Supplier’s cooperation strategy with two competing manufacturers under wholesale price discount contract considering technology investment

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Abstract
Cooperation between upstream suppliers and downstream manufacturers in technology investment is a popular way to improve production technology for reducing suppliers’ production costs of key components. The suppliers’ cooperation strategies are mainly influenced by manufacturers’ technology investments and wholesale price discount contracts provided by suppliers. This paper explores whether a supplier should cooperate with two downstream competing manufacturers to accept their technology investments to reduce the supplier’s production cost of a key component. Specifically, we consider the following three cooperation strategies: The supplier does not accept manufacturers’ technology investments, only accepts one manufacturer’s technology investment and accepts both manufacturers’ technology investments. Our results demonstrate that the wholesale price discount contract and the technology investment can enhance the profits of the supplier and two manufacturers when the discount degree is low. Further, we conclude that when the discount degree is relatively low or when both the discount degree and the technology investment efficiency are relatively high, the supplier’s optimal cooperation strategy with two manufacturers is to accept both manufacturers’ technology investments and both manufacturers are also willing to invest simultaneously. At last, we extend the model to the asymmetric potential market size and show that our theoretical results are robust.

Keywords Supply chain management · Technology investment · Game theory · Wholesale price discount contract

1 Introduction
Suppliers’ cooperation with downstream manufacturers in technology investments is becoming an effective way to improve the performance of the supply chain (Qi et al. 2015; Jin et al. 2019; Liu and Wang 2019; Li et al. 2021; Zhang et al. 2021). In the semiconductor industry, when downstream manufacturers launch new products which need a large number of key components, suppliers need to absorb significant technology investments to improve production technology and expand production capacities of key components. Meantime, some downstream manufacturers are also willing to invest in their suppliers in order to obtain a stable supply of key components and preferential prices. According to demands for technology investments, suppliers sometimes accept only one downstream manufacturer’s technology investment. For example, in May 2017, Corning, a glass supplier, accepts $200 million from a downstream-manufacturer-Apple to improve its production technology to produce the front and rear glass panels of Apple’s iPhone series, meantime Apple obtains adequate supplies and preferential prices of glass panels. However, suppliers sometimes need to accept multiple down-
stream manufacturers’ technology investments. For example, Sharp, a LCD panels supplier, accepts not only downstream-manufacturer-Foxconn’s $1.6 billion investment including a 46.5% stake for developing LCD to enhance its capacity, but also downstream-manufacturer-Samsung’s $110 million after Foxconn’s investment. Both downstream manufacturers Foxconn and Samsung gain steady supplies and low prices of LCD panels (Dignan 2012). However, the more manufacturers’ technology investments the suppliers accept, the lower prices the manufacturers obtain, which may not be beneficial to the suppliers. Therefore, it is worthy to investigate the suppliers’ cooperation strategy with downstream manufacturers.

For reducing the production cost of key components, suppliers often accept downstream manufacturers’ investments to improve production technology (Porter 1998; Gilbert et al. 2006; Ge et al. 2014). For example, Toshiba accepts large investments from downstream-manufacturer-Apple to improve nano-manufacturing process for reducing chips’ production costs. However, technology investments in the suppliers’ production cost reduction of key components do not always benefit the suppliers. Because the suppliers’ profits are also related to the technology investment efficiency. When manufacturers’ technology investment efficiency is low, the suppliers’ production cost reduction of the key components becomes inefficient. Similarly, manufacturers’ profits are also affected by the technology investment efficiency. When the technology investment efficiency is low, the technology investment costs undertaken by these manufacturers are high, and vice versa. Therefore, in this study we explore the impact of technology investment efficiency on the profits of supply chain members.

To encourage downstream manufacturers to make technology investments, suppliers usually offer manufacturers a wholesale price discount contract (Zhou 2007; Cai et al. 2009; Yan et al. 2017). For example, LG who is a screen supplier, accepts around downstream-manufacturer-Apple’s $1.75–2.62 billion investments for expanding the capacity of displays and provides a wholesale price discount contract to Apple in return for the investment (Seitz 2017). Some investing manufacturers obtain wholesale prices discount contract, which makes them to be at a competitive advantage in the wholesale price compared to these non-investing manufacturers, but these technology investments also increase their costs. Other non-investing manufacturers may free-ride the investing manufacturers to obtain a low wholesale price. Although non-investing manufacturers are at a competitive disadvantage comparing with these investing manufacturers, the advantages of free-rider and without additional technology investment costs possibly benefit these non-investing manufacturers. Therefore, whether the downstream manufacturers should invest to their suppliers for a wholesale price discount contract is worth exploring.

Based on these considerations, we explore suppliers’ cooperation strategies in which suppliers who provide wholesale price discount contracts decide whether to cooperate with downstream manufacturers in technology investments for reducing the production costs of key components. More specifically, we try to answer the following questions: (1) How the discount degree and the technology investment efficiency affect the profits of the supply chain members? (2) Whether the wholesale price discount contract and technology investment in production cost reduction can enhance the profits of supply chain members? (3) What is the suppliers’ optimal cooperation strategies with downstream manufacturers?

To answer these questions, we consider a supply chain consisting of a supplier who produces a key component and two competing manufacturers who use key components to produce replaceable products for consumers. For reducing the production cost of the key component, the supplier considers whether to cooperate with two competing manufacturers to accept their technology investments. If the supplier decides to accept a manufacturer’s technology investment, the manufacturer would be provided with a wholesale price discount contract. Otherwise, the manufacturer will be provided with a regular wholesale price contract. Based on these considerations, we propose three cases to discuss the supplier’s cooperation strategies: (1) The supplier does not accept manufacturers’ technology investments. (2) The supplier only accepts one manufacturer’s technology investment. (3) The supplier accepts both manufacturers’ technology investments. After obtaining the equilibrium decisions, we get some interesting results on the supplier’s cooperation strategies.

First, we find that when the supplier accepts both manufacturers’ technology investments, with the increase of the discount degree the supplier’s profit always increases and the two manufacturers’ profits increase firstly and then decrease. When the supplier accepts only one manufacturer’s technology investment, with the increase of the discount degree, the supplier’s profit increases firstly and then decreases while the investing manufacturer’s profit firstly increases and then decreases and the non-investing manufacturer’s profit always decreases. When the supplier accepts only one manufacturer’s investment or both manufacturers’ investments, the profits of the supplier and the two manufacturers always increase with the technology investment efficiency.

Second, we conclude that the wholesale price discount contract and technology investment in production cost reduction can enhance the profits of the supplier and the two manufacturers when the discount degree is relatively low, but when the discount degree is relatively high the whole-

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2 https://www.163.com/money/article/CI7IP2KJ002580S6.html.
sale price discount contract and technology investment do not always benefit the supply chain members.

Third, when the discount degree is relatively low or when both the discount degree and the technology investment efficiency are relatively high, the supplier prefers to accept both manufacturers’ technology investments and both manufacturers are also willing to make technology investments in production cost reduction simultaneously, which leads to “win-win-win” outcomes. If the discount degree is relatively high and the technology investment efficiency is relatively low, the supplier prefers to accept both manufacturers’ technology investments, the investing manufacturer prefers to invest alone while the non-investing manufacturer prefers to invest together with the other manufacturer, which can not lead to a equilibrium outcome.

Our research contributes to the literature in two aspects. First, this study combines technology investments in production cost reduction from upstream manufacturers and the wholesale price discount contract offered by upstream supplier into the supply chain models, and explores whether the supplier should cooperate with two competing manufacturers to accept their technology investments, which will contribute to the supply chain management. Second, this paper constructs a wholesale price discount contract based on the production cost reduction level. The higher the production cost reduction level, the lower the discount wholesale price the manufacturer obtains. This will contribute to the field of discount contract research.

The rest of the paper is organized as follows. Section 2 briefly reviews the related research works. Section 3 sets up a model with a supplier and two competing manufacturers. Section 4 analyzes the optimal decisions of the supplier and two manufacturers in three cases and discusses the effects of the discount degree and the technology investment efficiency on them. Section 5 compares the supply chain members’ optimal profits and discusses their preferences. Section 6 extends the basic model to the asymmetric potential market size and discusses our results’ robustness. Section 7 concludes the study and gives some suggestions for future research.

2 Literature review

Our research contributes to two streams of the literature. The first stream of the research explores the technology investment in the supply chain and the second stream of our work studies discount contracts. Next, we explore how our paper is related to the following works.

The first stream of the research is closely related to the technology investment in improving the supplier performance, including reducing supplier’s production cost (Gilbert et al. 2006; Ge et al. 2014; Ha et al. 2017; Sun et al. 2019), improving product’s reliability (Wang et al. 2014; Dong et al. 2021), expanding the production capacity (Qi et al. 2015) and improving product’s quality (Agrawal et al. 2016; Zhang et al. 2020). More specifically, Gilbert et al. (2006) examine the strategy of the production or outsourcing for two competing manufacturers who invest to reduce the production cost, and explore the effect of outsourcing strategy on dampening the cost-based competition between two manufacturers. Ge et al. (2014) explore two firms’ cooperation strategies in research and development by investing to reduce their production costs, and analyze the effects of cartelization and spillover on their profits. Ha et al. (2017) explore the effect of production cost reduction on the demand information sharing in two competing supply chain, the result shows that if the manufacturer can effectively invest to reduce production cost, it is beneficial to the supply chain. Sun et al. (2019) consider the effect of the interactive between manufacturer’s production cost reduction investment and information asymmetry on manufacturer encroachment in a supply chain consisting of a manufacturer and a retailer. Wang et al. (2014) explore the effect of spillover on two manufacturers’ investments in improving their shared supplier’s product reliability and profits, and show that the spillover can improve the two manufacturers’ profits. Dong et al. (2021) investigate the strategic sourcing choice of manufacturer considering the reliability investment and show that if the reliability investment cost is high, the manufacturer prefers dual sourcing strategy. Qi et al. (2015) investigate a supply chain with two competing firms’ investment in the production capacity to their shared supplier and further analyze the effects of the different contractual forms on the investment decisions. Agrawal et al. (2016) study the optimal strategy of two competing firms investing to their shared supplier for improving product quality and analyze effects of learning, spillover and competition on the investment decisions. Zhang et al. (2020) explore the influence of the interaction between firms’ quality investments and green investments on the green investment decision of two level differentiated firms. Our paper differs from the abovementioned researches in two aspects. First, the literature abovementioned studies whether manufacturers invest to the upstream suppliers or to themselves, while we mainly study whether the shared supplier is willing to accept investments from two downstream competing manufacturers. Second, the returns for investments in the abovementioned researches are the low production cost, the high product reliability, adequate production capacity and high product quality. In our paper, the return for investments of two manufacturers is to obtain a discount wholesale price for enhancing their market competitiveness and the return for the supplier is to obtain a low production cost of the key component.

The second stream of our research is also related to discount contracts in supply chain management. Researches on discount contracts are mainly divided into two parts:
quantity discount contract (Shin and Benton 2007; Zhou 2007; Chen and Roma 2011; Yan et al. 2017; Roshanak and Joseph 2018; Huang et al. 2021) and price discount contract (Bernstein and Federgruen 2005; Cai et al. 2009; Li et al. 2016, 2020). Shin and Benton (2007) study a quantity discount contract under uncertain demand conditions. The result shows that the proposed quantity discount contract can improve the performance of the supply chain. Further, Zhou (2007) proposes four quantity discount contracts in a supply chain with the stochastic and asymmetric demand information and analyzes the efficiency of the four quantity discount contracts. Chen and Roma (2011) explore a manufacturer provides a quantity discount contract to two competing retailers under group buying. Furthermore, Yan et al. (2017) extend the literature to study two asymmetric retailers with different moving sequences under a quantity discount contract. The second part mainly focuses on the price discount contract. Huang et al. (2021) propose a quantity discount contract to coordinate the supply chain with deteriorating inventory and show that it can efficiently decide a long-term ordering policy. Bernstein and Federgruen (2005) explore the coordination of a supply chain with competing retailers by a linear price discount contract. Cai et al. (2009) introduce a price discount contract to improve the performance of the dual channel supply chain and show that the model with price discount contract can outperform the non-contract model. Li et al. (2020) investigate a platforms discount pricing strategies with strategic consumers in a two-period supply chain model. The results demonstrate that the large online coupon discount will reduce the total demand under the instant strategy. The discount contracts in the above-mentioned literature are a linear function on the order quantity. By contrast, the wholesale price discount contract in our paper is a linear function on the production cost reduction level and the discount wholesale price offered to the manufacturer decreases with the production cost reduction level.

3 Model setting

We consider a supply chain consisting of a single supplier (denoted by $S$) who produces a key component and two competing manufacturers (denoted by $M_i$, $i = 1, 2$) who use the key component to produce replaceable products for consumers. In order to reduce the production cost of the key component, the supplier usually cooperates with manufacturers to accept their technology investments. However, the supplier will provide the investing manufacturer with a wholesale price discount contract in return for the technology investment. Therefore, we explore whether a supplier should cooperate with two downstream competing manufacturers to accept their technology investments to reduce the supplier’s production cost of the key component. Specifically, we study three supplier’s cooperation strategies, which are the supplier does not accept manufacturers’ investments, only accepts one manufacturer’s investment and accepts both manufacturers’ investments. For the convenience of calculation, we assume that the production cost of each product produced by manufacturers equals the wholesale price of the key component.

The demand functions of product $i$ are denoted by

$$D_i = a_i - p_i + b p_j, \quad i = 1, 2, \quad j = 3 - i,$$

in which $a_i$ is the potential market size, $p_i$ is the retail price for product $i$, $b$ is the cross-price sensitivity coefficient. We assume $0 < b < 1$ (Choi 1996; Ma et al. 2012; Li et al. 2017). The demand function is a linear function with respect to the retail price, which decreases with the self retail price and increases with the rival’s retail price. Similar types of demand functions are also adopted in the literature (Mcguire and Staelin 2008; Shavandi et al. 2015; Wang et al. 2017; Li et al. 2020; Liang et al. 2021). For computational convenience, we firstly focus on the simplest case and assume the potential market sizes of the two manufacturers’ products are symmetric, that is $a_1 = a_2 = a$. This form of assumption is in line with practices and also used in the literature (Gilbert et al. 2006; Xu et al. 2020). In the section of extension, we relax this assumption to the asymmetric potential market size. We also require that $a > (1 - b)c$, where $c$ is the production cost of the key component, which guarantees that the market demand and decision variables are non-negative.

Supplier utilizes the technology investments from downstream manufacturers to improve the production technology for reducing the production cost of the key component. More specifically, if the supplier accepts $M_i$’s technology investment, its production cost is reduced from $c$ to $c - t_i > 0$, ($i = 1, 2$), where $t_i > 0$ is the production cost reduction level; if the supplier accepts technology investments of $M_1$ and $M_2$, the supplier’s production cost is reduced to $c - t_1 - t_2 > 0$. This type of cost reduction function has been commonly used in the literature (Kamien et al. 1992; Amir et al. 2003; Gilbert et al. 2006; Ge et al. 2014; Zhou et al. 2020). We assume that the total technology investment cost invested by $i$ is quadratic in production cost reduction level $t_i$, that is $\frac{1}{2} \mu t_i^2$, in which $\mu > 0$ is technology investment cost coefficient and represents the technology investment efficiency in production cost reduction. This form of technology investment cost is in line with practices and commonly used in the literature (Gilbert et al. 2006; Ge et al. 2014; Jin et al. 2019). A higher $\mu$ implies a lower technology investment efficiency because of a higher technology investment cost for the same production cost reduction level. We assume that the technology investment cost coefficients of two manufacturers are the same, this
is because the key component invested by two downstream manufacturers is the same.

To encourage manufacturers to make technology investments, the supplier would provide a wholesale price discount contract to the investing manufacturer and a regular wholesale price contract to the non-investing manufacturer. More specifically, if the supplier accepts manufacturer $i$’s technology investment, the manufacturer $i$ would obtain a discount wholesale price, i.e., $w - \alpha_i > 0$, ($i = 1, 2$), $\alpha > 0$ represents the discount degree which reflects how quickly the discount wholesale price decreases with the production cost reduction level. Otherwise, the non-investing manufacturer will get a regular wholesale price $w$. Such discount contract is also used by previous works (Dolan 1987; Zhou 2007; Yan et al. 2017). In addition, we assume that $\alpha$ is exogenous. In order to ensure the uniqueness of optimal solutions, we require $\mu > \frac{\alpha}{\beta}$, that is $\alpha < \sqrt{2\mu}$, which implies that the upper bound of the discount degree is inversely proportional to the technology investment efficiency. In other words, when the technology investment efficiency of the key component is low the exogenous discount degree offered by the supplier is high to attract more technology investments, which is consistent with the reality.

According to whether to accept two competing manufacturers’ technology investments, we will study three cases in this paper. (i) The supplier does not accept two manufacturers’ technology investments (denoted by NN). (ii) The supplier accepts only one manufacturer’s technology investment (denoted by TN or NT). (iii) The supplier accepts both manufacturers’ technology investments (denoted by TT). Besides, the two manufacturers in cases TN and NT are symmetrical, which means that only three cases need to be considered in this paper. Table 1 shows the notations and explanations utilized throughout the paper.

The sequence of event in our model is as follows. First, the supplier decides whether to accept manufacturers’ technology investments. Second, the supplier determines the regular wholesale price of the key component. Third, after observing the wholesale price, the two downstream manufacturers play a simultaneous game. The investing manufacturer decides the production cost reduction level and the retail price of the product, while the non-investing manufacturer only decides the retail price. Finally, the retail price is realized, as are the profits of the supplier and two manufacturers. The production cost reduction level is determined by the investing manufacturer because the technology investment cost invested by the manufacturer is proportional to the production cost reduction level, which means that the more investments the manufacturer invests, the higher the production cost reduction level the supplier achieves, which leads to a low discount wholesale price.

### Table 1 List of notations and explanations

| Notations | Explanations |
|-----------|--------------|
| $i$       | Index of manufactures ($i = 1, 2$) |
| $a_i$     | The potential market size of the product produced by manufacturer $i$ |
| $p_i$     | The retail price of the product produced by manufacturer $i$ |
| $t_i$     | The production cost reduction level |
| $D_i$     | The demand of the product produced by manufacturer $i$ |
| $\mu$     | The technology investment cost coefficient |
| $\alpha$  | The discount degree |
| $w$       | The wholesale price of the product |
| $c$       | The technology investment coefficient |
| $\pi_{\text{NN}}^S$ ($\pi_{\text{NN}}^T$) | The profit of manufacturer $i$ (supplier) in case NN |
| $\pi_{\text{TN}}^T$ ($\pi_{\text{TN}}^S$) | The profit of manufacturer $i$ (supplier) in case TN |
| $\pi_{\text{TT}}^T$ ($\pi_{\text{TT}}^S$) | The profit of manufacturer $i$ (supplier) in case TT |

4 Analysis with respect to three cases

In this section, we derive the optimal decision variables and profits of the supplier and two manufacturers by backward induction in cases NN, TN and TT. Moreover, we discuss effects of the discount degree and the technology investment cost coefficient on the optimal decision variables and profits.

#### 4.1 Case NN

In case NN, we discuss the situation as a benchmark in which the supplier does not accept manufacturers’ technology investments, which implies that the two manufacturers purchase the key component at a regular wholesale price $w$ from the supplier.

We use the backward induction to derive the equilibrium outcomes. The profit functions of $M_i$ ($i = 1, 2$) as the Stackelberg followers are written as follows

$$\pi_{M_i}^\text{NN}(p_i) = (p_i - w)D_i, \quad i = 1, 2. \quad (2)$$

By maximizing the manufacturers’ profits, we obtain the optimal retail prices

$$p_i^\text{NN}(w) = \frac{a + w}{2 - b}, \quad i = 1, 2. \quad (3)$$

The profit function of the supplier who is the Stackelberg leader can be expressed as

$$\pi_S^\text{NN}(w) = (w - c)(D_1 + D_2). \quad (4)$$
By substituting Eq. (3) in Eq. (4) and maximizing the supplier’s profit function, we obtain the manufacturers’ and the supplier’s optimal decision variables and corresponding optimal profits, listed in Lemma 1.

Lemma 1 In case NN, the manufacturers’ and the supplier’s optimal decision variables and profits are as follows.

1. The optimal retail prices of two manufacturers and the optimal wholesale price of the supplier are

   \[ p_i^{\text{NN}} = \frac{(3a + c) - (2a + c)b}{2(1 - b)(2 - b)}, \quad i = 1, 2, \]  

   \[ w^{\text{NN}} = \frac{a - bc + c}{2(1 - b)}. \]  

2. The optimal profits of two manufacturers and the supplier are

   \[ \pi_{M_i}^{\text{NN}} = \frac{(a + bc - c)^2}{4(2b - c)^2}, \quad i = 1, 2, \]  

   \[ \pi_{S}^{\text{NN}} = \frac{(a + bc - c)^2}{2(1 - b)(2 - b)}. \]  

Lemma 1 illustrates the manufacturers’ and the supplier’s optimal decisions and profits in case NN and the proof of Lemma 1 is in Appendix.

4.2 Case TN

In case TN, the supplier accepts only one manufacturer’s technology investment. In this situation, the manufacturer with technology investment (denoted by \( M_1 \)) is provided with a discount wholesale price \( w - \alpha t_1 \), while the other manufacturer without technology investment (denoted by \( M_2 \)) is provided with a regular wholesale price \( w \). We utilize the backward induction to solve the model and firstly discuss the two manufacturers’ optimization problems.

The profit functions of \( M_1 \) and \( M_2 \) are as follows

\[ \pi_{M_1}^{\text{TN}}(p_1) = [p_1 - (w - \alpha t_1)]D_1 - \frac{1}{2} \mu t_1^2 \]  

and

\[ \pi_{M_2}^{\text{TN}}(p_2) = (p_2 - w)D_2. \]  

As the Stackelberg followers, \( M_1 \) and \( M_2 \) simultaneously decide their retail price \( p_1 \) and \( p_2 \) and production cost reduction level \( t_1 \) by maximizing their profits, which yields the optimal retail prices and optimal production cost reduction level

\[ p_1^{\text{TN}}(w) = \frac{-(b + 2)(a + w)\mu + (a + w)b + 2a}{(2b^2 - 4b + 4)\mu}, \]  

\[ p_2^{\text{TN}}(w) = \frac{-(b + 2)(a + w)\mu + (ab + a + w)\mu}{(2b^2 - 4b + 4)\mu}, \]  

and

\[ t_1^{\text{TN}}(w) = \frac{\alpha(b + 2)[(1 - b)w - a]}{(2b^2 - 4b + 4)\mu}. \]  

As the Stackelberg leader, the supplier determines the wholesale price with the purpose of optimizing the profit function

\[ \pi_{S}^{\text{TN}}(w) = [(w - \alpha t_1) - (c - t_1)]D_1 + [w - (c - t_1)]D_2. \]  

By substituting Eqs. (11) (12) and (13) in Eq. (14) and maximizing the supplier’s profit function, we derive the manufacturers’ and the supplier’s optimal decision variables and corresponding profits, as Lemma 2.

Lemma 2 In case TN, the manufacturers’ and the supplier’s optimal decision variables and profits are as follows.

1. The optimal retail prices of two manufacturers and the optimal production cost reduction level of manufacturer 1 are

\[ p_1^{\text{TN}} = \frac{(b + 1)\left[2b^2 + b - 4\right]a + bc(1 - b)\mu^2 + (b + 2)\left[4b^2 - b - 7 + (3b + 1)(b - 1)c\right]\mu^2 + A_1 + A_2}{2(1 - b)(B_1 + B_2)}, \]  

\[ p_2^{\text{TN}} = \frac{(b + 1)\left[2b^2 - 3\right]a + (b - 1)c\mu^2 + (b + 2)\left[4b^2 - 3b - 5\right]a + (b - 1)(b + 3)c\mu^2 + A_1 + A_2}{2(1 - b)(B_1 + B_2)}. \]  

\[ t_1^{\text{TN}} = \frac{(b + 2)[-(b + 1)\alpha^2 + 2\mu(b + 2)](a + bc - c)\alpha}{-2(B_1 + B_2)}. \]  

The optimal retail prices of two manufacturers and the optimal production cost reduction level of manufacturer 1 are
the optimal wholesale price of the supplier is

\[
w^{TN} = \frac{(b+1)(2-b^2)(a-bc+c)\alpha^4 + \left[-3b^3+4b^2+5b-6\right]c + a\left(b^2-3b-2\right)}{2(b-1)(B_1+B_2)}.
\]  

(2) The optimal profits of two manufacturers and the supplier are

\[
\pi^{TN}_{M_1} = \frac{(b+2)^2(a+bc-c)^2\left[\mu(b+2)-1/2\alpha^2(b+1)\right]^2\left(\mu-1/2\alpha^2\right)}{(B_1+B_2)^2},
\]

\[
\pi^{TN}_{M_2} = \frac{(a+bc-c)^2\left[-b/2-1/2\alpha^2+\mu(b+2)\right]^2\left[-b-1\alpha^2+\mu(b+2)\right]^2}{(B_1+B_2)^2}
\]

and

\[
\pi^{TN}_S = \frac{-a^2b-\alpha^2+2b\mu+4\mu(a+bc-c)^2}{4(b-1)(B_1+B_2)}.
\]  

(1) The wholesale price \(w^{TN}\) and the retail price \(p^{TN}_1\) firstly decrease and then increase with \(\alpha\). The production cost reduction level \(T^{TN}_1\) firstly increases and then decreases with \(\alpha\).

(2) The manufacturer \(i\)'s profit \(\pi^{TN}_{M_i}\) firstly increases and then decreases when \(\alpha\). The supplier's profit \(\pi^{TN}_S\) firstly increases and then decreases with \(\alpha\).

Figure 1 shows that along with the increased \(\alpha\), the wholesale price first decreases and then increases. This is very intuitive since when the discount degree is low, the supplier reduces the wholesale price for encouraging the manufacturers ordering more quantities. When the discount degree is high, the supplier enhances the wholesale price for achieving a positive profit. From Fig. 2a, we find that the production cost reduction level first increases and then decreases with \(\alpha\). The reason may be that when the discount degree is relatively low, manufacturer 1 increases production cost reduction level

![Fig. 1](image_url)
in order to obtain a lower discount wholesale price. When the discount degree is relatively high, manufacturer 1 decreases production cost reduction level to reduce technology investment cost. Figure 2b shows the retail price first decreases and then increases with $\alpha$. This is because when the discount degree is relatively low, a higher discount degree implies a lower wholesale price, which makes manufacturers to reduce their retail prices. When the discount degree is relatively high, a higher discount degree implies a higher wholesale price, which forces manufacturers to increase their retail prices.

From Fig. 3a, we find that the manufacturer $i$’s profit first increases and then decreases with $\alpha$. The reason may be that when the discount degree is relatively low, a higher discount degree implies a lower retail price and a higher market demand, which enhances the manufacturer $i$’s profit. However, when the discount degree is relatively high, a higher retail price leads to a higher retail price and a lower market demand, which reduces the manufacturer $i$’s profit. Figure 3b shows that the supplier’s profit first increases and then decreases with $\alpha$. This is very intuitive since when the discount degree is relatively low, a higher discount degree leads to a higher production cost reduction level and a lower production cost, which benefits the supplier. On the other hand, when the discount degree is relatively high, a higher discount degree leads to a lower production cost reduction level and a higher production cost, which hurts the supplier.

**Observation 2** In case TN, the effect of the technology investment cost coefficient $\mu$ on the optimal decision variables and profits is as follows.
4.3 Case TT

In case TT, we further consider the situation in which the supplier accepts both manufacturers’ technology investments. In this situation, both manufacturers are provided with a discount wholesale price $w - \alpha t_i$. The backward induction is used to solve the model and the two manufacturers’ optimization problems are investigated firstly.

The profit functions of two manufacturers are

$$
\pi_{\text{M}_i}^{\text{TT}}(p_i, t_i) = [p_i - (w - \alpha t_i)] D_i - \frac{1}{2} \mu t_i^2, \quad i = 1, 2.
$$

(22)

Both manufacturers who are the Stackelberg followers simultaneously determine their retail price $p_i$ and the production cost reduction level $t_i$ as the solution to Eq. (22), yielding their optimal retail prices and optimal production cost reduction levels

$$
p_i^{\text{TT}}(w) = \frac{a \alpha^2 - (a + w) \mu}{(b - 2) \mu - a^2 (b - 1)}, \quad i = 1, 2
$$

(23)

and

$$
t_i^{\text{TT}}(w) = \frac{\alpha [(1 - b) w - a]}{(b - 2) \mu - a^2 (b - 1)}, \quad i = 1, 2.
$$

(24)

The supplier who is the Stackelberg leader decides the wholesale price to optimize the profit function

$$
\pi^{\text{TT}}_{\text{S}}(w) = [(w - \alpha t_1) - (c - t_1 - t_2)] D_1 + [(w - \alpha t_2) - (c - t_1 - t_2)] D_2.
$$

(25)

By substituting Eqs. (23) and (24) in Eq. (25) and maximizing the supplier’s profit function, we obtain the manufacturers’ and the supplier’s optimal decisions and corresponding profits, listed in Lemma 3.

Lemma 3 In case TT, the manufacturers’ and the supplier’s optimal decision variables and profits are as follows.

(1) The optimal retail prices and the optimal production cost reduction levels of two manufacturers are

$$
p_i^{\text{TT}} = \frac{[(-2a - c)b + 3a + c] \mu + 4 \alpha \mu (b - 1)}{2[(b - 2) \mu + 2(1 - b) \alpha](b - 1)}, \quad i = 1, 2
$$

(26)

and

$$
t_i^{\text{TT}} = \frac{\alpha (a + bc - c)}{2(2 - b) \mu - 4(1 - b) \alpha}, \quad i = 1, 2.
$$

(27)
The optimal wholesale price of the supplier is

$$w_{TT} = \frac{(b - 1) (a + bc - c) \alpha^2 + 4 a (1 - b) \alpha + \mu (b - 2) (a - bc + c)}{2 [2 (b - 1) \alpha + (2 - b) \mu] (b - 1)}.$$

(2) The optimal profits of two manufacturers and the supplier are

$$\pi_{MT}^{TT} = \frac{(2 \mu - \alpha^2) (a + bc - c)^2 \mu}{8 [(b - 2) \mu + 2 \alpha (1 - b)]^2}, i = 1, 2$$

and

$$\pi_{ST}^{TT} = \frac{\mu (a + bc - c)^2}{2 [(b - 2) \mu + 2 (1 - b) \alpha] (b - 1)}.$$

Lemma 3 presents the optimal decision variables and profits in case TT. In order to ensure the uniqueness of the optimal decision variables, we need $\mu > \max \left\{ \frac{\alpha^2}{2}, \mu_{p}^{TT} \right\}$. In addition, under the conditions of $\mu > \mu_{p}^{TT}$, the optimal variables and profits are always positive. The proof of Lemma 3 is in Appendix.

Corollary 1 In case TT, the effect of the discount degree $\alpha$ on the optimal decision variables and profits is as follows.

(1) (i) If $0 < \alpha < 1$ and $\mu > \mu_{p}^{TT}$, then $\frac{\partial w_{TT}}{\partial \alpha} < 0$. If $1 < \alpha < \frac{4a(2-b)}{2a(2-b)+(a+bc-c)}$, when $\mu_{p}^{TT} < \mu < \frac{(1-b)\alpha^2}{2(2-b)\alpha^2}$,
then \( \partial w_T^a / \partial a < 0 \) when \( \mu > (1-b)a^2 (12-b)(a-1) \), then \( \partial w_T^a / \partial a > 0 \).

If \( \alpha > \frac{4a(2-b)}{2a(2-b)+(a+bc-c)} \) and \( \mu > \max\{\frac{a^2}{2}, \mu_p^T\} \), then \( \partial w_T^a / \partial a > 0. \)

If \( \alpha > \frac{4a(2-b)}{2a(2-b)+(a+bc-c)} \) and \( \mu > \max\{\frac{a^2}{2}, \mu_p^T\} \), then \( \partial w_T^a / \partial a > 0. \)

(ii) If \( \mu > \max\{\frac{a^2}{2}, \mu_p^T\} \), then \( \partial \pi_T^a / \partial a < 0. \)

(iii) If \( \mu > \max\{\frac{a^2}{2}, \mu_p^T\} \), then \( \partial \pi_T^a / \partial a > 0. \)

Corollary 1(1)(i) shows that the wholesale price is non-monotonic with respect to the discount degree. More specifically, when the discount degree is relatively small (i.e., \( 0 < \alpha < 1 \), \( \mu > \mu_p^T \)), the wholesale price decreases with the discount degree. This is very intuitive because when the discount degree is relatively small the supplier reduces the wholesale price for encouraging the manufacturers ordering more quantities. When the discount degree is intermediate (i.e., \( 1 < \alpha < \frac{4a(2-b)}{2a(2-b)+(a+bc-c)} \)), if the technology investment efficiency is high (i.e., \( \mu_p^T < \mu < \frac{(1-b)a^2}{2a(2-b)(a-1)} \)), the wholesale price decreases with the discount degree, if the technology investment efficiency is low (i.e., \( \mu > \frac{(1-b)a^2}{2a(2-b)(a-1)} \)), the wholesale price increases with the discount degree. The reason is that a higher technology investment efficiency leads to a higher production cost reduction level and a lower production cost, which leads to a lower wholesale price. However, a lower technology investment efficiency results in a higher production cost, which enhances the wholesale price. When the discount degree \( \alpha \) is sufficiently large (i.e., \( \alpha > \frac{4a(2-b)}{2a(2-b)+(a+bc-c)} \), \( \mu > \max\{\frac{a^2}{2}, \mu_p^T\} \)), the wholesale price increases with the discount degree. This is because when the discount degree is sufficiently large the supplier enhances the wholesale price for achieving a positive profit. Corollary 1(1)(ii) suggests that the production cost reduction level always increases with the discount degree. This is because a higher discount degree encourages manufacturers to make more technology investments in production cost reduction for a lower discount wholesale price, which leads to a higher production cost reduction level. Corollary 1(1)(iii) demonstrates that the retail price always decreases with the discount degree. The reason may be that a higher discount degree leads to a lower discount wholesale price, thus leading to a lower retail prices.

Corollary 1(2)(i) shows the trend of the manufacturers’ profits with the discount degree. With the increase of discount degree, the manufacturers’ profits first increase and then decrease. This is very intuitive since a higher discount degree expands the market demand when the discount degree is relatively small (i.e., \( 0 < \alpha < \frac{4(1-b)}{2-b}, \mu > \mu_p^T \)), which benefits the manufacturers. However, when the discount degree is sufficiently large (i.e., \( \alpha > \frac{4(1-b)}{2-b}, \mu > \max\{\frac{a^2}{2}, \mu_p^T\} \)), the manufacturers’ profits begin to decrease because the higher the discount degree the more technology investment cost manufacturers bear, which is not beneficial to the manufacturers. Corollary 1(2)(ii) suggests that the supplier’s profit increases with the discount degree. This is because a higher discount degree reduces the production cost and discount wholesale price of the key component, which is beneficial to expand the wholesale quantity of the component and increase the profit of the supplier.

Corollary 2 In case TT, the effect of the technology investment cost coefficient \( \mu \) on the optimal decision variables and profits is as follows.

1. (i) If \( 0 < \alpha < 2 \) and \( \mu > \mu_p^T \), then \( \partial w_T^a / \partial \mu > 0 \). If \( \alpha > 2 \) and \( \mu > \max\{\frac{a^2}{2}, \mu_p^T\} \), then \( \partial \pi_T^a / \partial \mu > 0 \).

(ii) If \( \mu > \max\{\frac{a^2}{2}, \mu_p^T\} \), then \( \partial \pi_T^a / \partial \mu < 0 \).

(iii) If \( \mu > \max\{\frac{a^2}{2}, \mu_p^T\} \), then \( \partial \pi_T^a / \partial \mu < 0 \).

Corollary 2(1)(i) demonstrates that the wholesale price is non-monotonic with respect to the technology investment cost coefficient. More specifically, when the discount degree is relatively low (i.e., \( 0 < \alpha < 2 \), \( \mu > \mu_p^T \)), the wholesale price increases with the technology investment cost coefficient. This is because a higher technology investment cost coefficient implies a higher supplier’s production cost, thus leading to a higher wholesale price. On the other hand, when the discount degree is relatively high (i.e., \( \alpha > 2 \), \( \mu > \max\{\frac{a^2}{2}, \mu_p^T\} \)), the wholesale price decreases with the technology investment cost coefficient. The reason is that the supplier places more emphasis on increasing wholesale quantity of key component by decreasing the wholesale price. Corollary 2(1)(ii) shows that the production cost reduction level always decreases with the technology investment cost coefficient. This is very intuitive since a higher technology investment cost coefficient implies a lower technology investment efficiency and a higher technology investment cost, which forces manufacturers to reduce production cost reduction level to maintain their technology investment costs. Corollary 2(1)(iii) depicts that the retail price of the product always increases with the technology investment cost coefficient. The reason may be that a higher technology investment
cost coefficient leads to a higher manufacturers’ technology investment costs, which forces manufacturers to enhance their retail prices.

Corollary 2(2)(i) shows the trend in the manufacturers’ profits with the technology investment cost coefficient. We conclude that the manufacturers’ profits are non-monotonic in the technology investment cost coefficient. Specifically, if the discount degree is sufficiently small (i.e., \(0 < \alpha < \frac{2\alpha(3-2b)+(a-bc+c)}{2a(1-b)}\)), manufacturers’ profits decrease as the technology investment cost coefficient increases. This is because the increased profits of manufacturers from the discount wholesale price cannot offset their technology investment costs. If the discount degree is moderate (i.e., \(\alpha > 2\)), manufacturers’ profits increase with the technology investment cost coefficient. This is because manufacturers’ increased profits from the discount wholesale price cannot compensate for the decreased profit from discount wholesale price, and thus the supplier’s profit in case T N is higher than in case N N. On the other hand, a lower technology investment efficiency benefits the manufacturer because of the higher discount wholesale price and lower technology investment costs invested to the supplier. Corollary 2(2)(ii) demonstrates that the supplier’s profit decreases with the technology investment cost coefficient. This is very intuitive because a higher technology investment cost coefficient implies a higher the production cost and a lower the market demand, which hurts the supplier.

5 Comparison and analysis

In this section, we compare the supply chain members’ optimal profits in cases NN, TN and TT and discuss their preferences with respect to the three cases. Further, we obtain the supplier’s optimal cooperation strategy with the two competing manufacturers.

Proposition 1 The supplier’s optimal profits in cases NN, TN and TT satisfy the following relationships.

1. If \(0 < \alpha < \max\{\alpha_1, \frac{2}{b-1}\}\) and \(\mu > \max\{\frac{a^2}{2}, \mu_{TT}\}\), then \(\pi_S^{TT} > \pi_S^{TN} > \pi_S^{NN}\).
2. If \(\alpha > \max\{\alpha_1, \frac{2}{b-1}\}\), when \(\frac{a^2}{2} < \mu < \frac{(b+1)(a+2w^2)}{4(b+2)}\), then \(\pi_S^{TT} > \pi_S^{NN} > \pi_S^{TN}\), and when \(\mu > \frac{(b+1)(a+2w^2)}{4(b+2)}\), then \(\pi_S^{TT} > \pi_S^{TN} > \pi_S^{NN}\).

Proposition 1(1) shows the comparison of the supplier’s profit in cases NN, TN and TT. We can find that when the discount degree is low (i.e., \(0 < \alpha < \max\{\alpha_1, \frac{2}{b-1}\}\)), the supplier’s profit is the greatest in case TT among three cases, as in Fig. 7a, b. We can interpret the potential reason of this result as follows. In case TT, the supplier accepts both manufacturers’ technology investments in production cost reduction, which leads to the lowest supplier’s production cost among three cases. In addition, both manufacturers’ technology investments in production cost reduction greatly expands the market demand of products. Therefore, the supplier obtains the greatest profit in case TT. In addition, we also find that the supplier’s profit is higher in case TN than in case NN, as shown in light shade in Fig. 7a, b. This is because when the discount is low, the increased supplier’s profit from the production cost reduction is higher than the decreased profit from the discount wholesale price.

Proposition 1(2) shows if the supplier provides a higher discount degree (i.e., \(\alpha > \max\{\alpha_1, \frac{2}{b-1}\}\)), the supplier’s profit is the greatest in case TT among three cases, as in Fig. 7a, b. The reason may be that technology investments from both manufacturers greatly reduce the supplier’s production cost, which benefits the supplier in despite of technology investment efficiency being high or low. Next, when the technology investment efficiency is relatively high (i.e., \(\max\{\frac{a^2}{2}, \mu_{TT}\} < \mu < \frac{(b+1)(a+2w^2)}{4(b+2)}\)), the supplier’s profit is lower in case TN than in case NN, as shown in dark shade in Fig. 7a, b, and when the technology investment efficiency is relatively low (i.e., \(\mu > \frac{(b+1)(a+2w^2)}{4(b+2)}\)), the supplier’s profit is higher in case TN than in case NN, as shown in light shade in Fig. 7a, b. The potential reasons of the results are as follows. The higher technology investment efficiency enhances the production cost reduction level, leading to not only a lower production cost but also a lower discount wholesale price. In case TN, the lower discount wholesale price and production cost reduction lead to the awkward situation that the supplier’s increased profit from the production cost reduction cannot compensate for the decreased profit from discount wholesale price, and thus the supplier’s profit in case TN is lower than in case NN. On the other hand, a lower technology investment efficiency reduces production cost reduction level, leading to not only a higher production cost but also a higher discount wholesale price. In case TN, the gains of the supplier from the production cost reduction is larger than the losses from discount wholesale price provided to the manufacturer because of the higher discount wholesale price and the higher production cost, and thus the supplier’s profit in case TN is larger than in case NN.

From the above results, we find that the supplier’s profit is always the largest in case TT among three cases no matter the discount degree is low or high. The implication is that the supplier always prefers to accept both manufacturers’ technology investments to reduce production cost of the key component.

Because the complexity of analytical expressions of two manufacturers’ profits in case TN, we cannot compare their analytic results in cases NN, TN and TT. We use numerical
examples to provide the comparisons of the two manufacturers’ optimal profits and obtain the following Observation with respect to the three cases. The basic parameters are considered as $a = 100, b = 0.5, c = 90, \mu_1 = 2, \mu_2 = 4$.

**Observation 3** Two manufacturers’ optimal profits in cases NN, TN and TT satisfy the following relationships.

1. If $\alpha$ is low, we have $\pi_{TT}^{M_1} > \pi_{TN}^{M_1} > \pi_{NN}^{M_1}$. If $\alpha$ is high, when $\mu$ is low, we have $\pi_{TT}^{M_1} > \pi_{TN}^{M_1} > \pi_{NN}^{M_1}$, when $\mu$ is high, we have $\pi_{TN}^{M_1} > \pi_{TT}^{M_1} > \pi_{NN}^{M_1}$.

2. If $\alpha$ is low, we have $\pi_{TT}^{M_2} > \pi_{TN}^{M_2} > \pi_{NN}^{M_2}$. If $\alpha$ is high, we have $\pi_{TN}^{M_2} > \pi_{TT}^{M_2} > \pi_{NN}^{M_2}$.

Figure 8a, b depicts the comparisons of two manufacturers’ optimal profits with $\mu_1 = 2$ and $\mu_2 = 4$ in cases NN, TN and TT. We find that when the discount degree is relatively low the manufacturer 1’s profit in case TT is the greatest among the three cases. The reason is that when the discount degree is relatively low, the discount wholesale price in case TT is lower than those in cases TN and NN. Therefore, the manufacturer 1’s profit is the greatest among the three cases.

When the discount degree and the technology investment efficiency are high, the manufacturer 1’s profit in case TT is the largest among three cases. Because the discount wholesale price in case TT is much lower than those in cases NN and TN, and there is little difference in technology investment cost bearded by manufacturer 1, so the manufacturer 1’s profit in case TT is the largest among the three cases. When the discount degree is high and the technology investment efficiency is low, the manufacturer 1’s profit in case TN is the largest among three cases. The reason is that the production cost reduction level increases with the discount degree in case TT and decreases with the discount degree in case TN, and thus the technology investment cost bearded by manufacturer 1 in case TT is far greater than this in case TN, which makes the manufacturer 1’s profit in case TT to be lower than this in case TN. Furthermore, the discount wholesale prices in case TN and TT are lower than this in case NN. Therefore, the manufacturer 1’s profit in case TN is the largest among three cases.

Figure 8a, b also shows that manufacturer 2 is always better off in case TT as compared to cases NN and TN. The reason may be that the wholesale price is lower in case TT than in cases NN and TN, and the market demand is higher in case TT than in cases NN and TN, which make the manufacturer 2’s profit being the greatest among the three cases.

In summary, from Proposition 1 and Observation 3, we conclude that when the discount degree is relatively low or when the discount degree and the technology investment efficiency are relatively high, the supplier prefers to accept both manufacturers’ technology investment for reducing production cost and both manufacturers are also willing to make technology investments to their supplier simultaneously. Therefore, the supplier’s optimal cooperation strategy with two competing manufacturers is to accept case TT, which leads to “win-win-win” outcomes. When the discount degree is relatively high and the technology investment efficiency is relatively low, the supplier prefers to accept both manufacturers’ technology investments, the investing manufacturer prefers to invest alone while the non-investing manufacturer prefers to invest together with the other manufacturer, which can not lead to equilibrium outcome.
6 Extension

In our original model, we assume that the potential market sizes of the two manufacturers products are symmetric. Now, we relax this assumption and evaluate our results’ robustness. In reality, the two competing manufacturers often have different market potential and then their demand functions usually are asymmetry. More specifically, we consider the following demand functions:

\[ D_1 = a(1 + \delta) - p_1 + bp_2, \]
\[ D_2 = a(1 - \delta) - p_2 + bp_1, \]

where \(-1 < \delta < 1\) represents the degree of the difference between the two manufacturers’ potential market size. Similar to the original analysis, we can derive the optimal decision variables and profits of the supplier and the two manufacturers through backward induction.

We use numerical examples to analyze the sensitivity with respect to \(\alpha, \mu\) and \(\delta\) and provide comparisons of the supplier’s and two manufacturers’ optimal profits in cases NN, TN and TT. The basic parameters are considered as \(a = 100, b = 0.5, c = 90, \alpha = 1, \mu = 2, \delta = 0.5\).

From Table 2, we can find that the supplier always prefers to accept case TT, which implies that the results in the extension of the original model are consistent with the results of Proposition 1. For example, when \(\alpha = 1.5, \mu = 2\) and \(\delta = 0.5\) the supplier and the two manufacturers all prefer to accept case TT, which implies that the supplier’s optimal cooperation strategy with two competing manufacturers does not change under the asymmetric potential market size. Moreover, we also find that the supplier’s profit is non-monotonic with respect to \(\delta\). More specifically, the supplier’s profit firstly decreases and then increases with \(\delta\) in case TT and firstly increases and then decreases in case TN. This implies that the greater the difference in potential market size between the two manufacturers, the more beneficial it is to the supplier’s profit in case TT. Otherwise it is beneficial to the supplier in case TN.

In summary, the extension demonstrates that the asymmetries between the two competing manufacturers does not qualitatively change the theoretical results achieved under the symmetric potential market size. Therefore, we show that our theoretical results are robust.

7 Conclusions

In this paper, we consider a supply chain consisting of a supplier who produces a key component and two competing manufacturers who use the component to produce a replaceable product for consumers. Under a wholesale price discount contract, we explore whether the supplier should cooperate with the two competing manufacturers to carry out technology innovation for reducing the production cost of the component. Based on this consideration, we explore three cases to analyze the supplier’s cooperation strategies: (1) The supplier does not accept manufacturers’ technology investments, (2) the supplier accepts one manufacturer’s technology investment, (3) the supplier accepts both manufacturers’ technology investments.

Our study generates some interesting results with respect to the supplier’s cooperation strategy under a wholesale price discount contract. First, we find that the supplier’s profit always increases with the discount degree and the technology investment efficiency in case TT. The two manufacturers’
Supplier’s cooperation strategy with two competing manufacturers

Table 2 The profits of the supplier and two manufacturers in cases NN, TN and TT

| α  | π^TN_S | π^TN_M1 | π^TN_M2 | π^NN_S | π^NN_M1 | π^NN_M2 | π^TT_S | π^TT_M1 | π^TT_M2 | π^IN_S | π^IN_M1 | π^IN_M2 |
|----|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 0.5| 2350   | 1910   | 1666   | 1624   | 1533   | 277    | 2      | 6      | 277    |
| 1   | 3316   | 1920   | 1666   | 2152   | 1750   | 277    | 9      | 38     | 277    |
| 1.5| 6173   | 671    | 1666   | 3937   | 1532   | 277    | 348    | 43     | 277    |
| μ  | 1      | 10000  | 1956   | 1666   | 5000   | 2270   | 277    | 0      | 170    | 277    |
| 2   | 3316   | 1910   | 1666   | 2152   | 1750   | 277    | 9      | 38     | 277    |
| 3   | 2560   | 1832   | 1666   | 1796   | 1597   | 277    | 10     | 24     | 277    |
| δ  | −0.5   | 3316   | 1601   | 1666   | 9      | 0.2    | 277    | 2152   | 1568   | 277    |
| 0   | 2500   | 2029   | 1666   | 468    | 427    | 277    | 468    | 279    | 277    |
| 0.5| 3316   | 1920   | 1666   | 2152   | 1750   | 277    | 9      | 38     | 277    |

Ethical approval This study does not contain any studies with human participants or animals performed by any of the authors.

Appendix

Proof of Lemma 1 For any given w, we derive π^NN_M1 is concave in p1 since \( \frac{d^2\pi^{NN}_{M1}}{dp_1^2} = -2 < 0 \). By the first-order condition, that is \( \frac{d\pi^{NN}_{M1}}{dp_1} = 0 \) and \( \frac{d\pi^{NN}_{M1}}{dp_2} = 0 \), we conclude the unique optimal retail price (3).

By substituting (3) in the supplier’s profit function, we get π^NN_S(w). In order to make π^NN_S(w) to be concave in w, we require that \( \frac{d^2\pi^{NN}_S}{dw^2} = \frac{-4(\delta - 1)}{\alpha^2} \) < 0. From the first order condition, \( \frac{d\pi^{NN}_S}{dw} = 0 \), we obtain the unique optimal wholesale price (6). Then substituting Eq. (6) in Eq. (3), we get the optimal retail price (5).

Substituting Eqs. (5) and (6) in Eqs. (2) and (4), we can derive the optimal profit of the manufacturers (7) and the supplier’s optimal profit (8).

Proof of Lemma 2 For the given w, it is easy to show that π^TN_M1 is jointly concave in p1 and t1, because the Hessian matrix of π^TN_M1

\[
H(\pi^TN_{M1}) = \begin{pmatrix}
\frac{\partial^2\pi^{TN}_{M1}}{\partial p_1^2} & \frac{\partial^2\pi^{TN}_{M1}}{\partial p_1 \partial t_1} \\
\frac{\partial^2\pi^{TN}_{M1}}{\partial t_1 \partial p_1} & \frac{\partial^2\pi^{TN}_{M1}}{\partial t_1^2}
\end{pmatrix}
\]

is negative definite when the leading principal minor \( H^1_{TN} = -2 < 0 \), \( H^2_{TN} = 2\mu - \alpha^2 > 0 \). Further, we conclude that π^TN_M2 is concave in p2 when \( \frac{d^2\pi^{TN}_{M2}}{dp_2^2} = -2 < 0 \).

When \( \mu > \frac{\alpha^2}{2} \), by the first order condition, that is \( \frac{\partial\pi^{TN}_{M1}}{\partial p_1} = 0 \), \( \frac{\partial\pi^{TN}_{M1}}{\partial t_1} = 0 \), and \( \frac{d\pi^{TN}_{M1}}{dp_2} = 0 \), we can conclude (11), (12)

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Declaration

Conflict of interest The authors declare that they have no conflict of interest.
and (13). By substituting Eqs. (11), (12) and (13) in the supplier’s profit (14), we obtain \( \pi_S^{\text{TN}}(w) \). To ensure that \( \pi_S^{\text{TN}}(w) \) is concave in \( w \), \( \frac{d^2\pi_S^{\text{TN}}}{dw^2} < 0 \) is required, that is \( \mu > \mu_u = \frac{b(1)(b+2)a+(2b-2)a^2-a\sqrt{(a^2b^2-2b^2-b^2a-2b(a+b+2)(1-b)(b+2))}}{2(b-b^2)} \).

From \( \frac{d\pi_S^{\text{TN}}}{dw} = 0 \), we can obtain the unique optimal wholesale price (18). Then substituting Eq. (18) in Eqs. (11), (12) and (13), we have the optimal retail prices (15), (16) and the optimal technology investment level (17).

Substituting Eqs. (15), (16), (17) and (18) in Eqs. (9), (10) and (14), we can get the optimal profits of the manufacturers (19), (20) and the supplier’s optimal profit (21).

**Proof of Lemma 3**

For any given \( w \), the Hessian matrix of \( \pi_{M_i}^{\text{TT}}, i = 1, 2 \) are as follows:

\[
H(\pi_{M_i}^{\text{TT}}) = \begin{pmatrix}
\frac{\partial^2\pi_{M_i}^{\text{TT}}}{\partial w^2} & \frac{\partial^2\pi_{M_i}^{\text{TT}}}{\partial w \partial \alpha} \\
\frac{\partial^2\pi_{M_i}^{\text{TT}}}{\partial w \partial \alpha} & \frac{\partial^2\pi_{M_i}^{\text{TT}}}{\partial \alpha^2}
\end{pmatrix} = \begin{pmatrix}
-2 & -\alpha \\
-\alpha & -\alpha - \mu
\end{pmatrix}.
\]

To ensure that \( \pi_{M_i}^{\text{TT}} \) is jointly concave in \( p_i \) and \( t_i \), we require that the leading principal minor \( H_1^{\text{TT}} = -2 < 0 \), \( H_2^{\text{TT}} = 2\mu - \alpha^2 > 0 \). By the first order condition, that is \( \frac{\partial\pi_{M_i}^{\text{TT}}}{\partial p_i} = 0 \), \( \frac{\partial\pi_{M_i}^{\text{TT}}}{\partial t_i} = 0 \), we can obtain the unique optimal retail price (23) and the optimal technology investment level (24).

Substituting Eqs. (23) and (24) in Eq. (25), we get the supplier’s profit \( \pi_S^{\text{TN}}(w) \). Because \( \frac{d^2\pi_S^{\text{TN}}}{dw^2} = 4\mu(1-b)(b-2)a(2b-2-a)\mu^2 < 0 \), that is \( \mu > \frac{2(1-b)a}{2b} \), we have \( \pi_S^{\text{TN}}(w) \) is concave in \( w \). By the first order condition, we get the unique optimal wholesale price (28). By substituting Eq. (28) in Eqs. (23) and (24), we obtain the unique optimal retail price (26) and the technology investment level (27).

Finally, substituting Eqs. (26), (27) and (28) in Eqs. (22) and (25), we derive the manufacturers’ optimal profits (29) and the supplier’s optimal profit (30).

**Proof of Corollary 1**

In order to make the decision variables to be positive and the uniqueness of optimal solutions in case TT, \( a + (b-1)c > 0, \mu > \max\{\frac{a^2}{2}, \mu_p\} \) are needed.

With resect to map \( \{\frac{a^2}{2}, \mu_p\} \), we can simplify it as follows.

When \( 0 < \alpha < \frac{8a(1-b)}{2a(1-b)+(a-bc+c)} \), we have \( \frac{a^2}{2} < \mu_p^{\text{TT}} \), then \( \mu_p^{\text{TT}} = \max\{\frac{a^2}{2}, \mu_p^{\text{TT}}\} \), when \( \alpha > \frac{8a(1-b)}{2a(1-b)+(a-bc+c)} \), we have \( \mu_p^{\text{TT}} < \frac{a^2}{2} < \max\{\frac{a^2}{2}, \mu_p^{\text{TT}}\} \).

For any given \( \alpha \), we have

\[
\frac{d\mu_p^{\text{TT}}}{d\alpha} = -\mu \frac{(b-1)c}{2[\mu (b-2)-2\alpha (b-1)]^2}.
\]

From (31), we have the following results.

(i) Apparently, when \( \mu > \max\{\frac{a^2}{2}, \mu_p\} \), we have \( \frac{d\pi_p^{\text{TT}}}{d\alpha} > 0 \) and \( \frac{d\pi_p^{\text{TT}}}{d\mu} < 0 \). Therefore, results (i) and (iii) hold.

(ii) If \( 0 < \alpha < 1 \), we have \( \mu_p^{\text{TT}} > \frac{a^2}{2} \), when \( \mu > \mu_p^{\text{TT}} \), then \( \frac{d\pi_p^{\text{TT}}}{d\mu} < 0 \). If \( 1 < \alpha < \frac{8a(1-b)}{2a(1-b)+(a-bc+c)} \), we have \( \frac{a^2}{2} < \mu_p^{\text{TT}} < \frac{(1-b)a^2}{(b-2)(a-\alpha)} \), when \( \mu_p^{\text{TT}} < \frac{(1-b)a^2}{(b-2)(a-\alpha)} \), then \( \frac{d\pi_p^{\text{TT}}}{d\mu} > 0 \). If \( \alpha > \frac{8a(1-b)}{2a(1-b)+(a-bc+c)} \), when \( \mu > \frac{a^2}{2} \), then \( \frac{d\pi_p^{\text{TT}}}{d\alpha} > 0 \). That is, if \( \alpha > \frac{8a(1-b)}{2a(1-b)+(a-bc+c)} \), when \( \mu > \max\{\frac{a^2}{2}, \mu_p^{\text{TT}}\} \), then \( \frac{d\pi_p^{\text{TT}}}{d\alpha} > 0 \). Therefore, result (ii) holds.

(2) (i) From \( \frac{4(1-b)}{2b} < \frac{8a(1-b)}{2a(1-b)+(a-bc+c)} \), if \( 0 < \alpha < \frac{4(1-b)}{2b} \), when \( \mu > \mu_p^{\text{TT}} \), we have \( \frac{d\pi_p^{\text{TT}}}{d\alpha} > 0 \). If \( \frac{4(1-b)}{2b} < \alpha < \frac{8a(1-b)}{2a(1-b)+(a-bc+c)} \), when \( \mu > \mu_p^{\text{TT}} \), we have \( \frac{d\pi_p^{\text{TT}}}{d\alpha} < 0 \), if \( \alpha > \frac{8a(1-b)}{2a(1-b)+(a-bc+c)} \), when \( \mu > \frac{a^2}{2} \), we have \( \frac{d\pi_p^{\text{TT}}}{d\alpha} < 0 \). That is, if \( \alpha > \frac{4(1-b)}{2b} \), when \( \mu > \max\{\frac{a^2}{2}, \mu_p^{\text{TT}}\} \), then \( \frac{d\pi_p^{\text{TT}}}{d\alpha} < 0 \). Therefore, result (ii) holds.

(ii) Apparently, if \( \mu > \max\{\frac{a^2}{2}, \mu_p^{\text{TT}}\} \), then \( \frac{d\pi_p^{\text{TT}}}{d\alpha} > 0 \). Therefore, result (ii) holds.

**Proof of Corollary 2**

For any given \( \mu \), we have

\[
\frac{d\mu_p}{d\mu} = \frac{\alpha[(b-1)c+a](b-2)}{2[\mu (b-2)-2\alpha (b-1)]^2},
\]

\[
\frac{d\mu_p}{d\alpha} = \frac{(b-2)(b-1)(a+c+\alpha)}{2[\mu (b-2)-2\alpha (b-1)]^2},
\]

\[
\frac{d\pi_p^{\text{TT}}}{d\alpha} = \frac{\alpha[(b-1)c+a]^2}{8[\mu (b-2)-2\alpha (b-1)]^2},
\]

\[
\frac{d\pi_p^{\text{TT}}}{d\mu} = \frac{(b-2)(b-1)\alpha}{2[\mu (b-2)-2\alpha (b-1)]^2}.
\]
From (32), we have the following results.

(1) Apparently, if \( \mu > \max\{ \frac{a^2}{2}, \mu_p^{TT} \} \), we can obtain \( \frac{\partial \mu}{\partial T} < 0 \) and \( \frac{\partial \mu}{\partial \mu} > 0 \). Therefore, results (i) and (iii) hold.

(ii) From \( \frac{8a(1-b)}{2a(1-b)(a-b+c)} \leq 2 \), that is \( \beta > \frac{a-b+c}{2a} \), if \( \alpha < 2 \), when \( \mu \geq \max\{ \frac{a^2}{2}, \mu_p^{TT} \} \), then \( \frac{\partial \mu}{\partial \mu} > 0 \). If \( \alpha > 2 \), when \( \mu > 2 \), then \( \frac{\partial \mu}{\partial \mu} < 0 \). From \( \frac{8a(1-b)}{2a(1-b)(a-b+c)} > 2 \), that is \( \beta > \frac{a-b+c}{2a} \), if \( \alpha < 2 \), when \( \mu > \mu_p^{TT} \), then \( \frac{\partial \mu}{\partial \mu} < 0 \). If \( \alpha > 2 \), when \( \mu \geq \max\{ \frac{a^2}{2}, \mu_p^{TT} \} \), then \( \frac{\partial \mu}{\partial \mu} < 0 \). Therefore, result (ii) holds.

(2) If \( 0 < \alpha < \frac{2(1-b)a^2}{2a(3-2b)+a-b+c} \), we have \( \frac{\partial \mu}{\partial T} < \mu_p^{TT} \), when \( \mu > \mu_p^{TT} \), then \( \frac{\partial \mu}{\partial \mu} < 0 \). If \( \alpha < \frac{8a(1-b)}{2a(1-b)(a-b+c)} \), we have \( \frac{\partial \mu}{\partial \mu} < 0 \), when \( \mu_p^{TT} < \mu \), then \( \frac{\partial \mu}{\partial \mu} > 0 \). If \( \alpha > 2 \), when \( \mu > 2 \), then \( \frac{\partial \mu}{\partial \mu} > 0 \). That is, if \( \alpha < \frac{8a(1-b)}{2a(3-2b)+a-b+c} \), when \( \mu > \max\{ \frac{a^2}{2}, \mu_p^{TT} \} \), we have \( \frac{\partial \mu}{\partial \mu} > 0 \). When \( \alpha > 2 \), when \( \mu > 2 \), then \( \frac{\partial \mu}{\partial \mu} > 0 \). Therefore, result (ii) holds.

(ii) Apparently, when \( 0 < \alpha < \frac{8a(1-b)}{2a(1-b)+a-b+c} \) and \( \mu > \mu_p^{TT} \), or when \( \alpha > \frac{8a(1-b)}{2a(1-b)+a-b+c} \) and \( \mu > 2 \), \( \frac{\partial \mu}{\partial \mu} > 0 \). Therefore, result (ii) holds.

Proof of Proposition 1 (i) In order to make the decision variables be positive and the uniqueness of optimal solutions in cases TN and TT, we require \( a + (+1) > 0 \). \( B_1 + B_2 < 0 \), \( \mu > \max\{ \frac{a^2}{2}, \mu_u, \mu_p^{TT} \} = \max\{ \frac{a^2}{2}, \mu_p^{TT} \} \), because \( \mu_u < \max\{ \frac{a^2}{2}, \mu_p^{TT} \} \). With respect to \( \max\{ \frac{a^2}{2}, \mu_p^{TT} \} \), we can simplify it as follows. If \( 0 < \alpha < \frac{8a(1-b)}{2a(1-b)+a-b+c} \), then \( \max\{ \frac{a^2}{2}, \mu_p^{TT} \} = \mu_p^{TT} \). If \( \alpha > \frac{8a(1-b)}{2a(1-b)+a-b+c} \), then \( \max\{ \frac{a^2}{2}, \mu_p^{TT} \} = \frac{a^2}{2} \).

(1) \( \pi_s^{TT} = \pi_s^{TN} = a \mu^2 (a+b+c)^2 \), where \( a \mu \) is \( 4(b+2) \mu^2 + (b+1)(b+2)a^2(\alpha-6) + 2(b+1)^2a^2 \). For \( a \mu \), from \( \Delta = (b+1)^2(b+2)^2a^4[(\alpha-6)^2-32] \), we have \( a \mu > 0 \) when \( \Delta < 0 \) if \( 6 < 4\sqrt{2} < \alpha < 6 + 4\sqrt{2} \). Clearly, if \( 0 < \alpha < 6 - 4\sqrt{2} \) and \( \alpha > 6 + 4\sqrt{2} \), then \( \Delta > 0 \). For \( a \mu = 0 \), we have two different real roots \( \mu_1 = \frac{9a(4-a^2+2\sqrt{2a^2+12a+4})}{8(b+2)} \), \( \mu_2 = \frac{9a(4-a^2-2\sqrt{2a^2+12a+4})}{8(b+2)} \), \( i=1,2. \) Since \( \min\{ a \mu, \mu_p^{TT} \} = \mu_2 > \mu_1 \), when \( \mu > \max\{ \frac{a^2}{2}, \mu_p^{TT} \} \), we have \( a \mu > 0 \). Consequently, \( \pi_s^{TT} > \pi_s^{TN} \).

(2) \( \pi_s^{IN} - \pi_s^{IN} = \frac{a(b+2)(a+b+c)^2}{2(b+2)(b+c+2)^2}a \), where \( a = (b+2) \mu - (b+1)(a+2)^2a^2 \). Clearly, when \( \mu < \frac{a(b+2)(a+b+c)^2}{2(b+2)(b+c+2)^2}a \), we get \( a \mu < 0 \), when \( \mu > \frac{a(b+2)(a+b+c)^2}{2(b+2)(b+c+2)^2}a \), we get \( a \mu > 0 \).

From \( \mu_p^{TT} = \mu_p^{TT} - \frac{a(b+2)(a+b+c)^2}{2(b+2)(b+c+2)^2}a \), when \( \mu < \frac{a(b+2)(a+b+c)^2}{2(b+2)(b+c+2)^2}a \), we derive that \( a \mu > 0 \) if \( \mu > \frac{a(b+2)(a+b+c)^2}{2(b+2)(b+c+2)^2}a \).

When \( \mu > \frac{a(b+2)(a+b+c)^2}{2(b+2)(b+c+2)^2}a \), when \( \mu < \frac{a(b+2)(a+b+c)^2}{2(b+2)(b+c+2)^2}a \), we can conclude that if \( 0 < \alpha < \max\{ \alpha_1, \frac{2+3}{2+b+1} \} = \alpha_1 \), when \( \mu > \mu_p^{TT} \), we have \( a \mu > 0 \), that is \( \pi_s^{IN} > \pi_s^{IN} \). When \( \mu > \frac{a(b+2)(a+b+c)^2}{2(b+2)(b+c+2)^2}a \), when \( \mu < \frac{a(b+2)(a+b+c)^2}{2(b+2)(b+c+2)^2}a \), we get \( a \mu < 0 \), that is \( \pi_s^{IN} > \pi_s^{IN} \).

When \( \mu > \frac{a(b+2)(a+b+c)^2}{2(b+2)(b+c+2)^2}a \), when \( \mu < \frac{a(b+2)(a+b+c)^2}{2(b+2)(b+c+2)^2}a \), we have \( a \mu > 0 \), that is \( \pi_s^{IN} > \pi_s^{IN} \). When \( \mu > \frac{a(b+2)(a+b+c)^2}{2(b+2)(b+c+2)^2}a \), we get \( a \mu < 0 \), that is \( \pi_s^{IN} > \pi_s^{IN} \).

(3) When \( \mu > \frac{a(b+2)(a+b+c)^2}{2(b+2)(b+c+2)^2}a \), when \( \mu < \frac{a(b+2)(a+b+c)^2}{2(b+2)(b+c+2)^2}a \), we get \( a \mu < 0 \), that is \( \pi_s^{IN} > \pi_s^{IN} \). From results (1), (2) and (3), we conclude that Proposition 1 holds.

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