QUALITY COMPETITION AND COORDINATION IN A VMI SUPPLY CHAIN WITH TWO RISK-averse MANUFACTURERS

BIN CHEN
Institute of Transportation Development Strategy & Planning of Sichuan Province
Chengdu 610041, China

WENYING XIE
School of Transportation and Logistics, Southwest Jiaotong University
Chengdu 610036, China

FUYOU HUANG*
Institute of Transportation Development Strategy & Planning of Sichuan Province
Chengdu 610041, China

JUAN HE
School of Transportation and Logistics, Southwest Jiaotong University
Chengdu 610036, China

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Abstract. Quality competition and risk aversion have become more and more common in today’s many industries, making it a challenge to supply chain management and coordination. This paper considers a vendor-managed inventory (VMI) supply chain comprising two risk-averse manufacturers who sell their competing products through a common retailer. Market demand shared by each manufacturer is dependent on the quality level of its own product as well as on the competitor’s product quality. The Conditional Value-at-Risk (CVaR) criterion is employed to formulate the risk aversion of manufacturers. This study first develops basic models without coordination mechanism and analyzes the effect of the quality sensitivity, competition intensity, risk aversion degree and cost coefficient of quality improvement on equilibrium decisions and supply chain efficiency. Further, a combined contract composed of option and cost-sharing is proposed to investigate the supply chain coordination issue. The results reveal that the combined contract can coordinate the supply chain and achieve a win-win outcome only when the manufacturers are low in risk aversion, and the system-wide profit of the supply chain can be allocated arbitrarily only by the option price. Also, this research examines the effect of the quality sensitivity, competition intensity, risk aversion degree and cost coefficient of quality improvement on the feasible region of option price.

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* Corresponding author: Fuyou Huang.
1. Introduction. In today’s highly competitive marketplace, quality is an important dimension of a product, and product quality is increasingly important to the success of manufacturing firms [12]. From a consumer research study, product quality has been considered as the second most important factor affecting consumers' purchasing decision after product price [6]. In order to increase customer demand and market share, manufacturers in practice invest in technology and management used to make product, a larger investment in technology and management improves the quality of product, which results later in an increased demand potential for product [22]. As a result, competition nowadays is shifting from price to quality in many industries [20, 38]. For example, in the markets for fast food, soft drinks, clothing and telecommunications, competitors offer different quality of products rather than lower price to attract potential customers in a given market segment [43]. Thus, market demand shared by each manufacturer is dependent on the quality level of its own product as well as on the competitor’s product quality in a competitive marketplace. In order to enlarge market share, manufacturers have to improve their own product quality to attract more customers.

Currently, the issue of product quality decision has gained growing attention [6, 16, 37, 41, 47, 49, 52]. For example, Zhu et al. [52] proposed a deterministic model in which both a buyer and a supplier incur quality-related costs and therefore have incentives to invest in quality improvement. They examined how quality-improvement decisions interact with the buyer’s ordering quantity and the supplier’s production lot size. Chao et al. [6] discussed two contractual agreements by which product recall costs can be shared between a manufacturer and a supplier to induce quality improvement effort. EI Ouardighi [16] investigated the potential coordinating power of revenue sharing contract in a supply chain with one manufacturer and one supplier that collaborate to improve design quality of a particular finished product. Modak et al. [37] explored channel coordination and profit division issues of a manufacturer-distributor-duopolistic retailers supply chain for a product, where the manufacturer supplies lot size of the product that contains a random portion of imperfect quality item. Meanwhile, there are some studies on supply chain management with quality competition. Banker et al. [1] developed formal models of oligopolistic competition to investigate whether equilibrium levels of quality increase as competition intensifies under three different competitive settings. EI Ouardighi and Kim [17] formulated a non-cooperative dynamic game in which a single supplier collaborates with two manufacturers on design-quality improvements for their respective products. Xie et al. [43] studied the quality improvement strategy of two competing supply chains, where prices of products provided by the two supply chains are the same and competition between them is based on quality of products.

In addition, inventory management plays a vital role for the coordinated development of supply chain, which has always been an important issue concerned by scholars [29, 31]. Recently, some scholars have been making a deep study of the economic order/production quantity problem by relaxing some unrealistic assumptions of classical model [28, 30, 32]. Owing to channel restructuring and development of modern information technology, vendor-managed inventory (VMI) is increasingly becoming prevalent for improving inventory management in practice [13, 14, 48]. A classical success story for a VMI system is found in the partnership between Wal-Mart and Procter & Gamble, and it is confirmed that both of them can benefit from VMI partnership. The VMI partnership between Kimberly-Clark and Costco
is another VMI success story as it significantly improves inventory management and leads to a substantial increase in net incomes for both firms [45]. Besides, VMI partnership has been widely used across various industries by many other firms such as K-mart, Home Depot, Dell, HP, Campbell Soup, Shell Chemicals and Barilla [23, 36]. It has been shown that VMI partnership is a good way to reduce inventory cost and improve supply chain performance [15, 27], however, closer collaboration and coordination across the supply chain must be used to bring more benefits for each supply chain member in a decentralized system by a coordination mechanism such as supply chain contracts [7, 21]. Option contract is a viable alternative and increasingly popular to resolve the conflicting objectives of participating enterprises so as to obtain an efficient supply chain [2, 8, 25, 50]. There are some studies on supply chain coordination with option contract in a VMI system. For example, Cai et al. [3] showed that option contract is especially suitable for a supply chain operating under VMI system. Cai et al. [4] verified option contract is also effective to synchronously achieve supply chain coordination and Pareto-improvement under VMI model and yield uncertainty. Huang et al. [26] proposed a combined contract composed of option and cost-sharing to investigate coordination and profit allocation issues in a VMI supply chain, and proved that a win-win outcome is reachable.

Motivated by the above observations and studies, this paper addresses a channel coordination problem in a VMI supply chain with two quality-competing manufacturers by an option-based contract. Moreover, this research takes the risk preference of manufacturers into consideration, as they might have a profound effect on decisions [19, 35, 51]. The risk-averse preference of channel members play an important role in their decisions in areas such as production, ordering and investment [5, 11, 18]. In this paper, the CVaR criterion is employed to model the manufacturers’ risk aversion because it is a coherent risk measure with attractive computational characteristics [10, 42]. In fact, since the CVaR risk measure is popularized in the financial industry [39], it has received considerable attention and is increasingly being adopted in operations and supply chain management literature [9, 24, 33, 40, 46]. For example, in a CVaR framework, Yang et al. [46] studied coordination of supply chains with a risk-neutral supplier and a risk-averse retailer by the revenue-sharing, buy-back, two-part tariff and quantity flexibility contracts. Chen et al. [9] analyzed a decentralized supply chain with a single risk-averse retailer and multiple risk-averse suppliers under a CVaR objective, and showed that the supply chain can be coordinated only when the least risk-averse agent bears the entire risk and the lowest-cost supplier handles all production. Under CVaR, Li et al. [33] presented an improved risk-sharing contract to coordinate the dual-channel supply chain and achieve a win-win outcome. He et al. [24] investigated how to achieve supply chain coordination via a risk diversification contract in both symmetrical and asymmetrical demand information. To the best of our knowledge, however, there are no studies that address channel coordination problems of a VMI supply chain with quality competition and risk aversion under the CVaR criterion.

This paper extends knowledge of the situation in which two quality-competing manufacturers sell their substitutable products through a common retailer under VMI. Table 1 shows the position of this paper within the domain of extant works and identifies the contributions. The papers closely related to this study are Xie et al. [43] and Huang et al. [26]. Xie et al. [43] considered two supply chains compete for more consumers with respect to quality of their products, where retail prices of
Table 1. Differences between this paper and other relevant papers.

| Literature | 1   | 16  | 24  | 26  | 37  | 43  | 46  | This paper |
|------------|-----|-----|-----|-----|-----|-----|-----|------------|
| Product quality | Yes | Yes | No  | Yes | Yes | Yes | No  | Yes        |
| Competition | Yes | No  | No  | No  | Yes | No  | Yes | Yes        |
| Stochastic demand | No  | No  | Yes | No  | No  | Yes | Yes | Yes        |
| Risk aversion  | No  | No  | Yes | No  | No  | Yes | Yes | Yes        |
| Coordination  | No  | Yes | Yes | Yes | Yes | No  | Yes | Yes        |

both products are same and exogenous. This paper addresses a VMI supply chain in which two manufacturers sell their products at exogenous prices and compete on quality through a common retailer. Different from Xie et al. [43] in which the market demand faced by each supply chain is quality dependent and deterministic, the market demand faced by each manufacturer is quality dependent and stochastic in this work. Furthermore, this study discusses the effect of the manufacturers’ risk-averse preference on quality and production decisions, and investigate how to achieve supply chain coordination. Huang et al. [26] studied a VMI supply chain with a loss-averse manufacturer and a risk-neutral retailer, and proposed a combined contract composed of option and cost-sharing to investigate the channel coordination issue. This paper further examines the role of the combined contract in a VMI supply chain consisting of two risk-averse manufacturers and a risk-neutral retailer.

The contribution of this study is threefold as follows. Firstly, considering a VMI supply chain consisting of a risk-neutral retailer and two risk-averse manufacturers who compete on product quality, this study develops a basic model in the decentralized system without coordinating contract and examines the effect of the quality sensitivity, competition intensity, risk aversion degree and cost coefficient of quality improvement on equilibrium decisions and supply chain efficiency. The results show that competition can promote improvement of product quality and it will result in a loss for the manufacturers while the common retailer can benefit from competition. Consequently, moderate competition is conducive to the supply chain efficiency while excessive competition is prejudicial to the supply chain efficiency. Secondly, a combined contract composed of option and cost-sharing is introduced to investigate the supply chain coordination issue, the research shows that the supply chain can be coordinated by the combined contract and the system-wide profit of the supply chain can be allocated arbitrarily only by the option price. But it should be noted that coordination of the supply chain is reachable only when the manufacturers are low in risk aversion. Lastly, it is proved that there always exist some coordinating combined contracts that make each member better off, the effect of the quality sensitivity, competition intensity, risk aversion degree and cost coefficient of quality improvement on the feasible region of option price is also examined in this paper.

The remainder of this paper is organized as follows. Section 2 presents the model setting, notations and assumptions. Section 3 develops two basic models in the decentralized system without coordinating contract and in the centralized system, respectively. Section 4 investigates how to achieve supply chain coordination and a win-win outcome by a combined contract composed of option and cost-sharing. A series of numerical experiments and managerial observations are given in Section 5. The findings and possible future work are concluded in Section 6.
2. Model description. This study considers a VMI supply chain consisting of two risk-averse manufacturers, $M_i, i = 1, 2$, who sell their competing products through a risk-neutral retailer, denoted by $R$ (shown in Figure 1). Each manufacturer is assumed to produce single product whereas the retailer is not constrained to sell only one manufacturer’s product. The two risk-averse manufacturers comprise a duopoly essentially and compete for more consumers with respect to quality of their products instead of price under stochastic demand. This assumption is reasonable in many industries such as the fast food, soft drinks and clothing industries. In particular, Adidas and Nike sell shoes at almost a same price but offer different designs and product features [43].

![Figure 1. Structure of the supply chain.](image)

Notations used in this paper are listed in Table 2.

In this study, $s_i$ and $Q_i$ are decision variables and others are exogenous variables, which are known to all members of the supply chain. To focus on product substitutability, similar to Xie et al. [43], a linear duopoly quality dependent static demand function that captures product substitution is considered in our model, which is given by

$$d_i(s_i, s_j) = a_i + \alpha s_i - \beta(s_j - s_i) \quad \text{for } i = 1, 2 \text{ and } j = 3 - i,$$

where $d_i(s_i, s_j)$ is the quality dependent demand function of the $i$th product at the quality improvement level $s_i$, given that the quality improvement level of the other product is $s_j$, $a_i$ is the primary intrinsic demand for the $i$th product, which is irrespective of product quality improvement level. $\alpha$ is the product $i$’s own quality improvement sensitivity and $\beta$ is the competition intensity denoting the competitive effect of quality improvement for the product pair $(i, j)$. These parameters are required to satisfy $\alpha, \beta > 0$. The quality dependent static demand function implies that $d_i(s_i, s_j)$ has a positive correlation with product $i$’s quality improvement level and a negative correlation with the competitor’s quality improvement level. When the two manufacturers increase their quality improvement level by a unit, the market demand of each product increases. In our demand model, the competition intensity $\beta$ captures the substitutability between the two products, higher value of $\beta$ implies that the products are viewed as closer substitutes.

To account for the randomness in demand, the additive form for the stochastic component is adopted, just as in [26, 44]. Thus the final market demand for product $i$, denoted by $D_i(s_i, s_j, x_i)$, can be expressed as

$$D_i(s_i, s_j, x_i) = d_i(s_i, s_j) + x_i \quad \text{for } i = 1, 2 \text{ and } j = 3 - i,$$

where $x_i$ for each $i$ is an independent random variable which is defined on the range $[L_i, U_i]$. Let $f_i(x_i)$ and $F_i(x_i)$ denote probability density function and cumulative distribution function of $x_i$ for $i = 1, 2$. To ensure that for all values of $s_j$, there exists some range of $s_j$ such that $D_i(s_i, s_j, x_i) > 0$, we require $L_i > -a_i, i = 1, 2$. 


Table 2. Notations.

| Symbol | Definition |
|--------|------------|
| $i$    | Index for product, $i = 1, 2$ |
| $d_i$  | Quality dependent deterministic demand for the $i$th product |
| $D_i$  | Demand faced by the retailer for the $i$th product |
| $c_i$  | Production cost per unit of the $i$th product |
| $w_i$  | Wholesale price per unit of the $i$th product |
| $p_i$  | Retail price per unit of the $i$th product |
| $v_i$  | Salvage value per unit of the $i$th product |
| $x_i$  | Random demand faced by the retailer for the $i$th product |
| $L_i, U_i$ | Lower bound and upper bound on $x_i$ |
| $f_i(x_i)$ | Probability density function of the random variable $x_i$ |
| $F_i(x_i)$ | Cumulative distribution function of the random variable $x_i$ |
| $a_i$  | Initial market size of the $i$th product |
| $\alpha$ | Demand sensitivity of product $i$'s own quality improvement level |
| $\beta$ | Competition intensity |
| $s_i$  | Quality improvement level of the $i$th product |
| $Q_i$  | Production quantity for the $i$th product |
| $\eta_i$ | Risk aversion coefficient of the $i$th manufacturer |
| $k_i$  | Cost coefficient of investment in quality improvement of product $i$ |

It is assumed that cost of investment in quality improvement of product $i$ at level $s_i$ is $k_i s_i^2$, aligning with Lin et al. [34], which implies that the cost of quality improvement has a decreasing-return property.

The CVaR criterion is employed to model the risk aversion of manufacturers. Let $\pi_m$ be the random profit function for a risk-averse firm, a general definition of the CVaR is given as $CVaR_{\eta}(\pi_m) = E[\pi_m | \pi_m \leq q_{\eta}(\pi_m)]$, where $q_{\eta}(\pi_m)$ is the $\eta$-quantile of the random profit function $\pi_m$. According to Rockafellar and Uryasev [39], an equivalent and analytically definition of the CVaR can be expressed as

$$CVaR_{\eta}(\pi_m) = \max_{\varphi \in \mathbb{R}} \left\{ \varphi - \frac{1}{\eta} E[\varphi - \pi_m]^+ \right\},$$

where $\eta \in (0, 1]$ reflects the degree of risk aversion for the decision-maker, the smaller $\eta$ is, the more risk-averse the decision-maker is. Especially, $\eta = 1$ corresponds to the risk neutrality scenario. Under the CVaR criterion, the aim of the risk-averse decision maker is to minimize the downside risk of its profit. In other words, the objective of decision maker is to maximize the CVaR. Throughout this paper, the notation $x^+ = \max \{0, x\}$ is used.

3. Basic models. This section first develops basic models in the decentralized system without coordination mechanism and in the centralized system, respectively. Then, the section analyzes the effect of the key factors (such as the quality sensitivity, competition intensity, risk aversion degree and cost coefficient of quality improvement) on equilibrium decisions.

3.1. Decentralized system. Superscript $wp$ is used for the corresponding value under the decentralized system without coordination mechanism, the decision sequence of the VMI supply chain is described as follows. Before the start of the
Theorem 3.1. In the decentralized system without coordination mechanism, there exists a unique optimal production quantity $Q_i^{wp}$ for product $i$ $(i = 1, 2)$ simultaneously. Then, the two manufacturers observe each other’s quality improvement level and decide the production quantity $Q_i^{wp}$ for product $i$ through forecasting the final market demand. At the beginning of the selling season, according to the actual demand information and the manufacturers’ inventory levels, the retailer may purchase a quantity of product $i$ up to $Q_i^{wp}$ units from the $i$th manufacturer at the wholesale price $w_i$, and resell to the end consumer at retail price $p_i$. At the end of the selling period, any excess inventory for product $i$ is salvaged by the $i$th manufacturer. Non-cooperative game is considered between the two manufacturers, and the objectives of them are to maximize the CVaR because they take inventory risk.

In order to avoid the unreasonable cases, it is necessary to assume $p_i > w_i > c_i$. According to the above decision sequence, the profit of manufacturer $i$, denoted as $\pi_{im}$, is given by

$$\pi_{im} = w_i \min \{Q_i^{wp}, D_i^{wp}\} + v_i \max \{Q_i^{wp} - D_i^{wp}, 0\} - c_i Q_i^{wp} - k_i (s_i^{wp})^2.$$

The first term is the sales revenue, the second term is the revenue from disposing of unsold product, the third term is the manufacturing cost, and the last term is the cost of investment in quality improvement. Through rearranging the terms, the profit of manufacturer $i$ can be rewritten as

$$\pi_{im} = (w_i - c_i)Q_i^{wp} - (w_i - v_i)(Q_i^{wp} - D_i^{wp}) + k_i (s_i^{wp})^2.$$

Therefore, under the CVaR criterion, the risk-averse manufacturer $i$’s problem is expressed as

$$\max_{Q_i^{wp}, s_i^{wp}} CVaR_{\eta_i}(\pi_{im}) = \max_{Q_i^{wp}, s_i^{wp}} \max_{\phi_i, \phi_i \in \mathcal{R}} \left\{ \phi_i - \frac{1}{\eta_i} E[\phi_i - \pi_{im}^{wp}]^+ \right\}.$$

Solving the problem, we can obtain the equilibrium production quantity and quality improvement level for both the manufacturers.

**Theorem 3.1.** In the decentralized system without coordination mechanism, there exists a unique optimal production quantity $Q_i^{wp}$ and a unique optimal quality improvement level $s_i^{wp}$ for manufacturer $i$ which are jointly determined by

$$Q_i^{wp} = F_i^{-1} \left( \eta_i \frac{w_i - c_i}{w_i - v_i} \right) + d_i(s_i^{wp}, s_j^{wp})$$

and

$$s_i^{wp} = \frac{(w_i - c_i)(\alpha + \beta)}{2k_i}.$$

**Proof.** From the definition of CVaR, for any given $s_i^{wp}, s_j^{wp} > 0$, the optimal production quantity for manufacturer $i$ satisfies $Q_i^{wp} = \arg \max_{Q_i^{wp}} \max_{\phi_i, \phi_i \in \mathcal{R}} g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \phi_i)$, we have

$$g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \phi_i) = \phi_i - \frac{1}{\eta_i} E[\phi_i - \pi_{im}^{wp}]^+ = \phi_i - \frac{1}{\eta_i} \int_{Q_i^{wp} - d_i(s_i^{wp}, s_j^{wp})}^{Q_i^{wp}} [\phi_i - \phi_i]^+ dF_i(x_i)$$

$$= \phi_i - \frac{1}{\eta_i} \int_{Q_i^{wp} - d_i(s_i^{wp}, s_j^{wp})}^{Q_i^{wp}} [\phi_i - \phi_i]^+ dF_i(x_i),$$
where \( \varphi_{i1} = (w_i - c_i)Q_i^{wp} + (w_i - v_i)(d_i(s_i^{wp}, s_j^{wp}) + x_i) - k_i(s_i^{wp})^2 \) and \( \varphi_{i2} = (w_i - c_i)Q_i^{wp} - k_i(s_i^{wp})^2 \). For any fixed \( Q_i^{wp} \), we first solve \( \max g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i) \).

Since the integrand is a piecewise function, we consider three cases.

(i) When \( \varphi_i < \varphi_{i1} \), we have \( g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i) = \varphi_i \). Given any \( \varphi_i < \varphi_{i1} \), we get

\[
\frac{\partial g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i)}{\partial \varphi_i} = 1 > 0.
\]

(ii) When \( \varphi_{i1} < \varphi_i < \varphi_{i2} \), we have

\[
g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i) = \varphi_i - \frac{1}{\eta_i} \int_{L_i} (\varphi_i - \varphi_{i1} - (w_i - v_i)x_i)dF_i(x_i) - \frac{1}{\eta_i} \int_{U_i} (\varphi_i - \varphi_{i2} - (w_i - v_i)x_i)dF_i(x_i) + \alpha_i.
\]

Then, \( \frac{\partial g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i)}{\partial \varphi_i} = 1 - \frac{1}{\eta_i} F_i(\varphi_i - \varphi_{i1})/\eta_i < 0 \).

Let \( \varphi_i^*(Q_i^{wp}) \) be the optimal solution for fixed \( s_i^{wp}, s_j^{wp} \) and \( Q_i^{wp} \), we can get \( \varphi_i^*(Q_i^{wp}) \in (\varphi_{i1}, \varphi_{i2}) \). If \( Q_i^{wp} \geq F_i^{-1}(\eta_i) + d_i(s_i^{wp}, s_j^{wp}) \), then must exist some \( \varphi_i^*(Q_i^{wp}) \) which satisfy \( \partial g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i)/\partial \varphi_i = 1 - F_i((\varphi_i - \varphi_{i1})/(w_i - v_i))/\eta_i = 0 \), then we get \( \varphi_i^*(Q_i^{wp}) = (w_i - v_i)F_i^{-1}(\eta_i) + \alpha_i \).

Inserting \( \varphi_i^*(Q_i^{wp}) = (w_i - v_i)F_i^{-1}(\eta_i) + \alpha_i \) into Equation (9), we obtain

\[
g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i^*(Q_i^{wp})) = (w_i - v_i)F_i^{-1}(\eta_i) + \alpha_i - \frac{1}{\eta_i} \int_{L_i} (w_i - v_i)(F_i^{-1}(\eta_i) - x_i)dF_i(x_i).
\]

Because \( \partial g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i^*(Q_i^{wp}))/\partial Q_i^{wp} = v_i - c_i < 0 \), we get \( g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i^*(Q_i^{wp})) \) is strictly decreasing in \( Q_i^{wp} \), then \( Q_i^{wp*} = F_i^{-1}(\eta_i) + d_i(s_i^{wp}, s_j^{wp}) \), which is contradictory to \( Q_i^{wp*} > F_i^{-1}(\eta_i) + d_i(s_i^{wp}, s_j^{wp}) \). This indicates that \( 1 - F_i((Q_i^{wp} - d_i(s_i^{wp}, s_j^{wp}))/\eta_i) > 0 \), and then we can get \( \varphi_i^*(Q_i^{wp}) = \varphi_{i2} \). So far, we have shown that \( g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i) \) takes its maximum value if and only if \( \varphi_i = \varphi_{i2} \) when \( Q_i^{wp} \) is optimized.

Inserting \( \varphi_i^*(Q_i^{wp}) = \varphi_{i2} \) into Equation (9), we have

\[
g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i^*(Q_i^{wp})) = \varphi_{i2} = \frac{1}{\eta_i} \int_{L_i} (w_i - v_i)(Q_i^{wp} - d_i(s_i^{wp}, s_j^{wp}) - x_i)dF_i(x_i).
\]

Then, we get

\[
\frac{\partial g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i^*(Q_i^{wp}))}{\partial Q_i^{wp}} = w_i - c_i - \frac{w_i - v_i}{\eta_i} F_i((Q_i^{wp} - d_i(s_i^{wp}, s_j^{wp}))/\eta_i),
\]

\[
\frac{\partial^2 g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i^*(Q_i^{wp}))}{\partial Q_i^{wp}^2} = -\frac{w_i - v_i}{\eta_i} f_i((Q_i^{wp} - d_i(s_i^{wp}, s_j^{wp}))/\eta_i) < 0.
\]
Therefore, \( g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i^*(Q_i^{wp})) \) is concave in \( Q_i^{wp} \). Let
\[
\partial g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i^*(Q_i^{wp})) / \partial Q_i^{wp} = 0,
\]
we get \( Q_i^{wp} = F_i^{-1}((\eta_i(w_i - c_i)/(w_i - v_i)) + d_i(s_i^{wp}, s_j^{wp})) \).

Substituting \( Q_i^{wp} = F_i^{-1}((\eta_i(w_i - c_i)/(w_i - v_i)) + d_i(s_i^{wp}, s_j^{wp})) \) into Equation (12), we have
\[
g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i^*(Q_i^{wp})) = \varphi_i - \frac{w_i - v_i}{\eta_i} \int_{L_i}^{F_i^{-1}((\eta_i(w_i - c_i)/(w_i - v_i)) - x_i)} dF_i(x_i).
\]

Taking the first-order and second-order derivative of \( g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i^*(Q_i^{wp})) \) with respect to \( s_i^{wp} \), we have \( \partial g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i^*(Q_i^{wp})) / \partial s_i^{wp} = (w_i - c_i)(\alpha + \beta) - 2k_i s_i^{wp} \) and \( \partial^2 g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i^*(Q_i^{wp})) / \partial (s_i^{wp})^2 = -2k_i < 0 \). Therefore, \( g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i^*(Q_i^{wp})) \) is concave in \( s_i^{wp} \). By solving \( \partial g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i^*(Q_i^{wp})) / \partial s_i^{wp} = 0 \), there exists a unique optimal \( s_i^{wp} \) by solving \( \partial g(s_i^{wp}, s_j^{wp}, Q_i^{wp}, \varphi_i^*(Q_i^{wp})) / \partial s_i^{wp} = 0 \). Then, we get Equation (8). 

Theorem 3.1 shows that the optimal production quantity of each manufacturer relies on its own risk aversion coefficient while the optimal product quality improvement level is independent on the risk aversion coefficient. Furthermore, it is obvious that \( Q_i^{wp} \) is strictly increasing in \( \eta_i \) since \( \partial Q_i^{wp} / \partial \eta_i > 0 \). That is, the risk-averse manufacturer's production quantity is not more than that of the risk-neutral manufacturer.

From Theorem 3.1, it is straightforward that \( \partial s_i^{wp} / \partial \alpha > 0, \partial s_i^{wp} / \partial \beta > 0 \) and \( \partial s_i^{wp} / \partial k_i < 0 \). Namely, as the demand sensitivity of product \( i \)'s quality increases, the optimal quality improvement level of manufacturer \( i \) increases, and with the increase of the cost coefficient of quality improvement of product \( i \), the optimal quality improvement level of manufacturer \( i \) decreases. Moreover, the competition can promote improvement of product quality. Next, we discuss the effect of changes in key parameters on equilibrium production quantity.

**Corollary 1.** The optimal production quantity of manufacturer \( i \) \( Q_i^{wp} \) has the following relationships with \( k_i, k_j, \alpha \) and \( \beta \): (i) \( \partial Q_i^{wp} / \partial k_i < 0 \); \( \partial Q_i^{wp} / \partial k_j < 0 \). (ii) If \( 2k_j(\alpha + \beta)(w_i - c_i) > k_i(\alpha + \beta)(w_j - c_j) \), then \( \partial Q_i^{wp} / \partial \alpha > 0 \), otherwise, \( \partial Q_i^{wp} / \partial \alpha \leq 0 \). (iii) If \( 2k_j(\alpha + \beta)(w_i - c_i) > k_i(\alpha + 2\beta)(w_j - c_j) \), then \( \partial Q_i^{wp} / \partial \beta > 0 \), otherwise, \( \partial Q_i^{wp} / \partial \beta \leq 0 \).

**Proof.** From Theorem 3.1, we have
\[
Q_i^{wp} = F_i^{-1}((\eta_i(w_i - c_i)/(w_i - v_i)) + a_i + \frac{(w_i - c_i)(\alpha + \beta)^2}{2k_i} - \frac{(w_j - c_j)(\alpha + \beta)^2}{2k_j}).
\]

Then, we have \( \partial Q_i^{wp} / \partial k_i = -(w_i - c_i)(\alpha + \beta)^2 / (2k_i^2) < 0 \) and \( \partial Q_i^{wp} / \partial k_j = \beta(w_i - c_i)(\alpha + \beta)^2 / (2k_j^2) > 0 \).

Similarly, we have \( \partial Q_i^{wp} / \partial \alpha = (w_i - c_i)(\alpha + \beta)/k_i - (w_j - c_j)\beta/(2k_j) \). So if \( 2k_j(\alpha + \beta)(w_i - c_i) > k_i(\alpha + \beta)(w_j - c_j) \), then \( \partial Q_i^{wp} / \partial \alpha > 0 \), otherwise, \( \partial Q_i^{wp} / \partial \alpha \leq 0 \).

And we have \( \partial Q_i^{wp} / \partial \beta = (w_i - c_i)(\alpha + \beta)/k_i - (w_j - c_j)(\alpha + 2\beta)/(2k_j) \). So if \( 2k_j(\alpha + \beta)(w_i - c_i) > k_i(\alpha + 2\beta)(w_j - c_j) \), then \( \partial Q_i^{wp} / \partial \beta > 0 \), otherwise, \( \partial Q_i^{wp} / \partial \beta \leq 0 \).

Corollary 1(i) shows that the optimal production quantity of manufacturer \( i \) is decreasing in the cost coefficient of quality improvement of its own-product while
increasing in the cost coefficient of quality improvement of the other manufacturer’s product, which is intelligible and intuitional in practice. Corollary 1(ii) and (iii) identify the necessary and sufficient conditions under which the equilibrium production quantity is increasing in quality sensitivity and competition intensity. Especially, when the two manufacturers are identical, the optimal production quantity for each manufacturer increases with the demand sensitivity of product quality and the competition intensity.

In the VMI supply chain, the retailer does not have to make any other decision independently except for providing supply chain contract. Let \( E\pi^{wp}_i \) denote the expected profit of the retailer in the decentralized system, we have

\[
E\pi^{wp}_i = \frac{2}{2} E(p_i - w_i) \min \{Q_i^{wp}, D_i^{wp}\} = \int_{I_i} Q_i^{wp} - \int_{I_i} Q_i^{wp} - d_i(Q_i^{wp}, s_i^{wp}) F_i(x_i) dx_i.
\]

(17)

3.2. Centralized system. To derive the system-wide optimal expected profit for the supply chain, the supply chain is considered as a centralized entity. In the centralized system, there exist unique optimal solutions

Theorem 3.2. In the centralized system, there exist unique optimal solutions

\[
E\pi^{*}_i = E(p_i \min \{Q_i^{*}, D_i^{*}\} + v_i \max \{Q_i^{*} - D_i^{*}, 0\} - c_i Q_i^{*} - k_i(s_i^{*})^2]
\]

(18)

The first term is the sales revenue, the second term is the salvage value, the third term is the manufacturing cost, and the last term is the cost for product quality improvement. Thus, the total expected profit of the centralized entity, denoted as \( E\pi^{*}_{sc} \), can be written as

\[
E\pi^{*}_{sc} = \sum_{i=1}^{n} (p_i - c_i) Q_i^{*} - (p_i - v_i) \int_{I_i} Q_i^{*} - d_i(s_i^{*}, s_j^{*}) F_i(x_i) dx_i - k_i(s_i^{*})^2.
\]

(19)

Then, the optimal decisions of the centralized entity is derived as follows.

Theorem 3.2. In the centralized system, there exist unique optimal solutions \((Q_i^{*}, s_i^{*})\) which satisfy

\[
Q_i^{*} = F_i^{-1} \left( \frac{p_i - c_i}{p_i - v_i} + d_i(s_i^{*}, s_j^{*}) \right)
\]

(20)

and

\[
s_i^{*} = \frac{(p_i - c_i)(\alpha + \beta) - (p_j - c_j)\beta}{2k_i}.
\]

(21)

Proof. From Equation (19), for any given \( s_i^{*} (i = 1, 2) \), we have

\[
\left. \frac{\partial^2 E\pi^{*}_{sc}}{\partial Q_i^{*} \partial Q_j^{*}} \right|_{s_i^{*}, s_j^{*}, Q_i^{*}, Q_j^{*}} = (p_1 - v_1)(p_2 - v_2) f_1(Q_1^{*} - d_1(s_i^{*}, s_j^{*})) f_2(Q_2^{*} - d_2(s_i^{*}, s_j^{*})) > 0.
\]

(22)
The Hessian matrix of $E\pi_{sc}^I$ is negative definite, this implies that $E\pi_{sc}^I$ is jointly concave in $Q_{1i}^*$ and $Q_{2i}^*$. Thus, by the first-order condition, we obtain the optimal production quantity for product $i$ $Q_{1i}^*$ which satisfies $Q_{1i}^* = F_i^{-1}((p_i - w_i)/(p_i - v_i)) + d_i(s_i^1, s_i^2)$. Substituting $Q_{1i}^* = F_i^{-1}((p_i - w_i)/(p_i - v_i)) + d_i(s_i^1, s_i^2)$ into Equation (19), we also have

$$\begin{vmatrix} \frac{\partial^2 E\pi_{sc}^I}{\partial s_i^1 \partial s_i^2} & \frac{\partial^2 E\pi_{sc}^I}{\partial s_i^1 \partial s_j^2} \\ \frac{\partial^2 E\pi_{sc}^I}{\partial s_i^1 \partial s_i^2} & \frac{\partial^2 E\pi_{sc}^I}{\partial s_i^2 \partial s_j^2} \end{vmatrix} = 4k_1k_2 > 0. \quad (23)$$

The Hessian matrix of $E\pi_{sc}^I$ is negative definite, it implies that $E\pi_{sc}^I$ is jointly concave in $s_i^1$ and $s_i^2$. Thus, by the first-order condition, we obtain the optimal quality improvement level for product $i$ $s_i^I$ which satisfies Equation (21).

From Theorem 3.2, it is obvious that the optimal quality improvement level of product $i$ $s_i^I$ is increasing in $\alpha$ while decreasing in $k_i$. If $p_i - c_i > p_j - c_j$, then, $s_i^I$ is increasing in $\beta$; If $p_i - c_i < p_j - c_j$, then, $s_i^I$ is decreasing in $\beta$; If $p_i - c_i = p_j - c_j$, then, $s_i^I$ is independent on $\beta$. Next, Corollary 2 shows the effect of changes in key parameters on the production quantity of product $i$ in the centralized system.

**Corollary 2.** The optimal production quantity of product $i$ $Q_{1i}^*$ has the following relationships with $k_i$, $k_j$, $\alpha$ and $\beta$: (i) $\partial Q_{1i}^*/\partial k_i < 0$; $\partial Q_{1j}^*/\partial k_j > 0$; (ii) If $2k_j(\alpha + \beta)(p_i - c_i) > k_i\beta(p_j - c_j)$, then $\partial Q_{1i}^*/\partial \alpha > 0$, otherwise, $\partial Q_{1i}^*/\partial \alpha \leq 0$; (iii) If $k_j[2(\alpha + \beta)(p_i - c_i) - (\alpha + 2\beta)(p_j - c_j)] > k_i[(\alpha + 2\beta)(p_j - c_j) - 2\beta(p_i - c_i)]$, then $\partial Q_{1i}^*/\partial \beta > 0$, otherwise, $\partial Q_{1i}^*/\partial \beta \leq 0$.

**Proof.** From Theorem 3.2, we have

$$Q_{1i}^* = F_i^{-1}\left(\frac{p_i - c_i}{p_i - v_i}\right) + a_i + \frac{[(p_i - c_i)(\alpha + \beta) - (p_j - c_j)\beta](\alpha + \beta)}{2k_i} - \frac{[(p_j - c_j)(\alpha + \beta) - (p_i - c_i)\beta]\beta}{2k_j}. \quad (24)$$

Then, we have $\partial Q_{1i}^*/\partial k_i = -[(p_i - c_i)(\alpha + \beta) - (p_j - c_j)\beta](\alpha + \beta)/(2k_i^2) < 0$ and $\partial Q_{1i}^*/\partial k_j = [(p_i - c_i)(\alpha + \beta) - (p_j - c_j)\beta]\beta/(2k_j^2) > 0$.

Similarly, we have $\partial Q_{1i}^*/\partial \alpha = (p_i - c_i)(\alpha + \beta)/k_i - (p_j - c_j)\beta/(2k_j)$. So if $2k_j(\alpha + \beta)(p_i - c_i) > k_i\beta(p_j - c_j)$, then $\partial Q_{1i}^*/\partial \alpha > 0$, otherwise, $\partial Q_{1i}^*/\partial \alpha \leq 0$.

And we have $\partial Q_{1i}^*/\partial \beta = (2(\alpha + \beta)(p_i - c_i) - (\alpha + 2\beta)(p_j - c_j))/(2k_i)$ - $((\alpha + 2\beta)(p_j - c_j) - 2\beta(p_i - c_i))/(2k_j) - k_i[(\alpha + 2\beta)(p_j - c_j) - 2\beta(p_i - c_i)]$, then $\partial Q_{1i}^*/\partial \beta > 0$, otherwise, $\partial Q_{1i}^*/\partial \beta \leq 0$. \qed
4. Supply chain coordination and profit allocation. In this section, a combined contract composed of option and cost-sharing is introduced to investigate how to achieve supply chain coordination and a win-win outcome, which is similar to [26]. Superscript \( cc \) is used for the corresponding value under the decentralized system with the combined contract, the sequence of events can be described as follows. Before the selling season, the two manufacturers simultaneously decide their product quality improvement level \( s_i^{cc} \) \((i = 1, 2)\) according to the combined contract \((o_i, e_i, \lambda_i)\). Then, both the manufacturers observe each other’s quality improvement level and decide their own production quantity \( Q_i^{cc} \) through forecasting the final market demand. The retailer will pay the \( i \)th manufacturer unit option price \( o_i \) for all products. After market demand has been observed, the retailer may purchase a quantity of product \( i \) up to \( Q_i^{cc} \) units from the \( i \)th manufacturer at the exercise price \( e_i \) to satisfy the actual market demand during the selling season. After the selling season, the retailer pays the partial cost of quality improvement which the retailer should bear to each manufacturer, and any unsold product owned by each manufacturer can be salvaged at value \( v_i \). To avoid trivialities, we focus on the reasonable and non-trivial case where \( c_i - v_i > o_i \geq 0, e_i > v_i > 0 \) and \( p_i > o_i + e_i > c_i > v_i \).

Under the combined contract, the competition between the two manufacturers is still modeled as a non-cooperative game. The profit of manufacturer \( i \), denoted as \( \pi_{im}^{cc} \), is given by

\[
\pi_{im}^{cc} = o_i Q_i^{cc} + e_i \min \{Q_i^{cc}, D_i^{cc}\} + v_i \max \{Q_i^{cc} - D_i^{cc}, 0\} - c_i Q_i^{cc} - \lambda_i k_i (s_i^{cc})^2. \tag{25}
\]

The first term is the determined income for reservation, the second term is the revenue realized by the \( i \)th manufacturer from exercised option, the third term is the revenue from disposing of unsold product, the fourth term is the production cost, and the last term is the manufacturer \( i \)’s share of the cost of quality improvement. Using simply algebra, the manufacturer \( i \)’s profit function can be rewritten as

\[
\pi_{im}^{cc} = (e_i + o_i - c_i) Q_i^{cc} - (e_i - v_i) (Q_i^{cc} - D_i^{cc})^+ - \lambda_i k_i (s_i^{cc})^2. \tag{26}
\]

Under the CVaR criterion, the objective of manufacturer \( i \) is to maximize the CVaR. Hence, the manufacturer \( i \)’s problem is expressed as

\[
\max_{s_i^{cc}, Q_i^{cc}} CVaR_{\eta_i} (\pi_{im}^{cc}) = \max_{s_i^{cc}, Q_i^{cc}} \max_{\varphi_i, \epsilon_i, \epsilon_i} \left\{ \varphi_i - \frac{1}{\eta_i} E[\varphi_i - \pi_{im}^{cc}]^+ \right\}. \tag{27}
\]

Solving the problem, we can obtain the equilibrium decisions for both the manufacturers.

**Theorem 4.1.** Under the combined contract, there exist unique equilibrium decisions \((Q_i^{cc}, s_i^{cc})\) which satisfy

\[
Q_i^{cc} = F_i^{-1} \left( \frac{o_i + e_i - c_i}{e_i - v_i} \right) + d_i (s_i^{cc}, s_j^{cc}), \tag{28}
\]

\[
s_i^{cc} = \frac{(o_i + e_i - c_i)(\alpha + \beta)}{2\lambda_i k_i}. \tag{29}
\]

**Proof.** From the definition of CVaR, for any given \( s_i^{cc}, s_j^{cc} > 0 \), the optimal production quantity for product \( i \) \( Q_i^{cc} \) satisfies \( Q_i^{cc} = \arg \max_{Q_i^{cc}} \max_{\varphi_i} g(s_i^{cc}, s_j^{cc}, Q_i^{cc}, \varphi_i) \),
we have
\[ g(s_i^{cc}, s_j^{cc}, Q_i^{cc}, \varphi_i) = \varphi_i - \frac{1}{\eta_i} \int_{L_i}^{Q_i^{cc} - d_i(s_i^{cc}, s_j^{cc})} [\varphi_i - A]^+ dF_i(x_i) \]
\[ - \frac{1}{\eta_i} \int_{Q_i^{cc} - d_i(s_i^{cc}, s_j^{cc})}^{U_i} [\varphi_i - B]^+ dF_i(x_i), \quad (30) \]
where \( A = (\omega_i + v_i - c_i)Q_i^{cc} - (e_i - v_i)(d_i(s_i^{cc}, s_j^{cc}) + U_i) - \lambda_i k_i(s_i^{cc})^2 \)
and \( B = (e_i + c_i - c_i)Q_i^{cc} - \lambda_i k_i(s_i^{cc})^2 \).

Following similar reasoning process of Theorem 3.1, we can show that
\( g(s_i^{cc}, s_j^{cc}, Q_i^{cc}, \varphi) \) takes its maximum value if and only if \( \varphi^*(Q_i^{cc}) = B \) when \( Q_i^{cc} \) is optimized.
Inserting \( \varphi^*(Q_i^{cc}) = B \) into Equation (30), we have
\[ g(s_i^{cc}, s_j^{cc}, Q_i^{cc}, \varphi^*(Q_i^{cc})) = \varphi_i - \frac{1}{\eta_i} \int_{L_i}^{Q_i^{cc} - d_i(s_i^{cc}, s_j^{cc})} (e_i - v_i)(Q_i^{cc} - d_i(s_i^{cc}, s_j^{cc}) - x_i) dF_i(x_i). \]

Differentiating with respect to \( Q_i^{cc} \) gives
\[ \frac{\partial g(s_i^{cc}, s_j^{cc}, Q_i^{cc}, \varphi_i(Q_i^{cc}))}{\partial Q_i^{cc}} = a_i + e_i - c_i - \frac{e_i - v_i}{\eta_i} F_i(Q_i^{cc} - d_i(s_i^{cc}, s_j^{cc})), \]
\[ \frac{\partial^2 g(s_i^{cc}, s_j^{cc}, Q_i^{cc}, \varphi_i(Q_i^{cc}))}{\partial Q_i^{cc}^2} = -\frac{e_i - v_i}{\eta_i} F_i(Q_i^{cc} - d_i(s_i^{cc}, s_j^{cc})). \]

Therefore, \( g(s_i^{cc}, s_j^{cc}, Q_i^{cc}, \varphi_i(Q_i^{cc})) \) is concave in \( Q_i^{cc} \). Let
\[ \frac{\partial g(s_i^{cc}, s_j^{cc}, Q_i^{cc}, \varphi_i(Q_i^{cc}))}{\partial Q_i^{cc}} = 0, \]
we get \( Q_i^{cc} = F_i^{-1}(\eta_i (a_i + e_i - c_i)/(e_i - v_i) + d_i(s_i^{cc}, s_j^{cc})) \).
Substituting \( Q_i^{cc} = F_i^{-1}(\eta_i (a_i + e_i - c_i)/(e_i - v_i) + d_i(s_i^{cc}, s_j^{cc})) \) into Equation (31), we have
\[ g(s_i^{cc}, s_j^{cc}, Q_i^{cc}, \varphi_i) = \varphi_i - \frac{e_i - v_i}{\eta_i} \int_{L_i}^{F_i^{-1}(\eta_i (a_i + e_i - c_i)/(e_i - v_i) + d_i(s_i^{cc}, s_j^{cc}) - x_i)} dF_i(x_i). \]

Differentiating with respect to \( s_i^{cc} \) gives
\[ \frac{\partial g(s_i^{cc}, s_j^{cc}, Q_i^{cc}, \varphi_i)}{\partial s_i^{cc}} = (a_i + e_i - c_i)(\alpha + \beta) - 2\lambda_i k_i(s_i^{cc}), \]
\[ \frac{\partial^2 g(s_i^{cc}, s_j^{cc}, Q_i^{cc}, \varphi_i)}{\partial s_i^{cc}^2} = -2\lambda_i k_i < 0. \]

It implies that \( g(s_i^{cc}, s_j^{cc}, Q_i^{cc}, \varphi_i) \) is concave in \( s_i^{cc} \). Setting \( \frac{\partial g(s_i^{cc}, s_j^{cc}, Q_i^{cc}, \varphi_i)}{\partial s_i^{cc}} = 0 \) gives the optimal quality improvement level \( s_i^{cc*} \) which satisfies \( s_i^{cc*} = (a_i + e_i - c_i)(\alpha + \beta)/(2\lambda_i k_i) \).

Thus, the expected profit of the retailer, denoted as \( E \pi^{cc}_r \), can be given by
\[ E \pi^{cc}_r = \sum_{i=1}^{2} E[(p_i - e_i)\min\{Q_i^{cc*}, D_i^{cc*}\} - a_iQ_i^{cc} - (1 - \lambda_i)k_i(s_i^{cc*})^2]. \]
Theorem 4.2. Coordination of the supply chain can be achieved by setting

\[ E\pi_{cc}^c = \sum_{i=1}^{2} [(p_i - o_i - e_i)Q_{cc}^i] \]

\[ - \sum_{i=1}^{2} [(p_i - e_i) \int_{L_i}^{Q_{cc}^i} f_i(x_i)dx_i + (1 - \lambda_i)k_i(s_{cc}^i)^2]. \]  

(38)

Therefore, with the combined contract, the joint expected profit of the supply chain in the decentralized system, denoted as \( E\pi_{cc}^c \), is given by

\[ E\pi_{cc}^c = \sum_{i=1}^{2} [(p_i - c_i)Q_{cc}^i - (p_i - v_i) \int_{L_i}^{Q_{cc}^i} f_i(x_i)dx_i - k_i(s_{cc}^i)^2]. \]  

(39)

Then, we have the following proposition on supply chain coordination.

**Theorem 4.2.** Coordination of the supply chain can be achieved by setting

\[ e_i = \frac{\eta_i(c_i - o_i)(p_i - v_i) - (p_i - c_i)v_i}{\eta_i(p_i - v_i) - p_i + c_i}, \]  

(40)

\[ \lambda_i = \frac{(c_i - o_i - v_i)(p_i - c_i)(\alpha + \beta)}{(\eta_i p_i - \eta_i v_i - p_i + c_i)((p_i - c_i)(\alpha + \beta) - (p_j - c_j)\beta)}. \]  

(41)

where \( \eta_i \) satisfies \((p_i - v_i - o_i)/(p_i - v_i) < \eta_i \leq 1 \).

**Proof.** According to \([4, 8, 24, 26]\), coordination of the supply chain is achievable only when \( Q_i^{cc} = Q_i^f \) and \( s_i^{cc} = s_i^f \), which implies that \( F_i^{-1}((\eta_i(c_i + o_i - c_i)/(c_i - v_i)) = F_i^{-1}((p_i - c_i)/(p_i - v_i)) and (o_i + e_i - c_i)(\alpha + \beta)/(2\lambda_i k_i) = ((p_i - c_i)(\alpha + \beta) - (p_j - c_j)\beta)/(2k_i) \).

Because cumulative distribution function \( F_i(x_i) \) is monotonic increasing, its inverse function must be also monotonic increasing. Then, we get \( \eta_i(c_i + o_i - c_i)/(e_i - v_i) = (p_i - c_i)/(p_i - v_i) \). Rearranging, we obtain Equation (40) and Equation (41). Note that, some reasonable assumptions on the combined contract must always hold. To ensure \( p_i > o_i + e_i \), the indispensable condition (i.e., \((p_i - v_i - o_i)/(p_i - v_i) < \eta_i \leq 1 \)) must be required to achieve the supply chain coordination.

Theorem 4.2 shows the specific condition under which coordination of the supply chain is achievable. Under coordination with the combined contract \((e_i, o_i, \lambda_i)\), the joint expected profit in the decentralized system is identical to that of the vertically integrated entity. Different from \([8, 26]\), it is interesting that coordination of the supply chain is obtainable by the combined contract if and only if \( \eta_i \) satisfies \((p_i - v_i - o_i)/(p_i - v_i) < \eta_i \leq 1 \). In other words, the system-wide optimal expected profit of the supply chain can be achieved only when the manufacturers are low in risk aversion. When Equation (40) holds, if \( \eta_i \leq (p_i - v_i - o_i)/(p_i - v_i) \), then we have \( e_i + o_i \geq p_i \). We know that \( e_i + o_i \) is the unit cost of the \( i \)th product purchased by the retailer, which implies that the retailer earns nothing or even negative profit from product \( i \) when \( \eta_i \leq (p_i - v_i - o_i)/(p_i - v_i) \), and this kind of contracts are not applicable in practice.

Since \((p_i - v_i - o_i)/(p_i - v_i) < \eta_i \leq 1 \), we obtain \( \eta_i(p_i - v_i) - p_i + c_i > 0 \). From Equation (40), we get

\[ \frac{\partial e_i}{\partial o_i} = -\frac{\eta_i(p_i - v_i)}{\eta_i(p_i - v_i) - p_i + c_i} < 0, \]  

(42)
\[ \frac{\partial e_i}{\partial \eta_i} = \frac{(c_i - o_i - v_i)(p_i - c_i)(p_i - v_i)}{|\eta_i(p_i - v_i) - p_i + c_i|^2} < 0. \] (43)

These imply that the exercise price \( e_i \) is a linearly decreasing function of the option price \( o_i \). That is, the higher the option price is, the lower the exercise price is. Furthermore, the exercise price \( e_i \) is also a linearly decreasing function of \( \eta_i \), namely, the exercise price positively correlates with the risk aversion degree. When manufacturer \( i \) becomes more risk-averse, in order to achieve supply chain coordination, the retailer will be compelled to put up the exercise price \( e_i \) to boost production of manufacturer \( i \). Given the exercise price \( e_i \), the retailer can also induce manufacturer \( i \) to produce more products by raising the option price \( o_i \).

Under supply chain coordination with the combined contract \( (e_i, o_i, \lambda_i) \), both the exercise price and the cost-sharing coefficient are functions of the option price, thus the expected profit of each member is dependent only on the option price when other exogenous parameters are given. The expected profit of manufacturer \( i \) can be rewritten as

\[
E_{\pi_{im}}^{cc} = \frac{c_i - o_i - v_i}{\eta_i(p_i - v_i) - p_i + c_i} (p_i - c_i) Q_i^{i*} \\
- \frac{(c_i - o_i - v_i) \eta_i}{\eta_i(p_i - v_i) - p_i + c_i} (p_i - v_i) \int_{L_i}^{F_i^{-1}\left(\frac{p_i - c_i}{p_i - v_i}\right)} F_i(x_i)dx_i \\
- \frac{c_i - o_i - v_i}{\eta_i(p_i - v_i) - p_i + c_i} \frac{(p_i - c_i)(\alpha + \beta)}{((p_i - c_i)(\alpha + \beta) - (p_j - c_j)\beta)} k_i(s_i^{i*})^2. 
\] (44)

Taking the first-order derivative of \( E_{\pi_{im}}^{cc} \) with respect to \( o_i \), we have

\[
\frac{\partial E_{\pi_{im}}^{cc}}{\partial o_i} = -\frac{1}{\eta_i p_i - \eta_i v_i - p_i + c_i} (p_i - c_i) Q_i^{i*} \\
- \frac{1}{\eta_i p_i - \eta_i v_i - p_i + c_i} \frac{\eta_i(p_i - v_i)}{\eta_i(p_i - v_i) - p_i + c_i} (p_i - v_i) \int_{L_i}^{F_i^{-1}\left(\frac{p_i - c_i}{p_i - v_i}\right)} F_i(x_i)dx_i \\
- \frac{1}{\eta_i p_i - \eta_i v_i - p_i + c_i} \frac{(p_i - c_i)(\alpha + \beta)}{((p_i - c_i)(\alpha + \beta) - (p_j - c_j)\beta)} k_i(s_i^{i*})^2. 
\] (45)

When \( k_i \leq \frac{(p_i - c_i)(\alpha + \beta) - (p_j - c_j)\beta}{\beta(p_j - c_j)(s_i^{i*})} E_{\pi_{im}}^{i*} \), we get \( \frac{\partial E_{\pi_{im}}^{cc}}{\partial o_i} < 0 \). That is, the expected profit of manufacturer \( i \) is decreasing in the option price \( o_i \) under coordination with the combined contract \( (e_i, o_i, \lambda_i) \), so long as the cost of quality improvement is not prohibitively expensive. Since the sum of the common retailer’s expected profit and the two manufacturers’ expected profit under coordination is a constant which is equal to that of the vertically integrated entity, the expected profit of the retailer increases with the option price. It is clear that the option price can be used to control the division of profit between the manufacturers and the retailer.

In comparison with the decentralized system without coordinating contract, it is obvious that each member of the supply chain becomes better off just by setting an appropriate option price.

5. Numerical analysis. In this section, in order to derive more managerial insights for practical application, several numerical experiments are used to illustrate how the quality sensitivity, competition intensity, risk aversion degree and cost coefficient of quality improvement affect the expected profit and supply chain efficiency.
Also, this section shows how to achieve a win-win outcome via the combined contract and illustrates the impact of the key factors on the feasible region of option price. In this research, for convenience, both the stochastic variables $x_i (i = 1, 2)$ are assumed to follow a uniform distribution with $F_i(x_i) \sim U(-250, 250)$, the other parametric values are set to $a_i = 1000$, $c_i = 10$, $w_i = 18$, $p_i = 30$, $v_i = 5$, $k_i = 0.2$, $\eta_i = 0.9$, $\alpha = 5$ and $\beta = 1$.

To begin with, in order to represent the supply chain efficiency in channel performance, we define the efficiency of the decentralized system with respect to the centralized system as $E_f = \frac{2E\pi_{wp}^{m} + E\pi_{wp}^{r}}{E\pi_{sc}}$, where $2E\pi_{wp}^{m} + E\pi_{wp}^{r}$ represents the total expected profit of the decentralized system without coordinating contract, and $E\pi_{sc}^{*}$ is the system-wide expected profit of the supply chain in the centralized system.

Tables 3-6 show the effect of the quality sensitivity, competition intensity, risk aversion degree and cost coefficient of quality improvement on the expected profit and supply chain efficiency. To analyze the effect of quality sensitivity, we keep other parameters constant and vary the quality sensitivity coefficient. From Table 3, with the increase of quality sensitivity of demand, the expected profits of both the decentralized system and the centralized system increase, while the supply chain efficiency decreases with the increase of quality sensitivity. That is because the market demand will increase with the increase of quality sensitivity of demand. Accordingly, the manufacturers are willing to improve product quality and production quantity, which leads to an increase in profits for both the decentralized system and the centralized system. However, both the optimal product quality level and production quantity in the decentralized system are not increasing as fast as that in the centralized system. Consequently, the optimal expected profit in the decentralized system is not increasing as fast as that in the centralized system, which generates that the supply chain efficiency decreases with the increase of quality sensitivity. In other words, the difference in profits between the decentralized system and the centralized system increases as the quality sensitivity increases, this implies that it is more beneficial to offer a combined contract when the quality sensitivity increases, since perfect coordination ($E_f = 1$) can be obtained by the combined contract proposed in this paper.

As we can see from Table 4, with the competition intensity increases, the expected profit of the retailer increases while the expected profits of the manufacturers decrease with the competition intensity increases. Meanwhile, the optimal decisions in the centralized system are independent on the competition intensity, and we have $s_{1}^{*} = 250$, $Q_{1}^{*} = 2400$ and $E\pi_{sc}^{*} = 70960$. As a result, the supply chain efficiency firstly increases and then decreases with the increase of the competition intensity. These imply that, (1) competition can promote improvement of product quality; (2) competition will result in a loss for the manufacturers while the common retailer can benefit from competition; (3) moderate competition is conducive to the supply chain efficiency while excessive competition is prejudicial to the supply chain efficiency. That is because when the competition intensity increases, the manufacturers have to improve product quality to gain more market share, consequently, the optimal product quality level in the decentralized system is approaching that in the centralized system, and the supply chain efficiency increases accordingly. While the optimal product quality level in the decentralized system will exceed that in the centralized system when the competition between the two manufacturers is too intense, which leads to that the supply chain efficiency lowers gradually. Note that,
product quality improvement is costly, the two manufacturers in the decentralized system always suffer from competition although both the optimal product quality level and the total supply chain’s expected profit increase. Therefore, the two manufacturers in practice can keep moderate competition to improve product quality and the total supply chain’s expected profit. In the meantime, they can get more profits by coordinating the supply chain. In addition, vicious competition should be avoided since it not only reduces the expected profits of manufacturers but also makes the total supply chain suffer.

We can see from Table 5, as the risk aversion coefficient decreases, the supply chain efficiency decreases. This implies that the manufacturers’ risk-averse behaviors are harmful to the supply chain performance. That is because the manufacturers would lower product quality level and production quantity to avoid demand risk, as a result, the optimal decisions in the decentralized system keep moving away from that in the decentralized system, the supply chain efficiency decreases accordingly.
Table 6. Effect of the cost coefficient of quality improvement on the expected profits and supply chain efficiency.

| k   | \(E_{\pi^w}^m\)   | \(E_{\pi^w}^p\ast\) | \(E_{\pi^w}^{sc}\) | \(E_{\pi^f}^s\) | \(E_f\)  |
|-----|------------------|------------------|-----------------|-----------------|---------|
| 0.1 | 51973            | 11562            | 75097           | 95960           | 78.23%  |
| 0.2 | 37573            | 9642             | 56857           | 70960           | 80.13%  |
| 0.3 | 32773            | 9002             | 50777           | 62627           | 81.08%  |
| 0.4 | 30373            | 8682             | 47737           | 58460           | 81.66%  |
| 0.5 | 28933            | 8490             | 45913           | 55960           | 82.05%  |

In a word, all the manufacturers, retailer and total supply chain would suffer from the risk-averse behaviors of manufacturers, and thereby coordinating the supply chain is necessary for supply chain members to eliminate the effect of risk aversion so as to obtain the optimal system-wide profit. In addition, when the manufacturers become more risk-averse, it is also more beneficial to coordinate the supply chain since the difference in profits between the decentralized system and the centralized system increases as the risk aversion degree increases.

From Table 6, with the decrease of the cost coefficient, all the expected profits increase, it is intelligible and intuitional in practice. However, it is to be noted that the supply chain efficiency decreases with the decrease of the cost coefficient. That is because when the cost of product quality improvement decreases, both the optimal product quality level and production quantity in the decentralized system are not increasing as fast as that in the centralized system. Consequently, the optimal expected profit in the decentralized system is not increasing as fast as that in the centralized system, which generates that the supply chain efficiency decreases with the decrease of the cost of product quality improvement. In other words, the difference in profits between the decentralized system and the centralized system increases as the cost of product quality improvement decreases. Therefore, in practice, when quality improvement becomes less costly, it is necessary for enterprises to take effective cooperation to coordinate supply chains, like applying the proposed combined contract, since the optimal system-wide profit can be obtained by the combined contract.

Figure 2 depicts how to design contract to achieve a win-win outcome. As we have proved previously, with the increase of the option price, the retailer’s expected profit increases while the expected profits of the manufacturers decrease with the increase of the option price. In the feasible region \(o \in (3.12, 3.89)\), each supply chain member becomes better off compared with the decentralized system without coordinating contract. Also, Figure 2 verifies that the models for supply chain coordination in the previous sections are effective, and the proposed combined contract is an alternative source to avoid double marginalization and eliminate the effect of risk aversion so as to coordinate such supply chains. Since the other parameters of combined contract are functions of option price under coordination, thus the system-wide profit of supply chain can be allocated arbitrarily only by the option price, it is convenient for implementation in practice. From a cooperation perspective, the manufacturers and retailer just need to jointly confirm an appropriate option price to obtain that none of them becomes worse off.

Tables 7-10 show that the impact of the quality sensitivity, competition intensity, risk aversion degree and cost coefficient of quality improvement on the feasible region of option price under which none of supply chain members becomes worse
Figure 2. Effect of the option price on profit allocation under channel coordination.

Table 7. Effect of the quality sensitivity on the feasible region of option price.

| $\alpha$ | 1  | 2  | 3  | 4  | 5  |
|----------|----|----|----|----|----|
| feasible region of $o$ | [3.76, 4.16] | [3.75, 4.17] | [3.75, 4.20] | [3.74, 4.23] | [3.73, 4.27] |

Table 8. Effect of the competition intensity on the feasible region of option price.

| $\beta$ | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|----------|----|----|----|----|----|----|----|----|----|----|
| feasible region of $o$ | [3.73, 4.27] | [3.73, 4.23] | [3.72, 4.20] | [3.72, 4.17] | [3.71, 4.16] | [3.69, 4.16] | [3.68, 4.19] | [3.66, 4.26] | [3.63, 4.38] | [3.59, 4.59] |

Table 9. Effect of the risk aversion degree on the feasible region of option price.

| $\eta$ | 0.94 | 0.92 | 0.90 | 0.88 | 0.86 |
|--------|------|------|------|------|------|
| feasible region of $o$ | [3.24, 3.97] | [3.49, 4.12] | [3.73, 4.27] | [3.98, 4.42] | [4.24, 4.57] |

The higher the quality sensitivity of demand is, the greater the feasible region of option price is. With the increase of competition intensity, the feasible region of option price decreases first and then increases. Besides, with the increase of the risk aversion degree, both the upper bound value and lower bound value on the feasible region of option price increase but the feasible region shrinks. In addition, as the cost coefficient of quality improvement increases, the feasible region of option price will also shrink. These imply that all the key factors are also very important for contract design. In practice, it is necessary to take into consideration the effect of all the key factors on the feasible region of option price to select appropriate coordination contracts.
Table 10. Effect of the cost coefficient of quality improvement on the feasible region of option price.

| \( k \) | \( 0.1 \) | \( 0.2 \) | \( 0.3 \) | \( 0.4 \) | \( 0.5 \) |
|--------|--------|--------|--------|--------|--------|
| feasible region of \( o \) | \([3.72, 4.33]\) | \([3.73, 4.27]\) | \([3.74, 4.24]\) | \([3.75, 4.22]\) | \([3.75, 4.21]\) |

6. Conclusions. This paper has studied a VMI supply chain consisting of two risk-averse manufacturers who sell their competing products through a common retailer under stochastic demand. Competition between the two manufacturers is based on quality of products. The CVaR criterion is adopted to model the risk aversion of manufacturers. Two basic models are developed in this paper, one is developed in the decentralized system without coordinating contract, and another is developed in the centralized system which is controlled by a risk-neutral decision-maker. Also, the effect of the key factors on equilibrium decisions and supply chain efficiency is analyzed. A combined contract composed of option and cost-sharing is introduced to enable supply chain coordination. Further, this paper has investigated how the combined contract coordinates the supply chain and obtains a win-win outcome. The effect of the key factors on the feasible region of option price is also analyzed in this research.

The following is a summary of valuable conclusions of this paper. (1) The competition between the two manufacturers can promote quality improvement of products, and it will result in a loss for the manufacturers while the common retailer can benefit from that, as a result, moderate competition is conducive to the supply chain efficiency while excessive competition is prejudicial to the supply chain efficiency. (2) The optimal production quantity of each manufacturer is increasing in its own risk aversion coefficient, while the optimal quality improvement level is independent on the risk aversion coefficient. Moreover, the more risk-averse the manufacturers are, the lower the supply chain efficiency is. (3) With the increase of the quality sensitivity of demand, the expected profit of each member increases, while the supply chain efficiency decreases with the increase of quality sensitivity. Besides, as the cost coefficient of quality improvement decreases, the expected profit of each member increases. However, it is to be noted that the supply chain efficiency decreases with the decrease of the cost coefficient. (4) Under the combined contract, coordination of the supply chain is available only when the manufacturers are low in risk aversion. In the premise of coordination, the system-wide profit can be allocated arbitrarily only by the option price.

This work can be extended in a number of ways in future. For example, this paper only considers a single channel and the upstream competition scenario, the consideration of dual channel and both upstream and downstream competitions can be an important extension of the model. Moreover, a problem with asymmetric information is potentially meaningful research direction.

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