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Information Sharing in a Supply Chain with a Common Retailer

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We study the problem of information sharing in a supply chain with two competing manufacturers selling substitutable products through a common retailer. Our analysis shows that the retailer's incentive to share information strongly depends on nonlinear production cost, competition intensity, and whether the retailer can offer a contract to charge a payment for the information. Without information contracting, the retailer has an incentive to share information for free when production economy is large but has no incentive to do so when there is production diseconomy. With information contracting, the retailer has an incentive to share information when either production diseconomy/economy is large or competition is intense. We characterize the conditions under which the retailer shares information with none, one, or both of the manufacturers. We also show that the retailer prefers to sell information sequentially rather than concurrently to the manufacturers, whereas the manufacturers' preferences are reversed.

Keywords: supply chain management; common retailer; incentive; information sharing; nonlinear production cost; manufacturer competition
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1. Introduction

With the advance of information technology, retailers routinely and efficiently acquire rich market data to obtain information about product demand. Keifer (2010) observes that many retailers have started sharing such data with their suppliers to improve collaboration. These retailers vary significantly in size, from giant chains such as Costco, Kroger, and Target to relatively smaller chains such as Wegmans, Lowe's, and Dollar Tree. They offer data-sharing programs either directly or through third-party data service providers (e.g., SymphonyIRI) to their suppliers. There are several issues related to the adoption and implementation of these programs. As pointed out by the Retailer-Direct Data Report of the Grocery Manufactures Association (GMA 2009) and by Keifer (2010), one issue is whether the retailers have an incentive to share data with suppliers who may use it to gain an advantage in future dealings. According to Keifer (2010), (1) Capgemini investigated 16 retailers from 11 countries in Europe and North America in 2007, and found that only 40% of the retailers shared POS (point-of-sales) data with their manufacturers; and (2) Forrester Research performed a similar and broader study on 89 retailers in 2006, and reported that only 27% of retailers shared POS data. Another issue is whether the retailers should charge for the data. Keifer (2010) reveals that over 40% of retailers charge their suppliers for the data. More recently, Munves (2013) reports that many consumer packaged goods manufacturers such as Pepsi, Johnson & Johnson, and Procter & Gamble regularly buy data from their retailers. He also asserts that selling data could provide a lucrative revenue stream for the retailers. There is also an issue of whether a retailer should share data selectively with the suppliers or not. Keifer (2010) finds that a retailer usually shares information with some but not all of the suppliers. Similarly, Costco offers its CRX (Collaborative Retail Exchange) data-sharing program through SymphonyIRI to only some of its suppliers, who can get access to the data by paying an annual subscription fee (see http://www.symphonyiri.com). A supplier who wants to participate needs to be first approved by Costco.

Shared data allows firms to derive information about market demand. Because firms usually have access to standard technology (e.g., through a third-party data service provider) for converting data into information, for the purpose of this study, sharing data is equivalent to sharing information. Moreover, because our focus is on the data-sharing programs offered by retailers, sharing information in this paper means sharing a retailer's demand information with a manufacturer.

The incentive for firms to share information in a supply chain has been studied in the literature. Under a linear wholesale price contract, a manufacturer has an incentive to extract profit by charging a price that is higher than what is best for the supply chain, leading to a distortion in the retail decisions. This is the well-known double marginalization problem. Li and Zhang (2002, 2008) show that when a manufacturer receives demand information from a retailer, the manufacturer tries to extract more profit by adjusting his wholesale price to respond positively[1] to the demand information. This makes double marginalization stronger,[2], which benefits the manufacturer but hurts the retailer. This is called the double marginalization effect of information sharing. When the production cost is linear, this effect lowers the total supply chain profit and the retailer does not have an incentive to share information even if there is a side payment (because her loss is greater than the manufacturer's gain). Ha et al. (2011) consider the case of production diseconomy where the marginal production cost is increasing in the volume, and therefore the expected production cost is lower when the retailer's order quantity becomes less uncertain. They identify another effect of information sharing that can be called the order uncertainty effect.[3] When a manufacturer receives demand information from a retailer, he adjusts the wholesale price to respond positively to the demand information. This reduces order uncertainty and lowers the expected production cost. They show that the retailer has no incentive to share information for free because she is hurt by the stronger double marginalization. With a side payment, however, the retailer has an incentive to share information when production diseconomy is large. This is because information sharing has a positive value to the supply chain (the positive effect of a lower order uncertainty dominates the negative effect of a stronger double marginalization) and the retailer can now share this value via the side payment. The effect of retail competition on information sharing has been studied when either a manufacturer sells to competing retailers or two supply chains compete with each other. However, the incentive for a common retailer to share information with competing manufacturers, to the best of our knowledge, has not been studied in the literature. Such a supply chain structure is most relevant for studying the issue of how a retailer should offer data-sharing programs selectively to competing manufacturers.

Because there is no existing theory that can adequately explain the current practice of retailers' data-sharing programs, we propose to fill this gap by studying information sharing in a model with two competing manufacturers selling substitutable products through one common retailer. We hope to shed light on the following research questions. When does the retailer have an incentive to share demand information for free with self-interested manufacturers who will use it in making wholesale price decisions? How about the case when the retailer charges a side payment for the information? Should the retailer share information with one or both of the manufacturers? Should the retailer sell information concurrently or sequentially to the manufacturers? How do the answers to these questions depend on production cost and competition?

We formulate a multistage game to study the firms' information contracting, wholesale price, and retail price decisions. We consider different scenarios where the manufacturers face production diseconomy or economy,[4] and information contracts are offered concurrently or sequentially. With concurrent information contracting, the retailer makes concurrent and identical offers of selling information for a fixed payment to the manufacturers. With sequential information contracting, the retailer makes sequential offers of selling information for a fixed payment to the first manufacturer, then to the second manufacturer after the first manufacturer's decision of whether accepting the offer becomes public information. Before observing a private demand signal, the retailer decides whether to contract with each manufacturer on sharing this information for a fixed side payment. We say that a manufacturer is *informed* if he receives information from the retailer and *uninformed* otherwise.

Our study of information contracting is motivated by the trend that many manufacturers buy data from their retailers. Our model setup also allows us to study the conditions under which retailers may have an incentive to share data for free (i.e., without a fixed payment), a phenomenon that has been observed in

[1] Positive response means that the manufacturer raises his wholesale price when the information shows that demand is more likely to be high and lowers his wholesale price when it is more likely to be low.

[2] It is stronger on average. For more details, see the discussion after Lemma 1.

[3] It is called the order variability effect in Ha et al. (2011).

[4] Our notions of production diseconomy (marginal cost is increasing in volume) and production economy (marginal cost is decreasing in volume) are different from diseconomies of scale and economies of scale, which consider how the average cost changes as production volume increases, in the economics literature.

practice. Sequential contracting corresponds to the case when a retailer can adopt an approval process to offer the program sequentially to different manufacturers (as in the CRX example) and whether a manufacturer participates in the program is publicly known (e.g., through industry channels or public media). Concurrent contracting corresponds to the case when a retailer cannot offer the program sequentially or whether a manufacturer participates in the program is not publicly known.

Based on our model, we show how nonlinear production cost and competition intensity impact a manufacturer's wholesale price decision. When a manufacturer faces a higher order uncertainty, his expected production cost is higher with production diseconomy and lower with production economy. With either production diseconomy or a small production economy, information sharing induces a manufacturer's wholesale price to respond positively to the demand signal. This makes the double marginalization of the wholesale price stronger and reduces the order uncertainty faced by the manufacturer. With a large production economy, information sharing induces a manufacturer's wholesale price to respond negatively to the demand signal. This makes the double marginalization of the wholesale price weaker and generally increases the order uncertainty faced by the manufacturer, except when the rival manufacturer is informed and either production economy is large or competition is intense. In this exceptional case, an uninformed manufacturer faces a large order uncertainty due to the rival manufacturer's strongly responsive wholesale price. When the uninformed manufacturer receives information, both manufacturers' wholesale prices respond with the same strength to the demand signal and their effects on the order uncertainty mostly counterbalance each other. As a result, the order uncertainty faced by that manufacturer becomes smaller. When the wholesale price responds positively to the demand signal, more intense competition makes it respond less strongly and the effect of a stronger double marginalization due to information sharing becomes less significant. When the wholesale price responds negatively to the demand signal, the effects of competition are reversed.

Our analysis demonstrates that the retailer's incentive to share information strongly depends on information contracting, nonlinear production cost, and competition intensity. These drivers may explain the diverse data-sharing program practices observed in the industry. When there is no information contracting, the retailer has an incentive to share information for free if production economy is large, because she can benefit from the weaker double marginalization. She does not have any incentive to do so if there is production diseconomy. When there is information contracting, the retailer has an incentive to share information if either production diseconomy/economy is large or competition is intense. Under any of these conditions, information sharing creates a positive value to the supply chain, which can be explained as follows. With production diseconomy, the wholesale price responds positively to the demand signal, and either the positive effect of a lower order uncertainty becomes more significant or the negative effect of a stronger double marginalization becomes less significant. With production economy, when the wholesale price responds negatively to the demand signal, it makes the double marginalization weaker and the order uncertainty higher, both of which are beneficial to the supply chain.[5]

Regardless of whether there is production diseconomy or economy, and whether information contracting is done concurrently or sequentially, it is possible to have no information sharing or full information sharing (i.e., both manufacturers receive information). With production diseconomy, partial information sharing (i.e., one manufacturer receives information) is possible only under sequential but not concurrent information contracting, and it occurs when production diseconomy is neither too small nor too large. In this case, because neither manufacturer wants to be the only uninformed firm, the retailer can charge a high payment by selling information to only one manufacturer even though it is a less efficient outcome for the supply chain. With production economy, as discussed earlier, when the rival manufacturer is informed and either production economy or competition intensity is sufficiently large, sharing information with a manufacturer could reduce his order uncertainty. When this negative effect of a lower order uncertainty dominates the positive effect of a weaker double marginalization, partial information sharing occurs. Similar to the case of production diseconomy, partial information sharing is more likely to occur when information contracting is done sequentially rather than concurrently. With production diseconomy, more intense competition induces the retailer to share information with more manufacturers. However, with production economy, this may induce the retailer to share information with less manufacturers.

With either production diseconomy or economy, the retailer prefers to sell information sequentially rather than concurrently to the manufacturers, whereas the manufacturers' preferences are reversed. This is

[5] As explained earlier, when either production economy is large or competition is intense, information sharing could reduce the order uncertainty faced by a manufacturer if the rival manufacturer is informed. In this case, the retailer has an incentive to share information with one but not both of the manufacturers.

because sequential information contracting makes it easier for the retailer to achieve partial information sharing, which induces a manufacturer to pay more for the information. This may explain the practice of sequentially approving manufacturers in Costco's CRX program.

Our analysis also reveals the following counter-intuitive results. With information contracting, the retailer's profit may increase when production diseconomy becomes larger, and the manufacturers' total profit may increase when competition becomes more intense and there is production economy. For the former case, a larger production diseconomy increases not only the production cost but also the value of information sharing. For the latter case, though more intense competition lowers the wholesale prices, it could induce the retailer to share information with less manufacturers, which increases the manufacturers' total profit. Neither of these result is possible when there is no information sharing.

To the best of our knowledge, our paper is the first in the supply chain information sharing literature that considers production economy. It is also the first that examines information sharing in a supply chain with competing manufacturers selling through a common retailer. Our results extend the literature in several ways. First, by comparing the production diseconomy and economy models, we provide a more complete understanding of how nonlinear production cost impacts the incentive for information sharing. With production economy, we identify novel effects of information sharing on double marginalization and order uncertainty. We show that the information sharing decisions under the two models can be very different, and they can be explained by these effects. Second, by considering a supply chain with a common retailer, our results lead to interesting contrasts with the existing models. Ha et al. (2011) show that for two competing supply chains, a retailer has an incentive to share information when retail competition is not intense and she cannot benefit from a larger production diseconomy. We show that for a supply chain with a common retailer, the retailer has an incentive to share information when competition at the manufacturer level is intense and she may benefit from a larger production diseconomy. Third, the existing literature does not emphasize the issue of information contracting because it is relatively straightforward when the contract is between one manufacturer and one retailer. In our model with a common retailer offering information contracts to two competing manufacturers, we show that the information sharing decisions depend strongly on the contracting sequence (concurrent versus sequential offers). Fourth, in all the related models, because of the negative double marginalization effect, a retailer does not have an incentive to share demand information for free with a manufacturer who has no private information. In our model, we show that the double marginalization effect can be positive when production economy is large. As a result, it is possible for the retailer to have an incentive to share demand information for free even when it does not yield any operational improvement and only allows the manufacturer to adjust the wholesale price based on his self-interest. Our results show that production economy can be a driving force that leads to voluntary information sharing.

2. Literature Review

This paper is most related to the literature on incentive for vertical information sharing under different supply chain structures. Most of the papers in the literature consider information sharing in a supply chain with one manufacturer selling to several competing retailers. The focus of this stream of work is on the incentive for the retailers to share demand information with the manufacturer (Li 2002, Li and Zhang 2002, Zhang 2002) and how that incentive depends on confidentiality (Li and Zhang 2008) and the product wholesale contracts (Shin and Tunca 2010, Tang and Girotra 2010). Several papers consider information sharing in a one-to-one supply chain and investigate issues such as signaling unverifiable information (Cachon and Lariviere 2001), dual distribution channels (Yue and Liu 2006), and bilateral information sharing (Mishra et al. 2009). Ha and Tong (2008) and Ha et al. (2011) study information sharing in two competing supply chains. Zhang (2006) examines the issue of sharing inventory information among suppliers who produce different components for a manufacturer in a two-echelon assembly system. Özer et al. (2011) consider the role of trust in information sharing between a supplier and a manufacturer. Zhao et al. (2014) study the issue of information sharing in outsourcing. Kurtuluş et al. (2012) examine the conditions under which a supplier and a retailer have incentives to combine their information to form a shared demand forecast.

In economics, there is a related literature on information sharing in an oligopoly (see, e.g., Vives 1984, Gal-Or 1985, Li 1985). This body of research focuses on the incentive for a firm to share information with its competitors in an oligopoly and it does not consider the interactions between firms in a vertical chain.

Our paper is also related to the literature on supply chain coordination and competition when there are multiple manufacturers selling through a common retailer. Choi (1991) and Lee and Staelin (1997) consider channel competition under linear wholesale price contracts. More recently, Cachon and Kök (2010) study the impact of other contract forms (quantity discount and two-part pricing) on channel competition and coordination. See Cachon and Kök (2010) for a detailed discussion of this literature. None of the papers in this literature consider the issue of information sharing, which is the focus of this paper.

3. The Model

Consider a supply chain with two identical manufacturers (indexed by 1 or 2) selling substitutable products through a common retailer. The demand function of product i is given by

$$q_i = a + \theta - (1+\phi)p_i + \phi p_j,$$

where p_i is the retail price of product i, $\phi > 0$ is a parameter for competition intensity (larger ϕ means more intense competition), and the random variable θ, with zero mean and variance σ^2, represents demand uncertainty. Linear demand functions have been extensively used in the economics (e.g., Vives 1999) and operations management literatures (e.g., Li and Zhang 2008, Shin and Tunca 2010).

The retailer has access to a demand signal Y, which is an unbiased estimator[6] of θ (i.e., $E[Y \mid \theta] = \theta$). We assume a linear-expectation information structure: the expectation of θ conditional on signal Y is a linear function of the signal. This information structure is commonly used in the information sharing literature (e.g., Li 2002, Gal-Or et al. 2008 and Taylor and Xiao 2010) and includes well-known prior-posterior conjugate pairs like normal-normal, beta-binomial, and gamma-Poisson. Define the signal accuracy as $t = 1/E[\mathrm{Var}[Y \mid \theta]]$. It can be shown (Ericson 1969) that $E[\theta \mid Y]$ is a weighted average of the prior mean $E[\theta]$ and the signal Y:

$$E[\theta \mid Y] = \frac{1}{1+t\sigma^2}E[\theta] + \frac{t\sigma^2}{1+t\sigma^2}Y = \beta(t,\sigma)Y,$$

where $E[\theta] = 0$ as assumed earlier and $\beta(t,\sigma) = t\sigma^2/(1+t\sigma^2)$ is the weight for the signal Y. Note that $\beta(t,\sigma)$ is larger when the signal becomes more accurate (larger t). The information structure is common knowledge. For more details of the linear-expectation information structure, refer to Vives (1999, §2.7.2).

The retailer has a constant marginal retailing cost, which is normalized to zero. We consider two cases of nonlinear production cost. With production diseconomy, the cost incurred by a manufacturer for producing q units of his product is given by

$$bq + c_d q^2.$$

With production economy, the cost is given by

$$\begin{cases} bq - c_e q^2 & \text{if } q < \bar{q}, \\ b\bar{q} - c_e \bar{q}^2 & \text{otherwise,} \end{cases}$$

where $\bar{q} = b/(2c_e)$.[7] Here b, c_d, and c_e are all positive numbers. The use of quadratic functions to model nonlinear production costs is quite common in the literature (see, e.g., Anand and Mendelson 1997, Eliashberg and Steinberg 1991).

We consider several scenarios of a multistage game where the manufacturers face either production diseconomy or economy, and the retailer offers information contracts to the manufacturers either concurrently or sequentially. The sequence of events for the multistage game is given below.

1. Before the retailer observes any demand signal, the retailer and the manufacturers contract on information sharing. With concurrent contracting, the retailer makes concurrent and identical offers to the manufacturers by charging each a side payment T for the information. With sequential contracting, the retailer makes sequential offers by charging the first manufacturer a fixed payment T_f for the information, then charging the second manufacturer a payment T_s.[8]
2. The retailer observes a demand signal Y and truthfully discloses it to a manufacturer if an information sharing contract has been signed in the previous stage. Let X_i be the information status of manufacturer i, where $X_i = I$ if manufacturer i is informed (i.e., retailer shares information with him) and $X_i = U$ if he is uninformed (i.e., retailer does not share information with him). Let n be the number of informed manufacturers, where $n = 0, 1$, or 2.
3. Each manufacturer i determines his wholesale price w_i, and then the retailer determines retail prices p_1 and p_2.
4. Market demands q_1 and q_2 realize, each manufacturer i supplies q_i to the retailer and finally firms receive their payoffs.[9]

In our model, the demand signal can be interpreted as the information about a product's potential demand, which is derived from the historical data collected by the retailer.[10] Besides basic POS data,

[6] This is without loss of generalization because a biased estimator can be transformed into an unbiased one.

[7] Our results remain valid if we choose $\bar{q}$ to be smaller than $b/(2c_e)$; i.e., the marginal cost decreases to a positive level and remains constant as q increases.

[8] In §5, we provide more details about how the firms make information sharing decisions under concurrent and sequential contracting.

[9] We can show that, when σ and either c_d or c_e are small relative to a, it is optimal for manufacturer i, with a probability very close to one, to fully meet the demand.

[10] GMA (2009) states that historical data are available in retailers' data-sharing programs. *Business Wire* (2013) reports that manufacturers can access and analyze data in the past three years under the Costco CRX program.

Keifer (2010) identifies five other types of data that are commonly included in retailers' data-sharing programs: market basket, loyalty card programs, consumer demographics, trade promotions, and retailer pricing. Because these data are tangible and verifiable, it is reasonable to assume that information sharing is truthful. Without participating in a data-sharing program, a manufacturer cannot obtain such information by observing only the past orders. According to Oracle (2006), the expanded set of POS data allows firms to make better forecasts.

We assume the manufacturers choose their wholesale prices simultaneously so that neither of them can infer information by observing the rival's wholesale price. This is reasonable because a manufacturer's wholesale price is usually not observable to the rival manufacturer. Even if it is observable, the manufacturer and the retailer can still secretly renegotiate and they cannot make a credible commitment not to do so. (See Coughlan and Wernerfelt 1989 for more discussion about the observability of wholesale price.)

Information sharing contracts are long-term whereas wholesale contracts are short-term decisions. This is because if firms agree to share information, they have to set up systems for information transmission. After that, they engage in multiple wholesale contract interactions. Therefore, the manufacturers and the retailer do not negotiate information sharing contracts and wholesale contracts simultaneously. Based on the demand signal derived from the data (if available) in a wholesale contract period, the firms determine the wholesale and retail prices of the product for the next wholesale contract period. We assume that the manufacturers produce to meet the demand that realizes over the wholesale contract period and there is no demand uncertainty at the time when production occurs. Here q_i is the order quantity (the same as sales quantity or production quantity) of product i over the entire wholesale contract period.

A manufacturer faces production diseconomy when the marginal cost is increasing in the output volume. Because capacity is usually a long-term decision, a manufacturer does not adjust capacity every time before a wholesale contract is signed. If the capacity is tight, a higher volume means that the manufacturer has to incur a higher marginal cost because of overtime or using production resources that are less efficient. This could also be the case when the manufacturer has to add more expensive suppliers to his supply base or to incur a higher cost in coordinating with more suppliers as output volume increases. See Anand and Mendelson (1997) and Froeb and McCann (2009) for more discussion about the drivers that make the marginal cost increasing in production volume. A manufacturer faces production economy when the marginal cost is decreasing in the output volume. This could happen when there is a learning effect in production or a more efficient technology can be used with a larger production volume.

Like many models (e.g., Li 2002, Li and Zhang 2008, Gal-Or et al. 2008, Ha et al. 2011) in the related literature, we focus on studying how information sharing influences the strategic interactions between firms and ignore its impact on operational improvements such as inventory cost saving. Such an impact is not significant when, as assumed in our model, a production/ordering decision is made after demand realizes, and therefore the cost of mismatch between production and demand is not high. Here we focus on studying how self-interested manufacturers use the shared information to make wholesale price decisions, and whether the potential conflict of interest may discourage a retailer from sharing information with them. As discussed earlier, this could be an important hurdle to information sharing in practice.

We solve the multistage game backward by first solving for the equilibrium wholesale and retail prices, and based on these, computing the ex ante profits of the firms under different information sharing statuses of the manufacturers. The ex ante profits are then used to solve for the equilibrium information contracting decisions in the first stage.

4. Pricing Decisions and Firms' Ex Ante Profits

In this section, for any given set of the manufacturers' information statuses (X_1, X_2), we solve for the equilibrium wholesale and retail pricing decisions and then derive the firms' ex ante profits before the side payment, if any, because of information contracting. Because the side payment is a sunk cost, it will not have any impact on the pricing decisions. Our analysis here applies to both the production diseconomy and economy models.

4.1. Wholesale and Retail Price Decisions

Knowing the wholesale prices w_1 and w_2 as well as the demand signal Y, the retailer chooses p_1 and p_2 to maximize her expected profit

$$\begin{aligned}(p_1-w_1)\big(a+E[\theta\mid Y]-(1+\phi)p_1+\phi p_2\big)\\ +(p_2-w_2)\big(a+E[\theta\mid Y]-(1+\phi)p_2+\phi p_1\big),\end{aligned}$$

where $E[\theta\mid Y]=\beta(t,\sigma)Y$. The retailer's best-response retail price is

$$\hat{p}_i(w_i,w_j)=\tfrac{1}{2}\big(a+\beta(t,\sigma)Y+w_i\big),$$

and the resulting demand is

$$\begin{aligned}q_i(w_i,w_j) &= \tfrac{1}{2}\big(a+\beta(t,\sigma)Y-(1+\phi)w_i+\phi w_j\big)\\ &\quad+\big(\theta-\beta(t,\sigma)Y\big). \qquad (1)\end{aligned}$$

Next, we show how the manufacturers simultaneously determine their wholesale prices in anticipation of the retailer's response. We first derive manufacturer i's best-response wholesale price to manufacturer j's wholesale price w_j, which is a function of Y if manufacturer j is informed and does not depend on Y otherwise. For convenience, we will simply write w_j in the subsequent analysis, regardless of whether manufacturer j is informed or not. To simplify our presentation, let $c = c_d$ for the production diseconomy model and $c = -c_e$ for the production economy model.[11]

Assumption ($c_e < 2/(1+\phi)$). When this assumption is not true, it is optimal for the manufacturers not to produce and the problem is not interesting. When manufacturer i is informed, his expected profit is given by

$$(w_i - b)E[q_i(w_i, w_j) \mid Y] - cE[q_i^2(w_i, w_j) \mid Y].$$

When manufacturer i is uninformed, his expected profit becomes

$$(w_i - b)E[q_i(w_i, w_j)] - cE[q_i^2(w_i, w_j)].$$

It can be shown that the manufacturer's expected profit function is concave. An informed manufacturer i maximizes his expected profit by choosing the best-response wholesale price

$$\hat{w}_i(w_j) = \frac{(1+(1+\phi)c)(a+\beta(t,\sigma)Y)+(1+\phi)b}{(1+\phi)(2+(1+\phi)c)} + \frac{\phi(1+(1+\phi)c)w_j}{(1+\phi)(2+(1+\phi)c)}. \tag{2}$$

An uninformed manufacturer i maximizes his expected profit by choosing the best-response wholesale price

$$\hat{w}_i(w_j) = \frac{(1+(1+\phi)c)a+(1+\phi)b+\phi(1+(1+\phi)c)E[w_j]}{(1+\phi)(2+(1+\phi)c)}.$$

Here we use Bayesian Nash equilibrium as the solution concept, which is commonly used for static games of incomplete information. Manufacturer i conjectures about manufacturer j's wholesale price w_j (which is a function of Y if manufacturer j is informed and does not depend on Y otherwise). When manufacturer i is informed, he knows exactly the demand signal Y observed by an informed manufacturer j, and therefore his best-response wholesale price is a function of w_j. When manufacturer i is uninformed, he does not know the demand signal Y observed by an informed manufacturer j, and therefore his best-response wholesale price is a function of $E[w_j]$, where the expectation is taken over the distribution of Y. When manufacturer j is uninformed, w_j does not depend on Y, and $E[w_j]$ is interpreted simply as w_j. An equilibrium $(w_1^*, w_2^*, p_1^*, p_2^*)$ can be found by solving $w_i^* = \hat{w}_i(w_j^*)$ and $p_i^* = \hat{p}_i(w_i^*, w_j^*)$. Let $\bar{w}$ and $\bar{p}$ be the deterministic solutions when $\sigma = 0$, where $\bar{w} = [(1+(1+\phi)c)a+(1+\phi)b]/(2+\phi+(1+\phi)c)$ and $\bar{p} = [(3+\phi+2(1+\phi)c)a+(1+\phi)b]/[2(2+\phi+(1+\phi)c)]$.

Lemma 1. *Given n, the number of informed manufacturers, there exists a unique equilibrium such that*

$$w_i^* = \begin{cases} \bar{w} + \alpha_w(n)Y & \text{if } n = 0 \text{ or } 2, \\ \bar{w} + \alpha_w^{X_i}(1)Y & \text{if } n = 1, \end{cases}$$

$$p_i^* = \begin{cases} \bar{p} + \alpha_p(n)Y & \text{if } n = 0 \text{ or } 2, \\ \bar{p} + \alpha_p^{X_i}(1)Y & \text{if } n = 1, \end{cases}$$

where

$$\alpha_w(0) = \alpha_w^U(1) = 0,$$

$$\alpha_w^I(1) = \frac{1+(1+\phi)c}{(1+\phi)(2+(1+\phi)c)}\beta(t,\sigma),$$

$$\alpha_w(2) = \frac{1+(1+\phi)c}{2+\phi+(1+\phi)c}\beta(t,\sigma),$$

$$\alpha_p(0) = \alpha_p^U(1) = \frac{\beta(t,\sigma)}{2},$$

$$\alpha_p^I(1) = \frac{3+2\phi+(1+\phi)(2+\phi)c}{2(1+\phi)(2+(1+\phi)c)}\beta(t,\sigma),$$

$$\alpha_p(2) = \frac{3+\phi+2(1+\phi)c}{2(2+\phi+(1+\phi)c)}\beta(t,\sigma).$$

Lemma 1 shows that, in equilibrium, the retailer and an informed manufacturer adjust, respectively, the retail prices and the wholesale price in response to the demand signal by following a linear strategy. An uninformed manufacturer obviously does not respond to the demand signal. From Equation (2), given w_j, w_i responds positively (i.e., $\alpha_w^I(1)$ or $\alpha_w(2)$ is positive) to the demand signal if $1+(1+\phi)c > 0$ and negatively otherwise. When w_i responds positively/negatively, the double marginalization of w_i becomes stronger/weaker[12] and the order uncertainty

[11] For the production economy model, we assume that b ($b < a$) is large relative to c_e and σ is small enough so that the probability for the order quantity to be larger than $\bar{q} = b/(2c_e)$ is negligible. This is not restrictive because all the main results such as the equilibrium information sharing decisions do not depend on b and σ.

[12] When w_i responds positively to Y, it becomes higher when the signal is high and lower when it is low. On average, this allows manufacturer i to capture a larger share of the total revenue but also has a more damaging effect in distorting retail decisions. We say that double marginalization of w_i becomes stronger. Conversely, when w_i responds negatively to Y, it allows manufacturer i to capture a smaller share of the total revenue but has a less damaging effect in distorting retail decisions. We say that double marginalization becomes weaker.

of q_i generally becomes lower/higher.[13] These explain the following properties of the equilibrium wholesale price strategies.

Remark 1. With production diseconomy ($c = c_d$), a lower order uncertainty reduces the expected production cost. An informed manufacturer adjusts his wholesale price to respond positively to the demand signal so that he can benefit from both the stronger double marginalization and the lower order uncertainty.

Remark 2. With production economy ($c = -c_e$), a higher order uncertainty reduces the expected production cost. If production economy is small ($c_e < 1/(1+\phi)$), an informed manufacturer adjusts his wholesale price to respond positively to the demand signal because the positive effect of a stronger double marginalization dominates the negative effect of a lower order uncertainty. If production economy is large ($c_e > 1/(1+\phi)$), an informed manufacturer adjusts his wholesale price to respond negatively to the demand signal because the positive effect of a higher order uncertainty now dominates the negative effect of a weaker double marginalization.

In Lemma 1, it can be shown that $\alpha_w^I(1)$ and $\alpha_w(2)$ are decreasing in ϕ. This explains the following effects of competition.

Remark 3. When the wholesale price responds positively/negatively to the demand signal, more intense competition makes it respond less/more strongly and the effect of a stronger/weaker double marginalization due to information sharing becomes less/more significant.

4.2. Firms' Ex Ante Profits

Based on the equilibrium pricing decisions, for any given n, we take expectation with respect to the demand signal Y to obtain the firms' ex ante profits before the demand signal is observed. Let manufacturer i's profit be denoted by $\pi_M(n)$ when $n=0$ or 2, and by $\pi_M^{X_i}(1)$ when $n=1$. Let the retailer's profit be denoted by $\pi_R(n)$:

$$\pi_M(0) = \bar{\pi}_M - \frac{c\beta(t,\sigma)\sigma^2}{4} - c[1-\beta(t,\sigma)]\sigma^2,$$

$$\pi_M^U(1) = \bar{\pi}_M - \frac{c}{4}\left[\frac{2+3\phi+(1+\phi)(1+2\phi)c}{(1+\phi)(2+(1+\phi)c)}\right]^2 \beta(t,\sigma)\sigma^2 - c[1-\beta(t,\sigma)]\sigma^2,$$

$$\pi_M^I(1) = \bar{\pi}_M + \frac{1}{4(1+\phi)(2+(1+\phi)c)}\beta(t,\sigma)\sigma^2 - c[1-\beta(t,\sigma)]\sigma^2,$$

$$\pi_M(2) = \bar{\pi}_M + \frac{(1+\phi)(2+(1+\phi)c)}{4(2+\phi+(1+\phi)c)^2}\beta(t,\sigma)\sigma^2 - c[1-\beta(t,\sigma)]\sigma^2,$$

$$\pi_R(0) = \bar{\pi}_R + \frac{\beta(t,\sigma)\sigma^2}{2},$$

$$\pi_R(1) = \bar{\pi}_R + \left[\frac{1+2\phi}{1+\phi} + \frac{1}{(1+\phi)(2+(1+\phi)c)^2}\right] \cdot \frac{\beta(t,\sigma)\sigma^2}{4},$$

$$\pi_R(2) = \bar{\pi}_R + \frac{(1+\phi)^2}{2(2+\phi+(1+\phi)c)^2}\beta(t,\sigma)\sigma^2,$$

where

$$\bar{\pi}_M = \frac{(1+\phi)(2+(1+\phi)c)(a-b)^2}{4(2+\phi+(1+\phi)c)^2} \quad \text{and} \quad \bar{\pi}_R = \frac{(1+\phi)^2(a-b)^2}{2(2+\phi+(1+\phi)c)^2}$$

are the profits in the deterministic model. Note that $\beta(t,\sigma)=0$ when $t=0$ (demand signal has no information) and $\beta(t,\sigma)$ approaches to one when t approaches infinity (demand signal becomes perfect). We can decompose the demand uncertainty into two parts, where one can be predicted by the demand signal and the other cannot. We may interpret $\beta(t,\sigma)$ as the fraction of demand uncertainty that can be predicted by the demand signal. In the profit function of a firm, the second term accounts for the effect of the predictable demand uncertainty. For a manufacturer, the third term accounts for the effect of the unpredictable demand uncertainty. Consider the case of production diseconomy. An informed firm benefits from the predictable demand uncertainty because he or she can adjust his or her pricing decision in response to the demand signal. An uninformed manufacturer is hurt by the predictable demand uncertainty because of the resulting higher order uncertainty. A manufacturer, whether informed or not, cannot respond to the unpredictable demand uncertainty and is hurt by the resulting higher order uncertainty. Now consider the case of production economy. A firm, whether informed or not, benefits from both the predictable and unpredictable demand uncertainties because a higher order uncertainty is beneficial in this case.

5. The Production Diseconomy Model

5.1. Information Sharing Without Side Payment

Proposition 1. (a) *When a manufacturer receives information from the retailer, it benefits the manufacturer, hurts the retailer, and benefits the rival manufacturer if he is informed but hurts him otherwise.*

[13] From Equation (1), q_i becomes less uncertain when w_i responds positively to Y and more uncertain otherwise.

(b) *Without information contracting, the retailer does not share any information.*

Consider part (a) and suppose manufacturer i receives information from the retailer. From Remark 1, w_i responds positively to the demand signal. This makes the double marginalization of w_i stronger and the order uncertainty of q_i lower. Both effects benefit manufacturer i, whereas the first effect hurts the retailer. When w_i responds positively to the demand signal, it increases the order uncertainty of q_j.[14] This hurts manufacturer j if he is uninformed. Otherwise, he adjusts w_j to respond more strongly (and positively) to the demand signal to hedge against the higher order uncertainty and he benefits from the stronger double marginalization of w_j. Part (b) then follows from part (a).

5.2. Information Sharing with Side Payment

5.2.1. Concurrent Information Contracting. With concurrent information contracting, the retailer makes concurrent and identical offers to the manufacturers by charging each firm a side payment T for the information. The manufacturers then simultaneously decide whether to accept the offers or not. We solve the game backward by solving the manufacturer game for a given payment T. Denote a manufacturer's decision by $X_i = I$ if he agrees to pay the retailer for sharing information and $X_i = U$ otherwise. Based on the ex ante profits in §4 and the side payment T, we construct the payoff matrix of the manufacturer game in Table 1 and then solve for the equilibrium of the game, (X_1^*, X_2^*), as a function of T. When there are multiple equilibria, we can show that a Pareto-optimal equilibrium always exists and we assume that it is the outcome of the manufacturer game. We can then compute the retailer's profit in the equilibrium for a given T, and hence solve the retailer's problem of finding T that maximizes her profit.

Let n_d^C be the optimal number of informed manufacturers that maximizes the retailer's profit under concurrent information contracting.

Proposition 2. *There exists c_d^C such that $n_d^C = 0$ if $0 < c_d < c_d^C$ and $n_d^C = 2$ if $c_d^C \le c_d$.*

Proposition 2 shows that the retailer has an incentive to share information when production diseconomy is large. This is because information sharing induces the wholesale price to respond positively to the demand signal, which makes double marginalization stronger but reduces the order uncertainties. With a large production diseconomy, the second effect (which is positive) dominates the first effect (which is negative). It can be shown that the equilibrium information sharing decisions under concurrent information contracting maximize the total profit of the three firms. From the system's perspective, when compared with partial information sharing (i.e., $n_d^C = 1$), full information sharing (i.e., $n_d^C = 2$) makes both the double marginalization effect and order uncertainty effect more significant. It turns out that the second effect dominates the first one, and therefore partial information sharing is never optimal to the system.

Table 1 **Payoff Matrix of the Manufacturers Under Concurrent Information Contracting**

	Manufacturer 2	
Manufacturer 1	Share ($X_2 = I$)	Not share ($X_2 = U$)
Share ($X_1 = I$)	$(\pi_M(2) - T, \pi_M(2) - T)$	$(\pi_M^I(1) - T, \pi_M^U(1))$
Not share ($X_1 = U$)	$(\pi_M^U(1), \pi_M^I(1) - T)$	$(\pi_M(0), \pi_M(0))$

5.2.2. Sequential Information Contracting. With sequential information contracting, the retailer makes sequential offers to the manufacturers for selling information. First, the retailer randomly picks one of the two manufacturers and offers to charge him a payment T_f for the information. Next, the first manufacturer decides whether to accept the offer. Let $X_f = I$ if the first manufacturer agrees to accept the offer and $X_f = U$ otherwise. Then the retailer makes an offer to the second manufacturer, who has observed X_f, by charging another payment T_s for the information. Finally, the second manufacturer decides whether to accept the offer. Here we assume that the retailer cannot credibly commit on charging the second manufacturer the same payment T_f, which is reasonable because the retailer gives these offers at different times. Such an assumption is not critical because it can be shown that when it is optimal for the retailer to sell information to both manufacturers, she charges them the same payments in equilibrium. We solve the model backward by considering the optimal decision of a firm in each stage, given the decisions made in the previous stages and in anticipation of other firms' best responses in the subsequent stages. The firms' payoffs are determined based on the ex ante profits given in §4 and the side payments T_f and T_s.

Let n_d^S be the optimal number of informed manufacturers that maximizes the retailer's profit under sequential information contracting.

Proposition 3. *There exists c_d^{S1} and c_d^{S2} such that $n_d^S = 0$ if $0 < c_d < c_d^{S1}$, $n_d^S = 1$ if $c_d^{S1} \le c_d < c_d^{S2}$, and $n_d^S = 2$ if $c_d^{S2} \le c_d$.*

Similar to the case of concurrent contracting, the retailer has an incentive to share information when production diseconomy is large. However, partial information sharing (i.e., $n_d^S = 1$) is now possible

[14] For the effect of information sharing on order uncertainty under production diseconomy, see Lemma 2 in the appendix.

under sequential information contracting when production diseconomy is neither too small nor too large ($c_d^{S1} \le c_d < c_d^{S2}$). In this case, the value of information sharing to the retailer and the second manufacturer is negative, after the retailer has agreed to share information with the first manufacturer. Because neither manufacturer wants to be the only uninformed firm, the retailer can charge a high payment to extract profit from the manufacturers at the expense of a less efficient outcome for the supply chain.

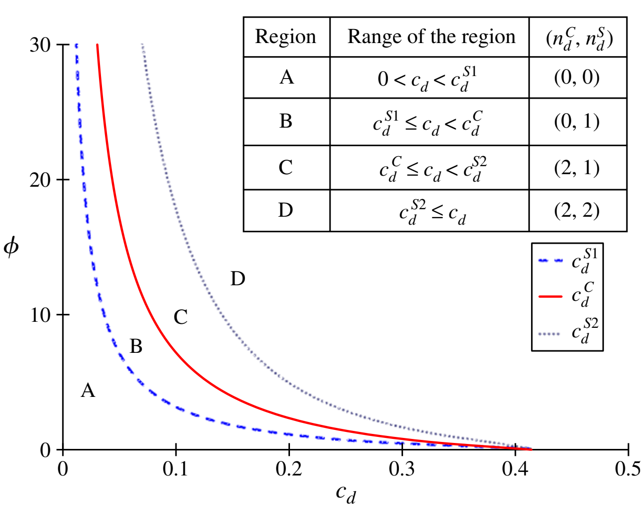
5.3. Model Comparison and Comparative Statics

Figure 1 illustrates the equilibrium information sharing decisions under the two contracting models. It fully characterizes the equilibrium regions because the threshold values c_d^C, c_d^{S1}, and c_d^{S2} depend only on ϕ.

Proposition 4. (a) $c_d^{S1} < c_d^C < c_d^{S2}$.
(b) c_d^C, c_d^{S1}, *and* c_d^{S2} *are decreasing in* ϕ.
(c) *A larger production diseconomy or more intense competition induces the retailer to sell information to more manufacturers.*
(d) *The retailer's profit is higher under sequential information contracting, whereas the total profit of the manufacturers is higher under concurrent information contracting.*

Part (c) shows that when either production diseconomy is large or competition is more intense, the retailer has an incentive to not only share information but also share it with more manufacturers. It follows from part (b) as well as Propositions 2 and 3. The effect of production diseconomy has been explained earlier. For the effect of competition, from Remark 1, an informed manufacturer adjusts his wholesale price to respond positively to the demand signal when there is production diseconomy. From Remark 3, more intense competition mitigates the damaging double marginalization effect and makes information sharing more valuable. It would be interesting to contrast the result with that in Ha et al. (2011). They show that for the case of two competing supply chains, a retailer has an incentive to share information when retail competition is not intense. This is because when information is shared in a supply chain, it triggers a negative competitive reaction from the rival chain but such a reaction is weaker when competition is less intense. Thus, the effect of competition on information sharing strongly depends on the supply chain structure. For part (d), the retailer prefers sequential contracting to concurrent contracting because she can either charge a higher fee under full information sharing, or take advantage of manufacturer competition to overcharge the only informed manufacturer under partial information sharing.

Figure 1 **(Color online) Equilibrium Information Sharing Decisions with Production Diseconomy**



Region	Range of the region	(n_d^C, n_d^S)
A	$0 < c_d < c_d^{S1}$	(0, 0)
B	$c_d^{S1} \le c_d < c_d^C$	(0, 1)
C	$c_d^C \le c_d < c_d^{S2}$	(2, 1)
D	$c_d^{S2} \le c_d$	(2, 2)

Let Π_R^S be the retailer's ex ante profit after accounting for the side payment under sequential information contracting.

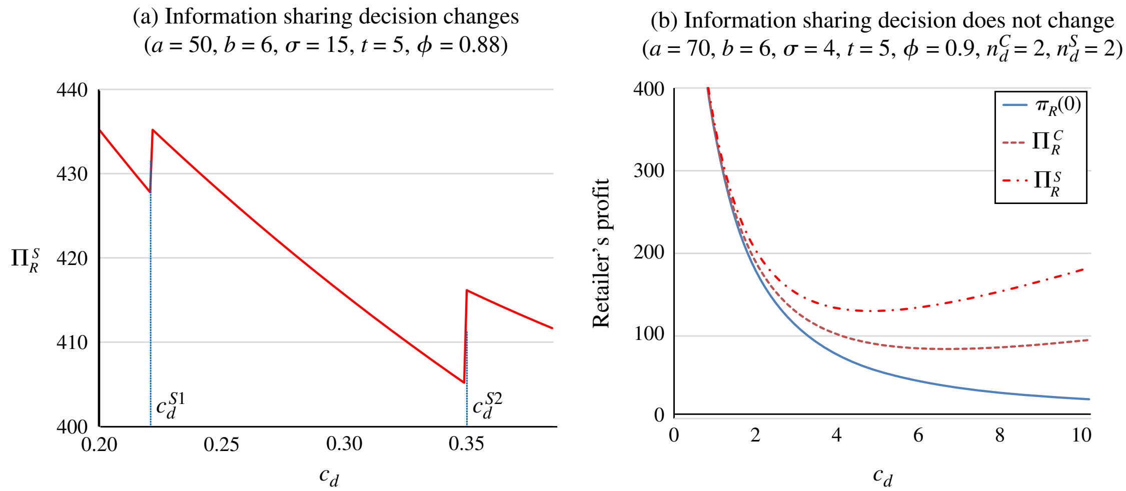
Proposition 5. (a) $\pi_R(0)$ *is decreasing in* c_d.
(b) *There exists* $\delta_d^{S1} > 0$ *such that* $\Pi_R^S(c_d^{S1} + \delta_d^{S1}) - \Pi_R^S(c_d^{S1} - \delta_d^{S1}) > 0$.
(c) *There exists* $\delta_d^{S2} > 0$ *such that* $\Pi_R^S(c_d^{S2} + \delta_d^{S2}) - \Pi_R^S(c_d^{S2} - \delta_d^{S2}) > 0$.

Without information contracting, a larger production diseconomy increases the production cost and softens the manufacturers' competition. Because both effects hurt the retailer, she is worse off. With sequential information contracting, however, there exists a neighborhood around c_d^{S1} or c_d^{S2} such that when an increase in production diseconomy induces a change in the information sharing equilibrium, the retailer is strictly better off. We can show that Π_R^S has positive jumps at c_d^{S1} and c_d^{S2}, and is continuous elsewhere. Similarly, the total ex ante profit of the manufacturers has a negative jump at c_d^{S1}. Besides these cases, the ex ante profit functions are all continuous in c_d.[15] Figure 2(a) illustrates the results of Proposition 5.

We have performed an extensive numerical study to investigate, with information contracting, how the retailer's profit depends on c_d when the information sharing equilibrium does not change. Our results show that the retailer's profit may increase in c_d for $n_d^C = 2$, or $n_d^S = 1$ or 2, when production diseconomy is large, competition is less intense, demand uncertainty is large and the signal is accurate. Figure 2(b) illustrates some of these numerical results.

[15] Similarly, we can show that there are cases where the retailer is strictly better off and the manufacturers are strictly worse off when an increase in ϕ induces the retailer to share information with more manufacturers. In our model, a change in σ or t does not affect the information sharing equilibrium outcome n, though it affects the firms' profits.

Figure 2 (Color online) Impact of Production Diseconomy on Retailer's Profit



Proposition 5 and the numerical results together show that when there is information contracting, production diseconomy has an additional effect on the retailer. A larger production diseconomy increases the value of information sharing, which benefits the retailer because she can then sell information to more manufacturers or charge a higher payment for the information. Note that for the case of two competing supply chains studied by Ha et al. (2011), a retailer cannot benefit from a larger production diseconomy when the manufacturers are the Stackelberg leaders in information contracting and they do not compete in buying information from the same retailer.

Our results in §5 highlight the roles of production diseconomy, competition intensity, and information contracting in understanding the diverse data-sharing program practices observed in the industry. For example, Propositions 1 and 4 may explain why some retailers charge for their data instead of sharing them for free, and why manufacturers are willing to pay for the data (GMA 2009, Munves 2013). They may also explain why some retailers prefer to share data with only a subset of their suppliers (Keifer 2010). Note that our results so far do not explain the observation that a retailer may be willing to share data for free (Keifer 2010). This is an important issue that we will address in the next section.

6. Production Economy Model

6.1. Information Sharing Without Side Payment

Let n_e^N be the number of informed manufacturers in equilibrium when there is no side payment (i.e., no information contracting).

Proposition 6. (a) *Suppose a manufacturer receives information from the retailer.*

(1) *If $0 < c_e < 1/(1+\phi)$, it benefits the manufacturer, hurts the retailer, and benefits the rival manufacturer.*

(2) *If $1/(1+\phi) < c_e < 2/(1+\phi)$, there exist c_e^a, c_e^b, and c_e^N such that* (i) *it benefits the manufacturer except when the rival manufacturer is informed and $c_e > c_e^a$;* (ii) *it benefits the retailer except when the rival manufacturer is informed and $c_e > c_e^N$; and* (iii) *it hurts the rival manufacturer except when the rival manufacturer is uninformed and $c_e > c_e^b$.*

(b) *$n_e^N = 0$ if $c_e < 1/(1+\phi)$, $n_e^N = 2$ if $1/(1+\phi) \le c_e < c_e^N$, and $n_e^N = 1$ if $c_e^N \le c_e < 2/(1+\phi)$.*

For part (a), suppose manufacturer i receives information from the retailer. If $c_e < 1/(1+\phi)$, from Remark 2, w_i responds positively to the demand signal because manufacturer i prefers a stronger double marginalization of w_i even though this comes at the expense of a lower order uncertainty of q_i. The retailer is hurt by the stronger double marginalization of w_i. When w_i responds positively to the demand signal, it increases the order uncertainty of q_j (see Lemma 4 in the appendix for details). This benefits manufacturer j by reducing his expected production cost. If $c_e > 1/(1+\phi)$, from Remark 2, w_i responds negatively to the demand signal and the double marginalization of w_i becomes weaker. If manufacturer j is uninformed, w_j will not be affected. Otherwise, from Equation (2), w_j is decreasing in w_i. When w_i responds to the demand signal, it induces w_j to respond less strongly and the double marginalization of w_j becomes stronger. Moreover, the order uncertainty of q_i generally becomes higher and that of q_j becomes lower (see Lemma 4 in the appendix for details). These explain why (i) manufacturer i is generally better off (the positive effect of a higher order uncertainty dominates the negative effect of a weaker double marginalization), (ii) the retailer is generally better off (the positive effect of a weaker double marginalization of w_i dominates the negative effect of a stronger double marginalization of w_j), and

(iii) manufacturer j is generally worse off (because of the lower order uncertainty of q_j). However, there are exceptions to (i)–(iii), which can be explained as follows. Suppose only manufacturer j is informed. When either production economy is large or competition is intense, w_j responds strongly and negatively to the demand signal.[16] From Equation (1), the uncertainty of q_i is large and driven by the strongly responsive w_j. For (i), if manufacturer i receives information, both w_i and w_j respond with the same strength to the demand signal and the effects of w_i and w_j on q_i mostly counterbalance each other. As a result, the order uncertainty of q_i becomes lower, which makes manufacturer i worse off. For (ii), if manufacturer i receives information, w_i becomes responsive and w_j becomes much less responsive.[17] Because the positive effect of a weaker double marginalization of w_i is dominated by the negative effect of a stronger double marginalization of w_j, the retailer is worse off. Now suppose both manufacturers are not informed. For (iii), if manufacturer i receives information, in Equation (1), the strong responsiveness of w_i dominates the uncertainty of Y. Consequently the order uncertainty of q_j becomes higher and manufacturer j is better off. Part (b) then follows from part (a).

6.2. Information Sharing with Side Payment

Unlike the case of production diseconomy, the retailer may have an incentive to share information either when there is no information contracting or after a manufacturer rejects the information contract. Obviously the retailer would like to avoid the latter case, which could be a subgame perfect equilibrium (SPE), because she does not want to share information for free. Here we assume that the retailer can commit on not sharing information for free after a manufacturer rejects the information contract, which can be justified by either repeated interactions or reputation. By not deviating from the no-free-sharing commitment, the retailer can avoid the SPE in the long run, which improves her profit. See Liu and van Ryzin (2008) for a similar assumption on price commitment and the relevant discussion. In §7, we relax this assumption and show that the information sharing equilibrium has the same threshold structure, though the firms' profits are different.

Let Z denote the contracting arrangement, where $Z = C$ if information contracts are offered concurrently, and $Z = S$ if they are offered sequentially. Let n_e^Z be the number of informed manufacturers in equilibrium.

[16] From Lemma 1, when $-(1+\phi)c = (1+\phi)c_e$ is close to 2, $\alpha_w^I(1)$ becomes very negative.

[17] The responsiveness of w_i changes from 0 to $\alpha_w(2)$, the responsiveness of w_j changes from $\alpha_w^I(1)$ to $\alpha_w(2)$, and $\alpha_w^I(1)$ is much more negative than $\alpha_w(2)$ when $(1+\phi)c_e$ is close to 2.

Proposition 7. *There exist c_e^C and c_e^S such that $n_e^Z = 0$ if $c_e < 1/(1+\phi)$, $n_e^Z = 2$ if $1/(1+\phi) \le c_e < c_e^Z$, and $n_e^Z = 1$ if $c_e^Z \le c_e < 2/(1+\phi)$.*

Proposition 7 shows that the retailer has an incentive to share information when production economy is large, regardless of the contracting sequence. From Remark 2, when production economy is small, a manufacturer's wholesale price responds positively to the demand signal. The system as a whole suffers from both the stronger double marginalization and the lower order uncertainty. As a result, there is no information sharing in equilibrium. When production economy is large, a manufacturer's wholesale price responds negatively to the demand signal. There is information sharing in equilibrium because the system as a whole benefits from the weaker double marginalization and the higher order uncertainty.

6.3. Model Comparison and Comparative Statics

Figure 3 illustrates the equilibrium information sharing decisions under the three models (without information contracting, concurrent contracting, and sequential contracting). It fully characterizes the equilibrium regions because the threshold values of c_e depend only on ϕ. Note that region D is very narrow.

Proposition 8. (a) $c_e^N < c_e^S \le c_e^C$.

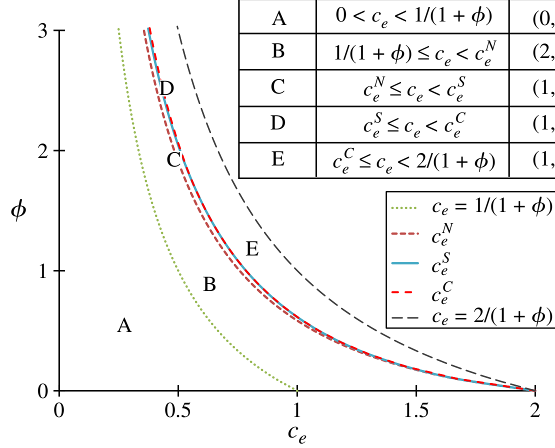
(b) *c_e^N, c_e^C, and c_e^S are decreasing in ϕ.*

(c) *With or without information contracting, the retailer has an incentive to share information if and only if $c_e > 1/(1+\phi)$, i.e., either production economy is large or competition is intense. She shares with one manufacturer when either production economy or competition intensity is sufficiently large, and shares with both manufacturers otherwise.*

(d) *The retailer's profit is higher under sequential information contracting whereas the total profit of the manufacturers is higher under concurrent information contracting.*

Figure 3 (Color online) Equilibrium Information Sharing Decisions with Production Economy

Region	Range of the region	(n_e^N, n_e^C, n_e^S)
A	$0 < c_e < 1/(1+\phi)$	(0, 0, 0)
B	$1/(1+\phi) \le c_e < c_e^N$	(2, 2, 2)
C	$c_e^N \le c_e < c_e^S$	(1, 2, 2)
D	$c_e^S \le c_e < c_e^C$	(1, 2, 1)
E	$c_e^C \le c_e < 2/(1+\phi)$	(1, 1, 1)



Part (c) follows from part (b) as well as Propositions 6 and 7. It shows that the retailer has an incentive to share information if and only if it induces the manufacturer's wholesale price to respond negatively to the demand signal (i.e., $c_e > 1/(1+\phi)$). This is true when either production economy is large or competition is intense. The effect of production economy has been discussed earlier. The effect of competition can be explained as follows. When production economy is not large and competition is not intense (i.e., $c_e < 1/(1+\phi)$), an informed manufacturer adjusts his wholesale price to respond positively to the demand signal because the positive effect of a stronger double marginalization dominates the negative effect of a lower order uncertainty. If competition becomes more intense, from Remark 3, the positive effect of a stronger double marginalization becomes less significant. If competition becomes sufficiently intense, the manufacturer prefers to adjust his wholesale price to respond negatively instead of positively to the demand signal. Similar to the case of production diseconomy, a larger production economy or more intense competition induces the retailer to share information. However, unlike the case of production diseconomy, these changes may induce her to share information with less manufacturers. From Proposition 6, when production economy is large enough, all the three firms could be worse off when the number of informed manufactures increases from one to two. Parts (a) and (d) show, respectively, that, when compared with concurrent contracting, sequential contracting induces more partial information sharing and is preferred by the retailer. This is because, similar to the case of production diseconomy, sequential contracting allows the retailer to charge a higher fee for the information.

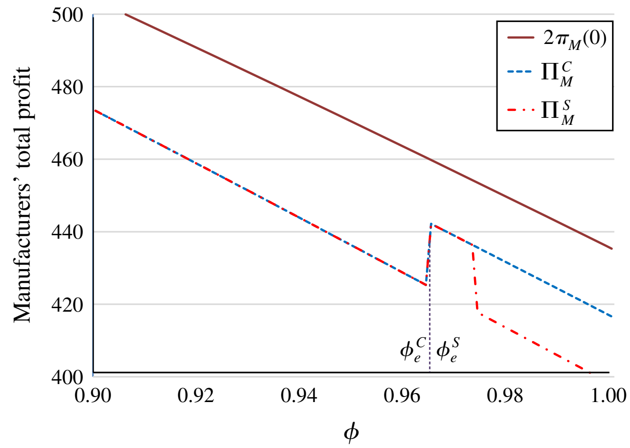
In our model, the common retailer always prefers sequential information contracting with either production diseconomy or economy. However, sequential contracting is not always more preferable to concurrent contracting in other models. For example, Horn and Wolinsky (1988) consider how a common seller bargains wholesale prices either concurrently or sequentially with two competing buyers. They demonstrate that, depending on the parameters, the common seller may prefer either concurrent or sequential bargaining.

Let Π_M^Z be the total ex ante profit of the two manufacturers after accounting for the side payment for information sharing, where $Z = C$ or S. Let ϕ_e^C and ϕ_e^S be, respectively, the inverse functions of $c_e^C(\phi)$ and $c_e^S(\phi)$.

Proposition 9. (a) *$\pi_M(0)$ is decreasing in ϕ.*

(b) *There exists $\delta_e^C > 0$ such that $\Pi_M^C(\phi_e^C + \delta_e^C) - \Pi_M^C(\phi_e^C - \delta_e^C) > 0$.*

Figure 4 (Color online) Impact of Competition Intensity on Manufacturers' Total Profit ($a = 50$, $b = 6$, $\sigma = 10$, $t = 5$, $c_e = 0.8$)



(c) *There exist $\phi^a > 0$ and $\delta_e^S > 0$ such that $\Pi_M^S(\phi_e^S + \delta_e^S) - \Pi_M^S(\phi_e^S - \delta_e^S) > 0$ if $\phi_e^S < \phi^a$.*

Without information sharing, the manufacturers' total profit decreases as competition becomes more intense. With production economy and information contracting, however, more intense competition can increase the manufacturers' total profit if it induces the retailer to stop sharing information with one of the two informed manufacturers. This is because when competition intensity is large enough and the number of informed manufacturers is reduced from two to one, both manufacturers' order quantities become more uncertain, which lowers their costs.[18] In this case, the retailer has an incentive to share information with less manufacturers because she can share the efficiency gain via information contracting. Figure 4 illustrates the results of Proposition 9. Note that ϕ_e^C is the same as ϕ_e^S in this example.

Our results in §§5 and 6 show how production cost, competition intensity, and information contracting may explain the diverse data-sharing program practices reported in §1. In particular, Proposition 6 demonstrates that a retailer may have an incentive to share data for free (Keifer 2010), an interesting practice that cannot be explained by the existing literature.

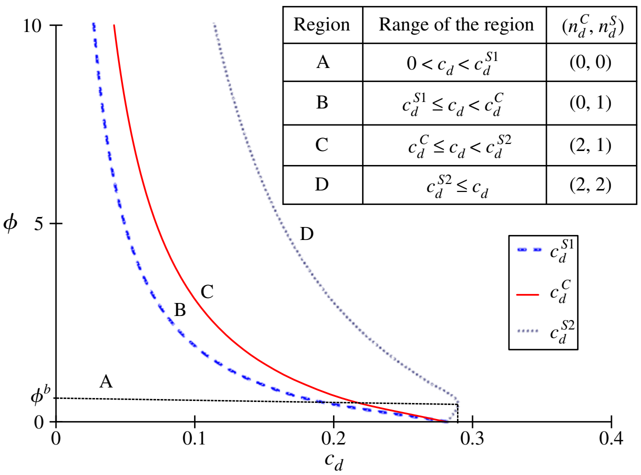
7. Extensions

7.1. Vertical Nash Under Production Diseconomy

We consider the case when wholesale prices and retail prices are determined under vertical Nash. The

[18] Refer to Lemma 4 in the appendix. If ϕ increases, the threshold $[(5+10\phi+3\phi^2) - (1+\phi)\sqrt{1+2\phi+9\phi^2}]/[2(1+\phi)(1+2\phi)]$ decreases and when it becomes smaller than c_e, we have $V_q(2) \le V_q^U(1) < V_q^I(1)$.

Figure 5 (Color online) Equilibrium Information Sharing Decisions with Production Diseconomy and Vertical Nash



sequence of events is the same as that given in §3 with the following exception. In event 3 of the basic model, the manufacturers are Stackelberg leaders who simultaneously offer wholesale prices to the retailer before she determines the retail prices. For the case of vertical Nash, each manufacturer determines a wholesale price for his own product, the retailer determines the retail margins for both products, and all these decisions are made simultaneously. This corresponds to the case when the manufacturers and the retailer have similar power in determining the wholesale prices.

As shown in Figure 5, the equilibrium information sharing decisions exhibit the same threshold structure as before. The results of Propositions 1–4 remain qualitatively the same (with the thresholds having different values) except that the threshold c_d^{S2} may not be decreasing in ϕ.[19]

Proposition 10. *A larger production diseconomy or more intense competition induces the retailer to share information with more manufacturers. The only exception is under sequential contracting, there exists ϕ^b such that if $\phi \le \phi^b$ and $c_d^{S2}(\phi) \le c_d \le c_d^{S2}(\phi^b)$, more intense competition induces the retailer to share information with less manufacturers.*

Here $c_d^{S2}(\phi)$ is defined as in Proposition 3 and we show explicitly its dependence on ϕ. Proposition 10 shows that the qualitative results under vertical Nash are almost the same as before except when ϕ is small and c_d takes some intermediate values. This can be explained as follows. With sequential contracting, information sharing between the retailer and manufacturer i leads to a revenue loss (because the double marginalization of w_i becomes stronger) for the retailer and a saving in production cost (because the order uncertainty becomes lower) for manufacturer i. When manufacturer j is informed, more intense competition increases both the cost saving and the revenue loss.[20] Under the conditions in Proposition 10, the impact of competition intensity on revenue loss is more significant than that on cost saving.[21] As a result, the value of information sharing between the retailer and manufacturer i decreases when competition becomes more intense.

As before, we can also show that the retailer's profit is higher under sequential information contracting and the equilibrium information sharing decisions under concurrent information contracting maximize the total profit of the three firms. Details are omitted.

7.2. Information Contracting with Voluntary Sharing Under Production Economy

Here we relax the assumption that the retailer can commit on not sharing information for free. The sequence of events is the same as that given in §3, except for the information contracting event (i.e., event 1). After the manufacturers decide whether to accept the information contracts, the retailer can decide whether to share information for free with a manufacturer who does not accept the information contract. As before, let $Z = C$ denote concurrent contracting and $Z = S$ denote sequential contracting.

Proposition 11. (a) *There exist $\tilde{c}_e^C$ and $\tilde{c}_e^S$ such that $n_e^Z = 0$ if $c_e < 1/(1+\phi)$, $n_e^Z = 2$ if $1/(1+\phi) \le c_e < \tilde{c}_e^Z$, and $n_e^Z = 1$ if $\tilde{c}_e^Z \le c_e < 2/(1+\phi)$.*

(b) *$\tilde{c}_e^C$ and $\tilde{c}_e^S$ are decreasing in ϕ.*

(c) *There exist $c_e^I < \tilde{c}_e^Z$ and $c_e^{II} > \tilde{c}_e^Z$ such that if $1/(1+\phi) \le c_e \le c_e^I$ or $c_e^{II} < c_e < 2/(1+\phi)$, the retailer does not receive any payment for sharing information.*

(d) *$\tilde{c}_e^C < c_e^C$.*

Parts (a) and (b) show that the equilibrium information sharing decisions have the same threshold structure as that of the basic model, and the effect of the competition intensity ϕ is also similar. Part (c) shows that there are two regions in which the retailer receives no payment for sharing information. In each region, the retailer has an incentive to share information for free because of the resulting weaker double marginalization. The manufacturers anticipate this, reject the information contracts, and eventually receive information free of charge. If both manufacturers reject the information contracts and the retailer shares information for free with one of them, there

[19] We abuse notations by using the same set of notations as before for the case of vertical Nash.

[20] With concurrent contracting, more intense competition reduces the revenue loss caused by information sharing.

[21] This is not true for the basic model because wholesale prices are more sensitive to competition intensity under vertical Nash when compared with the basic model.

are two possible pure-strategy equilibria depending on which manufacturer is chosen to receive the information. With concurrent contracting, $\tilde{c}_e^C$ is the same for both subgame equilibria. It follows from part (d) that when the retailer cannot commit on not sharing information for free, it is more likely to have partial information sharing. With sequential contracting, however, $\tilde{c}_e^S$ is smaller than c_e^S when the manufacturer who receives the information contract first is chosen to receive information for free (after both manufacturers have rejected the information contracts) but larger than c_e^S otherwise. When the retailer cannot commit on not sharing information for free, it is more likely to have partial information sharing under the first subgame equilibrium but less likely under the second subgame equilibrium.

8. Concluding Remarks

In this paper, we have examined the issue of information sharing in a supply chain with two competing manufacturers selling through a common retailer. We consider the case where the retailer possesses verifiable information and offers ex ante information sharing contracts to the manufacturers. Another interesting case is ex post information sharing where the retailer decides whether to share information after observing the demand signal. If the information is verifiable, this corresponds to strategic information sharing and it has been shown that the retailer uses a threshold policy to disclose information in a single supply chain (Guo 2009). If the information is not verifiable, the retailer could communicate her information via cheap talk. Chu et al. (2011) show that in a single supply chain where the manufacturer's only decision is wholesale price, the retailer always has an incentive to deflate demand information to induce a lower wholesale price. Because of this, no information can be shared credibly. Chu et al. (2011) also show that when the manufacturer uses the shared information to make both capacity and wholesale price decisions, it is possible for the retailer to share unverifiable information via cheap talk. It would be interesting to consider strategic information sharing or cheap talk for the supply chain structure studied in this paper.

We focus on investigating how information sharing influences strategic interactions between firms and ignore its impact on operational improvements such as inventory cost reduction. To address the latter issue, we need to consider the case where the manufacturers produce before demand realizes so that information sharing allows them to make production decisions with less uncertainty (and hence reduces the cost of mismatch between production and demand). This would be an interesting case to consider but, because it requires a very different mode of analysis, is left for further research.

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Appendix. Lemmas and Proofs

We first present four lemmas that are useful for showing the effect of information sharing on a manufacturer's order uncertainty or for the proofs of the propositions.

Consider the production diseconomy model. Let the variance of the order quantity be denoted by $V_q(n)$ for $n=0$ or 2, and by $V_q^X(n)$ for $n=1$, where $X=U$ if the manufacturer is uninformed and $X=I$ if he is informed. The following lemma shows the effect of information sharing on the order uncertainty. For example, the order uncertainty of an uninformed manufacturer becomes larger ($V_q(0) < V_q^U(1)$) when the rival manufacturer receives information from the retailer.

LEMMA 2. $V_q^I(1) < V_q(2) < V_q(0) < V_q^U(1)$.

The following lemma is useful for the proofs of Propositions 1–5. Note that the profit functions in the lemma are given in §4.2 with $c = c_d$.

LEMMA 3. (a) $\pi_M(2) > \pi_M^I(1) > \pi_M(0) > \pi_M^U(1)$.
(b) $\pi_R(0) > \pi_R(1) > \pi_R(2)$.
(c) $\pi_R(1) - \pi_R(2) > \pi_R(0) - \pi_R(1)$.

Now consider the production economy model. Using the same notations as the production diseconomy model, the following lemma shows the effect of information sharing on the order uncertainty.

LEMMA 4. (a) *If* $0 < c_e < 1/(1+\phi)$, $V_q^I(1) < V_q(2) < V_q(0) < V_q^U(1)$.

(b) *If* $1/(1+\phi) < c_e < (4+5\phi)/[(2+3\phi)(1+\phi)]$, $V_q^U(1) < V_q(0) < V_q(2) < V_q^I(1)$.

(c) *If* $(4+5\phi)/[(2+3\phi)(1+\phi)] \le c_e < [(5+10\phi+3\phi^2) - (1+\phi)\sqrt{1+2\phi+9\phi^2}]/[2(1+\phi)(1+2\phi)]$, $V_q(0) \le V_q^U(1) < V_q(2) < V_q^I(1)$.

(d) *If* $[(5+10\phi+3\phi^2) - (1+\phi)\sqrt{1+2\phi+9\phi^2}]/[2(1+\phi)\cdot(1+2\phi)] \le c_e < 2/(1+\phi)$, $V_q(0) < V_q(2) \le V_q^U(1) < V_q^I(1)$.

The following lemma is useful for the proofs of Propositions 6–9. Note that the profit functions in the lemma are given in §4.2 with $c = -c_e$.

LEMMA 5. (a) $\pi_M^I(1) \ge \pi_M(0)$. *There exists* $c_e^a \in (1/(1+\phi), 2/(1+\phi))$ *such that* $\pi_M(2) \ge \pi_M^U(1)$ *if* $c_e \le c_e^a$ *and* $\pi_M(2) < \pi_M^U(1)$ *otherwise.*

(b) $\pi_M(0) \ge \pi_M^U(1)$ *if* $1/(1+\phi) \le c_e \le (4+5\phi)/[(2+3\phi)\cdot(1+\phi)]$ *and* $\pi_M(0) < \pi_M^U(1)$ *otherwise.*

(c) $\pi_M(2) \ge \pi_M^I(1)$ *if* $c_e \le 1/(1+\phi)$ *and* $\pi_M(2) < \pi_M^I(1)$ *otherwise.*

(d) *There exists* $c_e^N \in (1/(1+\phi), 2/(1+\phi))$ *such that* $\pi_R(0) > \pi_R(1) > \pi_R(2)$ *if* $c_e < 1/(1+\phi)$, $\pi_R(2) \geq \pi_R(1) \geq \pi_R(0)$ *if* $1/(1+\phi) \leq c_e \leq c_e^N$, *and* $\pi_R(1) > \pi_R(2) > \pi_R(0)$ *if* $c_e^N < c_e < 2/(1+\phi)$.

We are now ready to present the proofs of the lemmas and the propositions.

Proof of Lemma 1. It is easy to verify that w_i^* and p_i^* satisfy $w_i^* = \hat{w}_i(w_j^*)$ and $p_i^* = \hat{p}_i(w_i^*, w_j^*)$, and hence they are an equilibrium. To show the uniqueness, it suffices to show the solution to equations $w_i^* = \hat{w}_i(w_j^*)$ (for $i = 1, 2$) is unique, because the retailer's best-response retail prices are uniquely determined by the wholesale prices. When $n = 0$ or 2, we have $E[w_j] = w_j$, and it is easy to check that the linear equations $w_i^* = \hat{w}_i(w_j^*)$ have a unique solution. When $n = 1$, without loss of generality, assume $X_i = I$. Take expectation of $\hat{w}_i(w_j)$ with respect to Y and substitute it into $\hat{w}_j(w_i)$, we can find a unique solution w_j^*. Then $w_i^* = \hat{w}_i(w_j^*)$ is also unique. □

Proof of Lemmas 2–5. It is straightforward and details are omitted.

Proof of Proposition 1. The results follow directly from Lemma 3. □

Proof of Proposition 2. Notice that $[\pi_R(2) + 2\pi_M(2)] - [\pi_R(0) + 2\pi_M(0)] > 0$ iff $c_d > c_d^C = (\sqrt{8 + 8\phi + \phi^2} - 2 - \phi)/[2(1+\phi)]$. Given any side payment T, the manufacturers' payoff matrix of the information sharing game is given in Table 1. When $T \leq \pi_M^I(1) - \pi_M(0)$, the dominant-strategy equilibrium is (I, I). When $T \geq \pi_M(2) - \pi_M^U(1)$, the dominant-strategy equilibrium is (U, U). When $\pi_M^I(1) - \pi_M(0) \leq T \leq \pi_M(2) - \pi_M^U(1)$, there are two equilibria (I, I) and (U, U). In this case, the manufacturers choose the Pareto-optimal equilibrium, which is (I, I) if $T \leq \pi_M(2) - \pi_M(0)$, and (U, U) otherwise. Therefore, the optimal decision for the retailer is either $n = 0$ or $n = 2$ with $T = \pi_M(2) - \pi_M(0)$. The retailer prefers $n = 2$ to $n = 0$ iff $\pi_R(2) + 2[\pi_M(2) - \pi_M(0)] \geq \pi_R(0)$. Therefore, $n_d^C = 2$ if $c_d \geq c_d^C$, and $n_d^C = 0$ otherwise. □

Proof of Proposition 3. We define

$$V_{R+M}^U = [\pi_M^I(1) + \pi_R(1)] - [\pi_M(0) + \pi_R(0)] \quad \text{and}$$
$$V_{R+M}^I = [\pi_M(2) + \pi_R(2)] - [\pi_M^U(1) + \pi_R(1)].$$

We can show that $V_{R+M}^U \geq 0$ iff $c_d \geq c_d^{S1} = (\sqrt{2} - 1)/(1+\phi)$. It can be proved that V_{R+M}^I is convex in c_d, $V_{R+M}^I|_{c_d=0} < 0$, $V_{R+M}^I|_{c_d=c_d^{S1}} < 0$, and $V_{R+M}^I|_{c_d\to\infty} > 0$. Hence, there exists a unique c_d^{S2} ($c_d^{S2} > c_d^{S1}$) such that $V_{R+M}^I \geq 0$ iff $c_d \geq c_d^{S2}$.

Without loss of generality, we assume that the retailer offers a contract to manufacturer 1 first. Now we consider the contracting outcome with manufacturer 2, given X_1. Suppose $X_1 = I$: with $n = 2$, the payoffs of the three firms equal $(\pi_R(2) + T_f + T_s, \pi_M(2) - T_f, \pi_M(2) - T_s)$; with $n = 1$, their payoffs equal $(\pi_R(1) + T_f, \pi_M^I(1) - T_f, \pi_M^U(1))$; manufacturer 2 agrees to buy information iff $T_s \leq \pi_M(2) - \pi_M^U(1)$, and hence the retailer induces $n = 2$ iff $V_{R+M}^I \geq 0$. Suppose $X_1 = U$: with $n = 1$, the payoffs of the three firms equal $(\pi_R(1) + T_s, \pi_M^U(1), \pi_M^I(1) - T_s)$; with $n = 0$, their payoffs equal $(\pi_R(0), \pi_M(0), \pi_M(0))$; manufacturer 2 agrees to buy information iff $T_s \leq \pi_M^I(1) - \pi_M(0)$, and the retailer induces $n = 1$ iff $V_{R+M}^U \geq 0$.

Then we consider the contracting outcome with manufacturer 1, in anticipation of its impact on manufacturer 2's decision. (i) If $V_{R+M}^U < 0$ (i.e., $0 < c_d < c_d^{S1}$), manufacturer 2 will not buy information, and manufacturer 1 will buy information iff $T_f \leq \pi_M^I(1) - \pi_M(0)$. Notice that $\pi_R(1) + T_f \leq \pi_R(0) + V_{R+M}^U < \pi_R(0)$, it is optimal for the retailer not to share information. (ii) If $V_{R+M}^U \geq 0$ and $V_{R+M}^I < 0$ (i.e., $c_d^{S1} \leq c_d < c_d^{S2}$), whatever decision manufacturer 1 makes, the retailer will induce a different information sharing outcome with manufacturer 2. Hence, manufacturer 1 agrees to buy information iff $T_f \leq \pi_M^I(1) - \pi_M^U(1)$. It is clear that the optimal decision of the retailer is to induce $n = 1$ with $T_f = \pi_M^I(1) - \pi_M^U(1)$. (iii) If $V_{R+M}^I \geq 0$ (i.e., $c_d \geq c_d^{S2}$), the retailer will share information with manufacturer 2 for sure. Manufacturer 1 agrees to buy information iff $T_f \leq \pi_M(2) - \pi_M^U(1)$. Notice that $\pi_R(2) + 2[\pi_M(2) - \pi_M^U(1)] = \pi_R(1) + [\pi_M(2) - \pi_M^U(1)] + V_{R+M}^I > \pi_R(1) + [\pi_M^I(1) - \pi_M(0)]$, the retailer will induce $n = 2$ by charging $T_f = T_s = \pi_M(2) - \pi_M^U(1)$. □

Proof of Proposition 4. For part (a), it is easy to check the ordering of $c_d^{S1} < c_d^C$. For the ordering of $c_d^C < c_d^{S2}$, it follows from the convexity of V_{R+M}^I with respect to c_d and $V_{R+M}^I|_{c_d=c_d^C} < 0$.

For part (b), it is obvious that c_d^{S1} and c_d^C are decreasing in ϕ. Let $\phi(c_d^{S2})$ denote the inverse function of $c_d^{S2}(\phi)$. We can show that $dV_{R+M}^I/dc_d|_{c_d=c_d^{S2}} > 0$ and $dV_{R+M}^I/d\phi|_{\phi=\phi(c_d^{S2})} > 0$. Taking derivative of ϕ on both sides of the equation $V_{R+M}^I = 0$, we have

$$\frac{dV_{R+M}^I}{dc_d}\bigg|_{c_d=c_d^{S2}} \frac{dc_d^{S2}}{d\phi} + \frac{dV_{R+M}^I}{d\phi}\bigg|_{\phi=\phi(c_d^{S2})} = 0,$$

which implies $dc_d^{S2}/d\phi < 0$.

Part (c) follows from Propositions 2 and 3 and part (b) of the proposition.

For part (d), the conclusion is obvious when $0 < c_d < c_d^{S1}$ and $c_d \geq c_d^{S2}$, because the retailer sells information to the same number of manufacturers under both models and the side payment under sequential information contracting is higher. When $c_d^{S1} \leq c_d < c_d^C$, the retailer prefers sequential information contracting because $(\pi_R(1) + [\pi_M^I(1) - \pi_M^U(1)]) - \pi_R(0) = [\pi_M(0) - \pi_M^U(1)] + V_{R+M}^U > 0$. When $c_d^C \leq c_d < c_d^{S2}$, again the retailer prefers sequential information contracting because $\pi_M^I(1) + 2\pi_M(0) - 2\pi_M^U(1) - \pi_M(2) > 0$ when $c_d \geq c_d^C$, and hence $(\pi_R(1) + [\pi_M^I(1) - \pi_M^U(1)]) - (\pi_R(2) + 2[\pi_M(2) - \pi_M(0)]) = [\pi_M^I(1) + 2\pi_M(0) - 2\pi_M^U(1) - \pi_M(2)] - V_{R+M}^I > 0$. □

Proof of Proposition 5. Part (a) can be obtained by taking derivative of $\pi_R(0)$ with respect to c_d. For parts (b) and (c), by definition, $V_{R+M}^U = [\pi_M^I(1) + \pi_R(1)] - [\pi_M(0) + \pi_R(0)] = 0$ at $c_d = c_d^{S1}$ and $V_{R+M}^I = [\pi_M(2) + \pi_R(2)] - [\pi_M^U(1) + \pi_R(1)] = 0$ at $c_d = c_d^{S2}$. Based on these two equations, Proposition 3, and Lemma 3, it is straightforward to prove the results. □

Proof of Proposition 6. Part (a) follows directly from Lemma 5. For part (b), we can show that $c_e^a > c_e^N$ and the result follows directly from part (a). □

Proof of Proposition 7. First consider $Z = C$. We can show that $\pi_M(2) - \pi_M^U(1) \geq \pi_M^I(1) - \pi_M(0)$ iff $c_e \leq c_{e1}$, for some $c_{e1} \in (1/(1+\phi), 2/(1+\phi))$. (i) When $c_e < c_{e1}$: if $T > \pi_M(2) - \pi_M^U(1)$, the unique equilibrium is (U, U); if $T \leq \pi_M^I(1) - \pi_M(0)$, the unique equilibrium is (I, I); when $\pi_M^I(1) - \pi_M(0) < T \leq \pi_M(2) - \pi_M^U(1)$, there are two equilibria (U, U) and (I, I), and the manufacturers pick up the Pareto-optimal equilibrium characterized as follows. If $c_e < 1/(1+\phi)$, then $\pi_M(2) - \pi_M(0) \geq \pi_M(2) - \pi_M^U(1)$ and the Pareto-optimal equilibrium is (I, I) (with the optimal side payment for $n = 2$ equals $T = \pi_M(2) - \pi_M^U(1)$); if $1/(1+\phi) \leq c_e < c_{e1}$, then $\pi_M(2) - \pi_M(0) < \pi_M^I(1) - \pi_M(0)$ and the Pareto-optimal equilibrium is (U, U) (in this case, the optimal side payment for $n = 2$ is $T = \pi_M^I(1) - \pi_M(0)$). Then for $c_e < 1/(1+\phi)$, we have $\pi_R(2) + 2[\pi_M(2) - \pi_M^U(1)] < \pi_R(0)$, and hence the retailer induces (U, U). For $1/(1+\phi) \leq c_e < c_{e1}$, since $\pi_R(2) + 2[\pi_M^I(1) - \pi_M(0)] > \pi_R(0)$, the retailer induces $n = 2$ with $T = \pi_M^I(1) - \pi_M(0)$. (ii) When $c_e^a < c_e < 2/(1+\phi)$, i.e., $\pi_M(2) < \pi_M^U(1)$, clearly $\pi_M(2) - T < \pi_M^U(1)$ for all $T \geq 0$. Hence, if the other manufacturer is informed already, a manufacturer would not buy information. The retailer prefers $n = 1$ with $T = \pi_M^I(1) - \pi_M(0)$ iff

$$V_{R+M}^U = ((1+\phi)c_e - 1)\frac{-(1+\phi)^2 c_e^2 + 2(1+\phi)c_e + 1}{4(1+\phi)(2-(1+\phi)c_e)^2}\beta(t, \sigma)\sigma^2$$

is nonnegative, which is always true for $c_e^a < c_e < 2/(1+\phi)$. (iii) $c_{e1} \leq c_e \leq c_e^a$, i.e., $0 \leq \pi_M(2) - \pi_M^U(1) < \pi_M^I(1) - \pi_M(0)$. When $T \leq \pi_M(2) - \pi_M^U(1)$, the dominant-strategy equilibrium is (I, I). When $T > \pi_M^I(1) - \pi_M(0)$, the dominant-strategy equilibrium is (U, U). When $\pi_M(2) - \pi_M^U(1) < T \leq \pi_M^I(1) - \pi_M(0)$, the equilibria are (I, U) and (U, I). Therefore, the optimal decision for the retailer is either $n = 0$, or $n = 1$ with $T = \pi_M^I(1) - \pi_M(0)$, or $n = 2$ with $T = \pi_M(2) - \pi_M^U(1)$. The retailer prefers $n = 1$ to $n = 0$ iff $V_{R+M}^U \geq 0$, which is always true for $1/(1+\phi) \leq c_e < 2/(1+\phi)$. She prefers $n = 2$ to $n = 1$ iff $(\pi_R(2) + 2[\pi_M(2) - \pi_M^U(1)]) - (\pi_R(1) + [\pi_M^I(1) - \pi_M(0)]) > 0$. For $c_e \in (1/(1+\phi), 2/(1+\phi))$, the inequality is true iff $c_e \leq c_{e2}$ for some $c_{e2} \in (1/(1+\phi), 2/(1+\phi))$. We define $c_e^C = \max\{c_{e1}, c_{e2}\}$, then the optimal information sharing outcome is as follows. If $c_e < 1/(1+\phi)$, $n_e^C = 0$; if $1/(1+\phi) \leq c_e < c_e^C$, $n_e^C = 2$ with $T = \min\{\pi_M^I(1) - \pi_M(0), \pi_M(2) - \pi_M^U(1)\}$; if $c_e^C \leq c_e < 2/(1+\phi)$, $n_e^C = 1$ with $T = \pi_M^I(1) - \pi_M(0)$.

Then consider $Z = S$. We can show that $V_{R+M}^I \geq 0$ if $1/(1+\phi) \leq c_e \leq c_{e3}$ for some $c_{e3} \in (1/(1+\phi), 2/(1+\phi))$. Again, we assume that the retailer offers a contract to manufacturer 1 first. The firm profits and manufacturer 2's best response remain the same as in the diseconomy case. (i) If $V_{R+M}^U < 0$ (i.e., $0 < c_e < 1/(1+\phi)$), manufacturer 2 will not buy information, and manufacturer 1 will buy information iff $T_f \leq \pi_M^I(1) - \pi_M(0)$. Notice that $\pi_R(1) + T_f \leq \pi_R(0) + V_{R+M}^U < \pi_R(0)$, it is optimal for the retailer not to share information. (ii) If $V_{R+M}^U \geq 0$ and $V_{R+M}^I < 0$ (i.e., $c_{e3} < c_e < 2/(1+\phi)$), whatever decision manufacturer 1 makes, the retailer will induce a different information sharing outcome with manufacturer 2. Manufacturer 1 agrees to buy information iff $T_f \leq \pi_M^I(1) - \pi_M^U(1)$, and manufacturer 2 will buy iff $X_1 = U$ and $T_s \leq \pi_M^I(1) - \pi_M(0)$. Hence, the retailer will induce $n = 1$ with $T = \pi_M^I(1) - \min\{\pi_M^U(1), \pi_M(0)\}$. (iii) If $V_{R+M}^I \geq 0$ (i.e., $1/(1+\phi) \leq c_e \leq c_{e3}$), the retailer will share information with manufacturer 2 for sure. Manufacturer 1 agrees to buy information iff $T_f \leq \pi_M(2) - \pi_M^U(1)$. Hence, the retailer chooses between sharing with both ($T_f = T_s = \pi_M(2) - \pi_M^U(1)$) and sharing with manufacturer 2 only ($T_s = \pi_M^I(1) - \pi_M(0)$), and she prefers $n = 2$ iff $c_e < c_{e2}$. To summarize, if $0 < c_e < 1/(1+\phi)$, $n_e^S = 0$; if $1/(1+\phi) \leq c_e \leq c_e^S = \min\{c_{e2}, c_{e3}\}$, $n_e^S = 2$ with $T_f = T_s = \pi_M(2) - \pi_M^U(1)$; if $c_e^S < c_e < 2/(1+\phi)$, $n_e^S = 1$, with $T = \pi_M^I(1) - \min\{\pi_M^U(1), \pi_M(0)\}$ if $c_{e3} < c_e < 2/(1+\phi)$, and $T_s = \pi_M^I(1) - \pi_M(0)$ otherwise. □

Proof of Proposition 8. For part (a), we can show that $c_e^N < c_{e2}$ and $c_e^N < c_{e3}$, then $c_e^N < c_e^S = \min\{c_{e2}, c_{e3}\} \leq c_e^C = \max\{c_{e1}, c_{e2}\}$.

For part (b), we can show that c_e^N, c_{e1}, c_{e2}, and c_{e3} are all decreasing in ϕ using the approach in the proof of part (b) of Proposition 4. Then the results follow immediately.

Part (c) follows from Propositions 6 and 7 and part (b) of this proposition.

For part (d), we can show that c_{e2} is between c_{e1} and c_{e3}. (i) If $c_{e1} \leq c_{e3}$, $c_e^S = c_e^C = c_{e2}$, the information sharing outcome is the same under the two models, and the side payment under sequential information contracting is higher. Then the results follow immediately. (ii) If $c_{e1} > c_{e3}$, then $c_e^C = c_{e1} > c_e^S = c_{e3}$. Concurrent information contracting induces sharing information with more manufacturers. When the information sharing outcome is the same under the two models, clearly the side payment under sequential information contracting is higher; otherwise ($c_e^S < c_e < c_e^C$), $n_e^S = 1$ with $T_s = \pi_M^I(1) - \pi_M^U(1)$ and $n_e^C = 2$ with $T = \pi_M^I(1) - \pi_M(0)$. The retailer prefers sequential information contracting because $(\pi_R(1) + [\pi_M^I(1) - \pi_M^U(1)]) - (\pi_R(2) + 2[\pi_M^I(1) - \pi_M(0)]) = -V_{R+M}^I + [\pi_M(2) - \pi_M^U(1)] - [\pi_M^I(1) - \pi_M(0)] + [\pi_M(0) - \pi_M^U(1)] \geq 0$. The manufacturer's total profit under concurrent information contracting is $2[\pi_M(2) + \pi_M(0) - \pi_M^I(1)]$, higher than their total profit under sequential information contracting $2\pi_M^U(1)$. □

Proof of Proposition 9. Part (a) can be obtained by taking derivative of $\pi_M(0)$ with respect to ϕ.

For part (b), we need to show that there is a positive jump in the total profit of the manufacturers at ϕ_e^C. If $c_{e1} < c_{e2}$, the total profit of the manufacturers increases from $2\pi_M^U(1)$ to $\pi_M(0) + \pi_M^U(1)$ as ϕ increases at ϕ_e^C; otherwise, the total profit increases from $2[\pi_M(2) + \pi_M(0) - \pi_M^I(1)]$ to $\pi_M(0) + \pi_M^U(1)$ because $\pi_M(2) < \pi_M^I(1)$ at $c_e = c_{e1}$.

For part (c), we can show that if $c_{e2} < c_{e3}$, the total profit of the manufacturers increases from $2\pi_M^U(1)$ to $\pi_M(0) + \pi_M^U(1)$ at $c_e = c_e^S$. The results follow because we can show that $c_{e2} < c_{e3}$ is equivalent to $\phi_e^S < \phi^a = 1.7602$. □

Proof of Proposition 10. We follow the approach in Choi (1991) to analyze the firms' wholesale and retail price decisions under vertical Nash. For convenience, we abuse notations by using the same set of notations as in the basic model where the manufacturers are the leaders in offering wholesale prices. Given w_1 and w_2, the retailer maximizes her expected profit $(p_1 - w_1)(a + E[\theta \mid Y] - (1+\phi)p_1 + \phi p_2) + (p_2 - w_2)(a + E[\theta \mid Y] - (1+\phi)p_2 + \phi p_1)$ by setting the retail prices to $\hat{p}_i(w_i, w_j) = \frac{1}{2}(a + \beta(t, \sigma)Y + w_i)$. Given the profit margins charged by the retailer, an informed manufacturer maximizes his expected profit $(w_i - b)E[q_i(p_i, p_j) \mid Y] - cE[q_i^2(p_i, p_j) \mid Y]$ by setting the wholesale price to $\hat{w}_i(p_i, p_j) = (2c + 1/(1+\phi))(a + \beta(t, \sigma)Y - (1+\phi)p_i + \phi p_j) + b$; an uninformed manufacturer maximizes his expected profit $(w_i - b)E[q_i(p_i, p_j)] - cE[q_i^2(p_i, p_j)]$

by setting the wholesale price to $\hat{w}_i(p_i, p_j) = (2c+1/(1+\phi))(a-(1+\phi)E[p_i]+\phi E[p_j])+b$. Following the proof of Lemma 1, we can find a unique equilibrium

$$w_i^* = \begin{cases} \bar{w}+\alpha_w(n)Y & \text{if } n=0 \text{ or } 2, \\ \bar{w}+\alpha_w^{X_i}(1)Y & \text{if } n=1, \end{cases}$$

$$p_i^* = \begin{cases} \bar{p}+\alpha_p(n)Y & \text{if } n=0 \text{ or } 2, \\ \bar{p}+\alpha_p^{X_i}(1)Y & \text{if } n=1, \end{cases}$$

where

$$\alpha_w(0)=\alpha_w^U(1)=0, \qquad \alpha_w^I(1)=\frac{1+2(1+\phi)c}{(1+\phi)(3+2(1+\phi)c)}\beta(t,\sigma),$$

$$\alpha_w(2)=\frac{1+2(1+\phi)c}{3+2\phi+2(1+\phi)c}\beta(t,\sigma), \qquad \alpha_p(0)=\alpha_p^U(1)=\frac{\beta(t,\sigma)}{2},$$

$$\alpha_p^I(1)=\frac{4+3\phi+2(1+\phi)(2+\phi)c}{2(1+\phi)(3+2(1+\phi)c)}\beta(t,\sigma),$$

$$\alpha_p(2)=\frac{2+\phi+2(1+\phi)c}{3+2\phi+2(1+\phi)c}\beta(t,\sigma).$$

Here $\bar{w}$ and $\bar{p}$ are the deterministic solutions when $\sigma=0$, where $\bar{w}=[(1+2(1+\phi)c)a+2(1+\phi)b]/[3+2\phi+2(1+\phi)c]$ and $\bar{p}=[(2+\phi+2(1+\phi)c)a+(1+\phi)b]/[3+2\phi+2(1+\phi)c]$. Based on the equilibrium pricing decisions, we obtain the firms' ex ante profits as follows:

$$\pi_M(0)=\bar{\pi}_M-\frac{c\beta(t,\sigma)\sigma^2}{4}-c[1-\beta(t,\sigma)]\sigma^2,$$

$$\pi_M^U(1) = \bar{\pi}_M-\frac{c}{4}\left[\frac{3+4\phi+2(1+\phi)(1+2\phi)c}{(1+\phi)(3+2(1+\phi)c)}\right]^2\beta(t,\sigma)\sigma^2 - c[1-\beta(t,\sigma)]\sigma^2,$$

$$\pi_M^I(1) = \bar{\pi}_M+\frac{1+(1+\phi)c}{(1+\phi)(3+2(1+\phi)c)^2}\beta(t,\sigma)\sigma^2 - c[1-\beta(t,\sigma)]\sigma^2,$$

$$\pi_M(2) = \bar{\pi}_M+\frac{(1+\phi)(1+(1+\phi)c)}{(3+2\phi+2(1+\phi)c)^2}\beta(t,\sigma)\sigma^2 - c[1-\beta(t,\sigma)]\sigma^2,$$

$$\pi_R(0)=\bar{\pi}_R+\frac{\beta(t,\sigma)\sigma^2}{2},$$

$$\pi_R(1)=\bar{\pi}_R+\left[\frac{1+2\phi}{1+\phi}+\frac{4}{(1+\phi)(3+2(1+\phi)c)^2}\right]\frac{\beta(t,\sigma)\sigma^2}{4},$$

$$\pi_R(2)=\bar{\pi}_R+\frac{2(1+\phi)^2}{(3+2\phi+2(1+\phi)c)^2}\beta(t,\sigma)\sigma^2,$$

where $\bar{\pi}_M=(1+\phi)(1+(1+\phi)c)(a-b)^2/(3+2\phi+2(1+\phi)c)^2$, $\bar{\pi}_R=2(1+\phi)^2(a-b)^2/(3+2\phi+2(1+\phi)c)^2$. The rest of the proof is similar to those for Propositions 2, 3, and 4, and we omit the details. □

Proof of Proposition 11. It is similar to that of Proposition 7 and we omit the details. □

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