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Research Article

Information Sharing in a Closed-Loop Supply Chain with Asymmetric Demand Forecasts

Pan Zhang and Zhongkai Xiong

School of Economics and Business Administration, Chongqing University, Chongqing, China

Correspondence should be addressed to Zhongkai Xiong; xiongzhongkai@cqu.edu.cn

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This paper studies the problem of sharing demand forecast information in a closed-loop supply chain with the manufacturer collecting and remanufacturing. We investigate two scenarios: the “make-to-order” scenario, in which the manufacturer schedules production based on the realized demand, and the “make-to-stock” scenario, in which the manufacturer schedules production before the demand is known. For each scenario, we find that it is possible for the retailer to share his forecast without incentives when the collection efficiency of the manufacturer is high. When the efficiency is moderate, information sharing can be realized by a bargaining mechanism, and when the efficiency is low, non-information sharing is a unique equilibrium. Moreover, the possibility of information sharing in the make-to-stock scenario is higher than that in the make-to-order scenario. In addition, we analyze the impact of demand forecasts’ characteristics on the value of information sharing in both scenarios.

1. Introduction

In the past two decades, numerous manufacturers, such as Xerox and Hewlett Packard, have engaged to collect and remanufacture their used products. Economic considerations, societal pressure, and legislation have been recognized as the main motivation for the manufacturers’ operations of collecting and remanufacturing. For example, the cost of remanufactured products is 40–65% less than that of new products. And legislators of Europe and North America have started to require manufacturers to collect and remanufacture its used products through the regulation of Extended Producer Responsibility [1]. For the collecting operations, many manufacturers tend to undertake it by themselves, although some manufacturers collect their used products by their resellers or the third party. A classic case is that Xerox collects their used products through providing prepaid mailboxes to their consumers, thereby improving the performance of recovery [2].

For the closed-loop supply chain with the manufacturer collecting used products, it is difficult for the supply chain members to make decisions of price and production in the face of a highly uncertain market environment, due to the rapid changes in economic and business conditions. Consequently, supply chain members try to forecast the market demand by using information technology. For example, manufacturers could acquire historical data of the past three years through the Collaborative Retail Exchange data-sharing program and convert it into demand information through the third-party data service provider. After obtaining demand information, whether to share it generally vexes the supply chain members. For instance, according to a study of Forrester Research in 2006, only 27% of retailers among 89 retailers shared the point-of-sales (POS) data with their manufacturers [3].

In view of the observations from current practice, in this paper, we mainly address the issues of sharing demand forecasts in a closed-loop supply chain under two different types of production. The first is the make-to-order scenario and the second is the make-to-stock scenario. And in each scenario both the members can forecast the demand in an uncertain market environment. In detail, we primarily investigate the following questions: when does the retailer share the forecast information voluntarily? If impossible, how to design a bargaining mechanism to induce supply chain members to share information? And how

Table 1: The main research problems of the closed-loop supply chain.

Main problems	Publications
Network designing	Zhou et al. [4]; Tokhmehchi et al. [5]
Remanufacturing operations	Atasu et al. [6]; Zhou et al. [7]; Wu and Zhou [8]
Reverse channel designing	Savaskan et al. [2]; Savaskan and Van Wassenhove [9]; Atasu et al. [10]; Wu and Zhou [11]
Inventory management	Hsueh [12]; Alinovi et al. [13]; Mitra [14]
Information asymmetry	Zhang et al. [15]; Li et al. [16]

do the forecast accuracy of supply chain members and the forecasting correlation affect the value of information sharing?

This paper is relevant to the literature on the closed-loop supply chain management. Most researchers focus on network design, remanufacturing operations, reverse channel design, inventory management, and information asymmetry, and the primary studies are illustrated in Table 1. In detail, with respect to network design, Zhou et al. [4] investigate an equilibrium model of a closed-loop supply chain network with multiproducts in a stochastic environment. Tokhmehchi et al. [5] address the issues of closed-loop supply chain network design, including plants, demand centers, collection centers, and disposal centers, through a hybrid approach. In terms of remanufacturing operations, Atasu et al. [6] examine the impact of green segments, original equipment manufacturers' competition, and product life cycle on the profitability of a remanufacturing system. Zhou et al. [7] study the control mode of manufacturing and remanufacturing activities for original equipment manufacturers in a decentralized closed-loop supply chain and find that the original equipment manufacturers could benefit from the decentralized control mode. Wu and Zhou [8] investigate the impact of the entry of third-party remanufacturers on the original equipment manufacturers and find that the original equipment manufacturers may benefit from the entry of third-party remanufacturers. With respect to reverse channel design, Savaskan et al. [2] first study the manufacturer's choices of the reverse channel among the manufacturer collecting mode, the retailer collecting mode, and the third-party collecting mode. Similarly, Savaskan and Van Wassenhove [9] investigate the manufacturer's optimal choice of the reverse channel but in a competing case; that is, the closed-loop supply chain has two retailers. Atasu et al. [10] further study the same problem under the case of different collection cost functions. Besides, Wu and Zhou [11] investigate the manufacturers' optimal reverse channel choice from the perspective of supply chain competition. In regard to inventory control, Hsueh [12] studies an inventory control model for a manufacturing/remanufacturing system, considering the product life cycle. Alinovi et al. [13] study the inventory management issue in systems with both manufacturing and remanufacturing, based on a stochastic Economic Order Quantity model. Mitra [14] studies inventory control in closed-loop supply chains with correlated demands and returns, based on deterministic and stochastic models. However, researchers conduct the above studies without the consideration of asymmetric information. On the information asymmetry side, Zhang et al. [15] study the manufacturer's optimal contract design in a closed-loop supply chain when the retailer's collection cost is asymmetric. Li et al. [16] analyze the same problem but in a reverse channel; that is, they study the contract designing for a manufacturer when the collector's cost is asymmetric under a recovery regulation. However, none of the papers examines asymmetric demand information in a closed-loop supply chain. As a complement, we mainly study the demand forecast sharing problem in a closed-loop supply chain with the manufacturer collecting used products.

This paper also belongs to the literature on information sharing in supply chains. Most researchers assume that only the retailer could forecast demand and study incentives for information sharing in various supply chain structures. For example, Zhang [17] studies information sharing in the supply chain with a manufacturer supplying to two competing retailers. Li and Zhang [18] investigate information sharing in the supply chain with a manufacturer and n retailers. Ha et al. [19] study incentives for information sharing in the two competing supply chains each consisting of one manufacturer and one retailer. Shang et al. [3] examine the supply chain with two competing manufacturers supplying to a common retailer. Furthermore, some researchers assume that both the manufacturer and the retailer can forecast the uncertain market demand and conduct the research on information sharing, which is most relevant to our paper. For example, Yue and Liu [20] study demand forecasts sharing in a dual-channel supply chain under the make-to-order scenario and the make-to-stock scenario. Similarly, Mishra et al. [21] study demand forecasts sharing in a supply chain consisting of one manufacturer and one retailer, and they further design a discount based wholesale price contract to induce the retailer to share information. Yan and Wang [22] study demand forecasts sharing in the supply chain of high-tech industries under the make-to-stock scenario and design a profit sharing mechanism to induce the franchisee to share its information. Yan et al. [23] study the value of manufacturer's cooperative advertising and the cooperative advertising's strategic impact on information sharing in a dual-channel supply chain. However, none of the papers investigate the information sharing problem in a closed-loop supply chain.

The remainder of this paper is organized as follows. Section 2 presents the model framework. Section 3 analyzes

Table 2: Notations of the closed-loop supply chain model.

Symbols	Definitions
c_m	The unit cost of manufacturing a new product from raw materials
c_r	The unit cost of remanufacturing a returned product into a new one
Δ	The unit cost of saving due to the remanufacturing operations
θ	The manufacturer's collection efficiency
ϕ	The potential market demand
β	The price sensitiveness of demand
D	The final market's demand
h	The holding cost per unit of inventory
s	The shortage cost per unit of exceeding quantity
q	The retailer's order quantity
w	The wholesale price of the manufacturer (decision variable)
τ	The manufacturer's collection rate of used products (decision variable)
p	The retail price of the retailer (decision variable)
Q	The manufacturer's output in the MTS scenario (decision variable)

the production mode of make-to-order. Section 4 analyzes the production mode of make-to-stock. Section 5 concludes the paper.

2. Model Framework

Referring to Savaskan et al. [2], we consider a closed-loop supply chain consisting of a manufacturer (she) and a retailer (he). And the manufacturer collects her used products directly from the customers. Hence, the manufacturer, on the one hand, produces products by using raw or remanufacturing materials and sells them to consumers through the retailer. On the other hand, she engages to collect used products and remanufacture them into new products. We assume that the unit cost of manufacturing a new product directly from raw materials is c_m and the unit cost of remanufacturing a returned product into a new one is c_r. Moreover, let Δ represent the unit cost of saving due to the remanufacturing operations. Therefore, we have $\Delta = c_m - c_r$. Furthermore, we assume $\Delta > 0$, which implies the manufacturer can benefit from the operations of remanufacturing. We further assume the new product and the remanufactured product without difference due to the advanced remanufacturing technology. As a result, consumer could not distinguish the remanufactured products between the new products. Furthermore, the products' wholesale price of the manufacturer is represented by w and the retail price of the retailer is represented by p. The final market's demand $D(p) = \phi - \beta p$, where β represents the price sensitiveness of demand and ϕ ($\phi > \beta c_m$) represents the potential market demand. In addition, the manufacturer's collection rate of used products is denoted by τ ($0 \leq \tau \leq 1$), which could evaluate the performance of the reverse channel. A higher (lower) collection rate implies a higher (lower) performance of the reverse channel. Correspondingly, the manufacturer bears the collection cost $\theta\tau^2$, where θ represents the manufacturer's collection efficiency. A higher (lower) θ implies a lower (higher) collection efficiency of the manufacturer. Note that the collection rate can also be interpreted as the fraction of current generation products remanufactured from returned units. As a result, the average unit cost of manufacturing can be written as $(1-\tau)c_m+\tau c_r$ or $c_m-\tau\Delta$. We analyze the decisions of the closed-loop supply chain in a single-period setting. The notations of the closed-loop supply chain model are shown in Table 2.

Because the market demand is uncertain, referring to Yue and Liu [20] and Mishra et al. [21], we further assume $\phi = \overline{\phi}+\varepsilon$, where $\overline{\phi}$ represents the mean of primary market demand and ε represents the uncertainty of the market. Besides, ε is a random variable and is normally distributed with zero mean and variance σ_0^2. In spite of this, the uncertainty demand can be forecasted by firms through analyzing historical data and other methods. We, therefore, assume the manufacturer and retailer, respectively, have access to demand forecasts f_m and f_r. Moreover, $f_i = \phi + \varepsilon_i$ ($i = m, r$), where ε_m and ε_r represent the forecast error of the manufacturer and retailer, respectively. Moreover, ε_i is normally distributed with mean zero and variance σ_i^2 and is independent of ϕ. A higher (lower) variance represents a less (more) accurate forecast. The forecast errors ε_m and ε_r can be correlated, because the manufacturer and the retailer may use similar technology and historical data during the forecasting process. Accordingly, the extent of correlation between ε_m and ε_r is denoted by ρ ($0 \leq \rho \leq 1$). A higher (lower) ρ implies a higher (lower) similarity of the technology and data the manufacturer and the retailer used in their forecasting process. We further assume that $\rho\sigma_r\sigma_m \leq \sigma_r^2$ and $\rho\sigma_r\sigma_m \leq \sigma_m^2$; that is, the covariance is not greater than the variance. The notations of the demand forecast model are shown in Table 3.

In order to mitigate the limitations of the normality assumption, which allows for negative values of demand, relative to σ_0^2, we assume $\overline{\phi}$ is large. All parameters of the model, except the forecasts, are common knowledge to the manufacturer and the retailer. Actually, the normality assumption and information structure are commonly used in the previous literature (e.g., [20, 24]).

Table 3: Notations of the demand forecast model.

Symbols	Definitions
$\overline{\phi}$	The mean of the potential market demand
ε	The random part of the market demand
σ_0^2	The variance of ε
f_m	The manufacturer's forecast
f_r	The retailer's forecast
ε_m	The forecast error of the manufacturer
ε_r	The forecast error of the retailer
ρ	The extent of correlation between ε_m and ε_r
σ_m^2	The variance of ε_m
σ_r^2	The variance of ε_r

Referring to Mishra et al. [21], we first give the following conditional expectations and variances, which will help in the analyses of next sections:

$$\begin{aligned} E\left[\phi \mid f_i\right] &= \left(1 - t_i\right)\overline{\phi} + t_i f_i, \\ E\left[\phi \mid f_r, f_m\right] &= H\overline{\phi} + J f_r + K f_m, \\ E\left[f_r \mid f_m\right] &= \left(1 - d_m\right)\overline{\phi} + d_m f_m, \\ \operatorname{Var}\left[\phi \mid f_m\right] &= t_m \sigma_m^2, \\ \operatorname{Var}\left[\phi \mid f_r, f_m\right] &= H\sigma_0^2, \end{aligned} \tag{1}$$

where

$$\begin{aligned} t_i &= \frac{\sigma_0^2}{\sigma_0^2 + \sigma_i^2}, \\ d_m &= \frac{\sigma_0^2 + \rho\varepsilon_r\varepsilon_m}{\sigma_0^2 + \sigma_m^2}, \\ d_r &= \frac{\sigma_0^2 + \rho\varepsilon_r\varepsilon_m}{\sigma_0^2 + \sigma_r^2}, \\ H &= \frac{\left(1 - \rho^2\right)\sigma_m^2\sigma_r^2}{\left(1 - \rho^2\right)\sigma_m^2\sigma_r^2 + \sigma_0^2\left(\sigma_m^2 + \sigma_r^2 - 2\rho\sigma_m\sigma_r\right)}, \\ J &= \frac{\left(\sigma_m^2 - \rho\sigma_m\sigma_r\right)\sigma_0^2}{\left(1 - \rho^2\right)\sigma_m^2\sigma_r^2 + \sigma_0^2\left(\sigma_m^2 + \sigma_r^2 - 2\rho\sigma_m\sigma_r\right)}, \\ K &= \frac{\left(\sigma_r^2 - \rho\sigma_m\sigma_r\right)\sigma_0^2}{\left(1 - \rho^2\right)\sigma_m^2\sigma_r^2 + \sigma_0^2\left(\sigma_m^2 + \sigma_r^2 - 2\rho\sigma_m\sigma_r\right)}. \end{aligned} \tag{2}$$

We analyze two scenarios of production in the following, that is, make-to-order scenario and make-to-stock scenario, respectively. In the make-to-order scenario (MTO), the manufacturer schedules her production according to market demand. Hence, there is no inventory in the supply chain. However, in the make-to-stock scenario (MTS), the manufacturer schedules her production Q before the demand is known but the retailer places the order after the demand is realized. As a result, while the retailer does not bear costs of inventories or shortage, the manufacturer may produce more or less products. And if the manufacturer produces more, she has to bear the cost of holding inventories. Accordingly, the holding cost per unit of inventory is represented by h. If the manufacturer produces less, she has to bear the shortage cost as she has to obtain additional units from an external source. Accordingly, the shortage cost per unit of exceeding quantity is represented by s.

We consider a multistage game with a sequence of events as follows: in stage 1, before the manufacturer and the retailer obtain forecasts, they negotiate on information sharing between them, mainly through a bargaining mechanism. Specifically, the retailer bargains with the manufacturer for the allocation of supply chain profit after sharing the information. If they finally reach an information sharing agreement, they will truthfully share their forecasts. In stage 2, both the manufacturer and the retailer obtain forecasts f_m and f_r, respectively. In stage 3, in the make-to-order scenario, the manufacturer determines her wholesale price w and collection rate τ, and then the retailer determines his retail price p. However, in the make-to-stock scenario, the manufacturer determines her wholesale price w, collection rate τ, and production level Q, and then the retailer determines his retail price p. In stage 4, market demand realizes and the manufacturer supplies the order to the retailer. Finally, the manufacturer and the retailer receive their payoffs.

We solve the multistage game by using a standard backward induction technique. Specifically, we first solve for the equilibrium decisions of the manufacturer and the retailer under the case of information sharing and the case of non-information sharing and then compute the firms' ex ante profits of both cases. Based on the ex ante profits, lastly, we address the equilibrium information sharing decisions.

In terms of the notations of the rest of the paper, Π and π represent the expected profit of the MTO scenario and MTS scenario, respectively. The subscripts M and R represent the manufacturer and the retailer, respectively. Besides, the subscripts N and S denote the case of non-information sharing and information sharing, respectively. For example, Π_{MN} denotes the manufacturer's expected profit of the non-information sharing case in the MTO scenario.

3. The Make-to-Order Scenario

3.1. No Information Sharing Case. In this case, the manufacturer and the retailer do not share their information. And the manufacturer and the retailer maximize their own expected profits, conditional on their own forecast information. However, the retailer, as a Stackelberg follower, can infer the manufacturer's forecast f_m in this non-information sharing case. This is because the manufacturer is a Stackelberg leader and she first optimizes her expected profit by using her own forecast information f_m; thus her private information will be revealed by her optimal policies w_N and τ_N. Hence, the retailer actually maximizes his expected profits based on forecasts f_m and f_r. Consequently, the expected profits of the manufacturer and the retailer, conditional on the forecast information, are given as follows:

$$\Pi_{MN} = E\left[\left((\phi - \beta p_N)(w_N - c_m + \Delta\tau_N) - \eta\tau_N^2\right) \mid f_m\right], \quad (3)$$
$$\Pi_{RN} = E\left[(\phi - \beta p_N)(p_N - w_N) \mid f_r, f_m\right].$$

In stage 3, as a follower, the retailer chooses p_N to maximize his expected profit Π_{RN}. Taking the first-order condition of Π_{RN} and setting it to zero, we derive the retailer's best response function:

$$p_N^* = \frac{w_N\beta + E[\phi \mid f_r, f_m]}{2\beta}, \quad (4)$$

which results in the retail quantity of the retailer:

$$q_N^* = \frac{1}{2}\left(E[\phi \mid f_r, f_m] - w_N\beta\right). \quad (5)$$

Next, in the game, by using the retailer's order quantity and her forecast f_m, the manufacturer actually maximizes

$$\Pi_{MN} = E\left[\left(q_N^*(w_N - c_m + \Delta\tau_N) - \eta\tau_N^2\right) \mid f_m\right]. \quad (6)$$

It can be shown that Π_{MN} is concave if $\eta > \eta_1 = \beta\Delta^2/8$. Taking the first-order conditions and setting it to zero, we derive the Bayesian Nash equilibrium outcomes of the manufacturer:

$$w_N^* = \frac{(\beta\Delta^2 - 4\eta)\left(H\overline{\phi} + JE[f_r \mid f_m] + Kf_m\right) - 4\beta\eta c_m}{\beta(\beta\Delta^2 - 8\eta)}, \quad (7)$$
$$\tau_N^* = \frac{\Delta\left(\beta c_m - \left(H\overline{\phi} + JE[f_r \mid f_m] + Kf_m\right)\right)}{\beta\Delta^2 - 8\eta}.$$

Substituting w_N^* into p_N^* and q_N^*, we can obtain the retailer's equilibrium price and order quantity:

$$p_N^* = \frac{E[\phi \mid f_r, f_m]}{2\beta} + \frac{(\beta\Delta^2 - 4\eta)\left(H\overline{\phi} + JE[f_r \mid f_m] + Kf_m\right) - 4\beta\eta c_m}{2\beta(\beta\Delta^2 - 8\eta)},$$
$$q_N^* = \frac{E[\phi \mid f_r, f_m]}{2} - \frac{(\beta\Delta^2 - 4\eta)\left(H\overline{\phi} + JE[f_r \mid f_m] + Kf_m\right) - 4\beta\eta c_m}{2(\beta\Delta^2 - 8\eta)}. \quad (8)$$

Based on the above equilibrium decisions, we can obtain supply chain member's expected profits of stage 2 through substituting w_N^*, τ_N^*, and p_N^* into Π_{MN} and Π_{RN}, which are given by

$$\Pi_{MN} = \frac{\eta\left(H\overline{\phi} + JE[f_r \mid f_m] + Kf_m - \beta c_m\right)\left(H\overline{\phi} + JE[f_r \mid f_m] + Kf_m - 2E[\phi \mid f_r, f_m] + \beta c_m\right)}{\beta(\beta\Delta^2 - 8\eta)},$$
$$\Pi_{RN} = \frac{\left((\beta\Delta^2 - 4\eta)\left(H\overline{\phi} + JE[f_r \mid f_m] + Kf_m\right) + (8\eta - \beta\Delta^2)E[\phi \mid f_r, f_m] - 4\beta\eta c_m\right)^2}{4\beta(\beta\Delta^2 - 8\eta)^2}. \quad (9)$$

Next, we aim to derive ex ante profits of the manufacturer and the retailer before the demand signal is observed. The ex ante profits of stage 1 can be obtained by taking expectations with respect to the forecasts f_m and f_r; that is,

$$\Pi_{MN}^* = \int_0^\infty \int_0^\infty \Pi_{MN}\, g(f_r, f_m)\, df_r\, df_m,$$
$$\Pi_{RN}^* = \int_0^\infty \int_0^\infty \Pi_{RN}\, g(f_r, f_m)\, df_r\, df_m, \quad (10)$$

where $g(f_r, f_m)$ is the density of the bivariate normal probability distribution of f_m and f_r. In Lemma 1, we give the firms' ex ante profits. All proofs are in the Appendix.

Lemma 1. *For the no information sharing case, the ex ante profits of the manufacturer and the retailer are as follows:*

$$\Pi_{MN}^* = \frac{\eta}{\beta(8\eta - \beta\Delta^2)}\left(\frac{\sigma_0^4}{\sigma_0^2 + \sigma_m^2} + \left(\overline{\phi} - \beta c_m\right)^2\right),$$
$$\Pi_{RN}^* = \frac{\sigma_0^4\left(16\eta^2\sigma_0^2 L_2 + \sigma_m^2\left((\beta^2\Delta^4 - 16\beta\Delta^2\eta + 48\eta^2)(\rho^2 - 1)\sigma_r^2 + (\beta\Delta^2 - 8\eta)^2 L_2\right)\right)}{4\beta L_1(\sigma_0^2 + \sigma_m^2)(\beta\Delta^2 - 8\eta)^2} + \frac{4\eta^2\left(\overline{\phi} - \beta c_m\right)^2}{\beta(\beta\Delta^2 - 8\eta)^2}, \quad (11)$$

where $L_1 = (1-\rho^2)\sigma_m^2\sigma_r^2 + \sigma_0^2 L_2$ $(L_1 > 0)$ *and* $L_2 = \sigma_m^2 - 2\rho\sigma_m\sigma_r + \sigma_r^2$ $(L_2 > 0)$.

3.2. Information Sharing Case. In this case, both the retailer and the manufacturer share their forecasts in stage 1 of the game, before the forecasts are observed. Hence, both the manufacturer and the retailer maximize their expected profits based on forecast information f_m and information f_r. The manufacturer then maximizes her expected profit

$$\Pi_{MS} = E\left[(\phi - \beta p)(w - c_m + \Delta\tau) - \eta\tau^2 \mid f_r, f_m\right]. \quad (12)$$

Note that the retailer's optimal problem of this case is the same as the case of non-information sharing. Therefore, the retailer's best response functions of price and quantity in this case are still similar to those of Section 3.1. Based on the retailer's best response functions, we further can derive the Bayesian Nash equilibrium outcomes in the case of information sharing:

$$\begin{aligned} w_S^* &= \frac{\left(\beta\Delta^2 - 4\eta\right)E\left[\phi \mid f_r, f_m\right] - 4\beta\eta c_m}{\beta\left(\beta\Delta^2 - 8\eta\right)}, \\ \tau_S^* &= \frac{\Delta\left(\beta c_m - E\left[\phi \mid f_r, f_m\right]\right)}{\beta\Delta^2 - 8\eta}, \\ p_S^* &= \frac{\left(\beta\Delta^2 - 6\eta\right)E\left[\phi \mid f_r, f_m\right] - 2\beta\eta c_m}{\beta\left(\beta\Delta^2 - 8\eta\right)}, \\ q_S^* &= \frac{2\eta\left(\beta c_m - E\left[\phi \mid f_r, f_m\right]\right)}{\beta\Delta^2 - 8\eta}. \end{aligned} \quad (13)$$

Based on the above equilibrium decisions, we can obtain supply chain member's expected profits of stage 2, which are given by

$$\begin{aligned} \Pi_{MS} &= \frac{\eta\left(E\left[\phi \mid f_r, f_m\right] - \beta c_m\right)^2}{\beta\left(8\eta - \beta\Delta^2\right)}, \\ \Pi_{RS} &= \frac{4\left(\eta E\left[\phi \mid f_r, f_m\right] - \beta\eta c_m\right)^2}{\beta\left(\beta\Delta^2 - 8\eta\right)^2}. \end{aligned} \quad (14)$$

Next, we aim to derive ex ante profits of the manufacturer and the retailer before the demand signal is observed (i.e., in stage 1), which can be obtained by taking expectations with respect to the forecasts f_m and f_r.

Lemma 2. *For the information sharing case, the ex ante profits of the manufacturer and the retailer are as follows:*

$$\begin{aligned} \Pi_{MS}^* &= \frac{\eta\left(\sigma_0^4 L_2 + \left(\overline{\phi} - \beta c_m\right)^2 L_1\right)}{\beta\left(8\eta - \beta\Delta^2\right)L_1}, \\ \Pi_{RS}^* &= \frac{4\eta^2\left(\sigma_0^4 L_2 + \left(\overline{\phi} - \beta c_m\right)^2 L_1\right)}{\beta\left(\beta\Delta^2 - 8\eta\right)^2 L_1}. \end{aligned} \quad (15)$$

3.3. Information Sharing and Bargaining. In order to analyze the equilibrium decisions of information sharing in stage 1, we first make comparisons about ex ante profits between no information sharing case and information sharing case. Let V_M^*, V_R^*, and V_S^* represent the value of information sharing to the manufacturer, the retailer, and the supply chain, respectively. Consequently, we have

$$\begin{aligned} V_M^* &= \Pi_{MS}^* - \Pi_{MN}^* = \frac{\eta\sigma_0^4\sigma_m^2\left(\sigma_m - \rho\sigma_r\right)^2}{\beta\left(8\eta - \beta\Delta^2\right)\left(\sigma_0^2 + \sigma_m^2\right)L_1}, \\ V_R^* &= \Pi_{RS}^* - \Pi_{RN}^* \\ &= -\frac{\left(\beta\Delta^2 - 12\eta\right)\left(\beta\Delta^2 - 4\eta\right)\sigma_0^4\sigma_m^2\left(\sigma_m - \rho\sigma_r\right)^2}{4\beta\left(\beta\Delta^2 - 8\eta\right)^2\left(\sigma_0^2 + \sigma_m^2\right)L_1}, \\ V_S^* &= V_M^* + V_R^* \\ &= -\frac{\left(\beta^2\Delta^4 - 12\beta\Delta^2\eta + 16\eta^2\right)\sigma_0^4\sigma_m^2\left(\sigma_m - \rho\sigma_r\right)^2}{4\beta\left(\beta\Delta^2 - 8\eta\right)^2\left(\sigma_0^2 + \sigma_m^2\right)L_1}. \end{aligned} \quad (16)$$

The value of information sharing can be analyzed in detail in Proposition 3.

Proposition 3. *(a)* $V_M^* > 0$; *(b)* $V_R^* \geq 0$ *if* $\eta_1 < \eta \leq \eta_2$ *and* $V_R^* < 0$ *if* $\eta > \eta_2$; *(c)* $V_S^* \geq 0$ *if* $\eta_1 < \eta \leq \eta_3$ *and* $V_S^* < 0$ *if* $\eta > \eta_3$, *where* $\eta_2 = \beta\Delta^2/4$ *and* $\eta_3 = (3 + \sqrt{5})\beta\Delta^2/8$.

Proposition 3(a) indicates that the manufacturer can always benefit from information sharing. The main reason is that after sharing the information the manufacturer can obtain more demand information and update it, thereby making better decisions and earning a higher profit.

Proposition 3(b) indicates that the retailer can also benefit from information sharing when the collection efficiency is high (i.e., $\eta_1 < \eta \leq \eta_2$*). This is mainly because the manufacturer tends to increase the collection rate in this scenario, thereby decreasing her cost of manufacturing. As a result, the manufacturer will decrease the wholesale price, which will decrease the double marginalization effect and will be of benefit to the retailer. Hence, the retailer's profit increases in this case, although he loses the benefits of keeping private information after sharing the information. However, when the collection efficiency is low (i.e.,* $\eta > \eta_2$*), the retailer's profit decreases. This is mainly because the retailer's loss of sharing information cannot be compensated from the manufacturer's collection operations.*

Proposition 3(c) implies that sharing the retailer's forecast with the manufacturer benefits the supply chain if the collection efficiency is high while hurting the supply chain if the collection efficiency is low. Hence, if $\eta_1 < \eta \leq \eta_2$*, the retailer will share his forecasts voluntarily without any incentives. If* $\eta_2 < \eta \leq \eta_3$*, it is possible for the manufacturer to induce the retailer to share his forecasts through incentives. And if* $\eta > \eta_3$*, information sharing will not be realized.*

Besides, we find that the value of information sharing to the supply chain members depends on the manufacturer's forecast accuracy (σ_m*), the retailer's forecast accuracy (*σ_r*), and the forecasting correlation (*ρ*). We, therefore, discuss the impact of* *these parameters on the value of information sharing, that is, V_M^*, V_R^*, and V_S^* in the following. And these results are given in Proposition 4.*

Proposition 4. *(a) $\partial V_M^*/\partial\sigma_m > 0$, $\partial V_M^*/\partial\sigma_r < 0$, and $\partial V_M^*/\partial\rho < 0$.*

(b) $\partial V_R^*/\partial\sigma_m > 0$, $\partial V_R^*/\partial\sigma_r < 0$, and $\partial V_R^*/\partial\rho < 0$ if $\eta_1 < \eta \leq \eta_2$ and $\partial V_R^*/\partial\sigma_m < 0$, $\partial V_R^*/\partial\sigma_r \geq 0$, and $\partial V_R^*/\partial\rho \geq 0$ if $\eta > \eta_2$.

(c) $\partial V_S^*/\partial\sigma_m > 0$, $\partial V_S^*/\partial\sigma_r < 0$, and $\partial V_S^*/\partial\rho < 0$ if $\eta_1 < \eta \leq \eta_3$ and $\partial V_S^*/\partial\sigma_m < 0$, $\partial V_S^*/\partial\sigma_r \geq 0$, and $\partial V_S^*/\partial\rho \geq 0$ if $\eta > \eta_3$.

Proposition 4(a) indicates that the value of information sharing to the manufacturer decreases as her forecasts become precise (i.e., σ_m decreases). This is because when the manufacturer's forecasts become more precise, she could make better decisions and earn a higher profit in the non-information sharing case. Moreover, V_M^* decreases as σ_r or ρ increases. This is because while the retailer's forecast accuracy exerts no impact on the manufacturer's profits of the non-information sharing case, the manufacturer's profits of the information sharing case increase as the retailer's forecasts become precise. Furthermore, a higher ρ means a higher similarity of f_m and f_r. As a result, the value of information sharing to the manufacturer decreases as ρ increases.

Parts (b) and (c) show that the effects of σ_m, σ_r, and ρ on V_R^* and V_S^* are similar to those on V_M^* when the collection efficiency is high. However, the effects will be opposite for a low collection efficiency. This is mainly because sharing information does harm to the retailer and the supply chain in this case.

Next, we will focus on the equilibrium decisions of information sharing. It is easy to derive the equilibrium when $\eta_1 < \eta \leq \eta_2$ and $\eta > \eta_3$, based on the results of Proposition 3. When $\eta_2 < \eta \leq \eta_3$, we try to design a bargaining mechanism to induce information sharing between the manufacturer and the retailer. In this case, we assume that while the manufacturer's negotiation power is α_1, the retailer's negotiation power is α_2. Moreover, $\alpha_1 + \alpha_2 = 1$. We let x represent the manufacturer's desired profit and y represent the retailer's desired profit. After sharing the information, neither the manufacturer nor the retailer will accept a profit that is less than what each party could obtain in the non-information sharing case. Besides, $\Pi_{MS}^* + \Pi_{RS}^*$ is the pie to be allocated. Referring to Nagarajan and Bassok [25], we then describe the problem of generalizing Nash bargaining as follows:

$$\begin{aligned} \max_{x,y} \quad & (x - \Pi_{MN}^*)^{\alpha_1} (y - \Pi_{RN}^*)^{\alpha_2} \\ \text{s.t.} \quad & x - \Pi_{MN}^* \geq 0, \\ & y - \Pi_{RN}^* \geq 0, \\ & x + y \leq \Pi_{MS}^* + \Pi_{RS}^*, \\ & \alpha_1 + \alpha_2 = 1. \end{aligned} \tag{17}$$

Solving the above problem, we derive $x = \Pi_{MN}^* + \alpha_1 V_S^*$, $y = \Pi_{RN}^* + \alpha_2 V_S^*$; that is, after information sharing, through bargaining, the manufacturer and the retailer obtain the payoffs $\Pi_{MN}^* + \alpha_1 V_S^*$ and $\Pi_{RN}^* + \alpha_2 V_S^*$, respectively. The bargaining results indicate that the allocation of the information sharing's value to supply chain depends on the bargaining power of supply chain members. Specifically, if a member's negotiating power is stronger, it will obtain a higher profit allocation. Lastly, we summarize the equilibrium decisions of information sharing in Proposition 5.

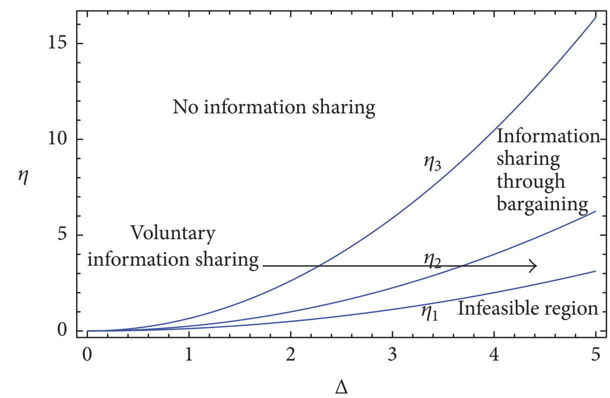

Figure 1: Equilibrium information sharing decisions of the make-to-order scenario.

Proposition 5. *(a) When $\eta_1 < \eta \leq \eta_2$, information sharing is a unique equilibrium without any incentives. (b) When $\eta_2 < \eta \leq \eta_3$, information sharing is a unique equilibrium under the bargaining mechanism. (c) When $\eta > \eta_3$, non-information sharing is a unique equilibrium.*

Proposition 5 can be better depicted by Figure 1. It can be further shown that $(\eta_2 - \eta_1)$ and $(\eta_3 - \eta_2)$ are increasing in β and Δ. Therefore, Proposition 5 implies that both the region of voluntarily sharing information and the region of sharing information through negotiation become larger as the price becomes more sensitive to the demand or as the benefits of remanufacturing become larger.

4. The Make-to-Stock Scenario

In this section, we analyze the make-to-stock scenario, in which the manufacturer may bear the holding cost or the shortage cost. Similar to the make-to-order scenario, we first analyze the case of non-information sharing and then the case of information sharing and lastly the profit sharing mechanism.

4.1. No Information Sharing Case. Similar to the make-to-order scenario, while the retailer knows the forecasts f_m and f_r, the manufacturer only knows f_m in this case. The retailer who does not hold inventories, therefore, maximizes his expected profits $\pi_{RN} = E[(\phi - \beta p_N)(p_N - w_N) \mid f_r, f_m]$. Note that the retailer's optimization problem is similar to the case of the make-to-order scenario. In consequence, we can derive the retailer's price decision $p_N^* = (w_N\beta + E[\phi \mid f_r, f_m])/2\beta$ and the order quantity $q_N^* = (1/2)(E[\phi \mid f_r, f_m] - w_N\beta)$.

Next, in the game, the manufacturer maximizes her expected profit, based on the retailer's order quantities q_N^* and her own forecast f_m:

$$\pi_{MN} = E\left[\left(\int_0^\infty \left(\left(\phi - \beta p_N\right)\left(w_N - c_m + \Delta\tau_N\right) - \eta{\tau_N}^2\right) \cdot f(\phi)\,d\phi - \int_0^{Q_N+\beta p_N} h\left(Q_N - \left(\phi - \beta p_N\right)\right) \cdot f(\phi)\,d\phi - \int_{Q_N+\beta p_N}^\infty s\left(\phi - \beta p_N - Q_N\right) \cdot f(\phi)\,d\phi\right) \mid f_m\right]. \quad (18)$$

And then the Bayesian Nash equilibrium can be derived. At last, we can derive the ex ante profits of supply chain members based on the optimal decisions of supply chain members, which are summarized in Lemma 6.

Lemma 6. *For the no information sharing case, the ex ante profits of the manufacturer and the retailer are as follows:*

$$\pi_{MN}^* = \frac{\eta}{\beta\left(8\eta - \beta\Delta^2\right)}\left(\frac{\sigma_0^4}{\sigma_0^2 + \sigma_m^2} + \left(\overline{\phi} - \beta c_m\right)^2\right) - \frac{1}{2}\sigma_N\left(\left(s+h\right)L(r) + hr\right),$$
$$\pi_{RN}^* = \frac{\sigma_0^4\left(16\eta^2\sigma_0^2 L_2 + \sigma_m^2\left(\left(\beta^2\Delta^4 - 16\beta\Delta^2\eta + 48\eta^2\right)\left(\rho^2 - 1\right)\sigma_r^2 + \left(\beta\Delta^2 - 8\eta\right)^2 L_2\right)\right)}{4\beta L_1\left(\sigma_0^2 + \sigma_m^2\right)\left(\beta\Delta^2 - 8\eta\right)^2} + \frac{4\eta^2\left(\overline{\phi} - \beta c_m\right)^2}{\beta\left(\beta\Delta^2 - 8\eta\right)^2}, \quad (19)$$

where $\sigma_N^2 = \sigma_m^2\sigma_0^2/(\sigma_0^2 + \sigma_m^2)$, $r = \Phi^{-1}(s/(s+h))$ ($\Phi(x)$ is the density function of the standard normal probability distribution), and $L(r) = \int_r^\infty (z - r)d\Phi(z)$.

4.2. Information Sharing Case. In this case, both the manufacturer and the retailer maximize their expected profits based on the forecast information f_m and information f_r. The retailer's best response functions of price and order quantity are the same as those of Section 4.1. And then the manufacturer maximizes

$$\pi_{MS} = E\left[\left(\int_0^\infty \left(\left(\phi - \beta p_S\right)\left(w_S - c_m + \Delta\tau_S\right) - \eta{\tau_S}^2\right) \cdot f(\phi)\,d\phi - \int_0^{Q_S+\beta p_S} h\left(Q_S - \left(\phi - \beta p_S\right)\right) \cdot f(\phi)\,d\phi - \int_{Q_S+\beta p_S}^\infty s\left(\phi - \beta p_S - Q_S\right) \cdot f(\phi)\,d\phi\right) \mid f_r, f_m\right]. \quad (20)$$

The ex ante profits of supply chain members can be obtained and given in Lemma 7.

Lemma 7. *For the information sharing case, the ex ante profits of the manufacturer and the retailer are as follows:*

$$\pi_{MS}^* = \frac{\eta\left(\sigma_0^4 L_2 + \left(\overline{\phi} - \beta c_m\right)^2 L_1\right)}{\beta\left(8\eta - \beta\Delta^2\right)L_1} - \frac{1}{2}\sigma_S\left(\left(s+h\right)L(r) + hr\right),$$
$$\pi_{RS}^* = \frac{4\eta^2\left(\sigma_0^4 L_2 + \left(\overline{\phi} - \beta c_m\right)^2 L_1\right)}{\beta\left(\beta\Delta^2 - 8\eta\right)^2 L_1}, \quad (21)$$

where $\sigma_S^2 = (1-\rho^2)\sigma_m^2\sigma_r^2\sigma_0^2/((1-\rho^2)\sigma_m^2\sigma_r^2 + \sigma_0^2(\sigma_m^2 + \sigma_r^2 - 2\rho\sigma_m\sigma_r))$.

4.3. Information Sharing and Bargaining. In the section, we are going to focus on the value of information sharing and profit sharing mechanism of the make-to-stock scenario. Comparing the ex ante profits of non-information sharing case with those of information sharing case, we have

$$v_M^* = \pi_{MS}^* - \pi_{MN}^* = \frac{\eta\sigma_0^4\sigma_m^2\left(\sigma_m - \rho\sigma_r\right)^2}{\beta\left(8\eta - \beta\Delta^2\right)\left(\sigma_0^2 + \sigma_m^2\right)L_1} + \frac{1}{2}\left(\sigma_N - \sigma_S\right)\left(\left(s+h\right)L(r) + hr\right),$$
$$v_R^* = \pi_{RS}^* - \pi_{RN}^* = -\frac{\left(\beta\Delta^2 - 12\eta\right)\left(\beta\Delta^2 - 4\eta\right)\sigma_0^4\sigma_m^2\left(\sigma_m - \rho\sigma_r\right)^2}{4\beta\left(\beta\Delta^2 - 8\eta\right)^2\left(\sigma_0^2 + \sigma_m^2\right)L_1}, \quad (22)$$
$$v_S^* = v_M^* + v_R^* = -\frac{\left(\beta^2\Delta^4 - 12\beta\Delta^2\eta + 16\eta^2\right)\sigma_0^4\sigma_m^2\left(\sigma_m - \rho\sigma_r\right)^2}{4\beta\left(\beta\Delta^2 - 8\eta\right)^2\left(\sigma_0^2 + \sigma_m^2\right)L_1} + \frac{1}{2}\left(\sigma_N - \sigma_S\right)\left(\left(s+h\right)L(r) + hr\right).$$

Comparing the information sharing's value of the make-to-order scenario with that of make-to-stock scenario, we

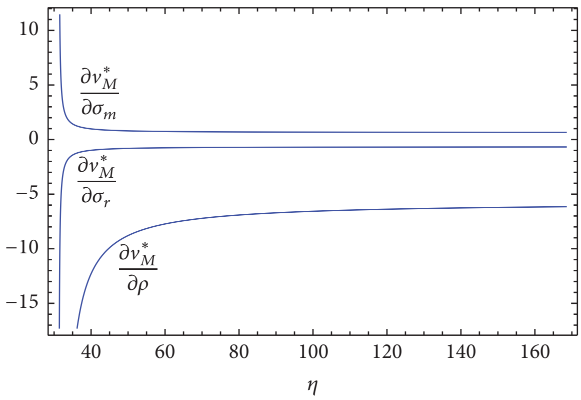

Figure 2: The impacts of σ_m, σ_r, and ρ on v_M^*.

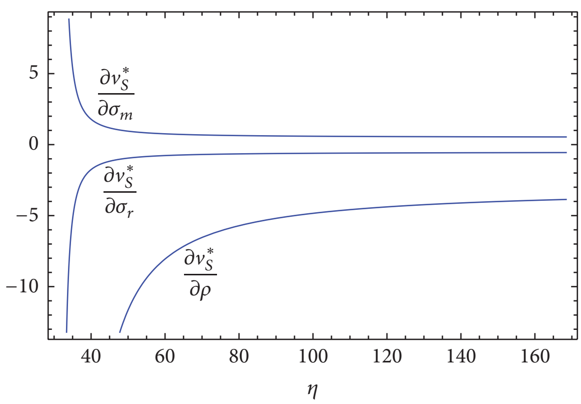

Figure 3: The impacts of σ_m, σ_r, and ρ on v_S^*.

find that while the value of information sharing to the retailer does not change, the value to the manufacturer and the supply chain is higher in the make-to-stock scenario due to $(1/2)(\sigma_N - \sigma_S)((s+h)L(r)+hr) > 0$ (note that $\sigma_N > \sigma_S$); this is mainly because the manufacturer and the supply chain can save the cost of inventories and shortage in this scenario.

In terms of the impact of σ_m, σ_r, and ρ on the value of information sharing in the make-to-stock scenario, we find that the effects of σ_m, σ_r, and ρ on the v_R^* are the same as those of the make-to-order scenario, because $v_R^* = V_R^*$. And for the impacts of σ_m, σ_r, and ρ on v_M^* and v_S^*, since the analytical expressions are too complex to provide meaningful insights, we, therefore, investigate them through a numerical study; see Figures 2 and 3. Figure 2 shows that the effects of σ_m, σ_r, and ρ on v_M^* are also the same as those of the make-to-order scenario; that is, while σ_m poses a positive effect on v_M^*, σ_r and ρ pose a negative effect on v_M^*. Figure 3 indicates that σ_m has a positive effect on v_S^*; σ_r and ρ have a negative effect on v_S^*. Note that the effects of σ_m, σ_r, and ρ on v_S^* in the make-to-stock scenario are opposite to those in the make-to-order scenario when the collection efficiency is low. This is mainly because the values of information sharing to the manufacturer are higher and these parameters have a more positive/negative effect on v_M^* in the make-to-stock scenario.

Furthermore, we can derive the equilibrium decisions of information sharing in Proposition 8.

Proposition 8. *(a) When $\eta_1 < \eta \leq \eta_2$, information sharing is a unique equilibrium, although there is no incentive mechanism. (b) When $\eta_2 < \eta \leq \eta_4$, information sharing is a unique equilibrium through a bargaining mechanism. And in the equilibrium, the payoffs of the manufacturer and retailer are $\pi_{MN}^* + \alpha_1 v_S^*$ and $\pi_{RN}^* + (1-\alpha_1)v_S^*$, respectively, where η_4 is the solution of $v_S^* = 0$ and $\eta_4 > \eta_3$. (c) When $\eta > \eta_4$, non-information sharing is a unique equilibrium.*

The result of Proposition 8(a) is similar to that of the make-to-order scenario, due to the same value of information sharing to the retailer in both scenarios. However, part (b) indicates that the possibility of information sharing through bargaining becomes higher in the make-to-stock scenario, which results from $v_S^* > V_S^*$ and $\eta_4 > \eta_3$.

5. Conclusion

In this paper, we investigate the equilibrium decisions of information sharing in a closed-loop supply chain under the production modes of make-to-order and make-to-stock, when the supply chain members can forecast the uncertain market demand. In both modes, we find that the retailer will share his forecasts voluntarily when the collection efficiency of the manufacturer is high, and the retailer will never share his forecasts when the collection efficiency is low. Moreover, when the collection efficiency is moderate, we have designed a bargaining mechanism, which can induce the retailer to share his forecast information. Besides, we find the information sharing's value to the manufacturer and the supply chain in the make-to-order scenario are lower than those in the make-to-stock scenario, and the region of information sharing through bargaining in the make-to-order scenario is smaller than that in the make-to-stock scenario.

We also analyze the impact of the forecast accuracy of supply chain members and the forecasting correlation on the value of information sharing and our research shows that in the make-to-order scenario if the manufacturer's forecasts become inaccurate or if the retailer's forecasts become precise or if the forecasts correlation decreases, the value of information sharing to the manufacturer increases. Moreover, when the collection efficiency of the manufacturer is high (low), the effects of these forecasting's parameters on the information sharing's value of the retailer and supply chain are similar (contrary) to those on the information sharing's value of the manufacturer. For the make-to-stock scenario, we find that the effects of supply chain members' forecast accuracy and the forecasting correlation on the information sharing's value of the retailer are the same as those in the make-to-order scenario.

Although the assumption of obtaining forecasts without incurring any cost is commonly used in the literature on information sharing, it would be also worthwhile to study the information sharing equilibrium in a closed-loop supply chain when obtaining forecasts incurs cost.

Appendix

Proof of Lemma 1. We first derive Π_{MN}^*. Substituting $E[f_r \mid f_m] = (1-d_m)\overline{\phi} + d_m f_m$ into Π_{MN} and expanding it, we have $\Pi_{MN} = \eta L_3/\beta(\beta\Delta^2 - 8\eta)$, where

$$\begin{aligned} L_3 = {} & 2\beta H\overline{\phi}c_m + 2J^2\overline{\phi}d_m f_r - 2J^2\overline{\phi}d_m^2 f_m \\ & + 2J^2\overline{\phi}d_m f_m + J^2\overline{\phi}^2 d_m^2 - 2J^2\overline{\phi}^2 d_m - 2HJ\overline{\phi}f_r \\ & - 2HK\overline{\phi}f_m - 2J^2\overline{\phi}f_r - H^2\overline{\phi}^2 + J^2\overline{\phi}^2 \\ & + 2\beta Jc_m f_r + 2\beta Kc_m f_m - \beta^2 c_m^2 - 2J^2 d_m f_m f_r \\ & + J^2 d_m^2 f_m^2 - 2JKf_m f_r - K^2 f_m^2. \end{aligned} \tag{A.1}$$

We know that $f_i = \phi + \varepsilon_i$; thus $E[f_i] = \overline{\phi}$. Because $\mathrm{Var}[\phi] = E[\phi^2] - (E[\phi])^2$, that is, $\sigma_0^2 = E[\phi^2] - \overline{\phi}^2$, hence, $E[\phi^2] = \sigma_0^2 + \overline{\phi}^2$. Moreover, $E[f_i^2] = \sigma_0^2 + \overline{\phi}^2 + \sigma_i^2$; this is because $f_i^2 = \phi^2 + 2\phi\varepsilon_i + \varepsilon_i^2$. Besides, $E[f_m f_r] = \overline{\phi}^2 + \rho\sigma_m\sigma_r + \sigma_0^2$. Consequently, simplifying the expectation of L_3, we can derive the manufacturer's ex ante profit Π_{MN}^*. Similarly, we can derive the retailer's ex ante profit Π_{RN}^*. □

Proof of Lemma 2. The proof of Lemma 2 is similar to that of Lemma 1; thus we omit the tedious work. □

Proof of Proposition 3. First, we verify the value of information sharing to the supply chain V_S^*. If $\beta\Delta^2/8 < \eta \leq (3+\sqrt{5})\beta\Delta^2/4$, we derive $-(\beta^2\Delta^4 - 12\beta\Delta^2\eta + 16\eta^2) > 0$; hence, $V_S^* > 0$. If $\eta > (3+\sqrt{5})\beta\Delta^2/4$, we derive $-(\beta^2\Delta^4 - 12\beta\Delta^2\eta + 16\eta^2) < 0$; hence, $V_S^* < 0$. Similarly, it is easy to verify V_M^* and V_R^*. □

Proof of Proposition 4. First, we prove part (c). We have

$$\begin{aligned} \frac{\partial V_S^*}{\partial \sigma_m} &= -\frac{\left(\beta^2\Delta^4 - 12\beta\Delta^2\eta + 16\eta^2\right)(\sigma_m - \rho\sigma_r)\sigma_0^4\sigma_m L_4}{2\beta\left(\sigma_m^2+\sigma_0^2\right)^2\left(\beta\Delta^2 - 8\eta\right)^2 {L_1}^2}, \\ \frac{\partial V_S^*}{\partial \sigma_r} &= \frac{\left(\beta^2\Delta^4 - 12\beta\Delta^2\eta + 16\eta^2\right)\left(1-\rho^2\right)(\sigma_m - \rho\sigma_r)\sigma_0^4\sigma_m^3\sigma_r}{2\beta\left(\beta\Delta^2 - 8\eta\right)^2 {L_1}^2}, \\ \frac{\partial V_S^*}{\partial \rho} &= \frac{\left(\beta^2\Delta^4 - 12\beta\Delta^2\eta + 16\eta^2\right)(\sigma_r - \rho\sigma_m)(\sigma_m - \rho\sigma_r)\sigma_0^4\sigma_m^2\sigma_r^2}{2\beta\left(\beta\Delta^2 - 8\eta\right)^2 {L_1}^2}, \end{aligned} \tag{A.2}$$

where

$$\begin{aligned} L_4 &= \sigma_0^4\left(\sigma_m^2(\sigma_m - \rho\sigma_r) + \sigma_r(\rho\sigma_m - \sigma_r)(\rho\sigma_r - 2\sigma_m)\right) \\ &\quad + 2\left(1-\rho^2\right)\sigma_0^2\sigma_m^3\sigma_r^2 + \rho\left(1-\rho^2\right)\sigma_m^4\sigma_r^3 > 0. \end{aligned} \tag{A.3}$$

Combining $\sigma_m > \rho\sigma_r$, $\sigma_r > \rho\sigma_m$, and the proof of Proposition 3, part (c) can be derived. Similarly, we can derive parts (a) and (b). □

Proof of Proposition 5. It is easy to derive Proposition 5; thus, we omit the tedious work. □

Proof of Lemma 6. For this non-information sharing case, the retailer's order quantity $q_N^* = (1/2)(E[\phi \mid f_r, f_m] - \beta w_N)$. However, the manufacturer does not know the retailer's forecast f_r; she, therefore, believes that the retailer's order quantity $\tilde{q}_N = (1/2)(\phi_N - \beta w_N)$, where ϕ_N is normally distributed with mean $\mu_N = H\overline{\phi} + JE[f_r \mid f_m] + Kf_m$ and variance $\sigma_N^2 = \sigma_m^2\sigma_0^2/(\sigma_0^2 + \sigma_m^2)$. Hence, the manufacturer's profit can be expressed as follows:

$$\pi_{MN} = \begin{cases} \tilde{q}_N\left(w_N - c_m + \Delta\tau_N\right) - \eta\tau_N^2 - h\left(Q_N - \tilde{q}_N\right) & \phi_N \leq 2Q_N + \beta w_N, \\ \tilde{q}_N\left(w_N - c_m + \Delta\tau_N\right) - \eta\tau_N^2 - s\left(\tilde{q}_N - Q_N\right) & \phi_N > 2Q_N + \beta w_N. \end{cases} \tag{A.4}$$

Furthermore, the manufacturer actually maximizes

$$\begin{aligned} \pi_{MN} &= \int_0^\infty \left(\tilde{q}_N\left(w_N + \Delta\tau_N - c_m\right) - \eta\tau_N^2\right) f\left(\phi_N\right) d\phi_N \\ &\quad - \int_0^{2Q_N+\beta w_N} h\left(Q_N - \tilde{q}_N\right) f\left(\phi_N\right) d\phi_N \\ &\quad - \int_{2Q_N+\beta w_N}^\infty s\left(\tilde{q}_N - Q_N\right) f\left(\phi_N\right) d\phi_N, \end{aligned} \tag{A.5}$$

where $f(\phi_N)$ is the probability density function of ϕ_N.

By solving

$$\begin{aligned} \frac{\partial \pi_{MN}}{\partial Q_N} &= s - (h+s)\,\Phi\left(\frac{2Q_N + \beta w_N - \mu_N}{\sigma_N}\right) = 0, \\ \frac{\partial \pi_{MN}}{\partial \tau_N} &= -\frac{1}{2}\left(4\eta\tau_N + \beta\Delta w_N - \Delta\mu_N\right) = 0, \\ \frac{\partial \pi_{MN}}{\partial w_N} &= \frac{1}{2}\left(\mu_N + \beta c_m + \beta s - \beta\Delta\tau_N - 2\beta w_N\right) \\ &\quad - \frac{1}{2}\beta(h+s)\,\Phi\left(\frac{2Q_N + \beta w_N - \mu_N}{\sigma_N}\right) = 0, \end{aligned} \tag{A.6}$$

simultaneously (note that $\Phi(x)$ is the density function of the standard normal probability distribution), we derive the Bayesian Nash equilibrium outcomes of the manufacturer:

$$w_N^* = \frac{(\beta\Delta^2 - 4\eta)(H\overline{\phi} + JE[f_r \mid f_m] + Kf_m) - 4\beta\eta c_m}{\beta(\beta\Delta^2 - 8\eta)},$$

$$\tau_N^* = \frac{\Delta(\beta c_m - (H\overline{\phi} + JE[f_r \mid f_m] + Kf_m))}{\beta\Delta^2 - 8\eta},$$

$$Q_N^* = \frac{(4\eta - \beta\Delta^2)(H\overline{\phi} + JE[f_r \mid f_m] + Kf_m) + 4\beta\eta c_m}{2(\beta\Delta^2 - 8\eta)} + \frac{1}{2}\sigma_N r, \quad (A.7)$$

where $r = \Phi^{-1}(s/(s+h))$.

Based on the optimal decisions of supply chain members, we derive the supply chain members' expected profits:

$$\pi_{MN} = \frac{\eta(H\overline{\phi} + JE[f_r \mid f_m] + Kf_m - \beta c_m)(H\overline{\phi} + JE[f_r \mid f_m] + Kf_m - 2E[\phi \mid f_r, f_m] + \beta c_m)}{\beta(\beta\Delta^2 - 8\eta)} - \frac{1}{2}\sigma_N((s+h)L(r) + hr), \quad (A.8)$$

$$\pi_{RN} = \frac{((\beta\Delta^2 - 4\eta)(H\overline{\phi} + JE[f_r \mid f_m] + Kf_m) + (8\eta - \beta\Delta^2)E[\phi \mid f_r, f_m] - 4\beta\eta c_m)^2}{4\beta(\beta\Delta^2 - 8\eta)^2}.$$

The ex ante profits of supply chain members can be derived by taking expectations of π_{MN} and π_{RN} with respect to the forecasts f_m and f_r. □

Proof of Lemma 7. For this information sharing case, the manufacturer believes that the retailer's order quantity $\tilde{q}_S = (1/2)(\phi_S - \beta w_S)$, where ϕ_S is normally distributed with mean $\mu_S = H\overline{\phi} + Jf_r + Kf_m$ and variance $\sigma_S^2 = H\sigma_0^2$. Hence, the manufacturer actually maximizes

$$\pi_{MS} = \int_0^{\infty} (\tilde{q}_S(w_N + \Delta\tau_N - c_m) - \eta\tau_N^2) f(\phi_S)\, d\phi_S - \int_0^{2Q_S + \beta w_S} h(Q_N - \tilde{q}_S) f(\phi_S)\, d\phi_S - \int_{2Q_S + \beta w_S}^{\infty} s(\tilde{q}_S - Q_N) f(\phi_S)\, d\phi_S, \quad (A.9)$$

where $f(\phi_S)$ is the probability density function of ϕ_S.

By solving $\partial\pi_{MS}/\partial Q_S = 0$, $\partial\pi_{MS}/\partial\tau_S = 0$, and $\partial\pi_{MS}/\partial w_S = 0$ simultaneously, we derive the fact that

$$w_S^* = \frac{(\beta\Delta^2 - 4\eta)E[\phi \mid f_r, f_m] - 4\beta\eta c_m}{\beta(\beta\Delta^2 - 8\eta)},$$

$$\tau_S^* = \frac{\Delta(\beta c_m - E[\phi \mid f_r, f_m])}{\beta\Delta^2 - 8\eta}, \quad (A.10)$$

$$Q_S^* = \frac{(\beta\Delta^2 - 4\eta)E[\phi \mid f_r, f_m] + 4\beta\eta c_m}{2(\beta\Delta^2 - 8\eta)} + \frac{1}{2}\sigma_S r.$$

Based on the above equilibrium decisions, we can obtain supply chain member's expected profits of stage 2, which are given by

$$\pi_{MS} = -\frac{\eta(E[\phi \mid f_r, f_m] - \beta c_m)^2}{\beta(\beta\Delta^2 - 8\eta)} - \frac{1}{2}\sigma_S((s+h)L(r) + hr), \quad (A.11)$$

$$\pi_{RS} = \frac{4(\eta E[\phi \mid f_r, f_m] - \beta\eta c_m)^2}{\beta(\beta\Delta^2 - 8\eta)^2}.$$

The ex ante profits of stage 1 can be obtained by taking expectations with respect to the forecasts f_m and f_r. □

Proof of Proposition 8. Similar to the proofs of Propositions 3 and 5, we can derive Proposition 8. □

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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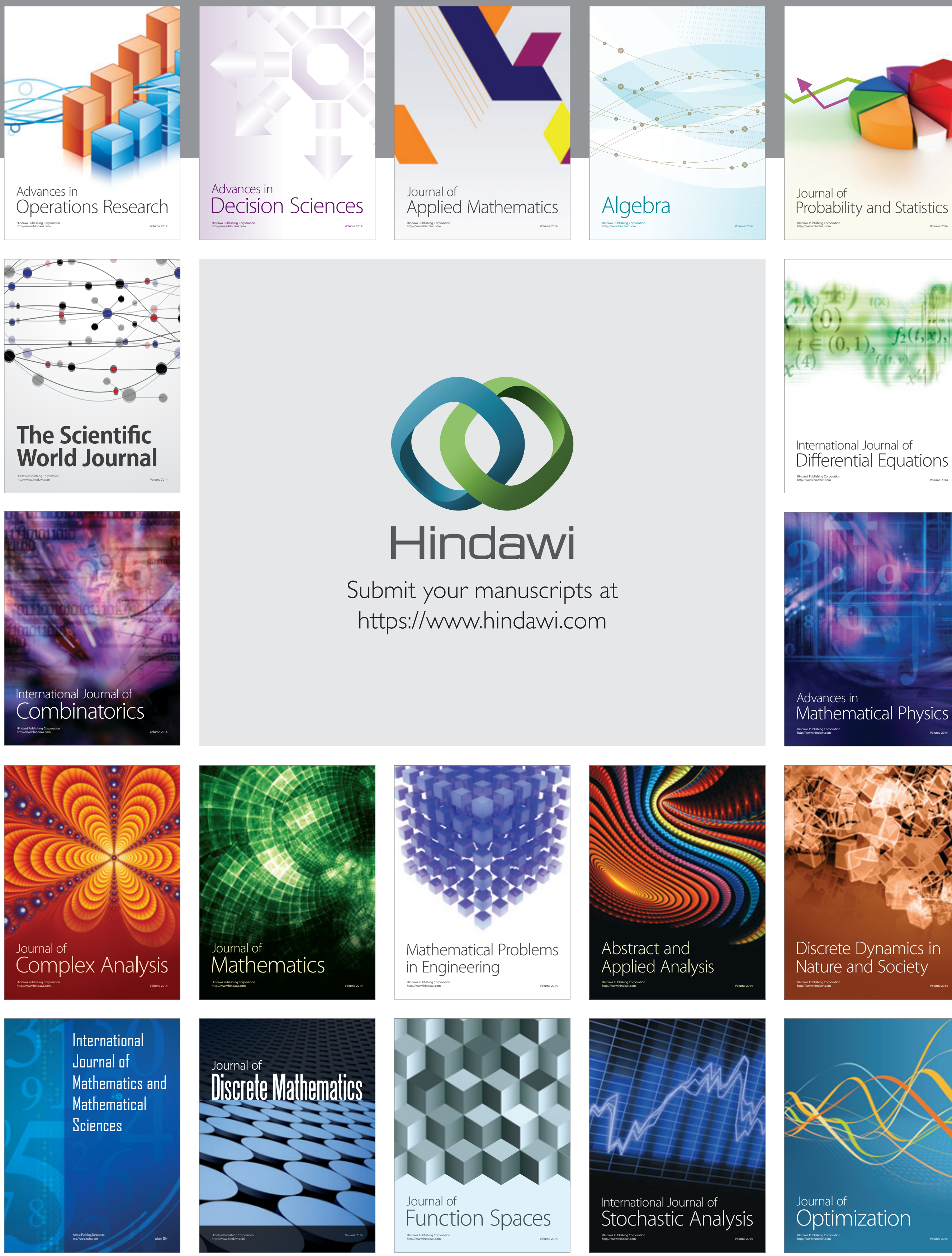
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