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Research Article

Vertical Cost-Information Sharing in a Food Supply Chain with Multiple Unreliable Suppliers and Two Manufacturers

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This paper considers a food supply chain where multiple suppliers provide completely substitutable food products to two manufacturers. Meanwhile, the suppliers face yield uncertainty and the manufacturers face uncertain production costs that are private information. While the suppliers compete on price, the manufacturers compete on quantity. We build a stylized multistage game theoretic model to analyze the issue of vertical cost-information sharing (VCIS) within the supply chain by considering key parameters, including the level of yield uncertainty, two manufacturers' cost correlation, the correlated coefficient of suppliers' yield processes, and the number of suppliers. We study the suppliers' optimal wholesale price and the manufacturers' optimal order quantities under different VCIS strategies. Finally, through numerical analyses, we examine how key parameters affect the value of VCIS to each supplier and each manufacturer, respectively. We found that the manufacturers are willing to share cost information with suppliers only when the two manufacturers' cost correlation is less than a threshold. While a high correlated coefficient of suppliers' yield processes and a large number of suppliers promote complete information sharing, a high level of yield uncertainty hinders complete information sharing. All these findings have important implications to industry practices.

1. Introduction

Information asymmetry between supply chain (SC) members is a great challenge for food SC management. Information sharing is an effect tool to eliminate the impact of information asymmetry on SC partners' performances [1]. Demand information sharing [2] and cost-information sharing [3] have been much discussed by scholars. Most of literature assumed that the suppliers are reliable, while in industry practices the suppliers are unreliable due to various uncontrollable factors including equipment error and natural hazards. Our work focuses on vertical cost-information sharing by considering the suppliers with yield uncertainty.

Yield uncertainty is a popular phenomenon in the agricultural and food industries. The quality of agricultural and food products is very sensitive to temperature, humidity, and other natural conditions. For example, in agribusinesses, the yield of crop per acre is uncertain as it depends on such factors as climate condition, irrigation level, and so forth (http://nca2014.globalchange.gov/report/sectors/agriculture). Recently Recha et al. [4] have provided a symmetric report about the effect of climate-correlated conditions on food quality. Some scholars analyzed food SC management in different views. For example, Nyamah et al. [5] and MacKenzie and Apte [6] investigated food quality risk management from the operations management perspective. Keizer et al. [7] and Jin et al. [8] investigated food SC by considering supply network and food traceability, respectively. They examined food SC in a complete information situation, whereas in reality information asymmetry between upstream and downstream SC firms often exists.

After the sourcing firms (i.e., manufacturers) have received the product from farmers (i.e., suppliers), they process these products into final products with one unit marginal cost and sell in a common market. The marginal costs are also uncertain due to uncertain labor cost, uncertain storage costs, and other uncontrollable factors. Both supply uncertainty and cost uncertainty directly affect upstream and downstream SC firms' wholesale prices and order quantity decisions. In this paper, we consider that two manufacturers' costs are their private information.

Motivated by the real business situation as mentioned above, this paper examines a SC with multiple suppliers and two manufacturers and aims to answer two important questions. First, how do suppliers and manufacturers make decisions on wholesale prices and order quantities, respectively, under different VCIS scenarios? (2) Are manufacturers willing to disclose cost information to suppliers?

To answer the above questions, we build a classic three-stage game model. At the 1st-stage VCIS game, each manufacturer has two VCIS strategies: share and not share. Hence, there are four VCIS scenarios: (1) both manufacturers share cost information (i.e., complete cost-information sharing, CCIS); (2) none of them share cost information (i.e., no cost-information sharing, NCIS); (3) manufacturer 1 shares cost information, but manufacturer 2 does not; (4) manufacturer 2 shares cost information, but manufacturer 1 does not. The 2nd stage is the multiple suppliers' selling price game, and the 3rd stage is the two manufacturers' selling quantities game. After solving each subgame, we obtain the suppliers' optimal wholesale prices and the two manufacturers' optimal order quantities under each VCIS scenario. Further, we found that both manufacturers are willing to share cost information with their suppliers. Moreover, we found that complete information sharing will benefit all SC partners and the whole SC.

The remainder of this paper is as follows. Section 2 summarizes the related work. The model framework is shown in Section 3. The equilibrium solutions for four VCIS scenarios are provided in Section 4. The VCIS game is analyzed in Section 5. Section 6 provides a numerical analysis. Conclusions are drawn in Section 7.

2. Related Work

Our research is closely related to information sharing. The literature in this area can be divided into two streams: horizontal information sharing (HIS) and vertical information sharing (VIS) [9].

Some scholars focus on HIS. For example, Clarke [10] and Galor [11] studied HIS in an oligopoly model and showed that no HIS is a unique equilibrium. Kirby [12] investigated the incentive for HIS in an oligopoly model where firms have nonlinear product costs and showed that HIS exists under some conditions. Vives [13] discussed firms' HIS under Cournot competition and Bertrand competition, respectively. Li [14] examined the inventive for demand and cost-information sharing. Zhu [3] and Zhou and Zhu [15] investigated the incentive for cost-information sharing in a business-to-business setting under Cournot competition. Wu et al. [16] examined HIS by considering firms with capacity constraints. Natarajan et al. [17] analyzed HIS by considering time as an important factor in their model. Jiang and Hao [18] showed that information sharing and cooperative price for firms are strategic complements.

On the other hand, some researchers focus on VIS in a SC context. Li [19] and Zhang [20] took information leakage into account when studying VIS within a SC. Subsequently, Anand and Goyal [21], Kong et al. [22], and Shamir [23] investigated VIS by taking into account the fact that information leakage comes from the upstream suppliers. Li and Zhang [2] examined how the level of confidentiality influences firms' VIS decisions. Ha et al. [24, 25] studied VIS in two competing SCs. Wu et al. [26] examined the relationship between channel construction and VIS. Jiang and Hao [27] examined VIS under different channel structures. Subsequently, Zhou et al. [28] explored the effect of group purchasing organizations (GPOs) on VIS. Zhang and Xiong [29] explored VIS in a closed-loop SC. These papers focused on demand information sharing. Cost-information sharing has also been researched by several scholars. For example, Yao et al. [30] explored cost-information sharing in a SC by considering value-added costs as retailers' private information. Liu et al. [31] examined the interplay between VCIS and channel choices. Kostamis and Duenyas [32] investigated the value of both cost and demand information sharing. Moreover, Cachon and Lariviere [33], Eksoz et al. [34], and Resende-Filho and Hurley [35] explored the value of information to SC operational decisions.

Our work is different from those works above in that we examine the incentive for VCIS within a SC which has n-suppliers and two competing manufactures. The suppliers are subject to yield uncertainty and are engaged in setting price. Therefore, this is the first study to address the above-mentioned business scenario.

3. Model Framework

In this paper, we consider a SC with n unreliable suppliers and two competing manufacturers with private cost information. The suppliers sell complete substitutable food products to the two manufacturers.

3.1. Supply and Cost-Information Structures. The suppliers' yield uncertainty is modeled as a random proportion [36]; that is, if one manufacture's order quantity for each supplier is q_{ik}, the final quantity received from each supplier is a random proportion y_k of q_{ik}, that is, $y_k q_{ik}$. We assume that $y_k \in (0, 1]$ and $E[y_k] = \mu \leq 1$ and $\mathrm{Var}[y_k] = \sigma_y^2$ (the same assumption is provided in [37–39]). Also, we assume that $\rho = \mathrm{Cov}(y_k, y_l)/\sigma_y^2$ and $\rho \in [-1, 1)$, $k \neq l$. In addition, let $\delta = \sigma_y/\mu$ denote the level of yield uncertainty. Each supplier's expected cost is c, where $c = c_1/\mu + c_2$ and c_1 and c_2 represent the unit manufacture cost and the unit transport cost, respectively.

Each manufacturer's marginal cost c_{m_i} is uncertain, and we assume that c_{m_i} follows a normal distribution with $E[c_{m_i}] = 0$ and $\mathrm{Var}[c_{m_i}] = \sigma^2$ [19]. It is also assumed that c_{m_i} and c_{m_j} satisfy the following: (1) $E[c_{m_i} \mid c_{m_j}] = \gamma_i + \gamma_j c_{m_j}$, where γ_i, γ_j are positive constants for all $j = 3-i$, $i = 1, 2$, and (2) c_{m_i} and c_{m_j} are identically distributed. Therefore, we have

$$E\left[c_{m_i} \mid c_{m_j}\right] = \eta c_{m_j};$$

$$E\left[c_{m_i} c_{m_j}\right] = \eta \sigma^2;$$

$$E\left[c_{m_i} c_{m_i}\right] = \sigma^2, \tag{1}$$

where $\eta = \mathrm{Cov}[c_{m_i} c_{m_j}]/\sigma^2$ and $\eta \in (0, 1)$.

3.2. The Demand Function. Similar to [19, 40], we assume that the inverse demand function is

$$P = a - Q_i - Q_j, \quad j = 3 - i, \ i = 1, 2, \tag{2}$$

where a is demand intercept, P is the product's retail price, and Q_i and Q_j are the manufacturer i's and the manufacturer j's selling quantities in the common market.

3.3. Sequence Decisions Made by the Manufacturers and Suppliers. The sequence of decisions made by SC members is specified as follows:

(1) Each downstream SC member (i.e., manufacturer) decides whether to share the cost information with upstream SC members (i.e., suppliers) or not.

(2) The suppliers make a decision on prices.

(3) The manufacturers make a decision on selling quantities.

(4) The suppliers make production decisions and transport products.

(5) The yield and cost uncertainties are realized, and the demand is satisfied.

This is a three-stage game problem based on the above sequence. The 1st-stage game is VCIS game. Let $Z_i = Y$ ($Z_i = N$) which means that manufacturer i shares (or does not share) cost information with each supplier. Thus, there exists four possible VCIS scenarios in the 1st-stage game: (Y, Y), (N, N), (Y, N), and (N, Y). The other two games are the selling price game for the suppliers and the selling quantity game for the manufacturers.

The main variables that will be used in the paper are summarized in "Notation for Variables" section.

4. Equilibrium Solutions

In this section, because strategies (Y, N) and (N, Y) are symmetrical, we only consider strategy (Y, N). We address the manufacturers' optimal decisions q_{ik}^* and suppliers' optimal decisions w_k^* under three possible VCIS scenarios: (Y, Y), (N, N), and (Y, N).

4.1. Subgame (Y, Y): Both Manufacturers Share Cost Information. If both manufacturers choose VCIS, the suppliers can make an optimal decision based on c_{m_1} and c_{m_2}. One manufacturer can infer the other manufacturer's private cost information from w_k^{YY*} [19].

Therefore, under subgame (Y, Y), manufacturer i's ($i = 1, 2$) optimization problem is

$$\max_{q_{i1}, q_{i1}, \dots, q_{in}} \quad E\left[\pi_{m_i} \mid c_{m_i}, c_{m_j}\right] = E\left\{\left(a - \sum_{i=1}^{2}\sum_{k=1}^{n} y_k q_{ik}\right)\sum_{k=1}^{n} y_k q_{ik} - \sum_{k=1}^{n} w_k y_k q_{ik} - c_{m_i}\sum_{k=1}^{n} y_k q_{ik} \mid c_{m_i}, c_{m_j}\right\}. \tag{3}$$

Supplier k's ($k = 1, 2, \dots, n$) optimization problem is

$$\max_{w_k} \quad \left[\pi_{s_k} \mid c_{m_1}, c_{m_2}\right] = E\left[\left(w_k - c\right) y_k \left(q_{1k} + q_{2k}\right) \mid c_{m_1}, c_{m_2}\right]. \tag{4}$$

q_{ik}^{YY*} ($i = 1, 2, k = 1, 2, \dots, n$) should satisfy the following 1st-order condition:

$$q_{ik}^{YY*} = \frac{(a - w_k)}{2\mu(1-\rho)\delta_y^2} - \frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}(a - w_k)}{2\mu(1-\rho)\delta_y^2\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]} - \frac{1}{2\mu\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]} \cdot E\left(c_{m_i} \mid c_{m_i}, c_{m_j}\right) - \frac{1}{2}E\left(q_{jk}^{YY*} \mid c_{m_i}, c_{m_j}\right). \tag{5}$$

By Proposition 1 in [14], the unique equilibrium solutions for the manufacturers are specified as

$$q_{ik}^{YY*} = \frac{(a - w_k)}{3\mu(1-\rho)\delta_y^2} - \frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}(a - w_k)}{3\mu(1-\rho)\delta_y^2\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]} - \frac{2}{3\mu\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]}c_{m_i} + \frac{1}{3\mu\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]}c_{m_j}. \tag{6}$$

By inserting q_{ik}^{YY*} into (4), we obtain w_k^{YY*} ($k = 1, 2, \dots, n$) which should satisfy the following 1st-order condition:

$$w_k^{YY*} = \frac{a+c}{2} - \frac{\left(1+\rho\delta_y^2\right)\sum_{l\neq k}^{n}\left[a - E\left(w_l \mid c_{m_1}, c_{m_2}\right)\right]}{2\left[\left(1-\rho\right)\delta_y^2 + \left(n-1\right)\left(1+\rho\delta_y^2\right)\right]} - \frac{\left(1-\rho\right)\delta_y^2}{4\left[\left(1-\rho\right)\delta_y^2 + \left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}\left(c_{m_1} + c_{m_2}\right). \quad (7)$$

Based on Proposition 1 in [14], there exist unique equilibrium solutions w_k^{YY*}. By substituting w_k^{YY*} into (5) and simplifying, we obtain Proposition 1.

Proposition 1. *The equilibrium solutions for subgame (Y, Y) are specified as follows.*

(1) The optimal decisions for the suppliers at equilibrium are

$$w_k^{YY*} = \overline{w}_k + \xi_{k1}^{YY} c_{m_1} + \xi_{k2}^{YY} c_{m_2}, \quad (8)$$

where

$$\overline{w}_k = \frac{\left(1-\rho\right)\delta_y^2 a + \left[\left(1-\rho\right)\delta_y^2 + \left(n-1\right)\left(1+\rho\delta_y^2\right)\right]c}{\left[2\left(1-\rho\right)\delta_y^2 + \left(n-1\right)\left(1+\rho\delta_y^2\right)\right]},$$
$$\xi_{k1}^{YY} = \xi_{k2}^{YY} = -\frac{\left(1-\rho\right)\delta_y^2}{2\left[2\left(1-\rho\right)\delta_y^2 + \left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}. \quad (9)$$

(2) The optimal decisions for the manufacturers at equilibrium are

$$q_{ik}^{YY*} = \overline{q}_{ik} + f_{iki}^{YY} c_{m_i} + f_{ikj}^{YY} c_{m_j}, \quad (10)$$

where

$$\overline{q}_{ik} = \frac{\left[\left(1-\rho\right)\delta_y^2 + \left(n-1\right)\left(1+\rho\delta_y^2\right)\right]\left(a-c\right)}{3\mu\left[\left(1+\delta_y^2\right) + \left(n-1\right)\left(1+\rho\delta_y^2\right)\right]\left[2\left(1-\rho\right)\delta_y^2 + \left(n-1\right)\left(1+\rho\delta_y^2\right)\right]},$$
$$f_{iki}^{YY} = -\frac{\left[7\left(1-\rho\right)\delta_y^2 + 4\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}{6\mu\left[\left(1+\delta_y^2\right) + \left(n-1\right)\left(1+\rho\delta_y^2\right)\right]\left[2\left(1-\rho\right)\delta_y^2 + \left(n-1\right)\left(1+\rho\delta_y^2\right)\right]},$$
$$f_{ikj}^{YY} = \frac{\left[5\left(1-\rho\right)\delta_y^2 + 2\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}{6\mu\left[\left(1+\delta_y^2\right) + \left(n-1\right)\left(1+\rho\delta_y^2\right)\right]\left[2\left(1-\rho\right)\delta_y^2 + \left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}. \quad (11)$$

In Proposition 1, both w_k^{YY*} and q_{ik}^{YY*} are composed of two parts: one is not dependent on c_{m_i} and c_{m_j} (i.e., $\overline{w}_k$ and $\overline{q}_{ik}$), while the other is dependent on c_{m_i} and c_{m_j} (i.e., $\xi_{k1}^{YY} c_{m_1} + \xi_{k2}^{YY} c_{m_2}$ and $f_{ii}^{YY} c_{m_i} + f_{ij}^{YY} c_{m_j}$). Clearly, $\xi_{k1}^{YY} = \xi_{k2}^{YY} < 0$, $f_{iki}^{YY} < 0$, and $f_{ikj}^{YY} > 0$. $\xi_{k1}^{YY} = \xi_{k2}^{YY} < 0$ means that w_k^{YY*} is negatively related to $c_{m_i} + c_{m_j}$. $f_{iki}^{YY} < 0$ means that q_{ik}^{YY*} responds negatively to c_{m_i}, and $f_{ikj}^{YY} > 0$ shows that q_{ik}^{YY*} is positively related to c_{m_j}.

4.2. Subgame (N, N): No Manufacturer Shares Cost Information. Suppose that no manufacturer shares private cost information with their suppliers. The suppliers' optimal decisions w_k^{NN*} are independent of the manufacturers' cost information. Therefore, one manufacturer cannot infer the other firm's cost information from w_k^{NN*} [19].

Therefore, under subgame (N, N), the manufacturer i's $(i = 1, 2)$ optimization problem is

$$\max_{q_{i1}, q_{i1}, \ldots, q_{in}} \quad E\left[\pi_{m_i} \mid c_{m_i}\right] = E\left\{\left(a - \sum_{i=1}^{2}\sum_{k=1}^{n} y_k q_{ik}\right)\sum_{k=1}^{n} y_k q_{ik} - \sum_{k=1}^{n} w_k y_k q_{ik} - c_{m_i}\sum_{k=1}^{n} y_k q_{ik} \mid c_{m_i}\right\}. \quad (12)$$

Supplier k's $(k = 1, 2, \ldots, n)$ optimization problem is

$$\max_{w_k} \quad \left[\pi_{s_k}\right] = E\left[\left(w_k - c\right) y_k \left(q_{1k} + q_{2k}\right)\right]. \quad (13)$$

Manufacturer i's optimal order quantities q_{ik}^{NN*} $(i = 1, 2,\ k = 1, 2, \ldots, n)$ should satisfy the following 1st-order condition:

$$q_{ik}^{NN*} = \frac{\left(a - w_k\right)}{2\mu\left(1-\rho\right)\delta_y^2} - \frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}\left(a - w_k\right)}{2\mu\left(1-\rho\right)\delta_y^2\left[\left(1+\delta_y^2\right) + \left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}$$

$$- \frac{1}{2\mu\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]} E\left(c_{m_i} \mid c_{m_i}\right) - \frac{1}{2} E\left(q_{jk}^{NN*} \mid c_{m_i}\right). \quad (14)$$

With reference to Proposition 1 in [14], the unique equilibrium solutions for the manufacturers are specified as

$$q_{ik}^{NN*} = \frac{(a-w_k)}{3\mu(1-\rho)\delta_y^2} - \frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}(a-w_k)}{3\mu(1-\rho)\delta_y^2\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]} - \frac{(1+t)}{\mu\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right][2(1+t)+1]} \cdot c_{m_i}. \quad (15)$$

By inserting q_{ik}^{NN*} into (13), we can obtain the supplier's optimal wholesale price w_k^{NN*} $(k=1,2,\ldots,n)$ which satisfies the following 1st-order condition:

$$w_k^{NN*} = \frac{a+c}{2} - \frac{\left(1+\rho\delta_y^2\right)\sum_{l\neq k}^{n}\left(a-w_l^{NN*}\right)}{2\left[(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]}. \quad (16)$$

Based on Proposition 1 in [14], there exist unique equilibrium solutions w_k^{NN*} for the manufacturers. Substituting w_k^{NN*} into (13) and simplifying, we obtain Proposition 2.

Proposition 2. *The equilibrium solutions for subgame (N,N) are specified as follows.*

(1) The optimal decisions for the suppliers at equilibrium are

$$w_k^{NN*} = \overline{w}_k. \quad (17)$$

(2) The optimal decisions for the manufacturers at equilibrium are

$$q_{ik}^{NN*} = \overline{q}_{ik} + f_{iki}^{NN} c_{m_i}, \quad (18)$$

where

$$f_{iki}^{NN} = -\frac{1}{\mu\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right](2+\eta)}. \quad (19)$$

Proposition 2 shows that the suppliers' optimal decisions are independent of the manufacturers' private cost information, and manufacturer i's optimal decision depends only on c_{m_i}. $f_{iki}^{NN} < 0$ indicates that manufacturer i responds negatively to c_{m_i}.

4.3. Subgame (Y,N): Only One Manufacturer Shares Cost Information. Suppose only manufacturer 1 shares cost information c_{m_1} with their suppliers. The suppliers set w_k^{SN*} based on c_{m_1}. Then manufacturer 2 can infer manufacturer 1's cost information from w_k^{SN*} [19].

Therefore, under subgame (Y,N), manufacturer 1's optimization problem is

$$\max_{q_{11},q_{11},\ldots,q_{1n}} E\left[\pi_{m_1} \mid c_{m_1}\right] = E\left\{\left(a-\sum_{i=1}^{2}\sum_{k=1}^{n} y_k q_{1k}\right)\sum_{k=1}^{n} y_k q_{1k} - \sum_{k=1}^{n} w_k y_k q_{1k} - c_{m_1}\sum_{k=1}^{n} y_k q_{1k} \mid c_{m_1}\right\}. \quad (20)$$

Manufacturer 2's optimization problem is

$$\max_{q_{21},q_{21},\ldots,q_{2n}} E\left[\pi_{m_2} \mid c_{m_1}, c_{m_2}\right] = E\left\{\left(a-\sum_{i=1}^{2}\sum_{k=1}^{n} y_k q_{2k}\right)\sum_{k=1}^{n} y_k q_{2k} - \sum_{k=1}^{n} w_k y_k q_{2k} - c_{m_2}\sum_{k=1}^{n} y_k q_{2k} \mid c_{m_1}, c_{m_2}\right\}. \quad (21)$$

Supplier k's $(k=1,2,\ldots,n)$ optimization problem is

$$\max_{w_k} \left[\pi_{s_k} \mid c_{m_1}\right] = E\left[(w_k-c)\, y_k\left(q_{1k}+q_{2k}\right) \mid c_{m_1}\right]. \quad (22)$$

The two manufacturers' optimal order quantities q_{1k}^{YN*} and q_{2k}^{YN*} $(k=1,2,\ldots,n)$ should satisfy the following 1st-order condition:

$$q_{1k}^{YN*} = \frac{(a-w_k)}{2\mu(1-\rho)\delta_y^2} - \frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}(a-w_k)}{2\mu(1-\rho)\delta_y^2\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]} - \frac{1}{2\mu\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]} E\left(c_{m_1} \mid c_{m_1}\right) - \frac{1}{2} E\left(q_{2k}^{YN*} \mid c_{m_1}\right),$$

$$q_{2k}^{YN*} = \frac{(a-w_k)}{2\mu(1-\rho)\delta_y^2}$$

$$
\begin{aligned}
&- \frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}\left(a-w_k\right)}{2\mu\left(1-\rho\right)\delta_y^2\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]} \\
&- \frac{1}{2\mu\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]} \\
&\cdot E\left(c_{m_2} \mid c_{m_1}, c_{m_2}\right) - \frac{1}{2}E\left(q_{1k}^{YN*} \mid c_{m_1}, c_{m_2}\right).
\end{aligned} \tag{23}
$$

With reference to Proposition 1 in [14], the unique equilibrium solutions for the two manufacturers are presented as follows:

$$
\begin{aligned}
q_{1k}^{YN*} &= \frac{\left(a-w_k\right)}{3\mu\left(1-\rho\right)\delta_y^2} - \frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}\left(a-w_k\right)}{3\mu\left(1-\rho\right)\delta_y^2\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]} \\
&+ \frac{\eta-2}{3\mu\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}c_{m_1},
\end{aligned} \tag{24}
$$

$$
\begin{aligned}
q_{2k}^{YN*} &= \frac{\left(a-w_k\right)}{3\mu\left(1-\rho\right)\delta_y^2} - \frac{\left(1+\rho\delta_y^2\right)\sum_{k=1}^{n}\left(a-w_k\right)}{3\mu\left(1-\rho\right)\delta_y^2\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]} \\
&+ \frac{2-\eta}{6\mu\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}c_{m_1} \\
&- \frac{1}{2\mu\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}c_{m_2}.
\end{aligned} \tag{25}
$$

By substituting q_{1k}^{YN*} and q_{2k}^{YN*} into (22), we can obtain the suppliers' optimal wholesale price w_k^{YN*} $(k = 1, 2, \ldots, n)$ that satisfies the following 1st-order condition:

$$
\begin{aligned}
w_k^{YN*} &= \frac{a+c}{2} - \frac{\left(1+\rho\delta_y^2\right)\sum_{l\neq k}^{n}\left(a-w_l^{YN*}\right)}{2\left[\left(1-\rho\right)\delta_y^2+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]} \\
&- \frac{\left(1-\rho\right)\delta_y^2\left(\eta+1\right)}{4\left[\left(1-\rho\right)\delta_y^2+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}c_{m_1}.
\end{aligned} \tag{26}
$$

Based on Proposition 1 in [14], there exist unique equilibrium solutions w_k^{YN*} for two manufacturers. By substituting w_k^{YN*} into (24) and (25), respectively, and simplifying, we obtain Proposition 3.

Proposition 3. *The equilibrium solutions for subgame* (Y, N) *are specified as follows.*

(1) The optimal decisions for the suppliers at equilibrium are

$$
w_k^{YN*} = \overline{w}_k + \xi_{k1}^{YN}c_{m_1}, \tag{27}
$$

where

$$
\xi_{k1}^{YN} = -\frac{\left(1-\rho\right)\delta_y^2\left(\eta+1\right)}{2\left[2\left(1-\rho\right)\delta_y^2+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}. \tag{28}
$$

(2) The optimal decisions for the manufacturers at equilibrium are

$$
\begin{aligned}
q_{1k}^{YN*} &= \overline{q}_{1k} + f_{1k1}^{YN}c_{m_1}, \\
q_{2k}^{YN*} &= \overline{q}_{2k} + f_{2k1}^{YN}c_{m_1} + f_{2k2}^{YN}c_{m_2},
\end{aligned} \tag{29}
$$

where

$$
\begin{aligned}
f_{1k1}^{YN} &= \frac{\left[5\left(1-\rho\right)\delta_y^2+2\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]\eta-\left[7\left(1-\rho\right)\delta_y^2+4\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}{6\mu\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]\left[2\left(1-\rho\right)\delta_y^2+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}, \\
f_{2k1}^{YN} &= \frac{\left[5\left(1-\rho\right)\delta_y^2+2\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]-\left[\left(1-\rho\right)\delta_y^2+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]\eta}{6\mu\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]\left[2\left(1-\rho\right)\delta_y^2+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}, \\
f_{2k2}^{YN} &= -\frac{1}{2\mu\left[\left(1+\delta_y^2\right)+\left(n-1\right)\left(1+\rho\delta_y^2\right)\right]}.
\end{aligned} \tag{30}
$$

Proposition 3 indicates that both the suppliers and manufacturer 1's optimal decisions only depend on c_{m_1}, while manufacturer 2's optimal decision depends on both c_{m_1} and c_{m_2}. This is because manufacturer 2 can infer manufacturer 1's cost information from w_k^{YN*}, while manufacturer 1 cannot infer manufacturer 2's cost information from w_k^{YN*}. $\xi_{k1}^{YN} < 0$, $f_{iki}^{YN} < 0$, and $f_{jkj}^{YN} < 0$, respectively, indicate that the suppliers, manufacturer 1, and manufacturer 2 respond negatively to c_{m_1}, c_{m_1}, and c_{m_2}. Moreover, f_{2k1}^{YN} negatively or positively depends on the value of key parameters: δ_y, ρ, and

t. When $[5(1-\rho)\delta_y^2 + 2(n-1)(1+\rho\delta_y^2)] < [(1-\rho)\delta_y^2 + (n-1)(1+\rho\delta_y^2)]\eta$, manufacturer 2 responds negatively to c_{m_1}, while manufacturer 2 responds positively to c_{m_1}.

All information from Propositions 1–3 is valuable to the suppliers and manufacturers in determining their wholesale prices and order quantities.

5. Information Sharing Game

We first calculate the suppliers and manufacturers' ex ante payoffs based on the equilibrium solutions for any pair of VCIS strategies and summarize the results in Table 1. Subsequently, we solve the cost-information sharing game.

Next, we analyze how manufacturers' VCIS affects each supplier by comparing SC partners' ex ante payoffs under strategy (Y, N) with (N, N) and comparing SC partners' ex ante payoffs under strategy (Y, Y) with (N, Y).

Proposition 4. *The SC members' ex ante payoffs have the following properties.*

(1) $\pi_{s_k}^{YY*} > \pi_{s_k}^{YN*} > \pi_{s_k}^{NN*}$.

(2) (a) $\pi_{m_1}^{YY*} > \pi_{m_1}^{NY*}$; *(b) if* $0 < \eta < \eta_1$, $\pi_{m_1}^{YN*} > \pi_{m_1}^{NN*}$; *if* $1 \geq \eta > \eta_1$, $\pi_{m_1}^{YN*} < \pi_{m_1}^{NN*}$, *where*

$$\eta_1 = \frac{2(1-\rho)\delta_y^2 + 2(n-1)\left(1+\rho\delta_y^2\right)}{5(1-\rho)\delta_y^2 + 2(n-1)\left(1+\rho\delta_y^2\right)}. \quad (31)$$

(3) (a) $\Pi_{m_2}^{YY*} > \pi_{m_2}^{NY*}$; *(b) if* $\varphi(n,\rho,\delta_y) > \psi(n,\rho,\delta_y,\eta)$, $\pi_{m_2}^{YN*} > \Pi_{m_2}^{NN*}$; *if* $\varphi(n,\rho,\delta_y) < \psi(n,\rho,\delta_y,\eta)$, $\pi_{m_2}^{YN*} < \Pi_{m_2}^{NN*}$, *where*

$$\varphi(n,\rho,\delta_y) = \frac{n\left[5(1-\rho)\delta_y^2 + 2(n-1)\left(1+\rho\delta_y^2\right)\right]^2\sigma_c^2 + 9n\left[2(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]^2\sigma_c^2}{36\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]^2},$$

$$\begin{aligned}\psi(n,\rho,\delta_y,\eta) = {} & \frac{n\left[7(1-\rho)\delta_y^2 + 4(n-1)\left(1+\rho\delta_y^2\right)\right]\left[5(1-\rho)\delta_y^2 + 2(n-1)\left(1+\rho\delta_y^2\right)\right]\eta\sigma_c^2}{18\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]^2} \\ & - \frac{n\left[(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[13(1-\rho)\delta_y^2 + 7(n-1)\left(1+\rho\delta_y^2\right)\right]\eta^2\sigma_c^2}{36\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]^2} \\ & + \frac{n\sigma_c^2}{\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right](2+\eta)^2}.\end{aligned} \quad (32)$$

Proof. See Appendix. □

Proposition 4 Part (1) means that the suppliers will gain more ex ante payoffs from more manufacturers disclosing their private cost information.

Proposition 4 Part (2) shows that CCIS and NCIS are two possible equilibrium solutions for the two manufacturers. The manufacturers always agree to VCIS when the correlated coefficient of two manufacturers' cost uncertainty is less than a threshold (i.e., $0 < \eta < \eta_1$).

Proposition 4 Part (3) states that a manufacturer does not always benefit from its competitor manufacturer's information sharing. If a manufacturer does not agree to VCIS, it benefits from the competitor manufacturer's VCIS only when $\varphi(n,\rho,\delta_y) > \psi(n,\rho,\delta_y,\eta)$.

Proposition 5. *Complete cost-information sharing Pareto-dominates no cost-information sharing.*

Proof. See Appendix. □

Proposition 5 suggests that the entire SC's ex ante payoff with CCIS is larger than NCIS.

6. Numerical Analysis

In this section, we examine the impact of key parameters on the value of information sharing. As the two manufacturers are symmetric, we only focus on the value of information sharing by manufacturer 1. Let $V_{s_k}^N = \Pi_{s_k}^{YN*} - \Pi_{s_k}^{NN*}$, $V_{m_2}^N = \Pi_{m_2}^{YN*} - \Pi_{m_2}^{NN*}$, and $V_{m_1}^N = \Pi_{m_1}^{YN*} - \Pi_{m_1}^{NN*}$, respectively, represent the effect of manufacturer 1's information sharing to each supplier, manufacturer 2, and manufacturer 1. Similarly, let $V_{s_k}^Y = \Pi_{s_k}^{YY*} - \Pi_{s_k}^{NY*}$, $V_{m_2}^Y = \Pi_{m_2}^{YY*} - \Pi_{m_2}^{NY*}$, and $V_{m_1}^Y = \Pi_{m_1}^{YY*} - \Pi_{m_1}^{NY*}$, respectively, denote the effect of manufacturer 1 information sharing on SC partners' ex ante payoffs.

We assume the following: $\sigma_\theta^2 = 2$, $\rho = 0.5$, $\delta_y = 0.5$, $\eta = 0.7$, and $n = 2$. The effects of ρ, δ_y, η, and n on $V_{s_k}^N$, $V_{m_2}^N$, $V_{m_1}^N$, $V_{s_k}^Y$, $V_{m_2}^Y$, and $V_{m_1}^Y$ are provided in Figures 1–4, respectively.

Figures 1(a) and 1(b) show that as ρ increases, $V_{s_k}^N$ and $V_{s_k}^Y$ decreases. It means that, whether manufacture 2 shares information or not, the higher ρ is, the less each supplier benefits from information sharing by manufacturer 1.

Figures 1(c) and 1(d) show that as ρ increases, $V_{m_2}^N$ increases, while $V_{m_2}^Y$ decreases. This shows that if manufacture

Table 1: The manufacturers' and suppliers' ex ante payoffs.

Subgame	The suppliers	The manufacturers
(Y, Y)	$\Pi_{s_k}^{YY*} = \overline{\Pi}_{s_k} + \dfrac{WR(\eta+1)\sigma_c^2}{3BC^2}$	$\Pi_{m_i}^{YY*} = \overline{\Pi}_{m_i} + \dfrac{n(U^2+T^2)\sigma_c^2}{36BC^2} - \dfrac{nUT\eta\sigma_c^2}{18BC^2}$
(N, N)	$\Pi_{s_k}^{NN*} = \overline{\Pi}_{s_k}$	$\Pi_{m_i}^{NN*} = \overline{\Pi}_{m_i} + \dfrac{n\sigma_c^2}{B(2+\eta)^2}$
(Y, N)	$\Pi_{s_k}^{YN*} = \overline{\Pi}_{s_k} + \dfrac{WR(\eta+1)^2\sigma_c^2}{6BC^2}$	$\Pi_{m_1}^{YN*} = \overline{\Pi}_{m_i} + \dfrac{n(\eta T-U)^2}{36BC^2}\sigma_c^2$ $\Pi_{m_2}^{YN*} = \overline{\Pi}_{m_i} + \dfrac{n(T-\eta R)^2\sigma_c^2}{36BC^2} + \dfrac{n\sigma_c^2}{4B} - \dfrac{n\eta(T-\eta R)\sigma_c^2}{6BC}$
(N, Y)	$\Pi_{s_k}^{NY*} = \overline{\Pi}_{s_k} + \dfrac{WR(\eta+1)^2\sigma_c^2}{6BC^2}$	$\Pi_{m_1}^{NY*} = \overline{\Pi}_{m_1} + \dfrac{n(T-\eta R)^2\sigma_c^2}{36BC^2} + \dfrac{n\sigma_c^2}{4B} - \dfrac{n\eta(T-\eta R)\sigma_c^2}{6BC}$ $\Pi_{m_2}^{NY*} = \overline{\Pi}_{m_2} + \dfrac{n(\eta T-U)^2\sigma_c^2}{36BC^2}$

Notes. $\overline{\Pi}_{m_i} = (nR^2/9BC^2)(a-c)^2$ and $\overline{\Pi}_{s_k} = (2(1-\rho)\delta_y^2 R/3BC^2)(a-c)^2$, $i = 1, 2$, $k = 1, 2, \ldots, n$; $B = (1+\delta_y^2) + (n-1)(1+\rho\delta_y^2)$ and $C = 2(1-\rho)\delta_y^2 + (n-1)(1+\rho\delta_y^2)$; $R = (1-\rho)\delta_y^2 + (n-1)(1+\rho\delta_y^2)$ and $T = 5(1-\rho)\delta_y^2 + 2(n-1)(1+\rho\delta_y^2)$; $U = 7(1-\rho)\delta_y^2 + 4(n-1)(1+\rho\delta_y^2)$ and $W = (1-\rho)\delta_y^2$.

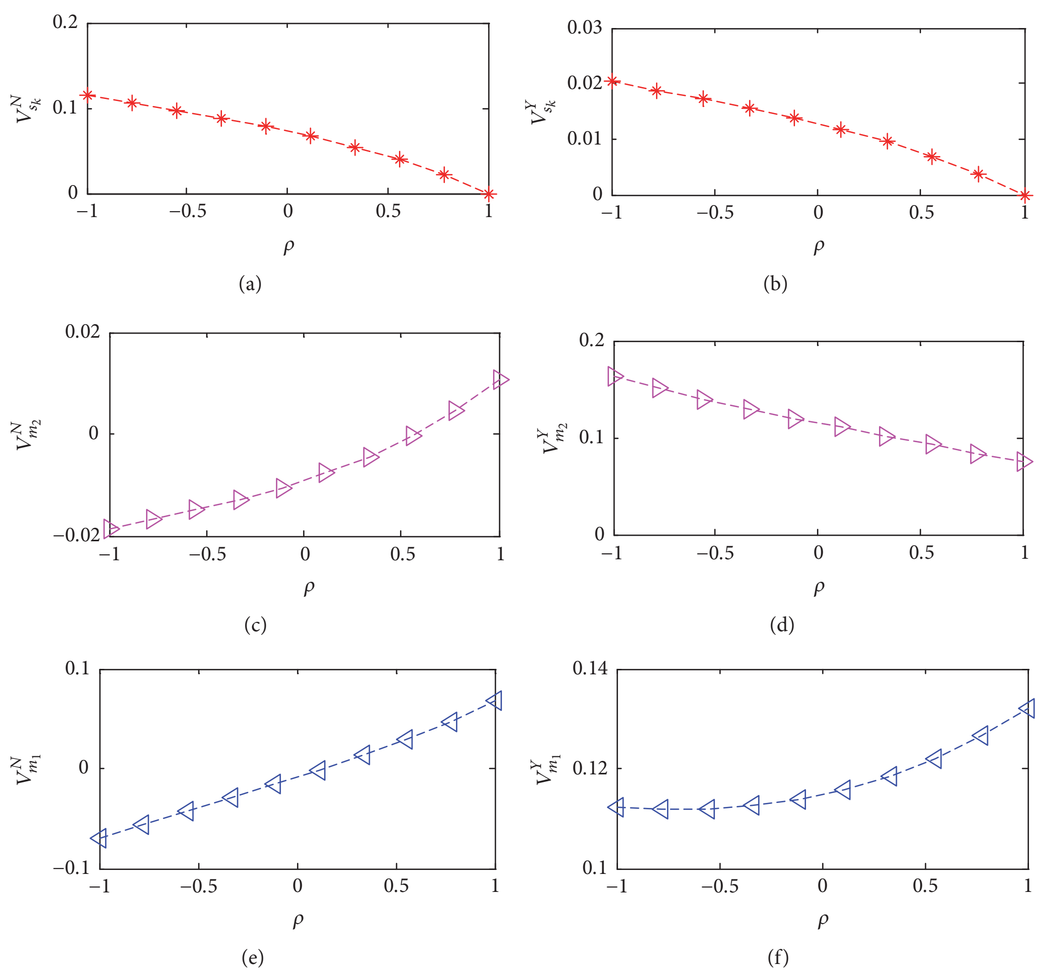

Figure 1: The effect of ρ on $V_{s_k}^N$, $V_{m_2}^N$, $V_{m_1}^N$, $V_{s_k}^Y$, $V_{m_2}^Y$, and $V_{m_1}^Y$.

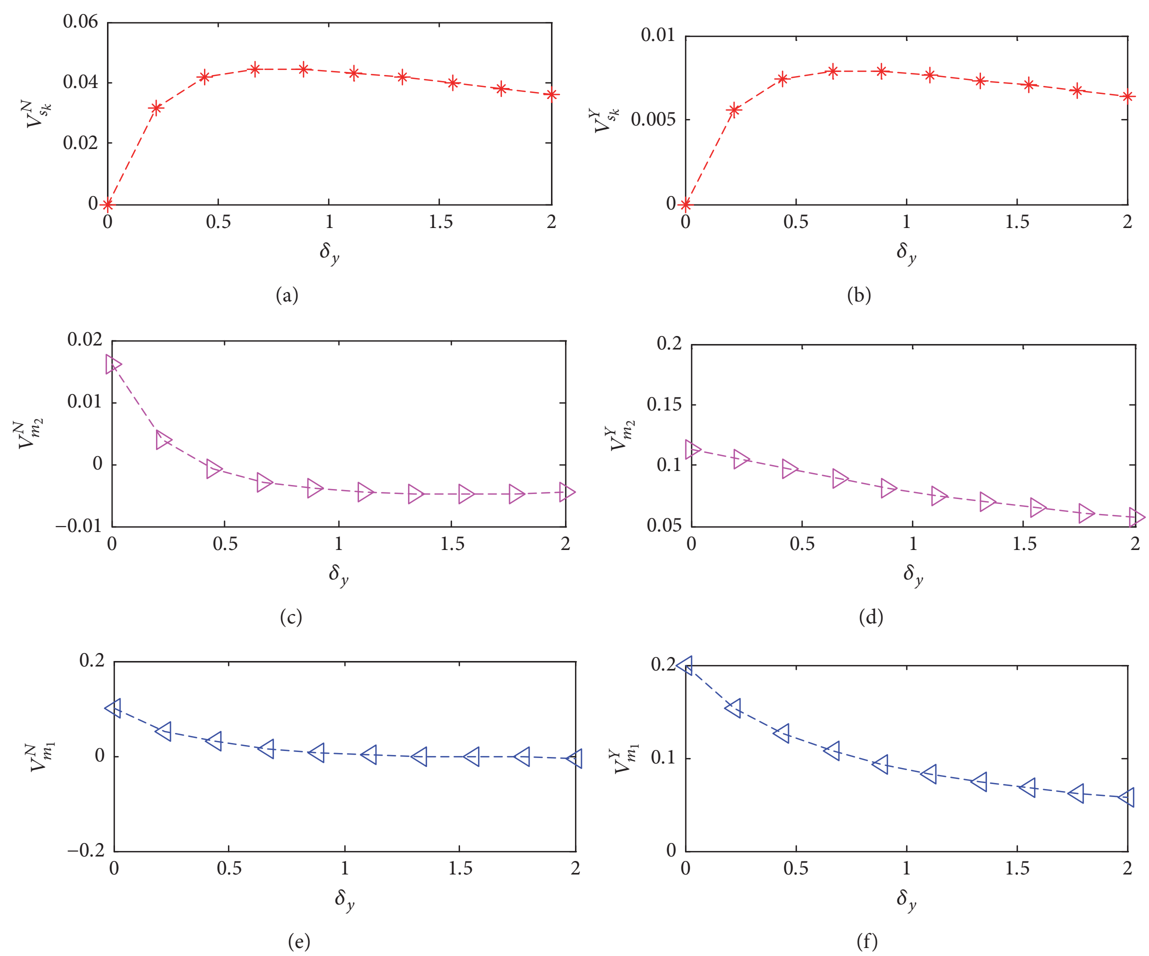

Figure 2: The impact of δ_y on $V_{s_k}^N$, $V_{m_2}^N$, $V_{m_1}^N$, $V_{s_k}^Y$, $V_{m_2}^Y$, and $V_{m_1}^Y$.

2 agrees to VCIS, high ρ increases manufacturer 2's benefits from manufacturer 1's VCIS. If it does not agree to VCIS, high ρ reduces manufacturer 2's benefits from manufacturer 1's VCIS.

Figures 1(e) and 1(f) show that both $V_{m_1}^N$ and $V_{m_1}^Y$ increase with ρ. These mean that high ρ increases the value of information sharing by manufacturer 1 to itself.

Figures 2(a) and 2(b) show that as δ_y increases, both of $V_{s_k}^N$ and $V_{s_k}^Y$ first increase and then decrease. This indicates that the impacts of δ_y on $V_{s_k}^N$ and $V_{s_k}^Y$ are in the same direction.

Figures 2(c)–2(f) show that as δ_y increases, $V_{m_2}^N$, $V_{m_2}^Y$, $V_{m_1}^N$, and $V_{m_1}^Y$ decrease. This means that high δ_y will decrease the value of information sharing by manufacturer 1 to both manufacturer 1 and manufacturer 2.

Figures 3(a) and 3(b) show that $V_{s_k}^N$ increases with η, while $V_{s_k}^Y$ decreases with η. This means that given the fact that manufacture 2 decides not to disclose its cost information to its suppliers, high η promotes manufacturer 2's benefit when manufacturer 1 shares its cost information. If manufacture 2 decides to disclose its private cost information to its suppliers, high ρ decreases manufacturer 2's benefit when manufacturer 1 shares its cost information.

Figures 3(c)–3(f) show that as η increases, $V_{m_2}^N$, $V_{m_2}^Y$, $V_{m_1}^N$, and $V_{m_1}^Y$ decrease. It means that no matter whether manufacturer 2 decides to disclose cost information to suppliers or not, the value of information sharing by manufacturer 1 to both manufacturer 1 and manufacturer 2 decreases with η.

Figures 4(a) and 4(b) show that $V_{s_k}^N$ and $V_{s_k}^Y$ decrease with n. Figures 4(e) and 4(f) show that $V_{m_1}^N$ and $V_{m_1}^Y$ increase with n. It means that as the number of suppliers increases, each supplier benefits less from information sharing by manufacturer 1, while manufacturer 1 benefits more from information sharing by itself.

Figures 4(c) and 4(d) show that as n increases, $V_{m_2}^N$ increases while $V_{m_2}^Y$ decreases. It means that as the number of suppliers increases, the value of information sharing by manufacturer 1 is determined by manufacturer 2's information sharing strategy.

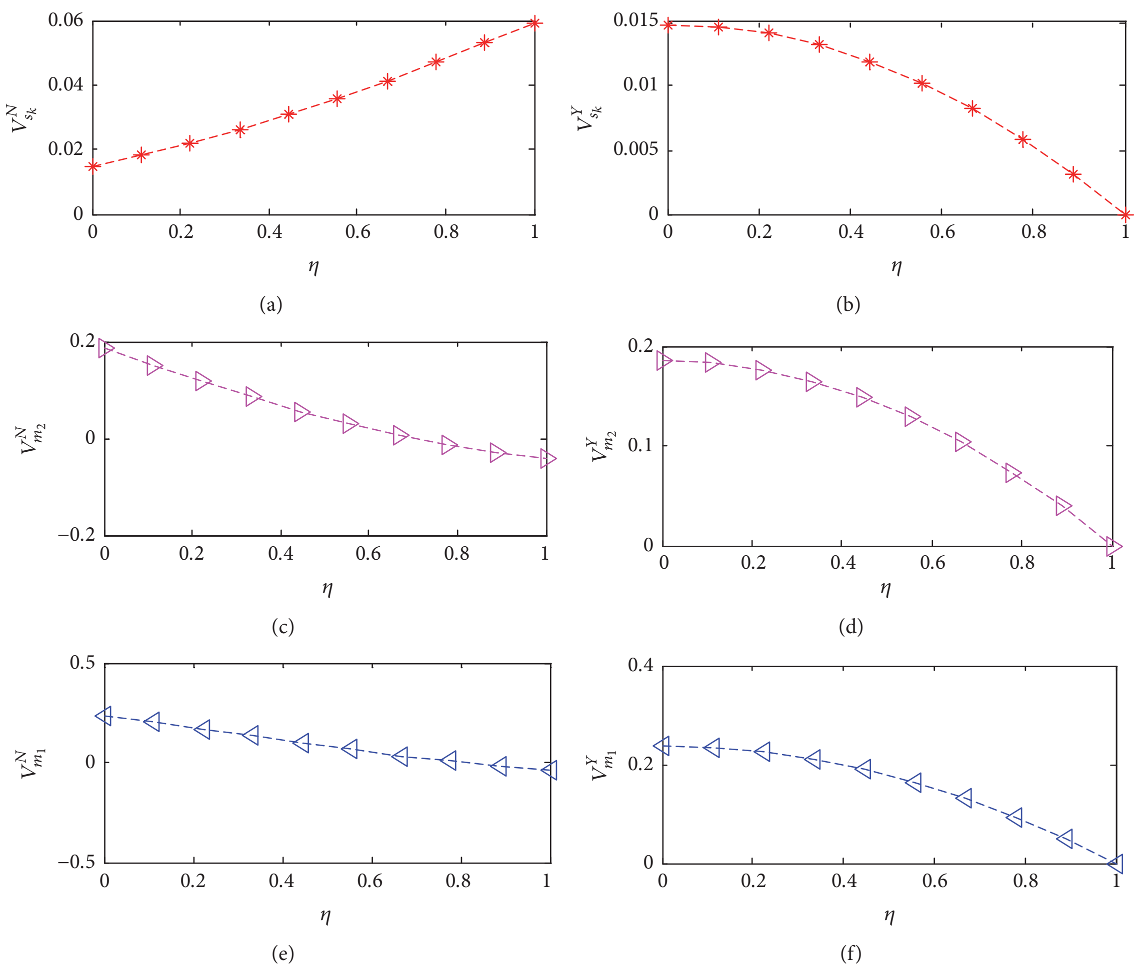

FIGURE 3: The impact of η on $V_{s_k}^N$, $V_{m_2}^N$, $V_{m_1}^N$, $V_{s_k}^Y$, $V_{m_2}^Y$, and $V_{m_1}^Y$.

Figures 1–4 show that $V_{s_k}^N$, $V_{s_k}^Y$, $V_{m_2}^Y$, and $V_{m_1}^Y$ are positive. Whether $V_{m_2}^N$ and $V_{m_1}^N$ are positive or negative is determined by the value of key parameters. $V_{m_1}^Y > 0$ indicates that if manufacturer 2 chooses to disclose its cost information to suppliers, manufacturer 1 will also reveal its cost information to suppliers. $V_{m_1}^N < 0$ suggests that given the fact that manufacturer 2 does not share information with suppliers, neither will manufacturer 1 with its own suppliers.

Moreover, we found that if manufacturer 1 shares its cost information, higher ρ means that manufacturer 1 would be more willing to share information (see Figure 1(f)), promoting complete information sharing. Similarly, higher n also promotes complete information sharing (see Figure 4(f)). However, higher δ_y and η undermine complete information sharing (see Figures 2(f) and 3(f)).

7. Conclusions

Information sharing is a hot topic in the literature of SC management. This study examines VCIS in a simplified SC which consists of two manufacturers with private cost information and n suppliers with yield uncertainty.

This work contributes to the area of research on incentive for VCIS. We analyze VCIS by considering the number of suppliers, the correlated coefficient of manufacturers' cost uncertainty, and the level of yield uncertainty and the correlated coefficient of the supply processes. We found that there exists only two equilibrium information sharing strategies: complete cost-information sharing and no cost-information sharing. The manufactures always agree to VCIS when the correlated coefficient of two manufacturers' cost uncertainty is less than a threshold. In addition, complete cost-information sharing will increase each supplier, each manufacturer, and the entire SC's ex ante payoffs when two manufacturers' cost uncertainty is less correlated. It suggests that the manufactures decide to perform VCIS.

This presented study can be further extended along the following three directions. First, other types of contract (e.g., two-part pricing contract) can be considered. Second, multiple manufacturers could be introduced to examine how the number of manufacturers affects the manufacturers' willingness to share information. Finally, our model could be expanded to include other types of competition such as newsvendor competition models.

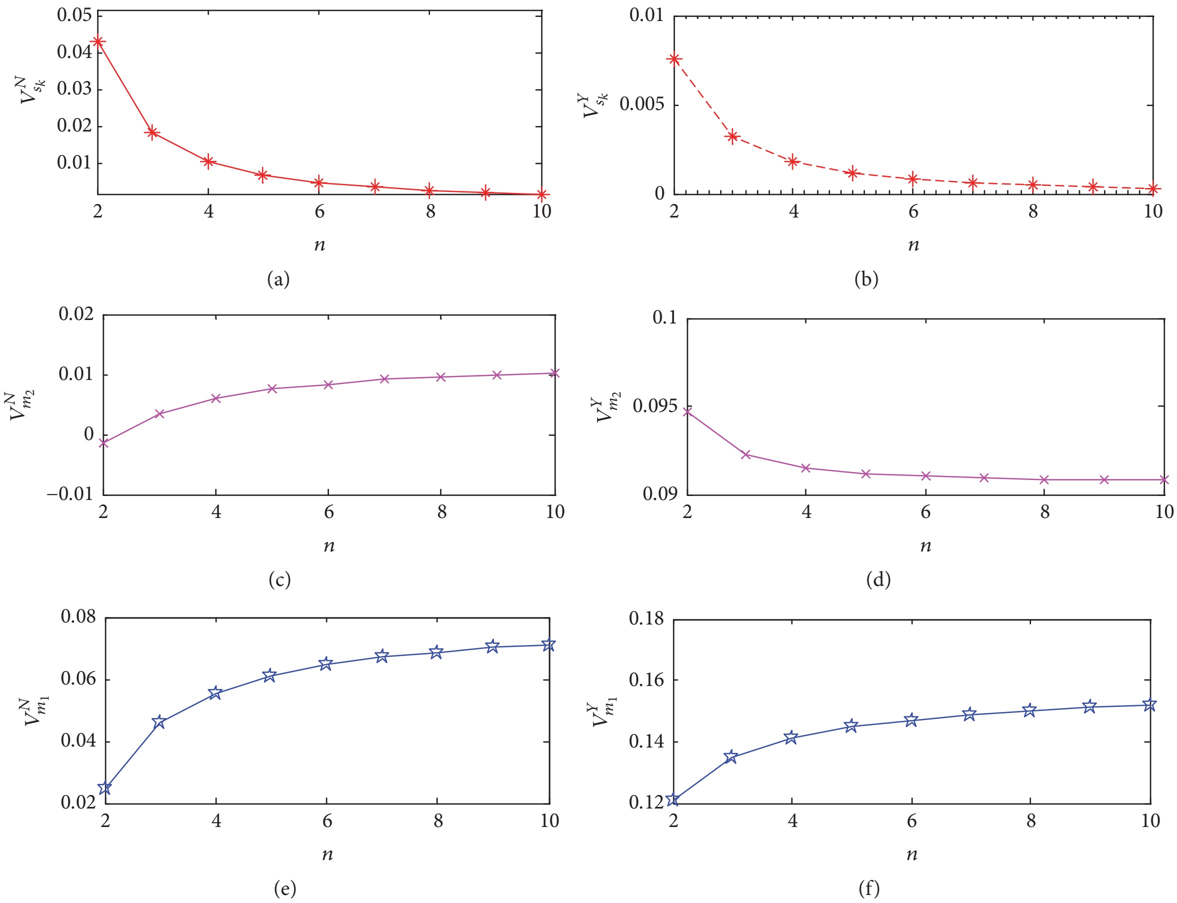

FIGURE 4: The impact of n on $V_{s_k}^N$, $V_{m_2}^N$, $V_{m_1}^N$, $V_{s_k}^Y$, $V_{m_2}^Y$, and $V_{m_1}^Y$.

Appendix

Proof of Proposition 4. From Table 1, we have

$$\Pi_{s_k}^{YN*} - \Pi_{s_k}^{NN*} = \frac{(1-\rho)\,\delta_y^2\left[(1-\rho)\,\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right](\eta+1)^2\,\sigma_c^2}{6\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\,\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]^2} > 0, \tag{A.1}$$

$$\Pi_{s_k}^{YY*} - \Pi_{s_k}^{YN*} = \frac{(1-\rho)\,\delta_y^2\left[(1-\rho)\,\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]\left(1-\eta^2\right)\sigma_c^2}{6\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\,\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]^2} > 0, \tag{A.2}$$

$$\begin{aligned}
&\Pi_{m_2}^{YN*} - \Pi_{m_2}^{NN*} \\
&= \frac{n\left[5(1-\rho)\,\delta_y^2 + 2(n-1)\left(1+\rho\delta_y^2\right)\right]^2\sigma_c^2 + 9n\left[2(1-\rho)\,\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]^2\sigma_c^2}{36\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\,\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]^2} \\
&\quad + \frac{n\left[(1-\rho)\,\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[13(1-\rho)\,\delta_y^2 + 7(n-1)\left(1+\rho\delta_y^2\right)\right]\eta^2\sigma_c^2}{36\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\,\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]^2} \\
&\quad - \frac{n\left[7(1-\rho)\,\delta_y^2 + 4(n-1)\left(1+\rho\delta_y^2\right)\right]\left[5(1-\rho)\,\delta_y^2 + 2(n-1)\left(1+\rho\delta_y^2\right)\right]\eta\sigma_c^2}{18\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\,\delta_y^2 + (n-1)\left(1+\rho\delta_y^2\right)\right]^2} - \frac{n\sigma_c^2}{\left[\left(1+\delta_y^2\right) + (n-1)\left(1+\rho\delta_y^2\right)\right](2+\eta)^2},
\end{aligned} \tag{A.3}$$

$$\Pi_{m_2}^{YY*} - \pi_{m_2}^{NY*} = \frac{n\left[5(1-\rho)\delta_y^2 + 2(n-1)\left(1+\rho\delta_y^2\right)\right]^2\left(1-\eta^2\right)\sigma_c^2}{36\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2} > 0, \quad (A.4)$$

$$\pi_{m_1}^{YN*} - \pi_{m_1}^{NN*} = \frac{-n\left\{(1-\rho)\delta_y^2\left(26-3\eta-5\eta^2\right)+2(n-1)\left(1+\rho\delta_y^2\right)\left(7-\eta^2\right)\right\}\cdot\left\{3(1-\rho)\delta_y^2\eta-2\left[(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right](1-\eta)\right\}(1+\eta)\sigma_c^2}{36\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2(2+\eta)^2}, \quad (A.5)$$

$$\pi_{m_1}^{YY*} - \pi_{m_1}^{NY*} = \frac{n\left[(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[13(1-\rho)\delta_y^2+7(n-1)\left(1+\rho\delta_y^2\right)\right]\left(1-\eta^2\right)\sigma_c^2}{36\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2} > 0. \quad (A.6)$$

In (A.3), let $\Pi_{m_2}^{YN*} - \Pi_{m_2}^{NN*} = 0$, and we obtain $\varphi(n,\rho,\delta_y) = \psi(n,\rho,\delta_y,\eta)$, where

$$\varphi\left(n,\rho,\delta_y\right) = \frac{n\left[5(1-\rho)\delta_y^2+2(n-1)\left(1+\rho\delta_y^2\right)\right]^2\sigma_c^2 + 9n\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2\sigma_c^2}{36\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2}, \quad (A.7)$$

$$\begin{aligned}\psi\left(n,\rho,\delta_y,\eta\right) &= \frac{n\left[7(1-\rho)\delta_y^2+4(n-1)\left(1+\rho\delta_y^2\right)\right]\left[5(1-\rho)\delta_y^2+2(n-1)\left(1+\rho\delta_y^2\right)\right]\eta\sigma_c^2}{18\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2} \\ &- \frac{n\left[(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[13(1-\rho)\delta_y^2+7(n-1)\left(1+\rho\delta_y^2\right)\right]\eta^2\sigma_c^2}{36\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2} \\ &+ \frac{n\sigma_c^2}{\left[\left(1+\delta_y^2\right)+(n-1)\left(1+\rho\delta_y^2\right)\right](2+\eta)^2}.\end{aligned} \quad (A.8)$$

In (A.5), let $\pi_{m_1}^{YN*} - \pi_{m_1}^{NN*} = 0$, and we obtain $\eta = \eta_1$, where

$$\eta_1 = \frac{2(1-\rho)\delta_y^2+2(n-1)\left(1+\rho\delta_y^2\right)}{5(1-\rho)\delta_y^2+2(n-1)\left(1+\rho\delta_y^2\right)}. \quad (A.9)$$

Thus, we have

(1) $\pi_{s_k}^{YY*} > \pi_{s_k}^{YN*} > \pi_{s_k}^{NN*}$.

(2) (a) $\pi_{m_1}^{YY*} > \pi_{m_1}^{NY*}$; (b) if $\eta < \eta_1$, $\pi_{m_1}^{YN*} > \pi_{m_1}^{NN*}$; if $\eta > \eta_1$, $\pi_{m_1}^{YN*} < \pi_{m_1}^{NN*}$.

(3) (a) $\Pi_{m_2}^{YY*} > \pi_{m_2}^{NY*}$; (b) if $\varphi(n,\rho,\delta_y) > \psi(n,\rho,\delta_y,\eta)$, $\pi_{m_2}^{YN*} > \Pi_{m_2}^{NN*}$; if $\varphi(n,\rho,\delta_y) < \psi(n,\rho,\delta_y,\eta)$, $\pi_{m_2}^{YN*} < \Pi_{m_2}^{NN*}$.

The proof of Proposition 4 is finished. □

Proof of Proposition 5. From Table 1, we obtain

$$\begin{aligned}\Pi^{YY*} - \Pi^{NN*} &= \left(\pi_{m_1}^{YY*} + \pi_{m_2}^{YY*} + n\pi_{s_k}^{YY*}\right) - \left(\Pi_{m_1}^{NN*} + \Pi_{m_2}^{NN*} + n\Pi_{s_k}^{NN*}\right) = \left(n\left\{2\left[4(1-\rho)^2\delta_y^4 + (n-1)^2\left(1+\rho\delta_y^2\right)^2\right]\left[30\eta^2 + 37\eta(1-\eta) + 11(1-\eta)^2\right](1-\eta) + (n-1)(1-\rho)\delta_y^2\left(1 + \rho\delta_y^2\right)\left[18\eta^3 + 273\eta^2(1-\eta) + 316\eta(1-\eta)^2 + 92(1-\eta)^3\right]\right\}\left(1/\eta^2\right)\sigma_c^2\right)\left(9\left[\left(1+\delta_y^2\right)+(n-1) \cdot \left(1+\rho\delta_y^2\right)\right]\left[2(1-\rho)\delta_y^2+(n-1)\left(1+\rho\delta_y^2\right)\right]^2 \cdot (3+2t)^2\right)^{-1} > 0.\end{aligned} \quad (A.10)$$

The proof of Proposition 5 is finished. □

Notation for Variables

w_k, q_{ik}:	Wholesale price and order quantity (decision variable)
π_{s_k}, π_{r_i}:	Supplier k's and manufacturer i's profit
$\overline{w}_k, \overline{q}_{ik}$:	The equilibrium wholesale price and order quantity under no cost uncertainty
$w_k^{Z_1Z_2*}, q_{ik}^{Z_1Z_2*}$:	The equilibrium wholesale price and order quantity under subgame (Z_1, Z_2)

$\xi_{ki}^{Z_1 Z_2}, f_{iki}^{Z_1 Z_2}$: Response coefficients for supplier k and manufacturer i to c_{m_i} under subgame (Z_1, Z_2)
$\Pi_{s_k}^{Z_1 Z_2 *}, \Pi_{r_i}^{Z_1 Z_2 *}$: The optimal ex ante payoffs for supplier k and manufacturer i under subgame (Z_1, Z_2)
$\overline{\Pi}_{s_k}, \overline{\Pi}_{r_i}$: The optimal profit for supplier k and manufacturer i under no cost uncertainty.

Parameters

a: Demand intercept
c_{m_1}: Cost uncertainty for manufacturer i
σ_c^2: Variance of c_{m_i}
y_k: Yield uncertainty
μ, σ_y^2: Mean and variance of y_k
δ_y: The level of yield uncertainty $\delta_y = \sigma_y^2/\mu^2$
ρ: Correlated coefficient of suppliers' supply processes
η: Correlated coefficient of manufacturers' cost uncertainty
c: Supplier k's expected cost and $c = c_1/\mu + c_2$

Indices

Subscript

s_k: It captures supplier k
m_i: It captures manufacturer i

Superscript

Y: It indicates that the manufacturer agrees to VCIS
N: It indicates that the manufacturer does not agree to VCIS.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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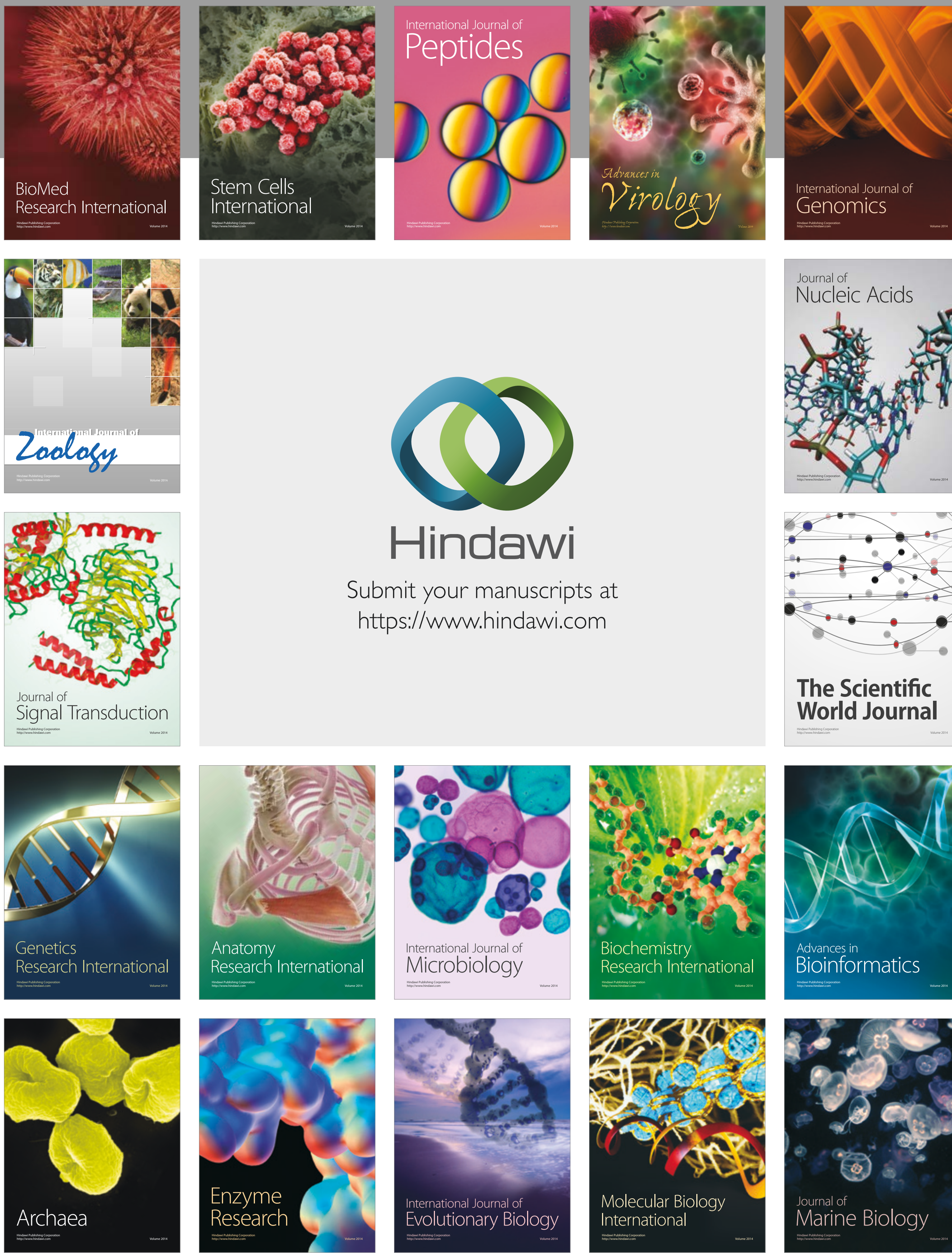
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