SUPPLIER’S INVESTMENT IN MANUFACTURER’S QUALITY IMPROVEMENT WITH EQUITY HOLDING

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Abstract. This paper considers a supply chain in which an upstream supplier sells a component to a downstream manufacturer facing a price and quality sensitive demand. The supplier has a chance to make investment in the manufacturer, which can not only enable the supplier to hold equity shares in the manufacturer and thus achieve profit sharing with the manufacturer, but also provide resources for the manufacturer to improve its product quality. Under any given investment strategy of the supplier, the equilibrium decisions of the two chain members on wholesale price and profit margin are characterized. Then, the supplier’s optimal investment strategy is derived. The paper considers three competition models: supplier Stackelberg (SS), manufacturer Stackelberg (MS), and vertical Nash (VN) models, which correspond to different market power structures. The paper shows that the investment can always increase the market demand. Moreover, in both the SS and VN models, the value of the supplier’s investment for the entire supply chain, comes from not only the quality improvement but also the profit sharing caused by equity holding; while in the MS model, the investment value comes only from the quality improvement.

1. Introduction. Product quality has been playing an increasingly important role in many industries, and it has been deemed to be one of the key elements in achieving competitive advantage [28]. The quality of a product highly depends on its design and a good product design usually requires firms to conduct many activities, such as financial analysis, portfolio analysis, technical analysis and so on [2]. In the past decades, many firms have paid intensive attention to their product quality. The higher the product quality, the higher the customer satisfaction will be. Without paying attention to product quality, firms may suffer heavy losses in the current competitive environment [37].

According to resource-based theory, valuable firm resources are scarce, and few firms own sufficient resources [11]. When downstream manufacturers lack quality-related resources (e.g., funding and technology), they may seek assistance from their upstream suppliers. Intuitively, suppliers can get competitive advantage from the

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quality improvement in the downstream product. Therefore, suppliers have incentives to help manufacturers and invest in them. In spite of this, suppliers should safeguard their investment from the possibility of relationship termination, and equity holding is a good choice in such a situation [21]. As a matter of fact, in reality, it is quite common that upstream suppliers invest in downstream manufacturers with equity holding to help them to conduct quality related activities. For example, in 2011, CPU supplier Qualcomm invests millions of dollars in smartphone manufacturer Xiaomi to help it to carry out product design activity, and acquires an undisclosed equity stake in Xiaomi [42]. Samsung Electronics, the supplier of chips, sensors and LCD to car manufacturer BYD [29], provides $450 million to BYD in 2016 to support its product development activity, and gets 1.92% equity shares in BYD [38]. However, its related questions have never been received enough attention from researchers. Motivated by this gap, this paper seeks to address quality management problem from the perspective of the supplier’s investment with equity holding.

When the supplier invests in the manufacturer with equity holding to improve its product quality, the supply chain operates at two levels of decision-making: One is concerned about the investment strategy of the supplier, and the other is concerned about the operating decisions (e.g., pricing and margin decisions) of the entire supply chain. Then, the following questions arise immediately: (i) How does the supplier’s investment strategy influence the operating decisions and corresponding profits of the two chain players? (ii) What is the source of the supplier’s investment value for the entire supply chain? (iii) What is the supplier’s optimal investment strategy? Answers to these research questions are important for understanding the problem of the supplier’s investment in the manufacturer’s quality improvement with equity holding. Additionally, in practice, different players usually have different influences on the market, and there exist three possible models of competition between the supplier and the manufacturer, i.e., supplier Stackelberg (SS) model, manufacturer Stackelberg (MS) model, and vertical Nash (VN) model, which correspond to three different market power structures. This study is conducted in the context of the three competition models, and thus can enable practitioners to strategically manage supply chains with different market power structures.

Specifically, this paper considers a supply chain consisting of one supplier and one manufacturer, who purchases a component from the supplier and then transforms it into a final product. The market demand depends on both the retail price and the product quality. The supplier has a chance to invest resources in the manufacturer, which not only allow the supplier to hold equity shares in the manufacturer and thus achieve profit sharing with the manufacturer, but also enable the manufacturer to improve its product quality (see, e.g., [38, 42]). By using non-cooperative game theory, the optimal pricing and margin decisions of the two supply chain members are characterized under any given investment strategy of the supplier, in the SS, MS and VN models, respectively. Then, the supplier’s investment value is derived, and the source of the value is identified. Finally, the supplier’s optimal investment strategy is analyzed under the assumption that the equity shares held by the supplier

\footnote{In the SS model, the supplier is the leader; in the MS model, the manufacturer is the leader; and in the VN model, the two players are equally powerful. All the three models have been extensively explored in supply chain management literature, please see [34, 43, 44] for more discussion on three competition models.}
and the quality level of the manufacturer’s product are both linearly dependent on the supplier’s investment cost.

In summary, the main contributions of this paper can be summarized as follows:

1. A model is established to study the problem of product quality management with equity holding. The main difference between the established model and existing models is that, the established model is on the combination of product quality management and equity holding.

2. The equilibrium decisions of two supply chain players on wholesale price and profit margin are characterized, under any given investment strategy of the supplier. The result shows that the supplier’s investment can increase the market demand.

3. The impacts of the supplier’s investment on the profits of the two players are analyzed. The analysis shows that the manufacturer may suffer losses from the investment in the SS and VN models, but can always benefit from the investment in the MS model; the optimal investment strategy is either “maximum-investment” or “zero-investment” in each of the three models.

4. The value of the supplier’s investment for the entire supply chain is derived. It is shown that in both the SS and VN models, the investment value comes not only from the quality improvement but also from the equity holding; while in the MS model, the investment value comes only from the quality improvement.

The reminder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 details the model assumptions. In Section 4, the optimal pricing and margin decisions are derived under any given investment strategy of the supplier. The impacts of the investment on the profits of the supply chain members are also investigated. In Section 5, the supplier’s optimal investment strategy is analyzed. Section 6 concludes the paper. All mathematical proofs are provided in the Appendix.

2. Literature review. The supply chain model considered in this study has two distinctive features: (1) product quality management, (2) equity holding. This section reviews studies related to these two model features.

There exists a significant body of research on product quality management. For example, Xu [45] examines pricing and quality decisions in a supply chain where the product quality is determined by the upstream firm. Zhu et al. [49] show that sharing the quality-related cost has a significant impact on the supply chain profit, and the downstream firm can not cede all responsibility of quality improvement to the upstream firm. Leng et al. [30] find that when the impact of quality relative to retail price on demand is higher, the downstream firm benefits more from its gatekeeping activity. The above three papers [30, 45, 49] assume that: (1) all players are risk neutral, (2) all players have symmetric information, (3) the product is produced with one quality level, (4) the product is delivered through one channel, (5) the market demand is independent of the sales effort, (6) the market demand is independent of the reference price and reference quality, (7) the supply chain consists of one upstream firm and one downstream firm.

Some researchers conduct studies on product quality management by relaxing the above assumptions. For example, Xie et al. [44] show that risk tolerances of chain members have different impacts on product quality in SS, MS and VN models. Yang and Xiao [46] find that the contract including a quantity discount scheme and a service subsidy rate scheme can coordinate the supply chain where consumers
are loss averse in the service quality. Chao et al. [8] develop a menu of contracts to mitigate the impact of quality information asymmetry and improve the product quality. Kaya and Özer [27] discuss pricing and quality decisions in a supply chain where quality cost information of the upstream firm’s product is unknown to the downstream firm, and find that the impact of noncontractible quality is higher than the impact of quality cost information. Seifbarghy et al. [39] divide the market into two segments, and derive the condition under which the market segmentation and presenting the product with different quality levels can benefit the supply chain. Chen et al. [10] demonstrate that quality improvement can be realized by introducing a new channel. Ha et al. [19] show that when the upstream firm has enough flexibility in adjusting the product quality, encroachment may make the downstream firm worse off. Ma et al. [33, 34] derive the equilibrium strategies and develop a coordination mechanism for a supply chain, where the market demand depends not only on the upstream firm’s quality improvement effort, but also on the downstream firm’s sales effort. He et al. [20] develop a dynamic model that incorporates the effects of the reference quality and reference price on the demand function of a supply chain. Chen et al. [9] consider quality investment strategy in a supply chain with one upstream firm and two downstream firms. Yu and Ma [48] and Li and Chen [32] study quality investment strategy in a supply chain with two upstream firms and one downstream firm. Li and Nagurney [31] investigate ordering and quality improvement strategies in a multi-tiered supply chain, which consists of multiple upstream firms and multiple downstream firms. Although existing studies have investigated quality management problem of supply chains from different perspectives (e.g., risk tolerance, asymmetric information, quality levels, distribution channels, reference effects, sales effort and supply chain structures, etc.), they do not consider equity holding in supply chains.

This study is also related to research on equity holding in supply chains. For example, Greenlee and Raskovich [18] and Brito et al. [5] analyze equity holding in a supply chain with one upstream firm and multiple downstream firms. Greenlee and Raskovich [18] find that when the products of downstream firms are differentiated, equity holding by downstream firms in the upstream firm harms the consumers. Brito et al. [5] find that when the products are homogeneous, equity holding by downstream firms in the upstream firm benefits the consumers. Gaigné et al. [16] and Fu et al. [14] study equity holding in a supply chain with multiple upstream firms and one downstream firm. Gaigné et al. [16] show that equity holding by upstream firms in the downstream firm benefits the entire supply chain. Fu et al. [14] show that the impact of equity holding by the downstream firm in upstream firms highly depends on power structures. Flath [13] and Hunold and Stahl [25] examine equity holding in a supply chain with multiple upstream firms and multiple downstream firms. Flath [13] reports that when downstream firms are first movers, equity holding by upstream firms in downstream firms has no impact on the production quantity and the supply chain performance. Hunold and Stahl [25] report that equity holding by downstream firms in upstream firms can relax upstream competition. In addition, under legal unbundling, Hößler and Kranz [22, 23] investigate the impact of equity holding by the downstream firm in the upstream firm on the production quantity. Hunold [24] extends Hößler and Kranz’s model by adding the choice of upstream prices.

This study differs from the aforementioned studies on equity holding in two ways. First, equity holding parameter is exogenous in the aforementioned studies, which
however is endogenous in this study. Second, the aforementioned studies neglect the possibility that equity holding may be accompanied by resources, which can lead to quality improvement in the product; while in this study, the resources invested by the supplier can lead to not only equity holding but also quality improvement.

At the end of this section, it should point out that the second model feature of this study (i.e., equity holding) is similar to but different from sharing contracts such as profit sharing contract and revenue sharing contract. One difficulty in implementing these sharing contracts is the administrative burden of tracking the revenues or profits obtained by supply chain partners [1]. However, according to equity holding, firms can easily share their partners’ profits. Many studies suggest that sharing schemes are important and useful to supply chain coordination. For example, by using profit sharing contracts, Jeuland and Shugan [26] coordinate a supply chain with one upstream firm and one downstream firm, Shao and Ji [40] coordinate a chain with multiple upstream firms and one downstream firm, Modak et al. [36] coordinate a chain with one upstream firm and multiple downstream firms. In addition, by using revenue sharing contracts, Cachon [6] and Giannoccaro and Pontrandolfo [17] coordinate a chain with price-independent demand, Cachon and Lariviere [7] coordinate a chain with price-dependent demand.

3. Modeling. In a supply chain with a single upstream supplier and a single downstream manufacturer, the supplier sells a component to the manufacturer at a wholesale price \(w\), and then the manufacturer transforms it into a final product and sells it to a market. Without loss of generality, it is assumed that one unit of the final product requires one unit of the component. The unit production cost of the supplier is \(c\), and the unit production cost of the manufacturer is normalized to zero [15, 47].

The supplier has a chance to invest in the manufacturer. The supplier’s investment may be in the form of funding, technology, etc., and can improve the manufacturer’s product quality. In return, the manufacturer rewards the supplier with equity holding (see, e.g., [38, 42]). The quality improvement level of the manufacturer’s product is \(x(k)\), where \(k\) represents the value of the resources invested by the supplier. The function \(x(k)\) is supposed to be increasing in \(k\), which means that the more resources invested by the supplier, the higher quality level of the product will be. If \(k = 0\), then \(x(k) = 0\), i.e., if the supplier does not invest, then there is no improvement in the product quality. The percentage of equity shares held by the supplier in the manufacturer is \(y(k)\), \(0 \leq y(k) \leq \overline{y} < 100\%\), where \(\overline{y}\) represents the highest percentage of equity shares that can be held by the supplier\(^2\). The function \(y(k)\) is also supposed to be increasing in \(k\), which means that the more resources invested by the supplier, the more equity shares are held by the supplier. If \(k = 0\), then \(y(k) = 0\), i.e., if the supplier does not invest, then there is no equity holding. The equity shares allow the supplier to achieve profit sharing with the manufacturer, but do not enable the supplier to influence the manufacturer’s decision making. Here, it is worth pointing out that, due to the separation of voting and cash flow rights, nonvoting shares does not require \(\overline{y} < 50\%\) [4]. In the subsequent study of the supplier’s investment strategy, other restrictions on \(x(k)\) and \(y(k)\) will

\(^2\) In reality, many countries impose restrictions on the foreign ownership of domestic equity to ensure domestic control of local firms. For example, in France and Sweden, foreign equity participation is limited to 20%; In India and Mexico, foreign equity participation is limited to 49% [12]. For more examples of restrictions on equity holding, please see [41].
be added. A graphic illustration of the supplier’s investment in the manufacturer, is shown in Figure 1.

![Figure 1. Supplier invests in the manufacturer](image)

Market demand for the product depends not only on the retail price $p$, but also on the quality level $l$. Let $l_0$ denote the initial quality level of the product, which is exogenously given. Then after the supplier’s investment, the quality level becomes $l = l_0 + x(k)$. Similar to Banker et al. [3] and Xie et al. [44] that, market demand is assumed to be linear in both the quality level $l$ and the retail price $p$. That is,

$$q(p, l) = a + \theta l - bp = a + \theta (l_0 + x(k)) - bp,$$

where $a$ represents the potential intrinsic demand for the product, $\theta$ and $b$ respectively denote the demand responsiveness to the quality level and the retailer price. For simplicity, we normalize the initial quality level to zero, i.e., $l_0 = 0$. Then, Eq.(1) reduces to

$$q(p, x(k)) = a + \theta x(k) - bp. \quad (2)$$

Based upon the above description, the profit functions of the supplier and the manufacturer can be written as follows, respectively:

$$\Pi_u(w, p|k) = \underbrace{w(a + \theta x(k) - bp)}_{operating\ profit} - \underbrace{c(a + \theta x(k) - bp)}_{cost} + y(k)(p - w)(a + \theta x(k) - bp) - k, \quad (3)$$

$$\Pi_d(w, p|k) = (1 - y(k))(p - w)(a + \theta x(k) - bp). \quad (4)$$

In Eq.(3), the first term is the revenue of the supplier by selling the component to the manufacturer; the second term is the cost for the supplier to produce the component; the third term represents the return from equity shares (the supplier can share the manufacturer’s profit according to the equity shares held in the manufacturer); the last term corresponds to the investment cost. The two supply chain players are risk-neutral and make decisions to maximize their own profits (see, e.g., [35, 43]).

This paper investigates three models of competition between the supplier and the manufacturer, i.e., SS model, MS model and VN model. These three models have been commonly studied in supply chain management research (see, e.g., [34, 43, 44]). The supply chain involves two levels of decision-making. The first level is concerned about the supplier’s investment strategy. The second level is concerned about the supplier’s decision on the wholesale price and the manufacturer’s decision on the profit margin, which is dependent on the first level.
4. Equilibrium pricing and margin decisions under any given investment strategy. This section studies the equilibrium pricing and margin decisions of two players in the SS, MS and VN models, respectively, assuming that the supplier’s investment strategy is given.

4.1. Supplier Stackelberg (SS) model. In the SS model, the supplier acts as the Stackelberg leader and chooses the component wholesale price $w$ in the first stage, and the manufacturer determines the profit margin $m$ in the second stage. Thus, the retail price is $p = w + m$. The sequential decision problem of two players can be solved by using backward induction.

Substituting $p = w + m$ into Eq.(4), the manufacturer’s profit function can be rewritten as

$$\Pi_d(w, m|k) = (1 - y(k)) m [a + \theta x(k) - b(w + m)].$$

(5)

The following lemma can be derived from Eq.(5).

**Lemma 4.1.** For any given wholesale price $w$, the manufacturer’s profit function $\Pi_d(w, m|k)$ is strictly concave in its margin $m$, and the best response margin $m(w)$ is

$$m(w) = \frac{a + \theta x(k) - bw}{2b}.$$  

(6)

**Proof.** It follows from Eq.(5) that

$$\frac{d\Pi_d(w, m|k)}{dm} = (1 - y(k)) (a + \theta x(k) - bw - 2bm),$$

$$\frac{d^2\Pi_d(w, m|k)}{dm^2} = -2b(1 - y(k)) < 0.$$ 

That is, $\Pi_d(w, m|k)$ is strictly concave in $m$. Solving the first-order condition $\frac{d\Pi_d(w, m|k)}{dm} = 0$ for $m$, yields Eq.(6). $\square$

Lemma 4.1 shows that the manufacturer’s best response margin $m(w)$ does not depend on $y(k)$, implying that the supplier’s profit sharing has no impact on the manufacturer’s response margin. This is due to the fact that, for a given wholesale price $w$, the manufacturer’s problem of deciding a margin $m$ to maximize $\Pi_d(w, m|k)$ of Eq.(5), is equivalent to deciding a margin $m$ to maximize $\frac{\Pi_d(w, m|k)}{1 - y(k)} = m [a + \theta x(k) - b(w + m)].$

The supplier anticipates the manufacturer’s best response margin and chooses a wholesale price to maximize its profit. By substituting $m(w)$ of Eq.(6) and $p = w + m$ into Eq.(3), the supplier’s profit function can be rewritten as

$$\Pi_u(w|k) = \frac{(w - c)(a + \theta x(k) - bw) + y(k)(a + \theta x(k) - bw)^2}{2} - k.$$  

(7)

This leads to the following theorem.

**Theorem 4.2.** In the SS model, the supplier’s profit function $\Pi_u(w|k)$ is strictly concave in $w$, and has the unique maximizer

$$w^* = \frac{(1 - y(k))(a + \theta x(k)) + bc}{(2 - y(k))b}.$$  

(8)

Consequently, the manufacturer’s optimal margin is

$$m^* = \frac{a + \theta x(k) - bc}{2(2 - y(k))b}.$$  

(9)
Proof. It follows from Eq.(7) that
\[ \frac{d\Pi_u(w|k)}{dw} = \frac{(1 - y(k))(a + \theta x(k) - bw) - b(w - c)}{2}, \]
\[ \frac{d^2\Pi_u(w|k)}{dw^2} = \frac{-b(2 - y(k))}{2} < 0. \]
That is, \( \Pi_u(w|k) \) is strictly concave in \( w \). Solving the first-order condition for \( w \), yields Eq.(8). Substituting Eq.(8) into Eq.(6), yields Eq.(9).

Theorem 4.2 completely characterizes the equilibrium pricing and margin decisions of the supply chain players under a given investment strategy in the SS model. The optimal retail price of the manufacturer and the corresponding market demand can be derived from \( p = w + m \) and Eq.(2), and are given by
\[ p^* = \frac{(3 - 2y(k))(a + \theta x(k)) + bc}{2(2 - y(k))b}, \]
\[ q^* = \frac{a + \theta x(k) - bc}{2(2 - y(k))}. \]

The following corollary can be obtained directly from Eq.(11).

**Corollary 1.** In the SS model, when the supplier makes an investment in the manufacturer, the market demand increases.

In this paper, the investment not only allows the supplier to share the manufacturer’s profit, but also enables the manufacturer to improve its product quality. That is, the impact of the investment on the market demand, is determined by the supplier’s profit sharing and the improvement in the manufacturer’s product quality. The detailed reason can be explained as follows, and a graphic illustration is given in Figure 2.

![Figure 2. Impact of the supplier’s investment on the demand in the SS model](image)

Firstly, to explore how the quality improvement affects the market demand, the supplier’s profit sharing is assumed to be negligible, i.e., \( y(k) = 0 \). On one hand, one can see from the demand function \( q(p, x(k)) = a + \theta x(k) - bp \) of Eq.(2) that the quality improvement has a direct positive impact on the market demand. On the other hand, one can verify from Eq.(8) and Eq.(9) that \( \frac{dm^*}{dx(k)} = \frac{\theta}{2(2 - y(k))b} > 0 \) and \( \frac{d^2w^*}{dx^2(k)} = \frac{\theta}{2(2 - y(k))^2} > 0 \), implying that when the product quality is improved, each
player chooses a higher markup above the cost, i.e., the supplier chooses a higher wholesale price \( w \) above the production cost \( c \), and the manufacturer chooses a higher retail price \( p \) above the wholesale price \( w \). A higher retail price leads to a lower market demand. That is, the quality improvement has an indirect negative impact on the market demand through the retail price. As a result, in equilibrium, the direct positive impact on the market demand outweighs the indirect negative impact (this can be confirmed by Eq.(11)); and the market demand is positively influenced by the quality improvement in equilibrium. In addition, the above discussion also suggests that when the product quality is improved, the profit margin of each player and the market demand increase. Thus, each player can benefit from the quality improvement.

Secondly, to explore how the supplier’s profit sharing affects the market demand, the improvement in the product quality is assumed to be negligible, i.e., \( x(k) = 0 \). Because the supplier’s profit sharing has no impact on the manufacturer’s best response margin (see, the discussion following Lemma 4.1), but increases the supplier’s marginal revenue (i.e., reduces the supplier’s relative marginal cost), the supplier who is the Stackelberg leader, will charge a lower wholesale price, which results in a lower retail price and thus a higher demand. That is, the market demand is positively influenced by the supplier’s profit sharing in equilibrium. In addition, the supplier can benefit from the profit sharing because he can gain competitive advantage from the relative marginal cost. As for the manufacturer, the benefit from the lower wholesale price caused by the profit sharing, can not outweigh the loss in the benefit that should be allotted to the supplier according to equity shares held by the supplier (this will be confirmed by subsequent analysis of the manufacturer’s profit function \( \Pi^*_d(k) \) of Eq.(12)). That is, the profit sharing harms the manufacturer’s performance.

Finally, because the impact of the supplier’s investment on the market demand is a mix of the above two impacts (i.e., the impact of the quality improvement on the market demand and the impact of the profit sharing on the market demand), the result shown in Corollary 1 follows directly.

Now, for any given investment strategy \( k \), substituting \( w^* \) of Eq.(8), \( m^* \) of Eq.(9) into Eq.(5) and Eq.(7), the profits of the downstream manufacturer, the upstream supplier and the entire supply chain, are obtained:

\[
\Pi^*_d(k) = \frac{(1 - y(k))(a + \theta x(k) - bc)^2}{4b(2 - y(k))^2}.
\]

\[
\Pi^*_u(k) = \frac{(a + \theta x(k) - bc)^2}{4b(2 - y(k))} - k.
\]

\[
\Pi^*_e(k) = \Pi^*_d(k) + \Pi^*_u(k) = \frac{(a + \theta x(k) - bc)^2(3 - 2y(k))}{4b(2 - y(k))^2} - k.
\]

Note from Eq.(12) that \( \Pi^*_d(k) \) increases in \( x(k) \), but decreases in \( y(k) \). This leads to the following corollary.

**Corollary 2.** In the SS model, the supplier’s investment may hurt the manufacturer’s performance.

The impact of the supplier’s investment on the manufacturer’s performance, depends on both the quality improvement and the profit sharing. Recall that in the discussion following Corollary 1, it has shown that the quality improvement benefits
the manufacturer, while the profit sharing causes detriment to the manufacturer’s profit. Then, Corollary 2 follows directly.

The following corollary can be derived from Eq.(13).

**Corollary 3.** In the SS model, the supplier benefits from the quality investment in the manufacturer, i.e., 
\[ \Pi_u^*(k) > \Pi_u^*(0), \]
if and only if
\[ \phi(k) > k, \] (15)

where
\[ \phi(k) = \frac{(a + \theta x(k) - bc)^2}{4b(2 - y(k))} - \frac{(a - bc)^2}{8b}. \]

The corollary above can be applied to evaluate whether the supplier should invest in its manufacturer in the SS model. As a matter of fact, when the supplier invests in the manufacturer, the supplier can benefit not only from the quality improvement, but also from the profit sharing (see the discussion following Corollary 1). Then, the supplier’s investment condition in the SS model can be explained as: The total benefit from the profit sharing and the quality improvement, i.e., \( \phi(k) \), outweighs the investment cost \( k \). This result is helpful to practitioners and managers, and suggests that in the SS model, practitioners and managers need to carefully evaluate the investment cost and the total benefit from the quality improvement and the profit sharing, and then choose their investment strategies.

The value of the supplier’s investment for the entire supply chain in the SS model can be derived from Eq.(14):
\[ \Pi_e^*(k) - \Pi_e^*(0) = \frac{1}{4b} \left[ \frac{(a + \theta x(k) - bc)^2(3 - 2y(k))}{(2 - y(k))^2} - \frac{3(a - bc)^2}{4} \right] - k. \] (16)

One can verify that the investment value \( \Pi_e^*(k) - \Pi_e^*(0) \) increases in both the quality improvement level \( x(k) \) and the percentage of equity shares \( y(k) \). That is, the investment value comes not only from the quality improvement, but also from the equity holding.

### 4.2. Manufacturer Stackelberg (MS) model

This subsection considers the MS model, where the manufacturer acts as the leader and chooses the profit margin \( m \), followed by the supplier’s decision on the wholesale price \( w \). The equilibrium of the game can be found by using backward induction.

Substituting \( p = w + m \) into Eq.(3), the supplier’s profit function can be reexpressed as:
\[ \Pi_u(w, m|k) = (w - c + y(k)m)[a + \theta x(k) - b(w + m)] - k. \] (17)

The following lemma can be obtained from Eq.(17).

**Lemma 4.3.** For any given margin \( m \), the supplier’s profit function \( \Pi_u(w, m|k) \) is strictly concave in its wholesale price \( w \), and the best response wholesale price \( w(m) \) is given by
\[ w(m) = \frac{a + \theta x(k) - bm - bmy(k) + bc}{2b}. \] (18)

**Proof.** The proof is similar to the proof of Lemma 4.1. So it is omitted. \( \square \)

One can verify from Eq.(18) that \( \frac{dw(m)}{dm} = -\frac{1 + y(k)}{2} < 0 \) and \( \frac{dw(m)}{dk} \) decreases as \( y(k) \) increases. This suggests that the supplier’s best response wholesale price \( w(m) \) decreases as the margin \( m \) increases, and the profit sharing enhances the sensitivity of the supplier’s best response wholesale price \( w(m) \) to the manufacturer’s margin \( m \). Second, for any given margin \( m \), supplier’s best response wholesale price \( w(m) \)
decreases as \( y(k) \) increases. This is not surprising, because the profit sharing increases the supplier’s marginal revenue (i.e., reduces the supplier’s relative marginal cost), and the supplier will charge a lower wholesale price to sell its component.

By substituting \( w(m) \) of Eq. (18) and \( p = w + m \) into Eq. (4), the manufacturer’s profit function can be rewritten as

\[
\Pi_d(m|k) = \frac{(1 - y(k))m(a + \theta x(k) - bm + bmy(k) - bc)}{2}.
\]

(19)

This results in the following theorem.

**Theorem 4.4.** In the MS model, the manufacturer’s objective profit function \( \Pi_d(m|k) \) is strictly concave in \( m \), and achieves its maximum at

\[
m^* = \frac{a + \theta x(k) - bc}{2b(1 - y(k))}.
\]

(20)

Accordingly, the supplier’s optimal wholesale price is

\[
w^* = \frac{(a + \theta x(k))(1 - 3y(k)) + bc(3 - y(k))}{4b(1 - y(k))}.
\]

(21)

**Proof.** The proof is similar to the proof of Theorem 4.2. Therefore it is omitted.

Theorem 4.4 characterizes the optimal pricing and margin decisions of the two players in the MS model. Note that \( p = w + m \) and \( q(p, x(k)) = a + \theta x(k) - bp \), which implies that the optimal retail price and the market demand are as follows, respectively:

\[
p^* = \frac{3(a + \theta x(k)) + bc}{4b},
\]

(22)

\[
q^* = \frac{a + \theta x(k) - bc}{4}.
\]

(23)

This leads to the following corollary.

**Corollary 4.** In the MS model, when the supplier invests in the manufacturer, the market demand increases.

Intuitively, when the supplier invests in the manufacturer’s quality improvement with equity holding, the market demand may influenced by both the profit sharing caused by the supplier’s equity holding in the manufacturer and quality improvement in the product. However, Eq. (23) suggests that the profit sharing has no impact on the market demand in equilibrium in the MS model, which can be seen from the independence of \( q^* \) of Eq. (23) on \( y(k) \). Flath [13] shows that in the supply chain with quality insensitive demand, if downstream firms act as Stackelberg leaders, then the profit sharing caused by upstream firms’ equity holding in downstream firms has no impact on the market demand. Eq. (23) states that no impact result still holds in the chain with quality sensitive demand.

To obtain an in-depth understanding of Corollary 4, one can first suppose that \( y(k) = 0 \), to investigate how the quality improvement influences the market demand in the MS model: Similar to the analysis in the SS model (see the discussion following Corollary 1), it is easy to show that the market demand is positively influenced by the quality improvement and each chain member benefits from the quality improvement in the MS model.

Second, one can suppose that \( x(k) = 0 \), to investigate how the supplier’s profit sharing influences the market demand in the MS model: On one hand, for any
given margin \( m \), because the profit sharing increases the supplier’s marginal revenue (i.e., reduces the supplier’s relative marginal cost), the supplier charges a lower wholesale price. A lower wholesale price indicates a lower margin, which has a positive impact on the market demand. On the other hand, anticipating that the profit sharing enhances the sensitivity of the supplier’s best response wholesale price to the margin (see the discussion following Lemma 4.3), the manufacturer who acts as the Stackelberg leader chooses a higher margin, which has a negative impact on the market demand. As a result, the positive impact and the negative impact offset each other in equilibrium, leading to no impact on the market demand (this can be confirmed by Eq.(23)). Meanwhile, in equilibrium, the increase in the margin offsets the manufacturer’s loss in the benefit that should be allotted to the supplier according to the equity shares held by the supplier in the manufacturer. That is, in equilibrium, the supplier’s profit sharing also has no impact on the profit of each chain member (this can be confirmed by Eq.(24) and Eq.(25), which will be given in the subsequent analysis).

Substituting \( m^* \) of Eq.(20), \( w^* \) of Eq.(21) into Eq.(19) and Eq.(17), the profits of the two chain members and the entire supply chain are as follows:

\[
\Pi_d^*(k) = \frac{(a + \theta x(k) - bc)^2}{8b},
\]

\[
\Pi_u^*(k) = \frac{(a + \theta x(k) - bc)^2}{16b} - k,
\]

\[
\Pi_e^*(k) = \frac{3(a + \theta x(k) - bc)^2}{16b} - k.
\]

It is straightforward from Eq.(24) to obtain the following corollary.

**Corollary 5.** In the MS model, the manufacturer can always benefit from the supplier’s investment.

The discussion following Corollary 4 has shown that the quality improvement benefits both the supplier and the manufacturer, while the supplier’s profit sharing has no impact on each player’s performance. Then, Corollary 5 follows directly from the fact that the manufacturer can always benefit from the quality improvement. Furthermore, it is easy to show from Eq.(24) that the benefit caused by the supplier’s investment for the manufacturer is

\[
\Pi_d^*(k) - \Pi_d^*(0) = \frac{(a + \theta x(k) - bc)^2 - (a - bc)^2}{8b}.
\]

The following corollary can be made from Eq.(25).

**Corollary 6.** In the MS model, the supplier benefits from the investment in the manufacturer, i.e., \( \Pi_u^*(k) > \Pi_u^*(0) \), if and only if

\[
\psi(k) > k,
\]

where \( \psi(k) = \frac{(a + \theta x(k) - bc)^2}{16b} - \frac{(a - bc)^2}{16b} \).

The above corollary can be used to evaluate whether the supplier should invest in the manufacturer in the MS model. Note that \( \phi(k) \geq \psi(k) \) for \( k \geq 0 \)\(^3\), implying that

\[
\frac{(a + \theta x(k) - bc)^2}{16b} - \frac{(a - bc)^2}{16b} \geq 0.
\]
the condition under which the supplier makes an investment in the manufacturer in the SS model, is weaker than that in the MS model. That is, the supplier is more likely to make an investment in the manufacturer in the SS model, as compared to the MS model. This is not surprising, because the supplier can benefit from both the quality improvement and the profit sharing in the SS model (see the discussion following Corollary 1), but can only benefit from the quality improvement in the MS model (see the discussion following Corollary 4). The intuition behind this result is that in the MS model, managers should only evaluate the investment cost and the benefit from quality improvement, and then determines whether to invest in their downstream manufacturers.

The value of the supplier’s investment for the entire supply chain in the MS model can be derived from Eq.(26):

$$\Pi^*_e(k) - \Pi^*_e(0) = \frac{3}{16b} [(a + \theta x(k) - bc)^2 - (a - bc)^2] - k. \quad (28)$$

Clearly, the investment value \(\Pi^*_e(k) - \Pi^*_e(0)\) increases as the quality improvement level \(x(k)\) increases, but is independent of the equity holding. That is, the investment value comes only from the quality improvement in the MS model. This is not surprising, since the profit sharing caused by the equity holding has no impact on the profit of each player (see the discussion following Corollary 4).

4.3. Vertical Nash (VN) model. In the NV model, the manufacturer and the supplier move simultaneously, and one player can not observe the other player’s reaction function. The equilibrium pricing and margin strategies \(\{w^*, m^*\}\) can be obtained by solving the two simultaneous equations, i.e., \(m(w)\) of Eq.(6) and \(w(m)\) of Eq.(18). The results are presented as follows:

**Theorem 4.5.** In the NV model, the pricing and margin game has a unique Nash equilibrium. The supplier’s equilibrium wholesale price is

$$w^* = \frac{(1 - y(k))(a + \theta x(k)) + 2bc}{(3 - y(k))b}. \quad (29)$$

The manufacturer’s equilibrium margin is

$$m^* = \frac{a + \theta x(k) - bc}{(3 - y(k))b}. \quad (30)$$

Theorem 4.5 shows that the quality improvement increases both the equilibrium wholesale price \(w^*\) and the equilibrium margin \(m^*\), i.e., \(\frac{dw^*}{dx(k)} > 0\) and \(\frac{dm^*}{dy(k)} > 0\). Accordingly, when the product quality is improved, each player chooses a higher markup above the cost, leading to a higher retail price, and thus a lower demand. That is, the quality improvement has an indirect negative impact on the demand via the retail price. The theorem also shows that the supplier’s profit sharing decreases the equilibrium wholesale price, i.e., \(\frac{dw^*}{dy(k)} < 0\); but increases the equilibrium margin, i.e., \(\frac{dm^*}{dy(k)} > 0\). This result can be illustrated by Figure 3: When the supplier holds equity shares in the manufacturer, on one hand, the manufacturer’s response curve \(m(w)\) of Eq.(6) does not change: On the other hand, the supplier’s response curve \(w(m)\) of Eq.(18) becomes more steep. As a result, the intersection point of the two curves will shift to the lower right, i.e., the equilibrium wholesale price \(w^*\) will decrease, while the equilibrium margin \(m^*\) will increase.
By substituting $w = w^*$ of Eq.(29) $m = m^*$ of Eq.(30) into $p = w + m$ and $q(p, x(k)) = a + \theta x(k) - bp$ of Eq.(2), respectively, one can show that

$$p^* = \frac{(2 - y(k))(a + \theta x(k)) + bc}{(3 - y(k))b}, \quad (31)$$

$$q^* = \frac{a + \theta x(k) - bc}{3 - y(k)}. \quad (32)$$

From Eq.(32), it is easy to find that $q^*$ increases in $x(k)$, i.e., the customer demand increases as the quality improvement level increases in equilibrium. As a matter of fact, the quality improvement has not only a direct positive impact on the demand in the model with quality and price sensitive demand, but also an indirect negative impact on the demand via the retail price. The finding states that in equilibrium, the above positive impact outweighs the above negative impact in the VN model. One can also see from Eq.(32) that $q^*$ increases in $y(k)$, i.e., the customer demand increases as the percentage of equity shares held by the supplier in the manufacturer increases. This is because when the supplier holds equity shares in the manufacturer, the supplier can achieve the profit sharing with the manufacturer, which increases the supplier’s revenue and thus reduces the supplier’s relative marginal cost. The supplier with a lower relative marginal cost will sell the component to the manufacturer at a lower wholesale price. The manufacturer with a lower procurement cost (i.e., a lower wholesale price) will sell the product at a lower retail price, which leads to a higher customer demand.
Moreover, comparing Eq.(36) with Eq.(27), it is easy to show that ϕ from the quality improvement. This is similar to the result obtained in the SS model.

Comparing Eq.(36) with Eq.(15), yields the supplier is more likely to invest in the manufacturer in the NV model than in the SS model. Additionally, the following discussion shows that it is uncertain whether the supplier is more likely to invest in the manufacturer in the NV model than in the MS model. Hence, the dependence of Π∗ on k, ≥ 0.

In the NV model, the supplier's investment may cause detriment to the manufacturer.

The following result can be derived from Eq.(33).

Although the manufacturer can always benefit from the quality improvement (this can be seen from the dependence of Π∗ on y(k)), the profit sharing harms the manufacturer's performance (this can be seen from the the dependence of Π∗ on y(k)). Consequently, the manufacturer benefits from the supplier's investment if and only if the benefit caused by the quality improvement outweighs the harm caused by the profit sharing.

From Eq.(34), the following corollary can be obtained.

In the NV model, the supplier benefits from its investment, i.e., Π∗(k) > Π∗(0), if and only if Corollary 8. In the NV model, the supplier's investment may cause detriment to the manufacturer.

where ϕ(k) = (a + θx(k) − bc)2 − (a − bc)2.

The above corollary can be applied by the supplier to evaluate whether it should invest in the manufacturer in the NV model. The dependences of ϕ(k) on x(k) and y(k) indicate that the supplier can benefit not only from the profit sharing, but also from the quality improvement. This is similar to the result obtained in the SS model. Moreover, comparing Eq.(36) with Eq.(27), it is easy to show that ϕ(k) ≥ ψ(k) for k ≥ 0, which implies that the condition under which the supplier invests in the manufacturer in the NV model, is weaker than that in the MS model. Hence, the supplier is more likely to invest in the manufacturer in the NV model than in the MS model. Additionally, the following discussion shows that it is uncertain whether the supplier is more likely to invest in the NV model than in the SS model: Comparing Eq.(36) with Eq.(15), yields

φ(k) − ϕ(k) = (a + θx(k) − bc)2 − (a − bc)2.

One can verify ϕ(k) − ψ(k) = (a + θx(k) − bc)2 [1/(3 − y(k))^2 − 1/3] − (a − bc)2 (1/3 − 1/3) ≥ 0.
If \( y(k) = 0 \), then \( \phi(k) - \varphi(k) > 0 \), indicating that the investment condition in the SS model is weaker than that in the VN model, and the supplier is more likely to invest in the SS model than in the VN model; If \( x(k) = 0 \) and \( y(k) = 0.45 \), then \( \phi(k) - \varphi(k) = -0.006(a - bc)^2 < 0 \), implying that the investment condition in the SS model is stronger than that in the VN model, and the supplier is more likely to invest in the VN model than in the SS model. Additionally, the market power of a firm usually varies in different stages of its life cycle, and the power structure between the supplier and the manufacturer is not stable. Thus, managers need to review and adjust their investment strategies in different stages of corporate life cycle.

The value of the supplier’s investment in the VN model can be derived from Eq.(35):

\[
\Pi^e_u(k) - \Pi^e_u(0) = \frac{1}{b} \left( \frac{(2 - y(k))(a + \theta x(k) - bc)^2}{(3 - y(k))^2} - \frac{2(a - bc)^2}{9} \right) - k. \tag{37}
\]

It is straightforward to see from Eq.(37) that \( \Pi^e_u(k) - \Pi^e_u(0) \) increases in both \( x(k) \) and \( y(k) \). Consequently, the supplier’s investment value in the VN model comes from not only the quality improvement but also the equity holding.

5. Supplier’s investment strategy. The previous section assumes that the investment strategy of the supplier is given and, focuses on the pricing and margin decisions of the two chain members. This section investigates the problem of the supplier’s investment. Recall that it is assumed that quality improvement level \( x(k) \), and the percentage of equity shares held by the supplier in the manufacturer \( y(k) \), both increase in the investment \( k \). More specifically, assume that \( x(k) \) is linearly dependent on \( k \) (see, e.g., [39]), and takes the form of

\[ x(k) = \delta k, \tag{38} \]

where \( \delta \) denotes the efficiency in terms of improving the product quality by the supplier’s investment \( k \). In addition, suppose that \( y(k) \) is a linear function of \( k \), and takes the form of

\[ y(k) = \frac{k}{\tau}, \tag{39} \]

where \( \tau \) denotes the marginal cost of equity holding by the supplier in the manufacturer. The actual value of \( \tau \) can be determined by the bargaining powers of the supplier and the manufacturer. Because \( 0 \leq y(k) \leq \bar{y} \), Eq.(39) indicates \( 0 \leq k \leq \tau \bar{y} \).

**Theorem 5.1.** In each of the three models, the supplier’s profit function \( \Pi^*_u(k) \) is strictly convex in \( k \) and thus reaches its maximum at \( k = \bar{y} \tau \) or \( k = 0 \). That is, the optimal investment in the manufacturer is either the maximum or null.

**Proof.** By substituting \( x(k) = \delta k \) of Eq.(38), \( y(k) = \frac{k}{\tau} \) of Eq.(39) into Eq.(13), Eq.(25) and Eq.(34), the profit functions of the supplier in the SS, MS and VN models can be expressed as follows:

\[
\Pi^*_I_u(k) = \frac{(a + \theta \delta k - bc)^2}{4b(2 - \frac{k}{\tau})} - k,
\]

\[
\Pi^*_II_u(k) = \frac{(a + \theta \delta k - bc)^2}{16b} - k,
\]
is relatively low, then the optimal investment strategy for the supplier is \( k^* = \bar{\tau} \).

(ii) In the MS model: When \( \delta < \delta_{II} \), the optimal investment strategy for the supplier is \( k^* = 0 \); When \( \delta > \delta_{II} \), the optimal investment strategy for the supplier is \( k^* = \bar{\tau} \).

(iii) In the VN model: When \( \delta < \delta_{III} \), the optimal investment strategy for the supplier is \( k^* = 0 \); When \( \delta > \delta_{III} \), the optimal investment strategy for the supplier is \( k^* = \bar{\tau} \).

Proof. Because \( \Pi^*_I(k) \) is strictly convex in \( k \), \( \Pi^*_I(k) \leq \max\{ \Pi^*_I(0), \Pi^*_I(\bar{\tau}) \} \). Therefore, if \( \Pi^*_I(0) < \Pi^*_I(\bar{\tau}) \), then the supplier’s optimal investment strategy is \( \bar{\tau} \); if \( \Pi^*_I(0) > \Pi^*_I(\bar{\tau}) \), then the supplier’s optimal investment strategy is 0. The optimal investment strategies as given in Corollary 10 are thus obtained.

Corollary 10 shows that, when \( \tau \) is fixed, if the quality improvement efficiency \( \delta \) is relatively low, then the optimal investment strategy for the supplier is \( k^* = 0 \), implying that the supplier does not make any investment in the manufacturer. If the quality improvement efficiency \( \delta \) is relatively high, then the optimal investment strategy for the supplier is \( k^* = \bar{\tau} \), indicating that the supplier makes a maximum investment in the manufacturer. On the other hand, when \( \delta \) is fixed, the parameter
\( \tau \) is crucial in determining the optimal investment strategy. Corollary 10 provides a threshold to compute the degree of the quality improvement efficiency \( \delta \) for the supplier to decide its optimal investment strategy.

6. **Concluding remarks.** In practice, it is quite common that upstream suppliers invest in downstream manufacturers with equity participation to help them to carry out quality-related activities. For example, Samsung Electronics invests $450 million and acquires 1.92% equity shares in its downstream manufacturer BYD; Qualcomm invests millions of dollars and gets an undisclosed amount of equity shares in its downstream manufacturer Xiaomi\[38, 42\]. In these examples, the invested resources are used by downstream manufacturers to design and develop their products\[38, 42\].

This study considered a supply chain with one supplier and one manufacturer. The supplier may make an investment in the manufacturer. The investment not only allows the supplier to hold equity shares in the manufacturer, but also enables the manufacturer to improve its product quality. Under any given investment strategy of the supplier, the equilibrium pricing and margin decisions in the supplier Stackelberg (SS), manufacturer Stackelberg (MS) and vertical Nash (VN) models were obtained. Moreover, the optimal investment strategy for the supplier was derived. The study found that when the supplier invests in the manufacturer’s quality improvement with equity holding:

1. The production quantity increases in each of the three models.
2. The supplier’s profit increases in both the quality improvement level and equity shares held in the manufacturer in the SS and VN models. However, the supplier’s profit increases in the quality improvement level, but is independent of the equity shares in the MS model.
3. The manufacturer’s profit increases in the quality improvement level, but decreases in the equity shares in the SS and VN models. However, the manufacturer’s profit increases in the quality improvement level, but is independent of the equity shares in the MS model.
4. The source of the investment value for the supply chain comes not only from the quality improvement, but also from the equity holding in the SS and VN models. However, the source of the investment value for the chain comes only from the quality improvement in the MS model.
5. The optimal investment strategy for the supplier follows a “bang-bang” policy in each of the three models, in the sense that the supplier makes either a “zero-investment” or a “maximum-investment” in the manufacturer in each model.

This study is limited in several respects. First, this study assumed that supply chain players are risk neutral and make decisions to maximize their own profits. Future research can extend this study by considering risk-averse players\[44\]. Second, this study assumed that the supply chain consists of one supplier and one manufacturer. It is interesting to extend the model to the case of multiple suppliers and multiple manufacturers. Finally, this study supposed that the yield is perfect and the demand is deterministic. It is also worthwhile to examine the impacts of yield uncertainty and demand uncertainty on supply chain operations.

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SUPPLIER’S EQUITY INVESTMENT IN MANUFACTURER’S QUALITY IMPROVEMENT

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