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Contracting and Information Sharing Under Supply Chain Competition

Albert Y. Ha, Shilu Tong
Department of Information and Systems Management, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong {imayha@ust.hk, tongsl@ust.hk}

We investigate contracting and information sharing in two competing supply chains, each consisting of one manufacturer and one retailer. The two supply chains are identical, except they may have different investment costs for information sharing. The problem is studied using a two-stage game. In the first stage, the manufacturers decide whether to invest in information sharing. In the second stage, given the information structure created in the first stage, the manufacturers offer contracts to their retailers and the retailers engage in Cournot competition. We analyze the game for two different contract types. For the case of contract menus, a supply chain that does not have information sharing will lower its selling quantities because of the negative quantity distortions in the contract menus, thus creating a strategic disadvantage in Cournot competition. The value of information sharing to a supply chain is positive, and the dominant strategy of each supply chain is to invest in information sharing when the investment costs are low. We fully characterize the equilibrium information sharing decisions under different investment costs. For the case of linear price contracts, the value of information sharing to a supply chain becomes negative, and the dominant strategy of each supply chain is not to invest in information sharing regardless of investment costs. Our results highlight the importance of contract type as a driver of the value of information sharing and the role of information sharing capability as a source of competitive advantage under supply chain competition.

Key words: supply chain competition; incentive contracts; asymmetric information; information sharing
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1. Introduction

This paper considers contracting and how contract type affects the value of information sharing in supply chains under horizontal competition and asymmetric information. With the advent of information technology, firms that do business with one another are interconnected as never before. To be successful in the marketplace, firms have to work together to optimize the supply chain so as to achieve a quantum jump in performance that cannot be achieved by optimizing individual processes. As a result, the classical model of firm versus firm competition is giving way to a new model: supply chain versus supply chain competition (Taylor 2003, Barnes 2006). Under this new model, it is essential for supply chain partners to have the right incentive and information to cooperate and respond in a coordinated way to threats posed by competing supply chains. Large computer manufacturers like IBM and Hewlett-Packard routinely ask for sell-through data from the resellers (Lee and Whang 2000). Under continuous replenishment program and vendor-managed inventory, powerful manufacturers such as Campbell Soup Company and VF Corporation get sales data from the retailers for the production and distribution planning of the supply chains (Simchi-Levi et al. 2003). How should incentive contracts be designed to coordinate operational decisions in supply chains under horizontal competition and asymmetric information? How does the value of information sharing depend on contract type? Should firms invest in information sharing or rely on incentive contracts to extract information from their supply chain partners? What are the benefits of a higher information sharing capability in supply chain competition? We hope to shed light on these important questions.

We consider the problem of vertical information sharing in two competing supply chains, each consisting of one manufacturer selling to one retailer. The two supply chains are identical except they may have different investment costs for information sharing. The demand state is observable by both retailers but not the manufacturers. The problem is modeled as a two-stage information sharing game. In the first stage, each manufacturer chooses to either invest in information sharing (and pay her retailer for the information) or not to invest. In the second stage, given the information sharing structure created in the first stage, each manufacturer offers a contract to the retailer of her own chain, and the retailers engage in

Cournot competition by determining selling quantities based on the contracts. We solve the information sharing game for the two cases when either quantity-based contract menus or linear price contracts are employed in the second stage. Our analysis leads to the following main insights:

1. Under quantity-based contract menus, information sharing always makes a supply chain better off but the competing supply chain worse off, regardless of whether the latter has information sharing or not. Thus, the value of information sharing to a supply chain is always positive. However, under linear price contracts, the value of information sharing to a supply chain becomes negative. Because contract menus provide enough flexibility for a manufacturer to both influence the retailer's actions and allocate supply chain profit, information sharing enables the manufacturer to improve the overall supply chain performance under competition, which is consistent with her self-interests. However, as linear price contracts do not have such flexibility, information sharing just allows the manufacturer to improve her own profit at the expense of the overall supply chain performance.

2. We show that both investment cost and contract type are key factors for information sharing decisions in supply chains. Under linear price contracts, both supply chains will not invest in information sharing no matter how low the investment costs are. Under quantity-based contract menus, however, lower investment costs make it more likely that supply chains will invest in information sharing. A lower investment cost from a higher information sharing capability can create a competitive advantage for a supply chain, which is usually beneficial to the manufacturer but not necessarily to the retailer, who has private information. Moreover, this advantage is more significant when the competing supply chain that has a higher investment cost is induced not to invest in information sharing and is made less aggressive through the use of contract menus.

3. It is well known that when there is no competition and a manufacturer uses quantity-based contract menus to extract information from her retailer, supply chain efficiency suffers because of the quantity distortions caused by the contract menus. We show that under Cournot competition, these quantity distortions will create not only inefficiency but also a strategic disadvantage because the competing supply chain will be induced to be more aggressive. When both manufacturers have to use contract menus to extract information, competition will be less intense because of the quantity distortions. Depending on how large these quantity distortions are, supply chain profits may be higher or lower when compared with both supply chains having information sharing. However, the manufacturers' profits are always lower, because any gain in supply chain profits from less-intense competition will be offset by the information rents captured by the retailers.

4. Under quantity-based contract menus, it is possible for the information sharing game to resemble the classical prisoner's dilemma game. That is, both manufacturers invest in information sharing in equilibrium, even though they will be better off if neither invests. No such prisoner's dilemma exists under linear price contracts.

These insights are useful for managers in developing supply chain strategies. To explore the advantage of information sharing, managers should not only improve the information sharing capability of the supply chain but also adopt contracts that can create incentive for information sharing. Our results imply that nonlinear price contracts (equivalent to the quantity-based contract menus when the demand state is continuous) are preferable to the linear price contracts commonly employed. Our results also show that when there is no information sharing and managers use sophisticated contracts to extract information from their supply chain partners, they have to account for the negative competitive effect of the quantity distortions caused by these contracts.

Our paper is most related to the literature on information sharing in supply chains. Chen (2003) offers an excellent survey of the literature. One stream of research evaluates the value of information in improving operational performance (see, for example, Lee et al. 2000, Cachon and Fisher 2000). Another stream of research more relevant to our work studies the incentive for firms in a supply chain to share information (Li 2002; Zhang 2002; Li and Zhang 2002, 2008).[1] Most of the work here assumes linear price contracts offered by a single manufacturer and considers imperfect demand signal. More recently, Anand and Goyal (2006) use a signaling game framework to study the issue of information leakage in a one-supplier-two-retailer chain under linear price contracts. Based on a stylized model with perfect demand signal, we examine how the value of information sharing depends on contract type and supply chain competition and how information sharing capability can be a source of competitive advantage for supply chains. These are important issues that have not been explored in the literature.

Cachon (2003) provides an excellent review of the literature on supply chain contracting under asymmetric information. Our paper is related to the screening models in this literature, which focus on the problem of designing contract menus to induce firms

[1] There is a literature in economics on horizontal information sharing (e.g., Li 1985, Gal-Or 1985), but it does not consider interaction in vertical chains.

to truthfully report their private information. Two examples of quantity-based contract menus studied in this literature are Ha (2001) and Corbett et al. (2004). Some recent relevant work on contracting under asymmetric demand information includes Lariviere (2002) and Ozer and Wei (2006). Most of the screening models are in the context of one-to-one contracting without market competition. Cachon (2003) points out the need for more research on other supply chain structures, such as one-to-many or many-to-many configurations. One example is Cachon and Lariviere (2005), which shows that a revenue-sharing contract can coordinate a supply chain with one manufacturer selling to multiple retailers under stochastic demand. We make a contribution to this literature by considering contract design in the context of two one-to-one chains. Our analysis yields interesting insights on how the incentive contracts change under different information structures in a competitive environment.

Our paper is also related to the literature on supply chain competition. A substantial amount of work in this literature considers inventory competition under demand uncertainty (see, e.g., Parlar 1988, Cachon 2001, and, more recently, Wu and Chen 2003). Corbett and Karmarkar (2001) examine quantity competition under different supply chain structures with deterministic demand. In these models, there is only one level of horizontal competition, or coordination is trivial under full information, or a linear pricing contract is assumed. None of them explicitly considers contracting in a competitive environment. The structure of two competing supply chains considered here is very similar to that in Boyaci and Gallego (2004). However, the issues studied and the results of the two papers are quite different. In Boyaci and Gallego (2004), both the manufacturers and the retailers can take actions to affect service quality competition, a wholesale price is assumed to be exogenously given, and the main issue is concerned with the value of coordination under full information. In our model, only the retailers take actions that directly affect market competition, the contracts are endogenously chosen by the manufacturers, and the main issues concern value of information sharing as well as contracting under different information sharing structures. Our work contributes to this literature by considering contracting under asymmetric information and competition, albeit using a rather stylized model to capture all these important issues.

The remainder of this paper is organized as follows. Section 2 provides model setup of the two-stage information sharing game. Section 3 analyzes supply chain competition in the second stage under different information sharing structures for the case of contract menus. Section 4 examines supply chain competition in the second stage under different information sharing structures for the case of linear price contracts. Section 5 investigates and compares the equilibrium information sharing decisions in the first stage for the two contract types. Finally, we offer our concluding remarks in §6. The proofs of all the formal results are given in the appendix. Additional proofs, which are straightforward, are given in the online supplement (provided in the e-companion).[2]

2. The Two-Stage Information Sharing Game

Consider two supply chains, each consisting of one manufacturer (she) selling a homogeneous product to one retailer (him). The two supply chains are identical except they may have different investment costs for information sharing. The manufacturers, the retailers, and the supply chains are indexed by $i = 1, 2$. The retailers compete in a market with a linear demand function given by

$$p = A - q_1 - q_2,$$

where p is the market clearing price and q_1 and q_2 are the selling quantities of the retailers. The intercept of the demand function, A, is a random variable given by

$$A = \begin{cases} A_H & \text{with probability } \beta, \\ A_L & \text{with probability } 1-\beta. \end{cases} \tag{1}$$

Thus A_H and A_L correspond respectively to the high and low demand states, where $A_H > A_L > 0$. The assumption of only two demand states is a simplification of reality, but it is sufficient to capture the main effect of information on contracting and competition in our problem. A two-state demand distribution has been employed in similar work in the supply chain contracting literature (see, for example, Cachon and Lariviere 2001, Chen 2005). The manufacturers have identical marginal production costs while the retailers have identical marginal operating costs, and these costs are normalized to zero.[3] We make the following additional assumptions:

Assumption 1. *The reservation profits of both retailers are zero, independent of the demand state.*

Assumption 2. *The manufacturers can contract only on quantities ordered by the retailers of their own chains.*

Assumption 3. *Both manufacturers use the same type of contracts, and the contract type is common knowledge*

[2] An electronic companion to this paper is available as part of the online version that can be found at http://mansci.journal.informs.org/.

[3] When the marginal cost c is such that $A_L > c > 0$, all the results will remain valid with A_d replaced by $A_d - c$, where $d = H$ or L.

to all the manufacturers and retailers. The contract terms within a supply chain are not observable by the firms of the competing supply chain.

Assumption 1 is a usual assumption in the supply chain contracting literature. It is common to contract on order quantity in a manufacturer-retailer relationship. Assumption 2, however, excludes the possibility of contracting on other measures such as revenue or market share. Such an assumption is appropriate when these measures are difficult to verify or their transaction costs are too high. For Assumption 3, it is common to have a prevailing contract type in an industry because of trade practice or other factors such as transaction cost or technology. However, the contract terms are usually not observable by rival firms. We consider an information sharing game with the following sequence of events:

1. Given the contract type, the manufacturers simultaneously and independently decide whether to invest in information sharing with the retailers of their own chains.
2. Demand state is revealed to the retailers, who will (or will not) share it with the manufacturers based on the information sharing decisions in event 1.
3. The manufacturers simultaneously and independently offer contracts (by choosing the contract parameters) to the retailers of their own chains.
4. Based on the contracts offered, the retailers engage in Cournot competition by simultaneously and independently determining their selling quantities.

The above events constitute a two-stage game. In the first stage, the manufacturers make and execute information sharing decisions (events 1 and 2). These decisions create three possible information sharing structures: Models *SS* (information sharing in both supply chains), *NS* (information sharing in one supply chain), and *NN* (no information sharing). Here the first and second letters in the model acronym denote the information sharing decisions of supply chains 1 and 2 (S for "share" while N for "not share"), respectively. In the second stage, given the information sharing structure created in the first stage, the manufacturers and the retailers make contracting and quantity decisions (events 3 and 4). In the first stage, if a manufacturer chooses to invest, she has to pay her retailer for the information and incur a fixed investment cost, which possibly includes the investment in information systems as well as management resources for setting up organizational processes to facilitate information interchange. Because the type of information considered in our model is more aggregate and forward looking in nature, the latter organizational cost may constitute a major part of the investment cost. Without loss of generality, this investment cost already includes any fixed cost a retailer has to incur for sharing information, because the manufacturer ultimately will have to pay the retailer for that cost. When the manufacturer and the retailer are in a long-term relationship, it may take less effort to reorganize their processes to facilitate information sharing. If the supply chain is more technology savvy, fewer management resources will be needed to adopt new information systems. Thus, the investment cost can be regarded as a measure of the information sharing capability of a supply chain.

We will consider the information sharing game under either contract menus or linear price contracts. A contract menu is a menu of quantity bundle contracts, each characterized by a fixed order quantity, and the associated total payment. Under asymmetric information, a menu of quantity bundle contracts is the optimal form of incentive contract for the one-manufacturer-one-retailer contracting problem, and it becomes a nonlinear pricing contract when the demand state is continuous (see Tirole 1988 or Corbett et al. 2004). Because of Assumption 3, a manufacturer cannot observe the contract terms within the competing supply chain, and her contract has direct (first-order) effect on only her own retailer, but not the competing retailer. In anticipation of the selling quantity of the competing retailer, a manufacturer will choose a menu of quantity bundles (or in practice a nonlinear pricing contract) as her best response. If we do not impose any restriction on the contract type in Assumption 3, as long as Assumption 2 is satisfied, menus of quantity bundles will emerge as the equilibrium contract choices. Note that this may not be valid when contracts are observable, because in this case contracts will have a direct (first-order) effect on the competing retailer. Under full information, a quantity bundle contract is attractive because it allows a manufacturer to coordinate her supply chain and extract all the profit. A linear price contract is very popular in practice and is commonly assumed in the information sharing literature. However, it is known to be quite inflexible because of the double marginalization effect. By comparing these two distinctively different contract types, we seek to obtain new insights on how contract type affects the value of information sharing under supply chain competition.

3. Stage-Two Problem Under Contract Menus

3.1. Model *SS*: Information Sharing in Both Supply Chains

Here the demand state d, where $d = H$ or L, is known to all the manufacturers and retailers. Given d, manufacturer i offers a contract (Q_{di}, T_{di}) to retailer i, where Q_{di} is the order quantity and T_{di} is the corresponding payment. Contracts are not observable by the rival firms, so the manufacturer and the retailer of a supply chain respond directly to the selling quantity but not the contract of the competing supply chain. Knowing the state d and given the contract (Q_{di}, T_{di}), in anticipation of the selling quantity q_{dj} of retailer j, retailer i determines a selling quantity q_{di} that cannot exceed the order quantity Q_{di} to maximize his profit that is given by

$$(A_d - q_{di} - q_{dj})q_{di} - T_{di}. \tag{2}$$

His best response function is given by

$$\hat{q}_{di}(Q_{di}, q_{dj}) = \arg\max_{0\le q_{di}\le Q_{di}} (A_d - q_{di} - q_{dj})q_{di} = \min\left[\frac{A_d - q_{dj}}{2}, Q_{di}\right]. \tag{3}$$

Let $f_d(Q_{di}, q_{dj})$ be retailer i's induced revenue, which is given by $(A_d - \hat{q}_{di}(Q_{di}, q_{dj}) - q_{dj})\hat{q}_{di}(Q_{di}, q_{dj})$. It is easy to show that

$$f_d(Q_{di}, q_{dj}) = \begin{cases} (A_d - Q_{di} - q_{dj})Q_{di} & \text{if } Q_{di} \le \dfrac{A_d - q_{dj}}{2}, \\ \dfrac{(A_d - q_{dj})^2}{4} & \text{otherwise.} \end{cases} \tag{4}$$

Manufacturer i's profit is given by T_{di}. By Assumption 1, because the reservation profit of retailer i is zero, the manufacturer always sets $T_{di} = f_d(Q_{di}, q_{dj})$. Knowing the best response of retailer i and in anticipation of the selling quantity q_{dj} of retailer j, manufacturer i chooses Q_{di} to maximize $f_d(Q_{di}, q_{dj})$. Her best response functions are given by[4]

$$\widehat{Q}^S_{di}(q_{dj}) = \frac{A_d - q_{dj}}{2} \tag{5}$$

$$\widehat{T}^S_{di}(q_{dj}) = f_d(\widehat{Q}^S_{di}(q_{dj}), q_{dj}) = \frac{(A_d - \widehat{Q}^S_{di}(q_{dj}))^2}{4}, \tag{6}$$

where the superscript S denotes that supply chain i has information sharing (and therefore manufacturer i knows d). Consequently,

$$\hat{q}_{di}(\widehat{Q}^S_{di}(q_{dj}), q_{dj}) = \widehat{Q}^S_{di}(q_{dj}). \tag{7}$$

That is, given the selling quantity q_{dj}, the order and selling quantities of supply chain i are the same under the best responses of manufacturer i and retailer i. Let Q^{SS}_{di} and q^{SS}_{di} be, respectively, the equilibrium order and selling quantities of supply chain i under Model SS when demand state is d, where $d = H$ or L and $i = 1$ or 2. An equilibrium $(Q^{SS}_{d1}, q^{SS}_{d1}, Q^{SS}_{d2}, q^{SS}_{d2})$ will satisfy $Q^{SS}_{di} = \widehat{Q}^S_{di}(q^{SS}_{dj})$ and $q^{SS}_{di} = \hat{q}_{di}(Q^{SS}_{di}, q^{SS}_{dj})$ for $i, j = 1$ or 2, and $i \ne j$. We do not need to include the fixed payments T_{di}s in defining the equilibrium because they only affect profit allocation within a supply chain and have no impact on the behavior of the competing supply chain. It is straightforward to show that for $d = H$ or L, there is a unique equilibrium given by

$$Q^{SS}_{d1} = Q^{SS}_{d2} = q^{SS}_{d1} = q^{SS}_{d2} = \frac{A_d}{3}. \tag{8}$$

Note that this is the same equilibrium for the case when the two supply chains are integrated.

3.2. Optimal Contract Design Under Asymmetric Information

In this subsection, we derive the best responses of the firms in a supply chain that does not have information sharing. The result will be used for solving Models NS and NN. Let q_{dj} be the selling quantity of supply chain j when the demand state is d. In anticipation of (q_{Hj}, q_{Lj}), the best response of manufacturer i can be determined by solving an optimal contract design problem, which incorporates the best response of retailer i. Because there are two demand states and only order quantities are contractible, without loss of generality, manufacturer i needs to consider only contract menus of the form $\{(Q_{Hi}, T_{Hi}), (Q_{Li}, T_{Li})\}$ (Kreps 1990), where Q_{di} is the order quantity intended for retailer i when the demand state is d, and T_{di} is the corresponding payment from retailer i to manufacturer i. By the revelation principle, it is sufficient for manufacturer i to consider only truth-telling contract menus, i.e., those menus that induce retailer i to choose the contract intended for the demand state he observes. Roughly speaking, if a menu does not induce truth telling, the manufacturer can always re-index the contracts to make it satisfy this requirement. Knowing that the demand state is d and in anticipation of the selling quantity q_{dj} of the competing supply chain, when retailer i chooses a contract (Q_i, T_i) from the contract menu, his best response selling quantity is $\hat{q}_{di}(Q_i, q_{dj})$ and his maximized revenue is $f_d(Q_i, q_{dj})$, where $\hat{q}_{di}$ and f_d are given by (3) and (4), respectively. The contract design problem, called Problem $\mathscr{C}$, is formulated as follows:

$$\textbf{(Problem } \mathscr{C}\textbf{)} \quad \max_{Q_{Hi}, T_{Hi}, Q_{Li}, T_{Li}} \beta T_{Hi} + (1-\beta)T_{Li} \tag{9}$$

subject to

$$f_H(Q_{Hi}, q_{Hj}) - T_{Hi} \ge f_H(Q_{Li}, q_{Hj}) - T_{Li} \tag{10}$$

$$f_L(Q_{Li}, q_{Lj}) - T_{Li} \ge f_L(Q_{Hi}, q_{Lj}) - T_{Hi} \tag{11}$$

$$f_H(Q_{Hi}, q_{Hj}) - T_{Hi} \ge 0 \tag{12}$$

[4] Because $f_d(Q_{di}, q_{dj})$ is increasing in Q_{di} when $Q_{di} \le (A_d - q_{dj})/2$ and remains constant otherwise, we choose the minimum Q_{di} that maximizes $f_d(Q_{di}, q_{dj})$ as the best response $\widehat{Q}^S_{di}(q_{dj})$. When the marginal production cost is positive, $\widehat{Q}^S_{di}(q_{dj})$ is the unique maximizer of $f_d(Q_{di}, q_{dj})$.

$$f_L(Q_{Li}, q_{Lj}) - T_{Li} \geq 0 \tag{13}$$

$$Q_{Hi} \geq 0, Q_{Li} \geq 0. \tag{14}$$

In the problem formulation, manufacturer i seeks to maximize her expected profit subject to three sets of constraints. Constraints (10) and (11) are incentive-compatibility constraints to induce retailer i to choose the truth-telling order quantity for each realized demand state. Constraints (12) and (13) are individual-rationality constraints to ensure that retailer i will participate by earning at least his reservation profit, which is assumed to be zero, in each demand state. Note that our assumption of full participation is without loss of generality, because a contract with zero order quantity is always feasible. Finally, constraints (14) show that the order quantities must be nonnegative. Let $\{(\widehat{Q}^N_{Hi}(q_{Hj}, q_{Lj}), \widehat{T}^N_{Hi}(q_{Hj}, q_{Lj})), (\widehat{Q}^N_{Li}(q_{Hj}, q_{Lj}), \widehat{T}^N_{Li}(q_{Hj}, q_{Lj}))\}$ be the optimal solution to Problem $\mathscr{C}$. Here N denotes that supply chain i does not have information sharing.

Proposition 1.
(a) *The best response functions of manufacturer i are given by*

$$\widehat{Q}^N_{Hi}(q_{Hj}, q_{Lj}) = \begin{cases} \max\left[\dfrac{A_H - q_{Hj}}{2}, 0\right] & \text{if } A_H - q_{Hj} \geq A_L - q_{Lj}, \\ \max\left[\dfrac{(A_H - q_{Hj})}{2} - \dfrac{(1-\beta)(A_L - q_{Lj} - A_H + q_{Hj})}{2\beta}, 0\right] & \text{otherwise}, \end{cases}$$

$$\widehat{Q}^N_{Li}(q_{Hj}, q_{Lj}) = \begin{cases} \max\left[\dfrac{(A_L - q_{Lj})}{2} - \dfrac{\beta(A_H - q_{Hj} - A_L + q_{Lj})}{2\beta}, 0\right] & \text{if } A_H - q_{Hj} \geq A_L - q_{Lj}, \\ \max\left[\dfrac{A_L - q_{Lj}}{2}, 0\right] & \text{otherwise}, \end{cases}$$

$$\widehat{T}^N_{Hi}(q_{Hj}, q_{Lj}) = \begin{cases} (A_H - q_{Hj} - \widehat{Q}^N_{Hi})\widehat{Q}^N_{Hi} - (A_H - q_{Hj} - \widehat{Q}^N_{Li})\widehat{Q}^N_{Li} \\ \quad + (A_L - q_{Lj} - \widehat{Q}^N_{Li})\widehat{Q}^N_{Li} & \text{if } A_H - q_{Hj} \geq A_L - q_{Lj}, \\ (A_H - q_{Hj} - \widehat{Q}^N_{Hi})\widehat{Q}^N_{Hi} & \text{otherwise}, \end{cases}$$

$$\widehat{T}^N_{Li}(q_{Hj}, q_{Lj}) = \begin{cases} (A_L - q_{Lj} - \widehat{Q}^N_{Li})\widehat{Q}^N_{Li} & \text{if } A_H - q_{Hj} \geq A_L - q_{Lj}, \\ (A_L - q_{Lj} - \widehat{Q}^N_{Li})\widehat{Q}^N_{Li} - (A_L - q_{Lj} - \widehat{Q}^N_{Hi})\widehat{Q}^N_{Hi} \\ \quad + (A_H - q_{Hj} - \widehat{Q}^N_{Hi})\widehat{Q}^N_{Hi} & \text{otherwise}. \end{cases}$$

(b) $\widehat{Q}_{di}(\widehat{Q}^N_{di}(q_{Hj}, q_{Lj}), q_{dj}) = \widehat{Q}^N_{di}(q_{Hj}, q_{Lj})$.

In part (a), given (q_{Hj}, q_{Lj}), $A_d - q_{dj}$ can be interpreted as the market size for supply chain i when the demand state is d. The high-demand state has a larger market size when $A_H - q_{Hj} \geq A_L - q_{Lj}$ and a smaller market size otherwise. In the best response function, there is a negative quantity distortion (when compared with the quantity under full information) for the small-market state, and the retailer earns a positive profit, called the information rent in the literature, in the large-market state. To maximize her profit, manufacturer i charges the fixed payment $\widehat{T}^N_{Hi}$ in such a way that retailer i will be indifferent between the two contracts when the market state is large. The negative quantity distortion makes it less attractive for retailer i to choose the small-market order quantity and allows manufacturer i to lower the information rent. In choosing the quantity distortion, manufacturer i balances the efficiency loss in the small-market state because of quantity distortion with the incentive cost in the large-market state due to information rent. Part (b) shows that under truth telling, the best response selling quantity of retailer i equals the best response order quantity chosen by manufacturer i. This is true because otherwise manufacturer i can always reduce the order quantity in the contract, keep the same payment, and induce the same selling quantity. (When the marginal cost of production is positive, this will improve the manufacturer's profit.) However, manufacturer i will not be able to perfectly match the order and selling quantities when retailer i does not truthfully select the order quantity. The contract design problem has properly accounted for these cases to ensure incentive compatibility and participation.

3.3. Model *NS*: Information Sharing in One Supply Chain

Without loss of generality, we assume that only supply chain 2 has information sharing. Manufacturer 1 does not know the demand state d, so she will offer a contract menu $\{(Q_{H1}, T_{H1}), (Q_{L1}, T_{L1})\}$ to retailer 1 by solving Problem $\mathscr{C}$. Because manufacturer 2 knows d, she will offer a single contract (Q_{d2}, T_{d2}) to retailer 2. As in Model *SS*, her profit will be given by the supply chain revenue $f_d(Q_{d2}, q_{d1})$ when the selling quantity of supply chain 1 is q_{d1}. Both retailers know d, and the profit of retailer i under a contract (Q_{di}, T_{di}) is given by (2) when the selling quantity of supply chain j is q_{dj}. We will consider Bayesian Nash equilibrium, which is similar to the notion of Nash equilibrium except each player now maximizes her expected utilities based on her beliefs about the distribution of the state and the opponents' state-dependent strategies.

In anticipation of the selling quantities of the competing supply chain, the best responses of manufacturer 1 and retailer 1 are given by Proposition 1, while the best responses of manufacturer 2 and retailer 2 are given by (5) and (3), respectively. Let Q^{NS}_{di} and

q_{di}^{NS} be, respectively, the equilibrium order and selling quantities of supply chain i under Model NS when the demand state is d. $(Q_{H1}^{NS}, q_{H1}^{NS}, Q_{L1}^{NS}, q_{L1}^{NS}, Q_{H2}^{NS}, q_{H2}^{NS}, Q_{L2}^{NS}, q_{L2}^{NS})$ is a Bayesian Nash equilibrium if

$$\begin{aligned} q_{d1}^{NS} &= \hat{q}_{d1}(Q_{d_1}^{NS}, q_{d_2}^{NS}) \\ Q_{d_1}^{NS} &= \widehat{Q}_{d1}^{N}(q_{H2}^{NS}, q_{L2}^{NS}) \\ q_{d2}^{NS} &= \hat{q}_{d2}(Q_{d_2}^{NS}, q_{d_1}^{NS}) \\ Q_{d_2}^{NS} &= \widehat{Q}_{d2}^{S}(q_{d1}^{NS}), \end{aligned}$$

where $d = H$ or L. As before, the fixed payments T_{di}s do not play any role in defining the equilibrium.

Proposition 2.

(a) *When $\beta \geq 1 - 3A_H/(4A_L)$, there exists a unique Bayesian Nash equilibrium to Model NS, which is given by*

$$Q_{H1}^{NSI} = q_{H1}^{NSI} = Q_{H2}^{NSI} = q_{H2}^{NSI} = \frac{A_H}{3}$$

$$Q_{L1}^{NSI} = q_{L1}^{NSI} = \begin{cases} \dfrac{A_L}{3} - \dfrac{4\beta(A_H - A_L)}{3(3-4\beta)} & \text{if } \beta \leq \dfrac{3A_L}{4A_H}, \\ 0 & \text{otherwise}, \end{cases}$$

$$Q_{L2}^{NSI} = q_{L2}^{NSI} = \begin{cases} \dfrac{A_L}{3} + \dfrac{2\beta(A_H - A_L)}{3(3-4\beta)} & \text{if } \beta \leq \dfrac{3A_L}{4A_H}, \\ \dfrac{A_L}{2} & \text{otherwise}. \end{cases}$$

(b) *When $\beta < 1 - 3A_H/(4A_L)$, there are three Bayesian Nash equilibria. In addition to the equilibrium given in* (a), *the other two are given by*

$$\begin{aligned} Q_{H1}^{NSII} &= q_{H1}^{NSII} = \frac{A_H}{3} - \frac{4(1-\beta)(A_H - A_L)}{3(1-4\beta)} \\ Q_{H2}^{NSII} &= q_{H2}^{NSII} = \frac{A_H}{3} + \frac{2(1-\beta)(A_H - A_L)}{3(1-4\beta)} \\ Q_{L1}^{NSII} &= q_{L1}^{NSII} = Q_{L2}^{NSII} = q_{L2}^{NSII} = \frac{A_L}{3} \\ Q_{H1}^{NSIII} &= q_{H1}^{NSIII} = 0 \\ Q_{H2}^{NSIII} &= q_{H2}^{NSIII} = \frac{A_H}{2} \\ Q_{L1}^{NSIII} &= q_{L1}^{NSIII} = Q_{L2}^{NSIII} = q_{L2}^{NSIII} = \frac{A_L}{3}. \end{aligned}$$

The equilibrium fixed payments T_{di}s can be determined from (6) and Proposition 1. Details are omitted. For part (a), when β (the probability of high demand) and A_H (the market size in the high-demand state) take some intermediate values, $1 - 3A_H/(4A_L) \leq \beta \leq 3A_L/(4A_H)$. In this case, *NSI* is the unique equilibrium. In the low-demand state, supply chain 1 has a negative quantity distortion, $4\beta(A_H - A_L)/[3(3-4\beta)]$, caused by the contract menu. This in turn induces a positive quantity distortion $2\beta(A_H - A_L)/[3(3-4\beta)]$ for supply chain 2. When either β or A_H becomes sufficiently large, $\beta \geq 3A_L/(4A_H)$. In this case, *NSI* is still the unique equilibrium, but the low-demand market becomes so insignificant that manufacturer 1 prefers not to participate in this market to avoid paying the information rent in the high-demand market. For part (b), when either β or A_H becomes sufficiently small, $\beta \leq 1 - 3A_H/(4A_L)$. Then there are three equilibria, with manufacturer 1 either employing a quantity distortion in the low-demand market (*NSI*), employing a quantity distortion in the high-demand market (*NSII*), or not participating in the high-demand market (*NSIII*). These scenarios can be viewed as three different options for manufacturer 1 to induce truth telling. Note that when $\beta \geq 1 - 3A_H/(4A_L)$, the last two options are not cost-effective, and therefore *NSI* is the unique equilibrium. In general, the quantity distortion from the contract menu makes manufacturer 1 less aggressive, which in turn induces manufacturer 2 to be more aggressive in Cournot competition.

3.4. Model *NN*: No Information Sharing

Neither manufacturer knows the demand state, so for $i = 1$ or 2, manufacturer i will offer a contract menu $\{(Q_{Hi}, T_{Hi}), (Q_{Li}, T_{Li})\}$ to retailer i by solving Problem $\mathscr{C}$. We will solve for the Bayesian Nash equilibrium. In anticipation of the selling quantities of supply chain j, the best responses of manufacturer i and retailer i are given by Proposition 1. Let Q_{di}^{NN} and q_{di}^{NN} be, respectively, the equilibrium order and selling quantities when the demand state is d, where $d = H$ or L and $i = 1$ or 2. An equilibrium $(Q_{H1}^{NN}, q_{H1}^{NN}, Q_{L1}^{NN}, q_{L1}^{NN}, Q_{H2}^{NN}, q_{H2}^{NN}, Q_{L2}^{NN}, q_{L2}^{NN})$ will satisfy

$$\begin{aligned} q_{di}^{NN} &= \hat{q}_{di}(Q_{di}^{NN}, q_{dj}^{NN}) \\ Q_{di}^{NN} &= \widehat{Q}_{di}^{N}(q_{Hj}^{NN}, q_{Lj}^{NN}), \end{aligned}$$

where $i, j = 1$ or 2, and $i \neq j$. Again, the fixed payments T_{di}s do not play any role in defining the equilibrium. To make the analysis tractable and to obtain stronger analytical results, we will consider only the symmetric equilibria of the contracting game, i.e., with $Q_{d1}^{NN} = Q_{d2}^{NN}$ and $q_{d1}^{NN} = q_{d2}^{NN}$. Such an approach has been adopted extensively in the literature. One justification is that it is more natural for firms to focus on a symmetric equilibrium, so it is more likely to occur than an asymmetric one. (See more discussion of the focal principle in Kreps 1990.) Moreover, the main insights obtained from a symmetric equilibrium are usually robust enough to remain valid for the asymmetric equilibrium of the problem (see Lee and Whang 2002 and Cachon and Netessine 2004 for more discussion).

Proposition 3. *There exists a unique symmetric equilibrium to Model NN*:

$$Q_{H1}^{NN} = q_{H1}^{NN} = Q_{H2}^{NN} = q_{H2}^{NN} = \frac{A_H}{3}$$

$$Q_{L1}^{NN} = q_{L1}^{NN} = Q_{L2}^{NN} = q_{L2}^{NN} = \begin{cases} \dfrac{A_L}{3} - \dfrac{2\beta(A_H - A_L)}{3(3-2\beta)} & \text{if } \beta \le \dfrac{3A_L}{2A_H}, \\ 0 & \text{otherwise}. \end{cases}$$

As before, the equilibrium fixed payments T_{di}s can be determined from Proposition 1, but details will be omitted. When β (the probability of high demand) or A_H (the market size in the high-demand state) is small, $\beta \le 3A_L/(2A_H)$. The order quantity has a negative distortion given by $2\beta(A_H - A_L)/[3(3-2\beta)]$ in the low-demand state. When β or A_H is larger, $\beta > 3A_L/(2A_H)$, the low-demand market becomes less significant. In this case, it is quite interesting that under a symmetric equilibrium, both manufacturers will choose to leave the low-demand market in order to avoid paying information rent in the high-demand market.

3.5. Model Comparisons

Define π_{Ci}^X, π_{Mi}^X, and π_{Ri}^X to be the expected profits of supply chain i, manufacturer i, and retailer i, respectively, under contract menus for equilibrium X, where $i = 1$ or 2, $X = SS, NSI, NSII, NSIII$, or NN, and $\pi_{Ci}^X = \pi_{Mi}^X + \pi_{Ri}^X$. Let $r_I = 2$ and $r_{II} = 11/9$.

Proposition 4.
(a) *For* $k = I, II$, *or* III, $\pi_{C2}^{NSk} \ge \pi_{Ci}^{NN} \ge \pi_{Ci}^{SS} \ge \pi_{C1}^{NSk}$ *if* $\beta \le 3A_L/(4A_H - 2A_L)$, *and* $\pi_{C2}^{NSk} \ge \pi_{Ci}^{SS} \ge \pi_{Ci}^{NN} \ge \pi_{C1}^{NSk}$ *otherwise.*
(b) *For* $k = I, II$, *or* III, $\pi_{M2}^{NSk} \ge \pi_{Mi}^{SS} \ge \pi_{Mi}^{NN} \ge \pi_{M1}^{NSk}$.
(c) *For* $k = I$ *or* II, *there exist* r_k *and* β_k *such that* $\pi_{R1}^{NSk} \ge \pi_{Ri}^{NN} \ge \pi_{Ri}^{SS} = \pi_{R2}^{NSk} = \pi_{Ri}^{NSIII} = 0$ *if* $A_H/A_L \le r_k$ *and* $\beta \le \beta_k$. *Otherwise,* $\pi_{Ri}^{NN} \ge \pi_{R1}^{NSk} \ge \pi_{Ri}^{SS} = \pi_{R2}^{NSk} = \pi_{Ri}^{NSIII} = 0$.

Part (a) shows that information sharing in a supply chain always makes it better off ($\pi_{C1}^{SS} \ge \pi_{C1}^{NSk}$ or $\pi_{C2}^{NSk} \ge \pi_{C2}^{NN}$) while the competing supply chains are worse off ($\pi_{C2}^{NSk} \ge \pi_{C2}^{SS}$ or $\pi_{C1}^{NN} \ge \pi_{C1}^{NSk}$), regardless of whether the latter has information sharing. As a result, a supply chain with information sharing always outperforms the competing supply chain that does not have information sharing ($\pi_{C2}^{NSk} \ge \pi_{C1}^{NSk}$). Thus, the direct effect of information sharing on a supply chain is always positive, and its spill-over effect on the competing supply chain is always negative. Part (a) also shows that the supply chain profits of Model *NN* can be higher than those of Model *SS* because of the quantity distortions of the contract menus, which make Cournot competition less intense and move the total market output closer to the monopoly solution. However, when β or A_H is large enough, the distortions become so large that the total market output is much smaller than the monopoly solution. Consequently, the supply chain profits of Model *NN* are smaller than those of Model *SS*.

Parts (b) and (c) show that information sharing in a supply chain always benefits its manufacturer ($\pi_{M1}^{SS} \ge \pi_{M1}^{NSk}$ or $\pi_{M2}^{NSk} \ge \pi_{M2}^{NN}$), but hurts both its retailer ($\pi_{R1}^{NSk} \ge \pi_{R1}^{SS}$ or $\pi_{R2}^{NN} \ge \pi_{R2}^{NSk}$) and the competing manufacturer ($\pi_{M2}^{NSk} \ge \pi_{M2}^{SS}$ or $\pi_{M1}^{NN} \ge \pi_{M1}^{NSk}$), regardless of whether the competing supply chain has information sharing. However, it hurts the competing retailer ($\pi_{R1}^{NN} \ge \pi_{R1}^{NSk}$) only when either β or A_H is large. A supply chain can be better off under Model *NN* than under Model *SS* because of less-intense competition, but the manufacturers are always worse off because of the information rents under Model *NN*.

4. Stage-Two Problem Under Linear Price Contracts

4.1. Model *SS*: Information Sharing in Both Supply Chains

Here all the firms know the demand state d. For any realized d, given the wholesale price w_{di} and in anticipation of the selling quantity q_{dj} of retailer j, retailer i determines the selling quantity q_{di} to maximize the following profit function:

$$(A_d - q_{di} - q_{dj} - w_{di})q_{di}.$$

From the first-order condition, we can derive his best response function, which is given by

$$\hat{q}_{di}(w_{di}, q_{dj}) = \frac{A_d - q_{dj} - w_{di}}{2}. \tag{15}$$

Given the best response function of retailer i and the selling quantitiy q_{dj} of retailer j, manufacturer i's profit is given by

$$w_{di}\hat{q}_{di}(w_{di}, q_{dj}).$$

Her best response function is given by

$$\widehat{w}_{di}(q_{dj}) = \frac{A_d - q_{dj}}{2}. \tag{16}$$

Let $\bar{w}_{di}^{SS}$ and $\bar{q}_{di}^{SS}$ be the equilibrium wholesale price and selling quantity, respectively, where $d = H$ or L and $i = 1$ or 2. From (15) and (16), we can show that the following is the unique equilibrium:

$$\bar{w}_{d1}^{SS} = \bar{w}_{d2}^{SS} = \frac{2A_d}{5}$$
$$\bar{q}_{d1}^{SS} = \bar{q}_{d2}^{SS} = \frac{A_d}{5}.$$

4.2. Model *NS*: Information Sharing in One Supply Chain

Here only manufacturer 1 does not know the demand state d and charges the same price w_1, regardless of the state. In anticipation of the selling quantity q_{d2} of supply chain 2, the profit of retailer 1 is the same as that in Model *SS*, with w_{d1} replaced by w_1. Consequently, his best response function is given by

$$\hat{q}_{d1}(w_1, q_{d2}) = \frac{A_d - q_{d2} - w_1}{2}.$$

Knowing the best response function of retailer 1, and in anticipation of the selling quantitiy q_{d2} of retailer 2 for each state d, manufacturer 1's expected profit can be expressed as

$$w_1[\beta\hat{q}_{H1}(w_1, q_{H2}) + (1-\beta)\hat{q}_{L1}(w_1, q_{L2})].$$

By differentiating the above expression, we can derive manufacturer 1's best response function as follows:

$$\widehat{w}_1(q_{H2}, q_{L2}) = \frac{\beta(A_H - q_{H2}) + (1-\beta)(A_L - q_{L2})}{2}.$$

As manufacturer 2 and retailer 2 know the demand state d, in anticipation of the selling quantity q_{d1} of supply chain 1, their profit functions are the same as those in Model *SS*. Therefore, their best response functions are given by (15) and (16), respectively. That is,

$$\hat{q}_{d2}(w_{d2}, q_{d1}) = \frac{A_d - q_{d1} - w_{d2}}{2}$$
$$\widehat{w}_{d2}(q_{d1}) = \frac{A_d - q_{d1}}{2}.$$

Let $\overline{w}_1^{NS}$ be the equilibrium wholesale price of firm 1, $\overline{w}_{d2}^{NS}$ be the equilibrium wholesale price of firm 2, and $\bar{q}_{di}^{NS}$ be the equilibrium selling quantity, where $d = H$ or L and $i = 1$ or 2. From the best response functions, we can show that the following is the unique equilibrium:

$$\overline{w}_1^{NS} = \frac{2\beta A_H + 2(1-\beta)A_L}{5}$$
$$\overline{w}_{H2}^{NS} = \frac{2A_H}{5} - \frac{4}{35}(1-\beta)(A_H - A_L)$$
$$\overline{w}_{L2}^{NS} = \frac{2A_L}{5} + \frac{4}{35}\beta(A_H - A_L)$$
$$\bar{q}_{H1}^{NS} = \frac{A_H}{5} + \frac{8}{35}(1-\beta)(A_H - A_L)$$
$$\bar{q}_{L1}^{NS} = \frac{A_L}{5} - \frac{8}{35}\beta(A_H - A_L)$$
$$\bar{q}_{H2}^{NS} = \frac{A_H}{5} - \frac{2}{35}(1-\beta)(A_H - A_L)$$
$$\bar{q}_{L2}^{NS} = \frac{A_L}{5} + \frac{2}{35}\beta(A_H - A_L).$$

4.3. Model *NN*: No Information Sharing

As both manufacturers do not know the demand state, each charges a price that does not depend on the state. Because the retailers know the demand state d, in anticipation of the selling quantity q_{dj} of supply chain j, the profit of retailer i is the same as that in Model *SS*, with w_{di} replaced by w_i. His best response function is given by

$$\hat{q}_{di}(w_i, q_{dj}) = \frac{A_d - q_{dj} - w_i}{2}.$$

Knowing the best response function of retailer i and in anticipation of the selling quantitiy q_{dj} of retailer j, manufacturer i's expected profit can be expressed as

$$w_i[\beta\hat{q}_{Hi}(w_i, q_{Hj}) + (1-\beta)\hat{q}_{Li}(w_i, q_{Lj})].$$

Her best response function is given by

$$\widehat{w}_i(q_{Hj}, q_{Lj}) = \frac{\beta(A_H - q_{Hj}) + (1-\beta)(A_L - q_{Lj})}{2}.$$

Let $\overline{w}_i^{NS}$ be the equilibrium wholesale price of firm i and $\bar{q}_{di}^{NS}$ be the equilibrium selling quantity, where $d = H$ or L and $i = 1$ or 2. From the best response functions, we can show that the unique equilibrium is given by

$$\overline{w}_1^{NN} = \overline{w}_2^{NN} = \frac{2\beta A_H + 2(1-\beta)A_L}{5}$$
$$\bar{q}_{H1}^{NN} = \bar{q}_{H2}^{NN} = \frac{A_H}{5} + \frac{2}{15}(1-\beta)(A_H - A_L)$$
$$\bar{q}_{L1}^{NN} = \bar{q}_{L2}^{NN} = \frac{A_L}{5} - \frac{2}{15}\beta(A_H - A_L).$$

4.4. Model Comparisons

Define $\overline{\pi}_{Ci}^X$, $\overline{\pi}_{Mi}^X$, and $\overline{\pi}_{Ri}^X$ to be the expected profits of, respectively, supply chain i, manufacturer i, and retailer i under linear price contracts for an equilibrium X, where $i = 1$ or 2, $X = SS, NS$, or NN, and $\overline{\pi}_{Ci}^X = \overline{\pi}_{Mi}^X + \pi_{Ri}^X$.

PROPOSITION 5.
(a) $\overline{\pi}_{C1}^{NS} \geq \overline{\pi}_{Ci}^{SS} \geq \overline{\pi}_{Ci}^{NN} \geq \overline{\pi}_{C2}^{NS}$.
(b) $\overline{\pi}_{Mi}^{SS} \geq \overline{\pi}_{M2}^{NS} \geq \overline{\pi}_{Mi}^{NN} = \overline{\pi}_{M1}^{NS}$.
(c) $\overline{\pi}_{R1}^{NS} \geq \overline{\pi}_{Ri}^{NN} \geq \overline{\pi}_{Ri}^{SS} \geq \overline{\pi}_{R2}^{NS}$.

Proposition 4 shows that under contract menus, information sharing has a positive direct effect on a supply chain and a negative spill-over effect on the competing supply chain, regardless of whether the latter has information sharing. Part (a) of Proposition 5 shows that under linear price contracts, these effects are completely reversed. Specifically, information sharing in a supply chain always makes it worse off ($\overline{\pi}_{C1}^{SS} \leq \overline{\pi}_{C1}^{NS}$ or $\overline{\pi}_{C2}^{NS} \leq \overline{\pi}_{C2}^{NN}$) and the competing supply chain better off ($\overline{\pi}_{C2}^{NS} \leq \overline{\pi}_{C2}^{SS}$ or $\overline{\pi}_{C1}^{NN} \leq \overline{\pi}_{C1}^{NS}$). Therefore, a supply chain that has information sharing always performs worse than the competing supply chain that does not have information sharing ($\overline{\pi}_{C2}^{NS} \leq \overline{\pi}_{C1}^{NS}$). Moreover, because information sharing makes double marginalization more significant and therefore Cournot competition less intense, supply chain profits in Model *SS* are higher than those in Model *NN*.

Parts (b) and (c) show that under linear price contracts, information sharing in a supply chain has the same direct effect on its firms but different spill-over effects on those of the competing supply chain when compared with contract menus. Although information sharing in a supply chain still benefits its manufacturer ($\overline{\pi}_{M1}^{SS} \geq \overline{\pi}_{M1}^{NS}$ or $\overline{\pi}_{M2}^{NS} \geq \overline{\pi}_{M2}^{NN}$) but hurts its retailer ($\overline{\pi}_{R1}^{NS} \geq \overline{\pi}_{R1}^{SS}$ or $\overline{\pi}_{R2}^{NN} \geq \overline{\pi}_{R2}^{NS}$), it benefits both the manufacturer ($\overline{\pi}_{M2}^{SS} \geq \overline{\pi}_{M2}^{NS}$ or $\overline{\pi}_{M1}^{NS} = \overline{\pi}_{M1}^{NN}$) and the retailer ($\overline{\pi}_{R2}^{SS} \geq \overline{\pi}_{R2}^{NS}$ or $\overline{\pi}_{R1}^{NS} \geq \overline{\pi}_{R1}^{NN}$) of the competing supply chain.

5. Stage-One Problem: Information Sharing Decisions

5.1. Equilibrium Analysis

In the first stage of the information sharing game, we index the supply chains (and the firms) by A and B. Based on the their information sharing decisions, they become supply chains 1 and 2 of Model *SS*, *NS*, or *NN* that we have analyzed in the previous sections. In the first stage, manufacturers A and B simultaneously and independently choose to invest in information sharing (action denoted by S) or not (action denoted by N). Thus, the strategy space of the manufacturer is given by $\{S, N\}$. Let the fixed investment costs of information sharing of supply chains A and B be K_A and K_B, respectively, with $0 \leq K_A \leq K_B$. If a manufacturer decides to invest in information sharing, she has to incur the investment cost and offer a payment for her retailer's information; the retailer then chooses to share (action denoted by s) or not share information (action denoted by n). The strategy space of the retailer is given by $\{s, n\}$ when the manufacturer of his supply chain has chosen S and is $\{n\}$ when that manufacturer has chosen N. Let m_s and m_n be the minimum payments a manufacturer has to make to induce her retailer to share information when the competing supply chain has and does not have information sharing, respectively. The payment m_s is given by $\pi_{R1}^{NSk} - \pi_{R1}^{SS}$ under contract menus and $\overline{\pi}_{R1}^{NS} - \overline{\pi}_{R1}^{SS}$ under linear price contracts, and the payment m_n is given by $\pi_{R2}^{NN} - \pi_{R2}^{NSk}$ under contract menus and $\overline{\pi}_{R2}^{NN} - \overline{\pi}_{R2}^{NS}$ under linear price contracts. Here k denotes one of the three possible equilibria of Model *NS* under contract menus as given in Proposition 2, where $k = I$, II, or III. The proof of the following result is straightforward and therefore omitted.

Lemma 1. *When both manufacturers invest in information sharing and each pays an amount of m_s to her retailer, the (weakly) dominant strategy of the retailer is to share information. When only one manufacturer invests in information sharing and pays an amount of m_n to her retailer, it is (weakly) optimal for that retailer to share information.*

Table 1 Payoff Matrix of the Information Sharing Game Under Contract Menus

	Manufacturer B: Invest (action $y = S$)	Manufacturer B: Not invest (action $y = N$)
Manufacturer A Invest (action $x = S$)	$(V_s^k + \pi_{M1}^{NSk} - K_A,$ $V_s^k + \pi_{M1}^{NSk} - K_B)$	$(V_n^k + \pi_{M2}^{NN} - K_A, \pi_{M1}^{NSk})$
Not invest (action $x = N$)	$(\pi_{M1}^{NSk}, V_n^k + \pi_{M2}^{NN} - K_B)$	$(\pi_{M2}^{NN}, \pi_{M2}^{NN})$

Here we assume a retailer will agree to share information if he is indifferent between sharing or not sharing. If this is not the case, the manufacturer can add an infinitesimal amount $\epsilon > 0$ to the minimum payments and the results will remain the same.

For the case of contract menus and a given equilibrium NSk of Model NS, where $k = I$, II, or III, let V_s^k and V_n^k be the values (or incremental profits) of information sharing to a supply chain when the competing supply chain has and does not have information sharing, respectively. We have

$$V_s^k = \pi_{C1}^{SS} - \pi_{C1}^{NSk} = (\pi_{M1}^{SS} + \pi_{R1}^{SS}) - (\pi_{M1}^{NSk} + \pi_{R1}^{NSk}) \quad (17)$$

$$V_n^k = \pi_{C2}^{NSk} - \pi_{C2}^{NN} = (\pi_{M2}^{NSk} + \pi_{R2}^{NSk}) - (\pi_{M2}^{NN} + \pi_{R2}^{NN}). \quad (18)$$

Define $\overline{V}_s$ and $\overline{V}_n$ analogously for the case of linear price contracts. Thus, $\overline{V}_n$ and $\overline{V}_s$ are given by (17) and (18), with π replaced by $\overline{\pi}$. For the case of contract menus, from Lemma 1, (17) and (18), the payoff matrix $[(\Pi_A(x, y), \Pi_B(x, y)]$ of the information sharing game is given by Table 1, where $\Pi_A(x, y)$ and $\Pi_B(x, y)$ are the payoffs of manufacturers A and B, respectively, when manufacturer A's action is x and manufacturer B's action is y. For the case of linear price contracts, the payoff matrix is the same as in Table 1, with π, V_s^k, and V_n^k replaced respectively by $\overline{\pi}$, $\overline{V}_s$, and $\overline{V}_n$.

5.2. Information Sharing Decisions Under Contract Menus

The following proposition characterizes the equilibrium information sharing decisions when the supply chains are under contract menus.

Proposition 6.

(a) $0 \leq V_s^k \leq V_n^k$ *for* $k = I, II$, *or* III.

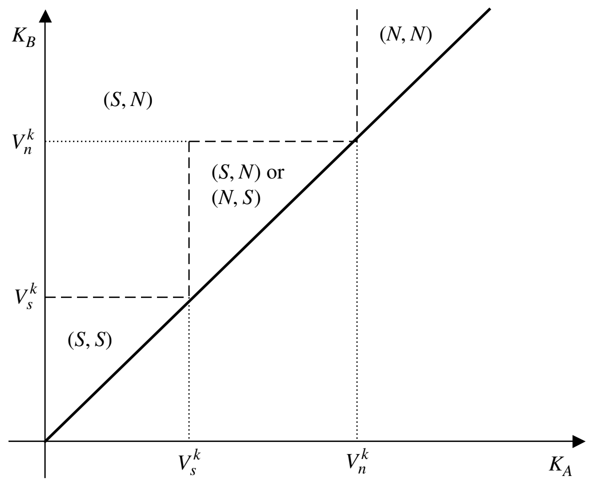
(b) *When* $K_A \leq K_B \leq V_s^k$, *investing in information sharing is the dominant strategy for both manufacturers, and the unique equilibrium of the information sharing game is* (S, S).

(c) *When* $K_A \leq V_s^k \leq K_B$ *or* $V_s^k \leq K_A \leq V_n^k \leq K_B$, *the unique equilibrium is* (S, N).

(d) *When* $V_s^k \leq K_A \leq K_B \leq V_n^k$, *the two possible equilibria are* (S, N) *and* (N, S).

(e) *When* $V_n^k \leq K_A \leq K_B$, *the unique equilibrium is* (N, N).

Figure 1 Equilibria of the Information Sharing Game Under Contract Menus ($K_A \le K_B$)



Part (a) shows that the value of information sharing is always positive, and the value is higher when the competing supply chain does not have information sharing. A manufacturer has incentive to invest in information sharing only when this value exceeds the investment cost. Figure 1 illustrates the equilibrium information sharing decisions. When $\pi_{M1}^{SS} - \pi_{R1}^{NSk} - \pi_{M1}^{NN} \le K_A \le K_B \le \pi_{M1}^{SS} - \pi_{M1}^{NSk} - \pi_{R1}^{NSk}$, the dominant strategy for each manufacturer is to invest in information sharing, even though they will be better off if neither invests. From the results in the previous sections, we can derive conditions for this to occur. For example, under the equilibrium *NSI*, this will be true if β is smaller than a critical value. Thus, under certain parametric conditions, the information sharing game resembles the classical *prisoner's dilemma* game. It is interesting to note that this resemblance has been observed in other settings in the supply chain literature, for example, the coordination/uncoordination decisions for two competing supply chains in Boyaci and Gallego (2004) and the early/delayed differentiation decisions for two competing firms under demand uncertainty in Anand and Girotra (2007).

Let Π_{Mi}^*, Π_{Ri}^*, and Π_{Ci}^* denote the equilibrium profits of manufacturer i, retailer i, and supply chain i, respectively, where $i = A$ or B. Table 2 summarizes these profits under different equilibria. The following proposition shows that a higher information sharing capability (due to a lower investment cost) usually makes the supply chain and its manufacturer better off, except under the condition in part (d) of Proposition 6, when there are two possible equilibria.

Proposition 7. *When $V_s^k \le K_A \le K_B \le V_n^k$, $\Pi_{CA}^* \ge \Pi_{CB}^*$ and $\Pi_{MA}^* \ge \Pi_{MB}^*$ under equilibrium (S, N), and $\Pi_{CA}^* \le \Pi_{CB}^*$ and $\Pi_{MA}^* \le \Pi_{MB}^*$ under equilibrium (N, S). Otherwise, $\Pi_{CA}^* \ge \Pi_{CB}^*$ and $\Pi_{MA}^* \ge \Pi_{MB}^*$.*

Table 2 Performance Comparison for the Information Sharing Game Under Contract Menus

	Equilibrium			
	(S, S)	(S, N)	(N, S)	(N, N)
Manufacturer A's profit Π_{MA}^*	$\pi_{M1}^{SS} - \pi_{R1}^{NSk} - K_A$	$\pi_{M2}^{NSk} - \pi_{R1}^{NN} - K_A$	π_{M1}^{NSk}	π_{M1}^{NN}
Manufacturer B's profit Π_{MB}^*	$\pi_{M1}^{SS} - \pi_{R1}^{NSk} - K_B$	π_{M1}^{NSk}	$\pi_{M2}^{NSk} - \pi_{R1}^{NN} - K_B$	π_{M1}^{NN}
Retailer A's profit Π_{RA}^*	π_{R1}^{NSk}	π_{R1}^{NN}	π_{R1}^{NSk}	π_{R1}^{NN}
Retailer B's profit Π_{RB}^*	π_{R1}^{NSk}	π_{R1}^{NSk}	π_{R1}^{NN}	π_{R1}^{NN}
Supply chain A's profit Π_{CA}^*	$\pi_{C1}^{SS} - K_A$	$\pi_{C2}^{NSk} - K_A$	π_{C1}^{NSk}	π_{C1}^{NN}
Supply chain B's profit Π_{CB}^*	$\pi_{C1}^{SS} - K_B$	π_{C1}^{NSk}	$\pi_{C2}^{NSk} - K_B$	π_{C1}^{NN}

In general, supply chains can either invest in information sharing or rely on contract menus to extract private information. From a supply chain perspective, there is a strategic cost associated with these contract menus, because they may interfere with the competitive decisions, making firms less aggressive in quantity-based competition. A higher information sharing capability allows a supply chain to avoid this strategic cost, and it can create a competitive advantage by inducing a heterogeneous information sharing structure[5] under which the competing supply chain does not invest in information sharing and is forced to be less aggressive because of the contract menus. Even when both supply chains invest in information sharing, a supply chain with a higher information sharing capability will have a higher profit because of the lower investment cost. Finally, from Table 2 and part (c) of Proposition 4, although a higher information sharing capability usually makes the supply chain and the manufacturer better off, it is not always beneficial to the retailer who has private information.

When the information sharing game is played sequentially, Proposition 6 will remain valid with the following exception. Under the condition in part (d) of Proposition 6, while the simultaneous game has two possible equilibria, the sequential game has a unique equilibrium in which the leader invests and the follower does not. Note that the following result will not be reversed when supply chain B is the leader.

Corollary 1. *If the information sharing game is played sequentially with manufacturer A as the leader, $\Pi_{CA}^* \ge \Pi_{CB}^*$ and $\Pi_{MA}^* \ge \Pi_{MB}^*$.*

[5] For example, when K_A decreases so that condition (d) of Proposition 6 becomes condition (c), the two possible equilibria (S, N) and (N, S) will collapse into the unique equilibrium (S, N).

5.3. Information Sharing Decisions Under Linear Price Contracts

The following proposition characterizes the equilibrium information sharing decisions when the supply chains are under linear price contracts.

Proposition 8.
(a) $\bar{V}_n \leq \bar{V}_s \leq 0$.
(b) *The dominant strategy for each manufacturer is not to invest in information sharing, and the unique equilibrium of the information sharing game is* (N, N) *for any* K_A *and* K_B.

Part (a) shows that the value of information sharing to a supply chain is negative under linear price contracts, regardless of whether the competing supply chain has information sharing, which drives the result of part (b). Suppose we move from the equilibrium point (N, N) to another point (S, S). From Proposition 5, both supply chains will be better off because of less-intense competition. However, the manufacturers will be worse off because of the large information rent $\bar{\pi}_{R1}^{NS}$ (see part (c) of Proposition 5), which necessitates a large payment to the retailers for revealing information. Unlike the case of quantity bundle contract menus, there is no prisoner's dilemma for the manufacturers' information sharing decisions.

5.4. The Role of a Contract in Information Sharing

Propositions 6 and 8 together demonstrate that the value of information sharing to a supply chain strongly depends on the contract type as well as the mode of competition. Li and Zhang (2002) show that for a one-manufacturer-one-retailer supply chain under linear price contracts, information sharing makes the manufacturer better off but both the retailer and the whole supply chain worse off, so no incremental profit can be created for the manufacturer to pay the retailer for sharing information. Here we show that these results remain valid in a competitive setting. Under linear price contracts, more information allows a manufacturer to extract a larger portion of supply chain profit by better adapting her prices to the demand states. However, the effect of double marginalization becomes more significant, which makes the supply chain less aggressive and the competing supply chain more aggressive in Cournot competition. Thus, more information just allows a manufacturer to improve her own profit at the expense of the overall supply chain performance, and the value of information sharing is always negative.

We also show that under quantity-based contract menus, more information allows the manufacturer to avoid the negative quantity distortions and to improve the overall supply chain performance in Cournot competition, which is consistent with her self-interests. This is because of the higher flexibility of contract menus, which allows a manufacturer to both influence the retailer's quantity decision and allocate supply chain profit. Therefore, the value of information sharing to a supply chain is always positive, and as long as the investment cost is not excessive, information sharing can create enough incremental profit to make both the manufacturer and the retailer better off.

Lee and Whang (2000) identify incentive and cost as two of the several key challenges of information sharing in supply chains. It is generally believed that lower investment costs will accelerate the practice of information sharing. Our results highlight the role of contracts in creating value and hence incentive for information sharing. In particular, a lower investment cost can encourage a supply chain to have information sharing only when the appropriate contracts are used.

6. Concluding Remarks

From §5, information sharing decisions depend only on the values of information sharing relative to the investment costs of the supply chains. This can be explained by the side payment, which allows a manufacturer to capture all the net value of information sharing so that she will make information sharing decisions that are consistent with the objective of her supply chain. If the retailers are the leaders in making information sharing decisions, the equilibrium results will remain the same, except each retailer will capture all the net value of information sharing in his supply chain by charging a maximum payment that makes the manufacturer indifferent between paying and not paying for the information. Note that our model does not capture the effect of information sharing on improving the manufacturers' operations, such as their responsiveness or inventory availability, which is beneficial to the retailers. It would be meaningful to account for these benefits in a model with the retailers as the leaders in making information sharing decisions. This will be left for future research.

Here we focus on a quantity bundle contract menu, which is a manufacturer's best response contract choice in anticipation of the quantity actions of the competing supply chain when contracts are not observable. We expect the main insights will remain valid when other quantity-based contracts are employed. For example, suppose we restrict contract type to menus of two-part pricing contracts (which is less desirable to the manufacturer because it will result in a higher information rent to the retailer). Similar to a quantity bundle contract, a two-part pricing contract offers a manufacturer much flexibility in using the wholesale price to influence retailer competition and the fixed payment to extract any portion of the supply chain profit. Indeed, both can coordinate the quantity decisions of a supply chain under full information, with the wholesale price equaling the marginal cost under a two-part pricing contract. Under asymmetric information, a two-part pricing contract menu will employ a positive distortion (above the marginal cost) in the wholesale price to reduce the incentive cost for inducing truth telling. This will have an effect similar to the negative quantity distortion of a quantity bundle contract menu on Cournot competition.

In the information sharing literature, it is common to employ an imperfect demand signal model and assume linear price contracts offered by a single manufacturer. To analyze contract menus offered by two competing manufacturers, we have adopted a perfect demand signal model. Although such a model cannot capture the effect of incremental information (e.g., the effect of acquiring information from more retailers), this is not critical to our setting, which involves information sharing between one manufacturer and one retailer. When demand signal is not perfect, as in the model of Li (2002), we expect that signal precision will have a moderating effect on the magnitude of the value of information sharing. It would be interesting to extend our basic framework to address other issues, such as imperfect demand signal, competition under different contract types, different forms of competition, and competition between supply chains with multiple retailers.

7. Electronic Companion

An electronic companion to this paper is available as part of the online version that can be found at http://mansci.journal.informs.org/.

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Appendix

Proof of Proposition 1. The selling quantities q_{Hj} and q_{Lj} of supply chain j are given. For part (a), consider first the case when $A_H - q_{Hj} \geq A_L - q_{Lj}$. We will find the optimal solution to a relaxed version of Problem $\mathscr{C}$ that ignores constraints (11) and (12), then show that this optimal solution satisfies (11) and (12) so that it is also optimal to Problem $\mathscr{C}$. For the relaxed problem, constraints (10) and (13) must be binding, or else manufacturer i can increase T_{Hi} and T_{Li} to improve her profit. Therefore, $T_{Li} = f_L(Q_{Li}, q_{Lj})$ and $T_{Hi} = f_H(Q_{Hi}, q_{Hj}) - f_H(Q_{Li}, q_{Hj}) + f_L(Q_{Li}, q_{Lj})$. By substituting these expressions back into (9) and rearranging terms, the objective function, denoted by $\pi_i(Q_{Hi}, Q_{Li})$, is given by

$$\pi_i(Q_{Hi}, Q_{Li}) = \beta[f_H(Q_{Hi}, q_{Hj})] + f_L(Q_{Li}, q_{Lj}) - \beta f_H(Q_{Li}, q_{Hj}).$$

From (4), $f_d(Q_i, q_j)$ is increasing in Q_i when $Q_i \leq (A_d - q_j)/2$ and remains constant otherwise. Therefore, the optimal solution Q^*_{di} must satisfy $Q^*_{di} \leq (A_d - q_{dj})/2$, where $d = H$ or L. For $Q_{di} \leq (A_d - q_{dj})/2$, from (4), we can rewrite $\pi_i(Q_{Hi}, Q_{Li})$ to be

$$\begin{aligned}\pi_i(Q_{Hi}, Q_{Li}) &= \beta[(A_H - Q_{Hi} - q_{Hj})Q_{Hi}] + (A_L - Q_{Li} - q_{Lj})Q_{Lj}\\ &\quad -\beta[(A_H - Q_{Li} - q_{Hj})Q_{Li}].\end{aligned}$$

Because $\pi_i(Q_{Hi}, Q_{Li})$ is separable and concave in Q_{Hi} and Q_{Li}, by differentiating the above expression, we can show that (Q^*_{Hi}, Q^*_{Li}) is a unique solution to the relaxed problem, where

$$Q^*_{Hi} = \frac{(A_H - q_{Hj})}{2},$$

$$\begin{aligned}Q^*_{Li} &= \max\left[\frac{(A_L - q_{Lj}) - \beta(A_H - q_{Hj})}{2(1-\beta)}, 0\right]\\ &= \max\left[\frac{(A_L - q_{Lj})}{2} - \frac{\beta(A_H - q_{Hj} - A_L + q_{Lj})}{2(1-\beta)}, 0\right].\end{aligned}$$

Because $Q^*_{Hi} = (A_H - q_{Hj})/2$ and $Q^*_{Li} \leq (A_L - q_{Lj})/2 \leq (A_H - q_{Hj})/2$, from (4),

$$\begin{aligned}T_{Hi} &= f_H(Q^*_{Hi}, q_{Hj}) - f_H(Q^*_{Li}, q_{Hj}) + f_L(Q^*_{Li}, q_{Lj})\\ &= \frac{(A_H - q_{Hj})^2}{4} - [(A_H - q_{Hj}) - (A_L - q_{Lj})]Q^*_{Li}.\end{aligned}$$

Because $f_H(Q^*_{Hi}, q_{Hj}) - T_{Hi} = [(A_H - q_{Hj}) - (A_L - q_{Lj})]Q^*_{Li} \geq 0$, (Q^*_{Hi}, Q^*_{Li}) satisfies (12). For (11), we have $f_L(Q^*_{Li}, q_{Lj}) - T_{Li} = 0$, and because $Q^*_{Hi} \geq (A_L - q_{Lj})/2$, from (4),

$$\begin{aligned}f_L(Q^*_{Hi}, q_{Lj}) - T_{Hi} &= \frac{(A_L - q_{Lj})^2}{4} - \frac{(A_H - q_{Hj})^2}{4}\\ &\quad + (A_H - q_{Hj} - A_L + q_{Lj})Q^*_{Li},\end{aligned}$$

which can be shown to be nonpositive. Therefore, (Q^*_{Hi}, Q^*_{Li}) also satisfies (13). Thus, $\widehat{Q}^N_{Hi}(q_{Hj}, q_{Lj}) = Q^*_{Hi}$ and $\widehat{Q}^N_{Li}(q_{Hj}, q_{Lj}) = Q^*_{Li}$. For the case of $A_H - q_{Hj} < A_L - q_{Lj}$, we can change the roles of H and L and replace β by $1-\beta$ in the above analysis to get the results. By combining both cases, we obtain part (a). Part (b) follows from (3) and $\widehat{Q}^N_{di}(q_{Hj}, q_{Lj}) \leq (A_d - q_{dj})/2$. □

Proof of Proposition 2. From (7) and part (b) of Proposition 1, the equilibrium quantities must satisfy $q^{NS}_{di} = Q^{NS}_{di}$. To obtain an equilibrium, we only need to find a solution $(Q_{H1}, Q_{L1}, Q_{H2}, Q_{L2})$ to the following reduced set of equilibrium conditions: $Q_{d1} = \widehat{Q}^N_{d1}(Q_{H2}, Q_{L2})$ and $Q_{d2} = \widehat{Q}^S_{d2}(Q_{d1})$ for $d = H$ or L. Consider the first region $\{(Q_{H1}, Q_{L1}, Q_{H2}, Q_{L2}) \mid A_H - Q_{H2} \geq A_L - Q_{L2}\}$. Because the best response functions $\widehat{Q}^N_{H1}(Q_{H2}, Q_{L2})$ and $\widehat{Q}^S_{H2}(Q_{H1})$ do not depend on Q_{L1} and Q_{L2}, by finding the intersection point of $\widehat{Q}^N_{H1}$ and $\widehat{Q}^S_{H2}$, any equilibrium must have $Q_{H1} = Q_{H2} = A_H/3$. Substituting Q_{H2} into $\widehat{Q}^N_{L1}(Q_{H2}, Q_{L2})$, we have

$$\widehat{Q}^N_{L1}(A_H/3, Q_{L2}) = \max\left[\frac{3(A_L - Q_{L2}) - 2\beta A_H}{6(1-\beta)}, 0\right].$$

It is easy to check that a unique interior intersection point of $\widehat{Q}^N_{L1}(A_H/3, Q_{L2})$ and $\widehat{Q}^S_{L2}(Q_{L1})$ is

$$Q_{L1} = \frac{A_L}{3} - \frac{4\beta(A_H - A_L)}{3(3-4\beta)}$$

$$Q_{L2} = \frac{A_L}{3} + \frac{2\beta(A_H - A_L)}{3(3-4\beta)},$$

when $\beta \le 3A_L/(4A_H)$, and it is feasible because $A_H - Q_{H2} \ge A_L - Q_{L2}$. For intersection on the boundary $Q_{L1} = 0$, we can check that $Q_{L1} = 0$, $Q_{L2} = A_L/2$ is a feasible solution when $\beta > 3A_L/(4A_H)$. Finally, it can be shown that there is no feasible intersection on the boundary $Q_{L2} = 0$. Therefore, $(Q_{d1}^{NSI}, Q_{d2}^{NSI})$, where $d = H$ or L is always an equilibrium. Now consider the second region $\{(Q_{H1}, Q_{L1}, Q_{H2}, Q_{L2}) \mid A_H - Q_{H2} < A_L - Q_{L2}\}$. Here the best response functions $\widehat{Q}_{L1}^N(Q_{H2}, Q_{L2})$ and $\widehat{Q}_{L2}^S(Q_{L1})$ do not depend on Q_{H1} and Q_{H2}. By finding the intersection point of $\widehat{Q}_{L1}^N$ and $\widehat{Q}_{L2}^S$, any equilibrium must have $Q_{L1} = Q_{L2} = A_L/3$. Substituting Q_{L2} into $\widehat{Q}_{H1}^N(Q_{H2}, Q_{L2})$,

$$\widehat{Q}_{H1}^N(Q_{H2}, A_L/3) = \max\left[\frac{3(A_H - Q_{H2}) - 2(1-\beta)A_L}{6\beta}, 0\right].$$

A unique interior intersection point of $\widehat{Q}_{H1}^N(Q_{H2}, A_L/3)$ and $\widehat{Q}_{H2}^S(Q_{H1})$ is given by

$$Q_{H1} = \frac{A_H}{3} - \frac{4(1-\beta)(A_H - A_L)}{3(1-4\beta)}$$
$$Q_{H2} = \frac{A_H}{3} + \frac{2(1-\beta)(A_H - A_L)}{3(1-4\beta)},$$

and it is feasible (i.e., $A_H - Q_{H2} < A_L - Q_{L2}$) when $\beta \le 1 - 3A_H/(4A_L)$. For intersection on the boundary $Q_{H1} = 0$, it can be shown that $Q_{H1} = 0$, $Q_{H2} = A_H/2$ is a feasible solution when $\beta \le 1 - 3A_H/(4A_L)$. Any intersection on the boundary $Q_{H2} = 0$ cannot be feasible because $A_H - Q_{H2} = A_H \ge A_L - Q_{L2}$ for any $Q_{L2} \ge 0$. The result follows. □

Proof of Proposition 3. From part (b) of Proposition 1, the equilibrium quantities must satisfy $q_{di}^{NN} = Q_{di}^{NN}$. To obtain a symmetric equilibrium, we only need to find a solution (Q_H, Q_L) to the following reduced set of equilibrium conditions: $Q_d = \widehat{Q}_{d1}^N(Q_H, Q_L)$ for $d = H$ or L. Consider first the region $\{(Q_H, Q_L) \mid A_H - Q_H \ge A_L - Q_L\}$. By solving $Q_H = \widehat{Q}_{H1}^N(Q_H, Q_L)$, we get $Q_H = A_H/3$. Now we solve $Q_L = \widehat{Q}_{L1}^N(Q_H, Q_L) = \widehat{Q}_{L1}^N(A_H/3, Q_L)$. It is straightforward to show that the solution is given by

$$Q_L = \begin{cases} \dfrac{A_L}{3} - \dfrac{2\beta(A_H - A_L)}{3(3-2\beta)} & \text{if } \beta \le \dfrac{3A_L}{2A_H}, \\ 0 & \text{otherwise.} \end{cases}$$

(Q_H, Q_L) is a feasible solution because it satisfies $A_H - Q_H \ge A_L - Q_L$. Now consider the region $\{(Q_H, Q_L) \mid A_H - Q_H < A_L - Q_L\}$. A unique solution (Q_H, Q_L) to $Q_d = \widehat{Q}_{d1}^N(Q_H, Q_L)$ is given by $Q_L = A_L/3$ and $Q_H = A_H/3 + 2(1-\beta)(A_H - A_L)/[3(1+2\beta)]$. However, it is easy to verify that it does not satisfy $A_H - Q_H < A_L - Q_L$ and is therefore not feasible. Hence the result. □

Proof of Proposition 6. The proof of part (a) is straightforward and can be found in the online supplement. For parts (b) to (e), refer to Table 1. When $K_A \le K_B \le V_s^k$, the dominant strategy of either manufacturer is S, so the unique equilibrium is (S, S). When $K_A \le V_s^k \le K_B$, the dominant strategy of manufacturer A is S and $\Pi_B(S, S) \le \Pi_B(S, N)$. When $V_s^k \le K_A \le V_n^k \le K_B$, the dominant strategy of manufacturer B is N and $\Pi_A(N, N) \le \Pi_A(S, N)$. Hence, in either case, the unique equilibrium is (S, N). When $V_s^k \le K_A \le K_B \le V_n^k$, we have $\Pi_A(S, S) \le \Pi_A(N, S)$, $\Pi_B(N, N) \le \Pi_B(N, S)$, $\Pi_A(N, N) \le \Pi_A(S, N)$, and $\Pi_B(S, S) \le \Pi_B(S, N)$. Thus, the two possible equilibria are (S, N) and (N, S). When $V_n^k \le K_A \le K_B^k$, the dominant strategy of either manufacturers is N; hence the unique equilibrium is (N, N). □

Proofs of Propositions 4, 5, 7, and 8. These proofs are straightforward and can be found in the online supplement.

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