) = m_L$ holds. Moreover, because each firm chooses its margin depending on its information, we state the linear strategies as: $m_L = A_L + B_L c_L$ and $m_F = A_F + B_F c_F + X_F m_L$. Based on the strategy, the follower conjectures $c_L = (m_L - A_L)/B_L$. Therefore, we restate Eq. (A13) as:

$$A_F + B_F c_F + X_F m_L = (a/b - (c_F + m_L + (m_L - A_L)/B_L))/2. \tag{A14}$$

As this equation holds irrespective of c_F and m_L, the following equations must hold.

$$a/(2b) + A_L/(2B_L) - A_F = 0 \tag{A15}$$

$$B_F = -1/2 \tag{A16}$$

$$X_F + 1/(2B_L) + 1/2 = 0 \tag{A17}$$

Next, the expected profit of the leader conditional on its information is:

$$E(\pi_L|c_L) = (a - b(m_L + c_L + E(m_F + c_F|c_L)))m_L. \tag{A18}$$

Substituting $m_F = A_F + B_F c_F + X_F m_L$ into Eq. (A18), we have:

$$E(\pi_L|c_L) = (a - b(m_L + c_L + E(A_F + B_F c_F + X_F m_L + c_F|c_L)))m_L. \tag{A19}$$

Further substituting $E(c_F|c_L) = \bar{c}_F + \sigma_{MR}(c_L - \bar{c}_L)/\sigma_L{}^2$ into Eq. (A19), we have:

$$\begin{aligned} E(\pi_L|c_L) = {} & (a - b((1 + X_F)m_L + c_L \\ & + (1 + B_F)(\bar{c}_F + \sigma_{MR}(c_L - \bar{c}_L)/\sigma_L{}^2) + A_F))m_L. \end{aligned} \tag{A20}$$

The leader chooses m_L to maximize Eq. (A20). The first-order condition is:

$$a - b\left(2(1 + X_F)m_L + c_L + (1 + B_F)\left(\bar{c}_F + \sigma_{MR}(c_L - \bar{c}_L)/\sigma_L{}^2\right) + A_F\right) = 0. \tag{A21}$$

Substituting $m_L = A_L + B_L c_L$ into the equation, we restate Eq. (A21) as:

$$\begin{aligned} & a - b\left(A_F + 2A_L(1 + X_F) + (1 + B_F)\left(\bar{c}_F - \sigma_{MR}\bar{c}_L/\sigma_L{}^2\right)\right) \\ & -b\left(1 + 2B_L(1 + X_F) + (1 + B_F)\sigma_{MR}/\sigma_L{}^2\right)c_L = 0. \end{aligned}$$

Because this equation holds irrespective of the value of c_L, the following equations must hold.

$$a - b\left(A_F + 2A_L(1 + X_F) + (1 + B_F)\left(\bar{c}_F - \sigma_{MR}\bar{c}_L/\sigma_L{}^2\right)\right) = 0 \tag{A22}$$

$$-b\left(1 + 2B_L(1 + X_F) + (1 + B_F)\sigma_{MR}/\sigma_L{}^2\right) = 0 \tag{A23}$$

Jointly solving Eqs. (A15)–(A17) and (A22) , (A23), we obtain:

$$A_L = \sigma_{MR}\left(a/b - \bar{c}_F + \sigma_{MR}\bar{c}_L/\sigma_L{}^2\right)/\left(2\left(\sigma_{MR} + \sigma_L{}^2\right)\right) \tag{A24}$$

$$A_F = \left(\sigma_{MR}(a/b - \bar{c}_L) + \sigma_L{}^2\bar{c}_F\right)/\left(2\left(\sigma_{MR} + \sigma_L{}^2\right)\right) \tag{A25}$$

$$B_L = -\sigma_{MR}/\left(2\sigma_L{}^2\right) \tag{A26}$$

$$B_F = -1/2 \tag{A27}$$

$$X_F = \sigma_L{}^2/\sigma_{MR} - 1/2. \tag{A28}$$

Substituting Eqs. (A24)–(A28) into $m_L = A_L + B_L c_L$ and $m_F = A_F + B_F c_F + X_F m_L$, we obtain:

$$m_L = \frac{1}{2}\sigma_{MR}\left(\frac{a/b + \sigma_{MR}\bar{c}_L/\sigma_L{}^2 - \bar{c}_F}{\sigma_{MR} + \sigma_L{}^2} - \frac{c_L}{\sigma_L{}^2}\right), \tag{A29}$$

$$m_F = \frac{\sigma_{MR}a + b\left(\sigma_L{}^2\bar{c}_F - \sigma_{MR}\bar{c}_L\right)}{2b\left(\sigma_{MR} + \sigma_L{}^2\right)} + m_L\left(\frac{\sigma_L{}^2}{\sigma_{MR}} - \frac{1}{2}\right) - \frac{c_F}{2}, \tag{A30}$$

which are restated as $m_i{}^L$ and $m_j{}^F$ shown in this lemma.

Finally, we substitute Eqs. (A29) and (A30), $E(c_i) = \bar{c}_i$, $\mathrm{var}(c_i) = \sigma_i{}^2$, and $\mathrm{cov}(c_M, c_R) = \sigma_{MR}$ into Eq. (8), yielding:

$$E(\pi_L) = \frac{\sigma_{MR}\left(\sigma_{MR} + 2\sigma_L{}^2\right)(a - b(\bar{c}_L + \bar{c}_F))^2}{8b\left(\sigma_{MR} + \sigma_L{}^2\right)^2} + \frac{b\sigma_{MR}\left(\sigma_{MR} + 2\sigma_L{}^2\right)}{8\sigma_L{}^2}, \tag{A31}$$

$$\begin{aligned} E(\pi_F) = {} & \frac{\left(\sigma_{MR} + 2\sigma_L{}^2\right)^2(a - b(\bar{c}_L + \bar{c}_F))^2}{16b\left(\sigma_{MR} + \sigma_L{}^2\right)^2} \\ & + \frac{b\left(4\sigma_L{}^2\left(\sigma_L{}^2 + \sigma_R{}^2\right) + 4\sigma_{MR}\sigma_L{}^2 - 3\sigma_{MR}{}^2\right)}{16\sigma_L{}^2}, \end{aligned} \tag{A32}$$

which are respectively restated as the unconditional expected profits of $E(\pi_i{}^L)$ and $E(\pi_j{}^F)$ shown in this lemma. □

Proof of Proposition 1. Given that $\sigma_{MR} = \rho\sigma_M\sigma_R$, Lemmas 2 and 3 suggest that if $\sigma_i \to 0$ and then $\sigma_j \to 0$ ($(i, j) = (M, R), (R, M)$), expected profits are:

$$E\left(\pi_i^N\right) \to (a - b(\bar{c}_M + \bar{c}_R))^2/(9b),$$

$$E\left(\pi_j^N\right) \to (a - b(\bar{c}_M + \bar{c}_R))^2/(9b),$$

$$E\left(\pi_i^L\right) \to (a - b(\bar{c}_M + \bar{c}_R))^2/(8b),$$

$$E\left(\pi_j^F\right) \to (a - b(\bar{c}_M + \bar{c}_R))^2/(16b).$$

Because $\mathrm{E}(\pi_i{}^L) > \mathrm{E}(\pi_i{}^N) = \mathrm{E}(\pi_j{}^N) > \mathrm{E}(\pi_j{}^F)$ holds, the leader in the Stackelberg game always achieves the highest expected profit. As a result, each supply chain member has an incentive to set a margin earlier. □

Proof of Proposition 2. Lemmas 2 and 3 suggest that the next three equations hold.

$$\begin{aligned} \mathrm{E}(\pi_i{}^L) - \mathrm{E}(\pi_i{}^N) = {} & \left(\rho\sigma_j - 2\sigma_i\right)\left(\frac{(4\sigma_i + \rho\sigma_j)(a - b(\bar{c}_M + \bar{c}_R))^2}{72b\left(\sigma_i + \rho\sigma_j\right)^2}\right. \\ & \left. + \frac{b(4(2 - \rho^2)^2\sigma_i + \rho(8 - 8\rho^2 + \rho^4)\sigma_j)}{8(4 - \rho^2)^2}\right) \end{aligned} \tag{A33}$$

$$\begin{aligned} & \mathrm{E}(\pi_i{}^N) - \mathrm{E}(\pi_i{}^F) = \left(\rho\sigma_i - 2\sigma_j\right) \\ & \times\left(\frac{\left(7\rho\sigma_i + 10\sigma_j\right)(a - b(\bar{c}_M + \bar{c}_R))^2}{144b\left(\rho\sigma_i + \sigma_j\right)^2} + \frac{b\left(\rho\left(16 - 12\rho^2 + 3\rho^4\right)\sigma_i + 2\left(16 - 12\rho^2 + \rho^4\right)\sigma_j\right)}{16\left(4 - \rho^2\right)^2}\right) \end{aligned} \tag{A34}$$

$$\begin{aligned} & \mathrm{E}(\pi_i{}^L) - \mathrm{E}(\pi_i{}^F) = -\frac{b\left(\left(4 - 3\rho^2\right)\sigma_i{}^2 + 2\left(2 - \rho^2\right)\sigma_j{}^2\right)}{16} \\ & - \frac{\left(\rho\left(4\sigma_i\sigma_j{}^3 + \rho\left(\sigma_i{}^4 + 2\sigma_j{}^4\right)\right) + \left(4 - \rho^4\right)\sigma_i{}^2\sigma_j{}^2 + 2\rho\left(2 - \rho^2\right)\sigma_i{}^3\sigma_j\right)(a - b(\bar{c}_M + \bar{c}_R))^2}{16b\left(\rho\sigma_i + \sigma_j\right)^2\left(\sigma_i + \rho\sigma_j\right)^2} < 0 \end{aligned} \tag{A35}$$

Because $0 < \rho < 1$, the formula included in the latter parentheses in Eq. (A33) is positive, thus $\mathrm{E}(\pi_i{}^N) \gtreqless \mathrm{E}(\pi_i{}^L)$ holds if $\sigma_i \gtreqless \rho\sigma_j/2$. Second, because $0 < \rho < 1$, the formula in the latter parentheses in Eq. (A34) is positive, thus $\mathrm{E}(\pi_i{}^N) \gtreqless \mathrm{E}(\pi_i{}^F)$ holds if $\sigma_i \gtreqless 2\sigma_j/\rho$. Finally, $\mathrm{E}(\pi_i{}^L) - \mathrm{E}(\pi_i{}^F) < 0$ holds in Eq. (A35) irrespective of the parameter values because $0 < \rho < 1$. Eqs. (A33)–(A35) give the order of the profit of Firm i depending on the parameters associated with the uncertainty (i.e., σ_i, σ_j, and ρ), as classified by the three cases in this proposition. □

Proof of Proposition 3. Lemmas 2 and 3 indicate that the following equations hold.

$$\begin{aligned}&\mathrm{E}(\pi_i{}^L)+\mathrm{E}(\pi_j{}^F)-(\mathrm{E}(\pi_j{}^L)+\mathrm{E}(\pi_i{}^F))\\&=\sigma_{MR}{}^2\left(\sigma_i{}^2-\sigma_j{}^2\right)\left(\frac{\left(2\sigma_{MR}+\sigma_i{}^2+\sigma_j{}^2\right)\left(a-b(\bar{c}_M+\bar{c}_R)\right)^2}{16b\left(\sigma_{MR}+\sigma_i{}^2\right)^2\left(\sigma_{MR}+\sigma_j{}^2\right)^2}+\frac{b}{16\sigma_i{}^2\sigma_j{}^2}\right)\end{aligned} \tag{A36}$$

$$\begin{aligned}&\mathrm{E}(\pi_i{}^N)+\mathrm{E}(\pi_j{}^N)-(\mathrm{E}(\pi_i{}^L)+\mathrm{E}(\pi_j{}^F))\\&=\left(\rho\sigma_j-2\sigma_i\right)\left(\frac{\left(2\sigma_i+5\rho\sigma_j\right)\left(a-b(\bar{c}_M+\bar{c}_R)\right)^2}{144b\left(\sigma_i+\rho\sigma_j\right)^2}\right.\\&\quad\left.+\frac{b\rho^2\left(\left(8-6\rho^2\right)\sigma_i+\rho\left(4+\rho^2\right)\sigma_j\right)}{16\left(4-\rho^2\right)^2}\right)\end{aligned} \tag{A37}$$

First, Eq. (A36) indicates that if $\sigma_i \gtreqless \sigma_j$, then $\mathrm{E}(\pi_i{}^L)+\mathrm{E}(\pi_j{}^F) \gtreqless \mathrm{E}(\pi_j{}^L)+\mathrm{E}(\pi_i{}^F)$ holds. Second, Eq. (A37) indicates that if $\sigma_i \gtreqless \rho\sigma_j/2$, then $\mathrm{E}(\pi_i{}^L)+\mathrm{E}(\pi_j{}^F) \gtreqless \mathrm{E}(\pi_i{}^N)+\mathrm{E}(\pi_j{}^N)$ holds. Because (i, j) represents either (M, R) or (R, M), Eqs. (A36) and (A37) yield the relationships described by the four cases in this proposition. □

Proof of Lemma 4. Using $M \equiv m_M + m_R$, $\mathrm{E}(\Pi) = \mathrm{E}(\pi_M) + \mathrm{E}(\pi_R)$ is described as:

$$\mathrm{E}(\Pi) = \mathrm{E}(M(a - b(M + c_M + c_R))). \tag{A38}$$

From Eq. (A38), the expected total profit of the supply chain conditional on c_i is:

$$E(\Pi|c_i) = M\left(a - b\left(M + c_i + \bar{c}_j + \sigma_{MR}(c_i - \bar{c}_i)/\sigma_i{}^2\right)\right). \tag{A39}$$

The first-order condition with respect to M yields the reaction function, which can be restated as the optimal margin M_i as shown in this lemma. We substitute M_i, $E(c_i) = \bar{c}_i$, $\mathrm{var}(c_i) = \sigma_i{}^2$, and $\mathrm{cov}(c_M, c_R) = \sigma_{MR}$ into Eq. (A38), yielding the equilibrium expected profit $\mathrm{E}(\Pi_i)$ shown in this equation. □

Proof of Proposition 4. From Lemma 4, the following equation holds.

$$E(\Pi_i) - E(\Pi_j) = b(1-\rho)(1+\rho)(\sigma_i - \sigma_j)(\sigma_i + \sigma_j)/4$$

This equation suggests that $\mathrm{E}(\Pi_i) \gtreqless \mathrm{E}(\Pi_j)$ holds if $\sigma_i \gtreqless \sigma_j$ because $0 < \rho < 1$. □

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