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Research Article

Manufacturer's R&D Investment Strategy and Pricing Decisions in a Decentralized Supply Chain

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Consider that a manufacturer Stackelberg supply chain consists of an upstream supplier and a downstream manufacturer. The manufacturer purchases a component from the supplier and then transforms it into a final product which is sold in a price and quality sensitive market. The manufacturer considers to make R&D investment to improve the product quality and reduce the production cost. We first investigate and derive the optimal investment strategy and pricing decisions by establishing a three-stage game model. We show that the optimal investment strategy and pricing decisions in the decentralized model may deviate from those in the centralized model. We then propose a mechanism to coordinate the decentralized supply chain, by introducing a profit sharing policy, a production cost sharing policy, and an investment cost sharing policy. Finally, we show that both the supplier and the manufacturer can benefit from participating in the proposed coordination mechanism.

1. Introduction

With the rapid development of economic globalization and the increasingly fierce market competition, the business environment of a firm becomes more changeable and complex. Under such a background, many firms have to maintain research and development (R&D) activities in quality improvement, cost reduction, and so on, to increase competitive edge [1]. For example, recent studies show that automakers spend more than $100 billion annually in R&D activities (please see http://www.autoalliance.org/auto-innovation/randd-investments).

This paper is related to two streams of OR/MS literature. One stream is on quality improvement investment in supply chains. For example, Wan and Xu [2] investigate inspection policies in a decentralized supply chain where manufacturer uses an inspection policy and a damage cost sharing contract to encourage the supplier to invests in quality improvement. They show that if the supplier's share of the damage cost exceeds a threshold, then all-or-none inspection policies are optimal for the manufacturer. Seifbarghy et al. [3] study the problem of the supplier's quality improvement investment in a supply chain, where the market demand is divided into two categories. Xie et al. [4] consider quality improvement in a given segment of the market which is shared by two supply chains and provide valuable insights into the selection of supply chain structure and quality improvement investment strategy by two competing supply chains. Shi et al. [5] consider quality improvement problem in a supply chain with two suppliers and one manufacturer, where one is an urgent supplier with low quality and short lead time while the other is a strategic supplier with high quality and long lead time. Gao et al. [6] consider quality improvement investment strategy in a supply chain with failure root analysis and develop a contract mechanism to coordinate the supply chain. Zhu et al. [7] consider a supply chain where both the supplier and the manufacturer conduct investment to improve product quality and find that the manufacturer's investment has a significant impact on the profits of each player and the entire supply chain. Please refer to Baiman et al. [8], Balachandran and Radhakrishnan [9], and Hwang et al. [10] for more discussions on quality improvement investment in supply chains. Although the above literature has investigated the problem of quality improvement investment from different perspectives, it supposes that all players in the supply chain do not make cost reduction investment.

The other stream of literature is on cost reduction investment in supply chains. For example, Iyer et al. [11], Ge et al. [12], and Huang et al. [13] consider the problem of cost reduction investment in a supply chain with one upstream supplier and one downstream manufacturer. Bernstein et al. [14] explore the problem of cost reduction investment in a supply chain consisting of multiple suppliers and one manufacturer. Banerjee and Lin [15] investigate the problem of cost reduction investment in a supply chain consisting of one supplier and multiple manufacturers. The above literature has investigated the problem of cost reduction investment from different perspectives; it assumes that each player in the supply chain does not conduct quality improvement investment.

The existing literature either supposes that players in the supply chain make investment to improve the product quality or assumes that players conduct investment to reduce the production cost. No study considers the problem of investment in both quality improvement and cost reduction. In this paper, we investigate a manufacturer Stackelberg supply chain, where the downstream manufacturer is the Stackelberg leader and the upstream supplier is the follower (see, e.g., [16]). The manufacturer buys a component from the supplier and then transforms it to the final product, which is sold in a price and quality sensitive market. We suppose that the manufacturer can make R&D investment not only to improve his product quality, but also to reduce his production cost. We first characterize the optimal pricing decisions of the two players under any given R&D investment strategy. We then derive the optimal investment strategy for the manufacturer. Finally, we propose a mechanism by introducing a profit sharing policy (see, e.g., [17]), a production cost sharing policy, and an investment cost sharing policy, to coordinate the decentralized supply chain. We also show that the proposed mechanism can result in a Pareto improvement.

The contributions of our paper to the OR/MS literature can be summarized as follows.

(1) We establish a model to investigate the manufacturer's R&D investment in both quality improvement activity and cost reduction activity.

(2) We characterize the optimal R&D investment strategy for the manufacturer and corresponding pricing decisions for both the supplier and the manufacturer in a decentralized supply chain.

(3) We develop a mechanism to coordinate the decentralized supply chain and show that the developed contract mechanism can achieve a win-win solution.

The rest of the paper is structured as follows. We introduce the model in Section 2. Section 3 investigates the decentralized supply chain, where the investment strategy and the pricing decisions are derived. Section 4 analyzes the problem of supply chain coordination. Some concluding remarks and further research directions are discussed in Section 5.

2. The Model

In this section, we describe the model. Consider a supply chain where an upstream supplier sells a component to a downstream manufacturer, who transforms the component into a final product and sells it into a price and quality sensitive market. The production cost and the wholesale price of the component are c_s and w, respectively; the retail price of the final product is p. Without loss of generality, we assume similar to Xie et al. [4] that the market demand faced by the manufacturer is given by

$$D(p,\alpha) = a - bp + \theta\alpha, \tag{1}$$

where a in (1) represents the potential intrinsic market demand, b represents the sensitivity of the market demand to the retail price, α corresponds to the quality level of the product, and θ corresponds to the sensitivity of the market demand to the quality level.

The manufacturer can make R&D investment to improve the product quality and/or reduce the production cost. We denote the initial quality and the initial production cost of the product to be α_m and c_m, and the quality improvement level and cost reduction level of the product caused by R&D investment are α_Δ and c_Δ, respectively. We require that $a - b(c_m + c_s) + \theta\alpha_m \geq 0$, in the sense that when the retail price of the product is set at its initial production cost (i.e., $c_m + c_s$), the market demand is nonnegative (see, e.g., [18]). After the manufacturer's investment, the product quality and the production cost are $\alpha_m + \alpha_\Delta$ and $c_m - c_\Delta$, respectively. We assume similar to Xie et al. [4] that the investment cost of quality improvement is $f(\alpha_\Delta)$, which is convexly increasing in α_Δ and is given by

$$f(\alpha_\Delta) = A(\alpha_\Delta)^2, \tag{2}$$

where A in (2) is a parameter related to the marginal cost of quality improvement investment and $A > 0$. Moreover, similar to Ge et al. [12], we assume that the investment cost of cost reduction is $g(c_\Delta)$, which is convexly increasing in c_Δ and is given by

$$g(c_\Delta) = B(c_\Delta)^2, \tag{3}$$

where B in (3) is a parameter related to the marginal cost of cost reduction investment and $B > 0$. Furthermore, we suppose that the manufacturer has capital constraint and thus his investment activity is constrained by $f(\alpha_\Delta) + g(c_\Delta) \leq K$; that is, the manufacturer can invest at most K to achieve quality improvement and/or cost reduction. To ensure that the production cost of the manufacturer is always positive, that is, $c_m - c_\Delta > 0$, we require that $c_m - (K/B)^{1/2} > 0$; that is, $B > K/c_m^2$.

We consider a manufacturer Stackelberg supply chain where the manufacturer has larger influence on the market than the supplier and endows the manufacturer with the first-mover advantage [16]. The two players engage in a three-stage game to determine their optimal decisions, specifically as follows.

(i) In the first stage, the manufacturer chooses his investment strategy, that is, $f(\alpha_\Delta)$ and $g(c_\Delta)$. Because there is a one-to-one correspondence between $f(\alpha_\Delta)$ and α_Δ and there exists a one-to-one relationship between $g(c_\Delta)$ and c_Δ, choosing values for $f(\alpha_\Delta)$ and $g(c_\Delta)$ is equal to choosing the corresponding values for α_Δ and c_Δ, respectively.

(ii) In the second stage, the manufacturer sets a markup m above his procurement cost, that is, the upstream firm's wholesale price w, and sells the product to the market at the price of $p = w + m$ (see, e.g., [19]).

(iii) In the last stage, the supplier determines a wholesale price w for the component to be charged to the manufacturer.

3. Decentralized Supply Chain

In a decentralized supply chain, both the supplier and the manufacturer are independent decision makers. They make decisions to maximize their own profits. Using backward induction, we first solve the problem of the supplier's wholesale price which is chosen in the third stage.

3.1. The Third Stage. Based upon the description provided in Section 2, we know that for any investment strategy (α_Δ, c_Δ) and markup m decision chosen by the manufacturer, the profit function of the supplier can be expressed as

$$\begin{aligned}\Pi_s(w \mid m, \alpha_\Delta, c_\Delta) &= (w - c_s)(a - bp + \theta\alpha) \\ &= (w - c_s)\left[a - b(w+m) + \theta(\alpha_m + \alpha_\Delta)\right].\end{aligned} \tag{4}$$

From (4), we can obtain the following result.

Proposition 1. *For any investment strategy $(\alpha_\Delta, c_\Delta)$ and markup m decision chosen by the manufacturer, the supplier's profit function $\Pi_s(w \mid m, \alpha_\Delta, c_\Delta)$ of (4) is strictly concave in its wholesale price w and reaches its maximum at*

$$w^*(m, \alpha_\Delta, c_\Delta) = \frac{a + \theta(\alpha_m + \alpha_\Delta) - b(m - c_s)}{2b}. \tag{5}$$

Proof of Proposition 1. Taking the first and the second derivatives of $\Pi_s(w \mid m, \alpha_\Delta, c_\Delta)$ of (4) with respect to w, we have

$$\begin{aligned}\frac{d\Pi_s(w \mid m, \alpha_\Delta, c_\Delta)}{dw} &= a - 2bw - bm + \theta(\alpha_m + \alpha_\Delta) \\ &\quad + bc_s, \\ \frac{d^2\Pi_s(w \mid m, \alpha_\Delta, c_\Delta)}{dw^2} &= -2b < 0.\end{aligned} \tag{6}$$

That is, the profit function of the supplier is strictly concave in the wholesale price. Thus, the optimal wholesale price satisfies the first-order condition, that is, $d\Pi_s(w \mid m, \alpha_\Delta, c_\Delta)/dw = 0$. Solving the first-order condition for w, we get (5). We thus complete the proof of Proposition 1. □

Proposition 1 gives the supplier's optimal response wholesale price. From Proposition 1, we can see that the supplier's optimal response wholesale price $w^*(m, \alpha_\Delta, c_\Delta)$ increases as the quality improvement level α_Δ increases. This is because when the quality improvement level increases, the quality sensitive demand will increase and the supplier will set a higher wholesale price to earn more profit. We can also see from Proposition 1 that the supplier's optimal response wholesale price $w^*(m, \alpha_\Delta, c_\Delta)$ decreases as the markup m increases. The reason is that a higher markup is chosen by the manufacturer, a higher retail price will be set for the product, and the price sensitive demand will decrease. Thus, the supplier will decrease his wholesale price. In addition, Proposition 1 states that the supplier's optimal response wholesale price $w^*(m, \alpha_\Delta, c_\Delta)$ does not directly depend on the reduction in the manufacturer's production cost c_Δ. In our subsequent analyses of the manufacturer's markup decision, we will show that cost reduction c_Δ influences the supplier's wholesale price decision via the manufacturer's markup decision.

3.2. The Second Stage. Knowing that the supplier chooses the wholesale price according to (5), the manufacturer sets its markup in the second stage to maximize his profit. Based upon the description provided in Section 2, the profit function of manufacturer can be written as

$$\begin{aligned}&\Pi_m(m \mid w, \alpha_\Delta, c_\Delta) \\ &\quad = \left[m - (c_m - c_\Delta)\right]\left[a - b(w+m) + \theta(\alpha_m + \alpha_\Delta)\right] \\ &\qquad - f(\alpha_\Delta) - g(c_\Delta).\end{aligned} \tag{7}$$

Then, by substituting $w = w^*(m, \alpha_\Delta, c_\Delta)$ of (5) into $\Pi_m(m \mid w, \alpha_\Delta, c_\Delta)$ of (7), the manufacturer's profit can be rewritten as

$$\begin{aligned}&\Pi_m(m \mid \alpha_\Delta, c_\Delta) \\ &\quad = \frac{\left[m - (c_m - c_\Delta)\right]\left[a + \theta(\alpha_m + \alpha_\Delta) - bc_s - mb\right]}{2} \\ &\qquad - f(\alpha_\Delta) - g(c_\Delta).\end{aligned} \tag{8}$$

This enables us to derive the following result.

Proposition 2. *For any given investment strategy $(\alpha_\Delta, c_\Delta)$, the manufacturer's profit function $\Pi_m(m \mid \alpha_\Delta, c_\Delta)$ of (8) is strictly concave in its markup m and achieves its maximum at*

$$m^*(\alpha_\Delta, c_\Delta) = \frac{a + \theta(\alpha_m + \alpha_\Delta) - bc_s + b(c_m - c_\Delta)}{2b}. \tag{9}$$

Consequently, the corresponding wholesale price of the supplier is given by

$$w^*(\alpha_\Delta, c_\Delta) = \frac{a + \theta(\alpha_m + \alpha_\Delta) + 3bc_s - b(c_m - c_\Delta)}{4b}, \tag{10}$$

and the corresponding retail price and the supply chain output are as follows:

$$p^*(\alpha_\Delta, c_\Delta) = \frac{3a + 3\theta(\alpha_m + \alpha_\Delta) + bc_s + b(c_m - c_\Delta)}{4b}, \quad (11)$$

$$q^*(\alpha_\Delta, c_\Delta) = \frac{a + \theta(\alpha_m + \alpha_\Delta) - bc_s - b(c_m - c_\Delta)}{4}. \quad (12)$$

Proof of Proposition 2. Taking the first and the second derivatives of $\Pi_m(m \mid \alpha_\Delta, c_\Delta)$ of (8) with respect to m, we have

$$\frac{d\Pi_m(m \mid \alpha_\Delta, c_\Delta)}{dm} = \frac{a + \theta(\alpha_m + \alpha_\Delta) - bc_s - 2mb + b(c_m - c_\Delta)}{2}, \quad (13)$$
$$\frac{d^2\Pi_m(m \mid \alpha_\Delta, c_\Delta)}{dm^2} = -b < 0.$$

That is, the profit function of the manufacturer is strictly concave in its markup. Thus, the optimal markup satisfies the first-order condition, that is, $d\Pi_m(m \mid \alpha_\Delta, c_\Delta)/dm = 0$. Solving the first-order condition for m, we get (9).

Second, substituting $m = m^*(\alpha_\Delta, c_\Delta)$ of (9) into $w^*(m, \alpha_\Delta, c_\Delta)$ of (5), we get $w^*(\alpha_\Delta, c_\Delta)$ of (10). Substituting $m = m^*(\alpha_\Delta, c_\Delta)$ of (9) and $w = w^*(\alpha_\Delta, c_\Delta)$ of (10) into $p = w + m$, we get $p^*(\alpha_\Delta, c_\Delta)$ of (11). Substituting $p = p^*(\alpha_\Delta, c_\Delta)$ of (11) into (1), we get $q^*(\alpha_\Delta, c_\Delta)$ of (12). We thus complete the proof of Proposition 2. □

Proposition 2 characterizes the manufacturer's optimal markup under any given investment strategy and the corresponding wholesale price, retail price, and the supply chain output. Firstly, from (9), one can see that the manufacturer's optimal markup $m^*(\alpha_\Delta, c_\Delta)$ increases as the quality improvement level α_Δ increases but decreases as the cost reduction level c_Δ increases. That is, the manufacturer with a high quality product or a higher production cost will choose a higher markup above the supplier's wholesale price. This is rather intuitive. Secondly, (10) confirms the discussion following Proposition 1 that the cost reduction influences the supplier's wholesale price choice via the manufacturer's markup choice. That is, the supplier's wholesale price $w^*(\alpha_\Delta, c_\Delta)$ increases as the cost reduction level c_Δ increases. Thirdly, (11) shows that the retail price $p^*(\alpha_\Delta, c_\Delta)$ increases as the quality improvement level α_Δ increases; this is because when the quality improvement level α_Δ increases, both the wholesale price and the markup increase, and hence the retail price $p = w + m$ increases; the retail price $p^*(\alpha_\Delta, c_\Delta)$ decreases as the cost reduction level c_Δ increases; this is because the impacts of the cost reduction on the wholesale price and the markup are opposite, and the impact of the cost reduction on the markup outweighs the impact of the cost reduction on the wholesale price. Finally, (12) indicates that the supply chain output $q^*(\alpha_\Delta, c_\Delta)$ increases not only with the quality improvement level α_Δ but also with the cost reduction level c_Δ. The reason for this result can be explained as follows. When either the product quality is improved or the production cost is reduced, the supply chain becomes more efficient, and hence, more product will be produced to meet the market demand.

Now, substituting $m = m^*(\alpha_\Delta, c_\Delta)$ of (9) and $w = w^*(\alpha_\Delta, c_\Delta)$ of (10) into $\Pi_s(w \mid m, \alpha_\Delta, c_\Delta)$ of (4) and $\Pi_m(m \mid \alpha_\Delta, c_\Delta)$ of (8), we can obtain the profits of the two players as follows, respectively,

$$\Pi_s^*(\alpha_\Delta, c_\Delta) = \frac{[a + \theta(\alpha_m + \alpha_\Delta) - bc_s - b(c_m - c_\Delta)]^2}{16b}, \quad (14)$$

$$\Pi_m^*(\alpha_\Delta, c_\Delta) = \frac{[a + \theta(\alpha_m + \alpha_\Delta) - bc_s - b(c_m - c_\Delta)]^2}{8b} - f(\alpha_\Delta) - g(c_\Delta). \quad (15)$$

From (14), we can show that the supplier's profit increases not only with the quality improvement level α_Δ but also with the cost reduction level c_Δ. This implies that the supplier can always benefit from the investment. The result is not surprising, because the supplier enjoys a more efficient supply chain but does not undertake any cost for improving the supply chain efficiency. However, the manufacturer may not benefit from his investment, because he should balance the investment cost and the corresponding benefit.

3.3. The First Stage. In this subsection, we consider the investment strategy of the manufacturer. Recall that we have assumed that the manufacturer's R&D investment activity is constrained by $f(\alpha_\Delta) + g(c_\Delta) \le K$, $f(\alpha_\Delta) = A(\alpha_\Delta)^2$ and $g(c_\Delta) = B(c_\Delta)^2$. Then, the manufacturer's investment problem can be formulated as the following two-dimensional constrained optimization problem:

$$\max_{x,y} \quad \Pi_m^*(\alpha_\Delta, c_\Delta) = \frac{[a + \theta(\alpha_m + \alpha_\Delta) - bc_s - b(c_m - c_\Delta)]^2}{8b} - A(\alpha_\Delta)^2 - B(c_\Delta)^2, \quad (16)$$
$$\text{s.t.} \quad \alpha_\Delta \ge 0,$$
$$c_\Delta \ge 0,$$
$$0 \le A(\alpha_\Delta)^2 + B(c_\Delta)^2 \le K.$$

This enables us to get the following result.

Proposition 3. *Let k denote the total capital invested by the manufacturer in both the quality improvement activity and the cost reduction activity, that is, $k = A(\alpha_\Delta)^2 + B(c_\Delta)^2$, $0 \le k \le K$, then $\Pi_m^*(\alpha_\Delta, c_\Delta)$ of (16) achieves its maximum at*

$$c_\Delta^*(k) = \left(\frac{Ab^2}{\theta^2 B^2 + ABb^2}\right)^{1/2} \cdot k^{1/2}, \quad (17)$$

$$\alpha_\Delta^*(k) = \left(\frac{A^{-1}B^2\theta^2}{\theta^2 B^2 + ABb^2}\right)^{1/2} \cdot k^{1/2}. \quad (18)$$

Proof of Proposition 3. For any given $k = A(\alpha_\Delta)^2 + B(c_\Delta)^2$, we have $\alpha_\Delta = ((k - B(c_\Delta)^2)/A)^{1/2}$, and then, the manufacturer's profit function $\Pi_m^*(\alpha_\Delta, c_\Delta)$ of (16) can be rewritten as

$$\Pi_m^*(c_\Delta) = \frac{\left\{a + \theta\left[\alpha_m + \left(\left(k - B(c_\Delta)^2\right)/A\right)^{1/2}\right] - bc_s - b(c_m - c_\Delta)\right\}^2}{8b} - k. \quad (19)$$

Obviously, for any given $k = A(\alpha_\Delta)^2 + B(c_\Delta)^2$, choosing a value to maximize $\Pi_m^*(c_\Delta)$ is equal to choosing a value to maximize

$$T(c_\Delta) = \theta\left[\alpha_m + \left(\frac{k - B(c_\Delta)^2}{A}\right)^{1/2}\right] - b(c_m - c_\Delta). \quad (20)$$

Taking the first derivative of $T(c_\Delta)$ with respect to c_Δ, we have

$$\frac{dT(c_\Delta)}{dc_\Delta} = b - \frac{\theta B}{\left(Ak/(c_\Delta)^2 - AB\right)^{1/2}}. \quad (21)$$

It is easy to verify that $dT(c_\Delta)/dc_\Delta$ decreases as c_Δ increases, implying that $d^2T(c_\Delta)/d(c_\Delta)^2 < 0$. That is, $T(c_\Delta)$ is strictly concave in c_Δ, and hence the optimal cost reduction level satisfies the first-order condition; that is, $dT(c_\Delta)/dc_\Delta = 0$. Solving the first-order condition for c_Δ, we get (17). Second, substituting $c_\Delta = c_\Delta^*(k)$ of (17) into $k = A(\alpha_\Delta)^2 + B(c_\Delta)^2$, we have $\alpha_\Delta^*(k)$ of (18). We thus complete the proof of Proposition 3. □

Proposition 3 implies that the optimal investment strategy requires that the capital should be invested not only in the quality improvement activity but also in the cost reduction activity. Moreover, one can see from Proposition 3 that if the total investment cost, that is, $k = A(\alpha_\Delta)^2 + B(c_\Delta)^2$, is given, then the investment costs for achieving quality improvement and cost reduction, respectively, are

$$A\left(\alpha_\Delta^*(k)\right)^2 = \left(\frac{B^2\theta^2}{\theta^2B^2 + ABb^2}\right) \cdot k, \quad (22)$$

$$B\left(c_\Delta^*(k)\right)^2 = \left(\frac{ABb^2}{\theta^2B^2 + ABb^2}\right) \cdot k. \quad (23)$$

Accordingly, the ratio of capital invested by the manufacturer in quality improvement activity and cost reduction activity in the decentralized supply chain is

$$\frac{A\left(\alpha_\Delta^*(k)\right)^2}{B\left(c_\Delta^*(k)\right)^2} = \frac{B\theta^2}{Ab^2}. \quad (24)$$

Equation (24) reveals the following important insights: when the total capital invested by the manufacturer is fixed, that is, $k = A(\alpha_\Delta)^2 + B(c_\Delta)^2$ is fixed, if the parameter A is relatively small or the parameter θ is relatively large, then a relatively more capital will be invested in quality improvement activity. This is because a smaller value of A implies that the marginal cost of quality improvement investment is lower and a larger value of θ indicates that the market demand is more sensitive to the quality improvement. Of course, the manufacturer is likely to invest a relatively more capital in quality improvement activity. Similar analysis can be conducted for the parameters B and b.

Because the manufacturer will allocate its capital $k = A(\alpha_\Delta)^2 + B(c_\Delta)^2$ in quality improvement activity and cost reduction activity according to (24), we can reduce the two-dimensional constrained optimization problem of (16) to the following one-dimensional constrained optimization problem:

$$\max_k \quad \Pi_m^*(k) = \frac{\left[a + \theta\alpha_m - bc_s - bc_m + \left(A^{-1}B^2\theta^4/\left(\theta^2B^2 + ABb^2\right)\right)^{1/2} \cdot k^{1/2} + \left(Ab^4/\left(\theta^2B^2 + ABb^2\right)\right)^{1/2} \cdot k^{1/2}\right]^2}{8b} - k,$$
$$\text{s.t.} \quad 0 \le k \le K. \quad (25)$$

That is, the manufacturer can first determines the total capital to be invested in quality improvement activity and cost reduction activity and then allocates the total capital between the two activities according to (24). The results are summarized below in Proposition 4.

Proposition 4. *The manufacturer's profit function $\Pi_m^*(k)$ of (25) is strictly concave in k and achieves its maximum at*

$$k^* = \left[\frac{(a + \theta\alpha_m - bc_s - bc_m)\left(A^{-1/2}B\theta^2 + A^{1/2}b^2\right)\left(\theta^2B^2 + ABb^2\right)^{1/2}}{8b\left(\theta^2B^2 + ABb^2\right) - \left(A^{-1/2}B\theta^2 + A^{1/2}b^2\right)^2}\right]^2. \quad (26)$$

Accordingly, the optimal total capital invested by the manufacturer is

$$\overline{k}^* = \begin{cases} k^*, & if\ k^* < K, \\ K, & if\ k^* \geq K, \end{cases} \quad (27)$$

and the optimal capital invested by the manufacturer in quality improvement activity and cost reduction activity, respectively, is

$$A\left(\alpha_\Delta^*\left(\overline{k}^*\right)\right)^2 = \left(\frac{B^2\theta^2}{\theta^2 B^2 + ABb^2}\right) \cdot \overline{k}^*, \quad (28)$$

$$B\left(c_\Delta^*\left(\overline{k}^*\right)\right)^2 = \left(\frac{ABb^2}{\theta^2 B^2 + ABb^2}\right) \cdot \overline{k}^*. \quad (29)$$

Proof of Proposition 4. Taking the first derivative of $\Pi_m^*(k)$ of (25) with respect to k, we have, after some algebra, that

$$\frac{d\Pi_m^*(k)}{dk} = \frac{\left[\left(\left(a+\theta\alpha_m - bc_s - bc_m\right)/k^{1/2}\right) + \left(A^{-1}B^2\theta^4/\left(\theta^2B^2+ABb^2\right)\right)^{1/2} + \left(Ab^4/\left(\theta^2B^2+ABb^2\right)\right)^{1/2}\right]\left[\left(A^{-1}B^2\theta^4/\left(\theta^2B^2+ABb^2\right)\right)^{1/2} + \left(Ab^4/\left(\theta^2B^2+ABb^2\right)\right)^{1/2}\right]}{8b} - 1. \quad (30)$$

It is easy to verify that $d\Pi_m^*(k)/dk$ decreases as k increases, implying that $d^2\Pi_m^*(k)/dk^2 < 0$. That is, $\Pi_m^*(k)$ is strictly concave in k, and hence the maximizer of profit function $\Pi_m^*(k)$ is uniquely determined by the first-order condition; that is, $d\Pi_m^*(k)/dk = 0$. Solving the first-order condition for k, we can get k^* of (26). This, together with the fact that $0 \leq k \leq K$, indicates that the optimal total capital for the manufacturer is given by $\overline{k}^*$ of (27). Second, substituting $k = \overline{k}^*$ of (27) into (22) and (23), respectively, we can get (28) and (29), respectively. We thus complete the proof of Proposition 4. □

Proposition 4 characterizes the optimal investment strategy for the manufacturer in the decentralized supply chain, which depends on supply chain parameters a, b, β, I, J, K. Substituting $p^*(\alpha_\Delta, c_\Delta)$ of (11), $q^*(\alpha_\Delta, c_\Delta)$ of (12), $A(\alpha_\Delta^*(\overline{k}^*))^2$ of (28), and $B(c_\Delta^*(\overline{k}^*))^2$ of (29) into $\Pi_s(w \mid m, \alpha_\Delta, c_\Delta)$ of (4) and $\Pi_m(m \mid w, \alpha_\Delta, c_\Delta)$ of (7), we can get the optimal profits of the supplier and the manufacturer in the decentralized supply chain, denoted by Π_s^* and Π_m^*, respectively.

4. Supply Chain Coordination

Because double marginalization [20] exists in the decentralized supply chain, the decentralization decisions are usually suboptimal, as compared to the centralized decisions. In this section, we investigate the problem of supply chain coordination. We first consider the centralized supply chain, which serves as a benchmark for supply chain coordination. We then develop a contract mechanism to coordinate the decentralized supply chain.

4.1. Centralized Supply Chain. In the centralized supply chain, there is a central planner who optimizes supply chain profit, that is, the total profit of the supplier and the manufacturer. From (4) and (7), we can obtain the supply chain profit

$$\begin{aligned}\Pi_c(w, m \mid \alpha_\Delta, c_\Delta) &= \Pi_s(w \mid m, \alpha_\Delta, c_\Delta) \\ &\quad + \Pi_m(m \mid w, \alpha_\Delta, c_\Delta) = (w + m - c_m - c_s + c_\Delta) \\ &\quad \cdot \left[a - b(w+m) + \theta(\alpha_m + \alpha_\Delta)\right] - f(\alpha_\Delta) - g(c_\Delta).\end{aligned} \quad (31)$$

This, together with the fact that $p = w + m$, indicates that the supply chain profit can be rewritten as follows:

$$\begin{aligned}\Pi_c(p \mid \alpha_\Delta, c_\Delta) &= (p - c_m - c_s + c_\Delta)\left[a - bp + \theta(\alpha_m + \alpha_\Delta)\right] \\ &\quad - f(\alpha_\Delta) - g(c_\Delta).\end{aligned} \quad (32)$$

As a matter of fact, if the investment strategy $(\alpha_\Delta, c_\Delta)$ is given, then, in the decentralized supply chain, the values for wholesale price w and markup m are, respectively, chosen by the supplier and the manufacturer to maximize their own profits. However, in the centralized supply chain, it needs only to choose a value for $w + m$, i.e., p, to maximize the entire supply chain profit.

From (32), we have the following result.

Proposition 5. *In a centralized model, for any given investment strategy $(\alpha_\Delta, c_\Delta)$, the supply chain's profit function $\Pi_c(p \mid \alpha_\Delta, c_\Delta)$ of (32) is strictly concave in the retail price p and achieves its maximum at*

$$p_c^*(\alpha_\Delta, c_\Delta) = \frac{a + \theta(\alpha_m + \alpha_\Delta) + bc_s + b(c_m - c_\Delta)}{2b}. \quad (33)$$

Consequently, the corresponding supply chain output is

$$q_c^*(\alpha_\Delta, c_\Delta) = \frac{a + \theta(\alpha_m + \alpha_\Delta) - bc_s - b(c_m - c_\Delta)}{2}. \quad (34)$$

Proof of Proposition 5. Taking the first and the second derivatives of $\Pi_c(p \mid \alpha_\Delta, c_\Delta)$ of (32) with respect to p, we have

$$\begin{aligned}\frac{d\Pi_c(p \mid \alpha_\Delta, c_\Delta)}{dp} &= a - 2bp + \theta(\alpha_m + \alpha_\Delta) \\ &\quad + b(c_s + c_m - c_\Delta),\end{aligned} \quad (35)$$

$$\frac{d^2\Pi_c(p \mid \alpha_\Delta, c_\Delta)}{dp^2} = -2b < 0.$$

That is, the supply chain's profit function $\Pi_c(p \mid \alpha_\Delta, c_\Delta)$ of (32) is strictly concave in the retail price p. Thus, the optimal retail price satisfies the first-order condition, that is, $d\Pi_c(p \mid \alpha_\Delta, c_\Delta)/dp = 0$. Solving the first-order condition for p, we get (33). Second, substituting $p = p_c^*(\alpha_\Delta, c_\Delta)$ of (33) into (1), we have (34). We thus complete the proof of Proposition 5. □

By comparing Propositions 5 and 2, we can make the following corollary.

Corollary 6. *For any given investment strategy $(\alpha_\Delta, c_\Delta)$, the optimal retail price in the centralized model is lower than that in the decentralized model; that is, $p_c^*(\alpha_\Delta, c_\Delta) < p^*(\alpha_\Delta, c_\Delta)$, and the optimal supply chain output in the centralized model is higher than that in the decentralized model; that is, $q_c^*(\alpha_\Delta, c_\Delta) > q^*(\alpha_\Delta, c_\Delta)$.*

Proof of Corollary 6. First, it follows from (11) and (33) that

$$\begin{aligned} & p_c^*(\alpha_\Delta, c_\Delta) - p^*(\alpha_\Delta, c_\Delta) \\ & \quad = -\frac{a + \theta(\alpha_m + \alpha_\Delta) - bc_s - b(c_m - c_\Delta)}{4b}. \end{aligned} \tag{36}$$

This, together with the fact $a - b(c_m + c_s) + \theta\alpha_m \geq 0$, indicates that $p_c^*(\alpha_\Delta, c_\Delta) - p^*(\alpha_\Delta, c_\Delta) < 0$. Second, it follows from (12) and (34) that

$$\begin{aligned} & q_c^*(\alpha_\Delta, c_\Delta) - q^*(\alpha_\Delta, c_\Delta) \\ & \quad = \frac{a + \theta(\alpha_m + \alpha_\Delta) - bc_s - b(c_m - c_\Delta)}{4}. \end{aligned} \tag{37}$$

This, together with the fact $a - b(c_m + c_s) + \theta\alpha_m \geq 0$, indicates that $q_c^*(\alpha_\Delta, c_\Delta) - q^*(\alpha_\Delta, c_\Delta) > 0$. We thus complete the proof of Corollary 6. □

Corollary 6 states that, for any given investment strategy $(\alpha_\Delta, c_\Delta)$, the optimal retail price and supply chain output in the decentralized model deviate from that in the centralized model. Such a deviation will lead to a profit loss for the entire supply chain.

Now, substituting $p = p_c^*(\alpha_\Delta, c_\Delta)$ of (33) and $q = q_c^*(\alpha_\Delta, c_\Delta)$ of (34) into $\Pi_c(p \mid \alpha_\Delta, c_\Delta)$ of (32), we can get the entire supply chain's profit:

$$\begin{aligned} \Pi_c^*(\alpha_\Delta, c_\Delta) = {} & \frac{[a + \theta(\alpha_m + \alpha_\Delta) - bc_s - b(c_m - c_\Delta)]^2}{4b} \\ & - f(\alpha_\Delta) - g(c_\Delta). \end{aligned} \tag{38}$$

This leads to the following result.

Proposition 7. *In a centralized model, the optimal total capital invested in the quality improvement activity and cost reduction activity is*

$$\bar{k}_c^* = \begin{cases} k_c^*, & \text{if } k_c^* < K, \\ K, & \text{if } k_c^* \geq K, \end{cases} \tag{39}$$

where

$$k_c^* = \left[\frac{(a + \theta\alpha_m - bc_s - bc_m)\left(A^{-1/2}B\theta^2 + A^{1/2}b^2\right)\left(\theta^2 B^2 + ABb^2\right)^{1/2}}{4b(\theta^2 B^2 + ABb^2) - \left(A^{-1/2}B\theta^2 + A^{1/2}b^2\right)^2} \right]^2. \tag{40}$$

Moreover, the optimal capital invested in quality improvement activity and cost reduction activity, respectively, is

$$A\left(\alpha_\Delta^*\left(\bar{k}_c^*\right)\right)^2 = \left(\frac{B^2\theta^2}{\theta^2 B^2 + ABb^2}\right) \cdot \bar{k}_c^*, \tag{41}$$

$$B\left(c_\Delta^*\left(\bar{k}_c^*\right)\right)^2 = \left(\frac{ABb^2}{\theta^2 B^2 + ABb^2}\right) \cdot \bar{k}_c^*. \tag{42}$$

Proof of Proposition 7. This proof is analog to the proof of Proposition 4; we omit it here. □

By comparing Propositions 7 and 4, we obtain the following corollary.

Corollary 8. *If $K \leq k^*$, then the optimal investment strategies are identical in the decentralized and centralized models; that is, $A(\alpha_\Delta^*(\bar{k}^*))^2 = A(\alpha_\Delta^*(\bar{k}_c^*))^2$ and $B(c_\Delta^*(\bar{k}^*))^2 = B(c_\Delta^*(\bar{k}_c^*))^2$; if $K > k^*$, then the optimal quality improvement investment level and cost reduction investment level in the decentralized model are both lower than those in the decentralized model; that is, $A(\alpha_\Delta^*(\bar{k}^*))^2 < A(\alpha_\Delta^*(\bar{k}_c^*))^2$ and $B(c_\Delta^*(\bar{k}^*))^2 < B(c_\Delta^*(\bar{k}_c^*))^2$.*

Proof of Corollary 8. First, if $K \leq k^*$, then $A(\alpha_\Delta^*(\bar{k}^*))^2 = (B^2\theta^2/(\theta^2 B^2 + ABb^2)) \cdot K = A(\alpha_\Delta^*(\bar{k}_c^*))^2$ and $B(c_\Delta^*(\bar{k}^*))^2 = (ABb^2/(\theta^2 B^2 + ABb^2)) \cdot K = B(c_\Delta^*(\bar{k}_c^*))^2$. Second, if $k^* < K < k_c^*$, then $A(\alpha_\Delta^*(\bar{k}^*))^2 = (B^2\theta^2/(\theta^2 B^2 + ABb^2)) \cdot k^* < (B^2\theta^2/(\theta^2 B^2 + ABb^2)) \cdot K = A(\alpha_\Delta^*(\bar{k}_c^*))^2$ and $B(c_\Delta^*(\bar{k}^*))^2 = (ABb^2/(\theta^2 B^2 + ABb^2)) \cdot k^* < (ABb^2/(\theta^2 B^2 + ABb^2)) \cdot K = B(c_\Delta^*(\bar{k}_c^*))^2$. Third, if $K \geq k_c^*$, then $A(\alpha_\Delta^*(\bar{k}^*))^2 = (B^2\theta^2/(\theta^2 B^2 + ABb^2)) \cdot k^* < (B^2\theta^2/(\theta^2 B^2 + ABb^2)) \cdot k_c^* = A(\alpha_\Delta^*(\bar{k}_c^*))^2$ and $B(c_\Delta^*(\bar{k}^*))^2 = (ABb^2/(\theta^2 B^2 + ABb^2)) \cdot k^* < (ABb^2/(\theta^2 B^2 + ABb^2)) \cdot k_c^* = B(c_\Delta^*(\bar{k}_c^*))^2$. We thus complete the proof of Corollary 8. □

Corollary 8 shows that the optimal investment strategy in the decentralized model may deviate from that in the centralized model. Specifically, when $K \leq k^*$, the investment strategies are identical in the two models. This is because when $K \leq k^*$, the whole capital will be invested in each of the two models. However, when $k^* < K < k_c^*$, the capital constraint has effect in the centralized model but has no effect in the decentralized model, and then the whole capital will be invested in the centralized model but will not be invested fully in the decentralized model. When $k > k_c^*$, the capital constraint has no effect in each of the two models and the investment level in the decentralized model is lower than that in the centralized model. Additionally, substituting $p_c^*(\alpha_\Delta, c_\Delta)$ of (33), $q_c^*(\alpha_\Delta, c_\Delta)$ of (34), $A(\alpha_\Delta^*(\overline{k}_c^*))^2$ of (41), and $B(c_\Delta^*(\overline{k}_c^*))^2$ of (42) into (32), we can get the optimal profit of the centralized supply chain, denoted by Π_c^*.

4.2. Coordination Mechanism. In Section 4.1, we have shown that the optimal investment strategy and retail price decision in the decentralized model may deviate from that in the centralized model. Thus, the supply chain profit under the decentralized decision making is suboptimal. In this subsection, we develop a contract mechanism to coordinate the decentralized supply chain. Our mechanism suggests that, in addition to the wholesale price policy in the decentralized model, the mechanism has three other policies: a profit sharing policy (see, e.g., [17]), a production cost sharing policy, and an investment cost sharing policy. For convenience, we denote the developed mechanism as $\{w, x, y, z\}$, specifically as follows.

(a) The wholesale price policy suggests that the supplier charges the manufacturer a wholesale price w per unit for its component, and then the manufacturer sets a markup m above wholesale price w and sells the product to the market at the price of $p = w + m$.

(b) The profit sharing policy suggests that the supplier shares x percentage of its net profit to the manufacturer.

(c) The production cost sharing policy suggests that the supplier shares y percentage of the manufacturer's production cost.

(d) The investment cost sharing policy suggests that the supplier shares z percentage of the manufacturer's R&D investment cost.

Then, under the above proposed mechanism $\{w, x, y, z\}$, the total transfer payment from the manufacturer to the supplier is given by

$$\begin{aligned} T(w, x, y, z) &= w[a - b(w+m) + \theta(\alpha_m + \alpha_\Delta)] \\ &\quad - x(w - c_s)[a - b(w+m) + \theta(\alpha_m + \alpha_\Delta)] \\ &\quad - y(c_m - c_\Delta)[a - b(w+m) + \theta(\alpha_m + \alpha_\Delta)] \\ &\quad - z[f(\alpha_\Delta) + g(c_\Delta)]. \end{aligned} \tag{43}$$

The first term in the above equation corresponds to the payment caused by the wholesale price policy, the second term corresponds to the payment caused by the profit sharing policy, the third term corresponds to the payment caused by the production cost sharing policy, and the last term is the payment caused by the investment cost sharing policy.

Consequently, the profit functions of the two players in the supply chain under the proposed mechanism $\{w, x, y, z\}$ are as follows:

$$\begin{aligned} \Pi_{T,s}(w, x, y, z) &= T(w, x, y, z) \\ &\quad - c_s[a - b(w+m) + \theta(\alpha_m + \alpha_\Delta)], \end{aligned} \tag{44}$$

$$\begin{aligned} \Pi_{T,m}(w, x, y, z) &= [p - (c_m - c_\Delta)][a - b(w+m) + \theta(\alpha_m + \alpha_\Delta)] \\ &\quad - [f(\alpha_\Delta) + g(c_\Delta)] - T(w, x, y, z). \end{aligned} \tag{45}$$

From (44) and (45), we have the following result.

Proposition 9. *Under mechanism $\{w, x, y, z\}$, if*

$$\begin{aligned} y &= 1 - x, \\ z &= 1 - x, \\ m &= 0, \end{aligned} \tag{46}$$

then, for any given $0 < x < 1$, the optimal pricing decisions and investment strategies are identical in the decentralized and centralized supply chains; that is, $p_T^*(\alpha_\Delta, c_\Delta) = p_c^*(\alpha_\Delta, c_\Delta)$, $A(\alpha_\Delta^*(\overline{k}_T^*))^2 = A(\alpha_\Delta^*(\overline{k}_c^*))^2$, and $B(c_\Delta^*(\overline{k}_T^*))^2 = B(c_\Delta^*(\overline{k}_c^*))^2$, where $p_T^*(\alpha_\Delta, c_\Delta)$, $A(\alpha_\Delta^*(\overline{k}_T^*))^2$, and $B(c_\Delta^*(\overline{k}_T^*))^2$ represent the optimal retail price, capital invested in quality improvement activity, and capital invested in cost reduction activity under the proposed mechanism, respectively. That is, the decentralized supply chain is coordinated.

Proof of Proposition 9. Substituting (43) and (46) into $\Pi_{T,s}(w, x, y, z)$ of (44) and $\Pi_{T,m}(w, x, y, z)$ of (45), respectively, we have, after some algebra, that

$$\begin{aligned} \Pi_{T,s}(x) &= (1 - x) \\ &\quad \cdot \{(p - c_m - c_s + c_\Delta)[a - bp + \theta(\alpha_m + \alpha_\Delta)] \\ &\quad - [f(\alpha_\Delta) + g(c_\Delta)]\} = (1 - x)\Pi_c(p \mid \alpha_\Delta, c_\Delta), \\ \Pi_{T,m}(x) &= x\{(p - c_m - c_s + c_\Delta)[a - bp + \theta(\alpha_m + \alpha_\Delta)] \\ &\quad - [f(\alpha_\Delta) + g(c_\Delta)]\} = x\Pi_c(p \mid \alpha_\Delta, c_\Delta). \end{aligned} \tag{47}$$

Thus, for any given x, $\Pi_{T,s}(x)$, $\Pi_{T,m}(x)$, and $\Pi_c(p \mid \alpha_\Delta, c_\Delta)$ achieve their maxima at the same point. Accordingly, under the proposed mechanism, the optimal retail price decision and investment strategy in the centralized model will be chosen. We thus complete the proof of Proposition 9. □

Proposition 9 shows that the decentralized supply chain can be coordinated by the proposed mechanism $\{w, x, y, z\}$ with appropriate parameters. Here we should point out that zero markup chosen by the downstream manufacturer is used to solve the double marginalization problem, while the profit sharing policy is to ensure that the manufacturer can get a positive profit, and thus the manufacturer has incentive to participate in the coordination. As a matter of fact, many downstream firms, such as Amazon (https://www.amazon.com/) and Joybuy (http://www.joybuy.com/), usually set a zero markup but share upstream suppliers' revenue. This is quite similar to our coordination mechanism, which requires that the downstream manufacturer sets a zero markup above the upstream supplier's wholesale price w but shares the supplier's profit.

In reality, an effective coordination mechanism should achieve Pareto improvement; otherwise, there exists at least one player having no incentive to participate in the coordination. At the end of this subsection, we will show that both the supplier and the manufacturer can benefit from participating in the proposed coordination mechanism, that is, $\Pi_{T,s}(x) > \Pi_s^*$ and $\Pi_{T,m}(x) > \Pi_m^*$, where Π_s^* and Π_m^* represent the optimal profits of the supplier and the manufacturer in the decentralized supply chain without coordination mechanism. Note from the proof of Proposition 9 that, under the proposed mechanism $\{w, x, y, z\}$, the profits earned by the supplier and the manufacturer are $\Pi_{T,s}(x) = (1-x)\Pi_c^*$ and $\Pi_{T,m}(x) = x\Pi_c^*$, respectively, where Π_c^* represents the optimal profit of the centralized supply chain. This together with the fact $\Pi_c^* > \Pi_s^* + \Pi_m^*$, that there must exist a set of values for parameter x, such that $(1-x)\Pi_c^* > \Pi_s^*$ and $x\Pi_c^* > \Pi_m^*$ holds.

5. Concluding Remarks and Future Research

In practice, it is quite common that the manufacturer conducts R&D activity, which can achieve quality improvement and/or cost reduction. However, The existing studies on R&D activity in supply chains assume that R&D activity can either only lead to quality improvement or only result in cost reduction. This paper considers a manufacturer Stackelberg supply chain with a price and quality sensitive demand and investigates the problem of the manufacturer's R&D activity, which can achieve not only quality improvement but also cost reduction. By establishing a three-stage game model, the paper derives the optimal R&D investment strategy for the manufacturer and corresponding pricing decisions for both the supplier and the manufacturer in the decentralized supply chain. Moreover, a contract mechanism is developed to coordinate the decentralized supply chain. The key findings obtained in this paper are as follows.

(1) In the decentralized supply chain, there exists a unique solution to the three-stage game model, in the sense that the optimal investment strategy and pricing decisions exist and are unique.

(2) The optimal investment strategy for the manufacturer requires that the manufacturer must simultaneously invest in both quality improvement activity and cost reduction activity.

(3) The optimal investment strategy and pricing decisions in the decentralized supply chain may deviate from those in the centralized supply chain. The mechanism consisting of a wholesale price policy, a profit sharing policy, a production cost sharing policy, and an investment cost sharing policy can be used to coordinate the decentralized supply chain and achieve Pareto improvement.

This paper can be extended in several directions. In this paper, we focus on the problem of the downstream manufacturer's R&D investment in both quality improvement activity and cost reduction activity. It would be interesting to study the upstream supplier's R&D investment in both quality improvement activity and cost reduction activity. Additionally, in this study, we assume that there is only one component supplier in the supply chain. A more general setting may involve multiple component suppliers.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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