Strategies for Improving the Capabilities of a Weak Main Manufacturer in Complex Products Systems

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ABSTRACT This paper examines possible strategies for helping a weak main manufacturer to improve its indigenous technological capabilities. We consider two competitive suppliers and one main manufacturer that exhibit differential abilities within a supply chain of complex product systems (CoPS). The weak main manufacturer is focused on encouraging a powerful supplier to license its technology to a domestic supplier and on cultivating a relationship with the domestic supplier. We have designed a cost-sharing (no-licensing, NL) contract and a technology licensing (TL) contract to facilitate cultivation of the supplier relationship and cooperation with regard to technology. The optimal decisions and comparative analysis are characterized under a scenario of cost-sharing and technology licensing based on a benchmark model. The results show that both contracts are effective with respect to technology cooperation and supplier cultivation. However, additional findings show that the most efficient scenario is associated with the TL contract. Numerical examples have been employed for analyzing the validity of a variety of strategies, as well as determining the effect of key parameters on optimal decisions. Useful management insights regarding cooperation strategy and optimal decisions are also obtained.

INDEX TERMS Technology cooperation, supplier cultivation, weak main manufacturer, technology licensing, cost-sharing contract.

I. INTRODUCTION Technology cooperation and supplier cultivation are crucial strategies in high-tech industries where companies are pursuing enhanced product design, timing and cost reductions, and improved indigenous technological capabilities [1]. In a specific example of a high-tech industry, the supply chain associated with complex product systems (CoPS) is subject to high research and development (R&D) costs due to the oligopolistic nature of the technology-intensive market for CoPS [2], [3]. For example, the global aircraft giants Airbus and Boeing have controlled the international market for several decades, thereby acquiring the ability to set technological standards. Not limited to this advantage, and based on long-term practice, they also operate under a management mode called “main manufacturer-supplier (MS)”’. In MS, the main manufacturer integrates a number of suppliers to produce the final products. MS helps the main manufacturer share risks with suppliers and control the operation of the supply chain throughout the product life cycle. While other manufacturers who wish to enter this industry often operate with MS, they cannot perform as well as an incumbent form. Therefore, we define them as weak main manufacturers, for whom technology cooperation with powerful suppliers and domestic supplier cultivation represent greater challenges. For instance, compared with Airbus and Boeing, latecomers
face entry barriers and lack crucial technology and mature domestic suppliers.

Technology licensing (TL) is viewed as a quick and effective way of achieving improvements in technology in high-tech firms [4]–[7]. With TL, a firm sells its technology patents to other firms for royalties or other benefits. TL yields both monetary and nonmonetary benefits for the licensor, such as revenue, the ability of the licensor to establish industry standards, and the removal of entry barriers. TL also helps the licensee improve technology and develop innovation. However, at the same time, negative effects are possible because the licensee might develop new products that become competitive with those of the licensor or that intensify existing competition. For these reasons, the question of whether or how much a firm should license technology to another firm is a strategic issue [8]–[10]. The published studies are focused on illustrating the strategies of parties who are directly involved in TL, but TL research should be extended. The work presented in this paper was conducted for further study.

For a weak main manufacturer of CoPS, domestic supplier cultivation is another urgent mission. As a latecomer to MS, a weak main manufacturer is underdeveloped partly because of a weak domestic industry chain that lacks key technology, such as that related to aviation power plant, flight control, and propulsion systems. Supplier cultivation has positive effects for a manufacturer: control of production processes and early detection of faulty components. According to existing research, joint ventures and TL are common methods of developing suppliers and realizing a collectively better outcome [11], [12]. For example, Dell helped its supplier, Lexmark, improve its printer technology, which ultimately resulted in enhanced performance for both firms [13]. The literature contains a wealth of studies of joint ventures and TL for both the horizontal and the vertical cooperation of two stakeholders. This work is based largely on the assumption that one of the stakeholders possesses advanced technology or that both stakeholders undertake collaborative R&D [14], [15].

However, supplier cultivation is not as simple as joint ventures and TL: the goals are to codevelop innovative technology and to improve the capacity for indigenous technology to succeed when faced with a weak domestic industry supply chain. The work presented in this paper thus explored the following questions: For a weak main manufacturer, which strategies are effective with respect to cultivating a supplier? When the competitive character of all stakeholders is taken into consideration, what strategies are optimal?

To address these research problems, we consider an MS mode with two competitive and heterogeneous suppliers and one weak main manufacturer: one of the suppliers is a domestic supplier and the other is an international supplier. Such an MS-mode structure is quite common in the supply chain for CoPS. For example, one main manufacturer of large passenger aircraft in China has competitive and heterogeneous suppliers who provide aeroengines; clearly, the Chinese main manufacturer is weaker than the global aircraft giants Airbus and Boeing. Additionally, the domestic supplier of its aeroengines is more underdeveloped with respect to technology than its international supplier, CFM International.

The ability of stakeholders is the capability of a company’s creativity, innovation, problem-solving, risk-taking, and directing resources. The three stakeholders differ in regard to ability; this feature is claimed to have a certain amount of significance in distribution and logistics, marketing, and business [16]–[18]. To address the potential entry barriers and risks associated with interruption in the availability of supplies from the powerful supplier, we explore two possible strategies for achieving technology cooperation and domestic supplier cultivation: a joint venture strategy with an NL contract and a TL strategy with a joint contract that combines cost-sharing and revenue-sharing. In summary, our research is concentrated on answering the following questions:

1) What incentive strategies of the weak main manufacturer are effective with respect to technology cooperation and supplier cultivation?

2) If the weak main manufacturer is not directly involved in TL, what should the optimal strategies be? If TL can benefit the main manufacturer indirectly, what can it do to expedite TL implementation?

3) What factors could affect optimal licensing strategies if TL is determined to be an optimal strategy, and should the licensor become a first-tier supplier of the main manufacturer?

To address the above problems, we consider an MS mode where a main manufacturer acts as a weak main manufacturer. The key challenge for the main manufacturer is to improve its capabilities. Technology cooperation and supplier cultivation are possible solutions. Therefore, two effective contracts, i.e., a cost-sharing contract and a joint TL contract, are designed to realize technology cooperation and supplier cultivation. We developed three multigame models to explore the optimal decisions.

The contributions of our study are as follows: i) this paper focuses on a leader that is the low-ability member of the supply chain in inverse cooperation with a powerful supplier, while other works have focused on the powerful members' decisions; ii) we design two incentive mechanisms, which are defined as cost-sharing contract and joint TL contract.

The remainder of this paper is organized as follows. Section II provides a literature review. Section III introduces the preliminary work and describes the establishment of a benchmark model. Section IV explains the development of multistage games under the NL and TL scenarios. Section V discusses the comparative analysis, and the conclusions of this study are presented in Section VI.

II. LITERATURE REVIEW

This paper is focused on the investigation of problems associated with technology cooperation and supplier cultivation in an MS mode. Considering related and similar
work, we divided the literature review into two sections: 1) technology innovation and 2) supply chain coordination.

The effects of technology on such parameters as performance, technology development, and technology licensing are the focus of the literature. For instance, the authors in [19] explored the effect of technological intensity in services on relationships based on an empirical study. The authors in [20] found that collaboration with skilled suppliers can access the effects of technology, and the collaboration concept is important to the development of firms. The authors in [21] declared that technology innovation is a critical resource, and improving technology innovation speed can enhance the performance of a new entrepreneur. In [22], it was further observed that the development of knowledge sourcing, such as technology, patents, and culture, was crucial to move from playing catch-up to forging ahead, and collaborative partners are necessary to approach cutting-edge technologies. However, two crucial challenges with technology innovation were found: whether to license technology and how to determine and use effective licensing strategies. The emphasis of the former is on proving the advantages of technology licensing, while the goal of the latter is to establish optimal licensing strategies. The authors in [23] investigated an optimal TL strategy that included consideration of network effects. The authors in [24] studied the impact of different contracts on the optimal TL strategy and found that in a mixed oligopolistic supply chain, optimal strategies are dependent on a number of factors. In investigating whether a firm should license technology to a potential rival, Yang et al. (2018) found that optimal TL strategies vary with the sourcing strategies of the downstream party. Duplat et al. (2018) [12] explored the conditions under which licensing partners may prefer arbitration over public ordering during the contract-design phase. Khoury et al. (2019) [25] analyzed how experiential learning, bargaining power, and exclusivity affect the determination of an optimal TL contract and presented a theoretical framework developed to explain and test the effects. Most of the existing research obviously concentrates on studying the interrelationship between the licensor and the licensee and especially focuses on the exploration of optimal TL strategies. An evident, important research gap is thus how a third party not directly involved in TL can expedite the process to benefit from TL. To fill this gap, the goal of the work presented here is to investigate possible strategies for encouraging TL between two competitive suppliers from the perspective of a weak main manufacturer so that it can achieve the objectives of cultivating domestic suppliers and improving indigenous technological capability.

Another stream in the coordination literature is similar to our study but with some differences. In those articles, a contract is often used as a classic way of coordinating the smooth operation of a supply chain, and the central focus is performance and coordination under multiple contracts. In [26]–[29], the authors examined the process from conception to the application of contract coordination, and their results and insights are significant with respect to supply chain management. For example, the authors in [30] applied an options contract to study channel coordination, and they determined the effects of an options contract on a supply chain involving pricing and inventory competition as well as an application condition in the options contract. Jokar et al. (2019) [31] researched how to coordinate order quantity and corporate social responsibility in a two-echelon supply chain and found that wholesale and buyback contracts can resolve channel conflicts and lead to win-win solutions. Sadeghi et al. (2019) [32] investigated price coordination in a reverse supply chain and presented insights about the most economic scenario. Zhu et al. (2012) [33] studied the diffusion of innovation and ecological modernization in the green supply chain. Niu et al. (2019) [34] explored the coordination of alternative suppliers in a dual-sourced supply chain. Basu et al. (2019) [35] examined supply chain coordination under asymmetric information and employed an option buyback contract to coordinate the supply chain. Tao et al. (2019) [36] declared that a consignment contract is conditional when coordinating a supply chain. Zhang et al. (2020) [37] found that effective collaboration strategies can improve enterprise performance. In addition, Cosma et al. (2019) concentrated on coordinating supply chain network design [38], [39].

Despite the large body of literature that provides abundant insights into supply chain coordination, gaps in the research still exist. For example, most studies have focused on solving a variety of problems arising from a leader or powerful party and how a powerful supply chain member can control and allocate resources. Previous researchers have failed to address resolution of the challenges faced by weak supply chain members. Compared with helping a powerful member coordinate a supply chain, an issue that possibly deserves greater consideration is how weak members can cooperate with powerful ones to expand their competitiveness. Therefore, we undertook the work presented in this paper with a desire to contribute to the literature on technology cooperation and supplier cultivation. Our focus is to explore possible solutions that enable a weak main manufacturer to improve its ability to facilitate indigenous technological capability based on motivating a powerful supplier to license technology to a domestic supplier.

**III. PRELIMINARY WORK AND BENCHMARK MODEL**

**A. PRELIMINARIES**

We consider two competitive suppliers $s_i (i \in \{1, 2\})$ and one weak main manufacturer $m$ in an MS mode. The three stakeholders differ in their ability to manufacture/supply, which is denoted by $\delta_k (0 < \delta_k < 1)$, where subscript $k (k \in \{1, 2, m\})$ represents supplier $s_i$ and the main manufacturer, respectively. The channel structure is shown in Figure 1. We define $s_1$ as an international supplier and $s_2$ as a domestic supplier. Because the international supplier performs well with regard to a partial key technology for CoPS and has the right to set technological standards, the ability of supplier $s_1$ is thus more powerful than that of supplier $s_2$, and we
employ $\Delta \delta = \delta_1 - \delta_2$ to denote the ability gap between the two competitive suppliers. The main manufacturer is also in a relatively weak position when trading with $s_1$ because of an underdeveloped domestic industry supply chain and a lack of key technology.

According to the existing research, a company’s abilities can be measured numerically and effectively compared. Expert evaluation and empirical study are used as common methods to measure ability. Without loss of generality, we therefore assume $1 > \delta_1 > \delta_2 > 0$ and $1 > \delta_1 > \delta_m > 0$ in a bilateral business relationship. The weak main manufacturer orders substitutable components from supplier $s_i$ with wholesale price $w_{mi}$ and order quantity $q_{mi}$. The final products are homogeneous because of the substitutable components, which means that the pricing of the final product is differential. Based on the research of Qing et al. (2017), market demand is assumed to be deterministic and dependent on price, and the inverse-demand functions are assumed to be

$$P_{mi} = P - \alpha q_{mi} - \beta q_{mj}$$

where $P_{mi}$ is the price of the final product using material from $s_i$, $P > 0$, $\alpha > 0$, $0 < \beta < \alpha$, $i \in \{1, 2\}$, and $i \neq j$. Parameter $\alpha$ represents the price sensitivity of the products. Parameter $\beta$ represents the substitutable degree of the final products using the components from the two competitive suppliers; it could reflect the competitive degree of the two suppliers. Such inverse-demand functions have commonly been used in economics and marketing literature to capture the level of competition between multiple products [11], [40], [41]. Because the technology levels of the two suppliers differ, the cost differences among the materials must be taken into consideration.

Let $c_i$ denote the material cost of supplier $s_i$ and $c_m$ denote the production cost of the weak main manufacturer; without loss of generality, we can assume that $c_1 < c_2$. Such a cost structure is mainly caused by gaps in ability. The powerful supplier has cost advantages due to its technological superiority.

To develop indigenous technological capability, the weak main manufacturer could cultivate the domestic supplier or expedite TL between the two suppliers. The remainder of the paper describes our study of two scenarios based on whether TL occurs. Let superscript or subscript $n \in \{BM, NL, TL\}$ denote different scenarios, where BM indicates a benchmark model, NL represents a scenario with no technology licensing, and TL designates a scenario with technology licensing.

Although TL from powerful supplier $s_1$ is helpful for improving technology, domestic supplier $s_2$ should invest in R&D. Let $t_n(0 \leq t_n \leq 1)$ denote the degree of technology effort of $s_2$ in scenario $n$ and $k_i(k_i > 0)$ represent the unit revenue of the technology effort for each quantity. Suppose that the cost of the technology effort of $s_2$ is convex and well approximated by the simple quadratic function $C(t_{NL}) = k_0 t_{NL}^2 / 2$, and $k_0 > 0$ is a scale factor. Such a quadratic function is commonly used for characterizing diminishing returns from investments [42], [43]. Suppose that using the components from $s_2$ would result in additional cost to the main manufacturer because of the ability gap between the two suppliers. The extra cost is caused mainly by design adjustments, changes in estimated expenses, costs of production delays, and so on. If the unit loss cost per ability gap unit is assumed to be $k_1(k_1 > 0)$ when one component from $s_2$ is used, then the total extra cost is $(\delta_1 - \delta_2)k_1 q_{n2}^n$ under scenario $n$.

An improvement in material quality can generate benefits for both the upstream and downstream chain members, so the main manufacturer can benefit from the technology investment of $s_1$, while the advantage could also depend on its ability. The revenue for the main manufacturer from the technology investment in $s_2$ is thus $\delta_{m2} k_1 t_n q_{n2}^n$. Under the NL scenario, the weak main manufacturer provides a cost-sharing, or NL, contract to share the cost of $s_2$’s technology effort, and the cost-sharing rate is $\varphi_{NL} (0 \leq \varphi_{NL} \leq 1)$. Cost-sharing is an effective contract for achieving risk-sharing and encouraging technological innovation [11], [12].

Technology licensing contracts are an effective method for supply chain coordination [1], [14]. Under the TL scenario, the weak main manufacturer designs a TL contract to cultivate domestic supplier $s_2$ and expedite TL from $s_1$ to $s_2$. The TL contract contains three elements: 1) The weak main manufacturer allocates a given portion of its revenue, which is acquired from the technology investment in $s_2$, to international supplier $s_1$ as an incentive; the revenue-sharing rate is denoted by $r(0 \leq r \leq 1)$; and the condition of the revenue-sharing is that $s_1$ should be a licensor and license its technology to domestic supplier $s_2$ under a royalty structure. 2) $s_1$ licenses technology to $s_2$ with a royalty rate of $\eta_1(\eta_1 > 0)$; the royalty fee to $s_1$ is paid by $s_2$, including a unit variable fee denoted by $\nu(v \geq 0)$ and a fixed fee denoted by $F(F \geq 0)$. 3) The weak main manufacturer shares a portion of the cost of the domestic supplier’s technology effort, with the cost-sharing rate denoted by $\varphi_{TL} (0 \leq \varphi_{TL} \leq 1)$. The royalty rate is still $\eta_1$, and the domestic supplier can transfer only part of $\eta_1$ because of limited technological ability. Suppose the technology transfer capability of $s_2$ is $\theta(0 < \theta < 1)$; the absorbed royalty is then $\theta \eta_1$, and it is clear that $\theta \eta_1 < \eta_1$. 

**FIGURE 1. Channel structure.**
According to [1], the effect of TL is that it contributes to a reduction in the cost of $s_2$’s technology effort with a specific percentage of $\theta \eta$. The cost of $s_2$’s technology effort would therefore be $C(t_{TL}) = (1 - \theta \eta) k_{0} t_{TL}^{2} / 2$ under the TL scenario. All of the notations are listed in Table 1.

### B. BENCHMARK MODEL

Since the validity and effect of a strategy for achieving technology cooperation and supplier cultivation should be well illustrated, we first develop a benchmark model (BM) to elucidate the validity and effect of the strategies described below. In the BM, coordination is ignored in the MS mode, and the three stakeholders are in a state of total competition. The decision problem is formulated as a two-stage game with the following sequence.

**Stage 1:** The two suppliers determine their wholesale price independently to maximize their individual profit. If $\pi_{BM}^{s_1}$ denotes the profit of supplier $s_1$ under the BM scenario, then $\pi_{BM}^{s_1}$ is

$$\max_{w_{m1}} \pi_{BM}^{s_1} = (w_{m1} - c_1) q_{m1}$$

(2)

$$\max_{w_{m2}} \pi_{BM}^{s_2} = (w_{m2} - c_2) q_{m2}$$

(3)

**Stage 2:** The weak main manufacturer makes a decision about production quantities to maximize its individual profit. If $\pi_{m}^{BM}$ denotes the profit of the main manufacturer under the BM scenario, then $\pi_{m}^{BM}$ is

$$\max_{q_{m1}, q_{m2}} \pi_{m}^{BM} = \sum_{i=1,2} (P_{m} - w_{m}^{BM} - c_{m}) q_{mi} - (\delta_1 - \delta_2) k_{l} d_{m2}^{BM}$$

(4)

Backward induction is utilized for solving the two-stage game. We can then acquire the optimal decisions of all stakeholders under the BM scenario and incorporate them into Proposition 1. Proofs of all subsequent propositions and conclusions are presented in the Appendix.

**Proposition 1:** Let $w_{m1}^{BM^*}$ denote the optimal wholesale price of supplier $s_1$ under the BM scenario and $q_{m1}^{BM^*}$ denote the optimal production quantity of the main manufacturer. The optimal decisions about wholesale prices and production quantities under the BM scenario are then given as follows $w_{m1}^{BM^*}$, as shown at the bottom of the page.

**Proposition 2:** Let $\pi_{s_1}^{BM^*}$, $\pi_{m}^{BM^*}$, and $\pi_{T}^{BM^*}$ denote the optimal total profit of supplier $s_1$, the main manufacturer, and the entire supply chain, respectively. The optimal profits

| Notation | Description | Notation | Description |
|----------|-------------|----------|-------------|
| $s_i$    | subscript that identifies supplier $s_i$, $i \in \{1,2\}$ | $\varrho_s$ | cost-sharing rate for $m$ under scenario $n$ |
| $m$      | subscript that identifies the main manufacturer | $\eta$ | royalty rate |
| $\delta_s$ | ability of suppliers $s$ | $\delta_m$ | ability of $m$ |
| $\delta_m$ | ability of main manufacturer $m$ | $P$ | fixed fee that $s_1$ charges for technology licensing |
| $P_{max}$ | price of the final product produced by using material from $s_1$ | $\alpha$ | sensitivity of price to demand |
| $\beta$ | degree of substitution of the final products | $k_r$ | scale factor |
| $P$ | maximum customer valuation | $k_i$ | per unit revenue from the technology effort of $s_2$ |
| $t_i$ | degree of technology effort for $s_i$ under scenario $n$ | $r$ | revenue-sharing rate |
| $c_i$ | unit cost of material from $s_i$ | $\theta$ | technology transfer capability of $s_2$ |
| $\pi_{BM}^{s_i}$ | total profit of $s_i$ under scenario $n$ | $\pi_{BM}^{s_i}$ | total profit for $s_i$ under scenario $n$ |
| $\pi_{BM}^{m}$ | total supply chain profit | $w_{m}$ | wholesale price of $s_i$ |
under the BM scenario are then given as follows:

\[ \pi_{Bm}^* = \sum_{i=1,2} (p_{mi}^B - w_{mi}^B - c_m)q_{mi}^B - (\delta_1 - \delta_2)k_i q_{mi}^B \]

\[ \pi_{S1}^B = (w_{m1}^B - c_1)q_{m1}^B \]

\[ \pi_{S2}^B = (w_{m2}^B - c_2)q_{m2}^B \]

\[ \pi^*_T = \pi^*_{S1} + \pi^*_{S2} + \pi^*_m \]

**Conclusion 1 (Impact of Cost and Supplier Ability Gaps on Optimal Wholesale Prices):**

1. \( \frac{\partial \pi_{S1}^B}{\partial c_1} > 0, \frac{\partial \pi_{S1}^B}{\partial \delta_1} > 0, \frac{\partial \pi_{S1}^B}{\partial \delta_2} < 0; \)
2. \( \frac{\partial \pi_{S2}^B}{\partial c_2} > 0, \frac{\partial \pi_{S2}^B}{\partial \delta_1} > 0, \frac{\partial \pi_{S2}^B}{\partial \delta_2} < 0; \)
3. \( \frac{\partial \pi^*_T}{\partial \Delta \delta} > 0, \frac{\partial \pi^*_T}{\partial \Delta \delta} < 0. \)

The optimal decisions under BM suggest that the optimal wholesale prices and quantities are determined by competition among the stakeholders, who also establish the optimal performance of the individual members and the entire supply chain. The suppliers’ ability gaps and the stakeholders’ cost structures affect the performance of the individual members and the entire supply chain. Conclusion 1 reveals the quantitative structure between the optimal wholesale prices and costs. For a particular party, optimal wholesale prices would rise with increases in either its own material cost or a rival’s material cost; however, when the weak main manufacturer’s cost is high, it is better to decrease the wholesale price regardless of supplier ability. Supplier ability gaps could affect optimal performance by changing the optimal wholesale price, and a greater ability gap would substantially benefit the powerful supplier.

**IV. COST-SHARING CONTRACT VS. TECHNOLOGY LICENSING CONTRACT**

In this section, we propose two strategies for achieving technology cooperation and supplier cultivation. In subsection A, we design a cost-sharing contract without technology licensing and then develop a multistage model to investigate optimal decisions in scenario NL. In subsection B, a TL contract, i.e., a joint contract combining cost-sharing and revenue-sharing, is designed to stimulate TL between two competitive suppliers. The cost-sharing contract works in two ways without technology licensing. On the one hand, it can motivate the domestic supplier to invest in R&D; on the other hand, it can effectively alleviate R&D cost and risk of the domestic supplier. The purpose of the TL contract lies in stimulating technology licensing and finally improving indigenous technological capabilities.

**A. COST-SHARING CONTRACT AND EQUILIBRIUM (NL)**

TL is more likely to be stagnant or absent when international trade disputes affect a business [10], [14]. For this reason, a weak main manufacturer should consider how to cultivate a domestic supplier under an NL contract from a powerful supplier. Generally, sharing the cost of R&D is a common strategy for reducing the risks associated with technological innovation. Therefore, in an NL scenario, the weak main manufacturer provides a cost-sharing contract to share a portion of the cost of the domestic supplier’s technology effort. On the one hand, the contract is helpful for sharing the R&D risk of the domestic supplier; on the other hand, the contract is conducive to enhancing the competitiveness of the domestic supplier and the industry supply chain. Because a powerful individual is likely to act first to obtain a first-mover advantage under the NL scenario, the decision problem is developed as a multistage game with the following sequence:

**Stage 1:** The two suppliers make a decision regarding their wholesale price simultaneously, and they decide on their wholesale price independently to maximize their individual profit. Let \( \pi_{s1}^N \) denote the profit of supplier \( s_1 \) under the NL scenario. Then, \( \pi_{s1}^N \) and the decision problem during the first stage are

\[ \max_{w_{m1}^N} \pi_{s1}^N = (w_{m1}^N - c_1)q_{m1}^N \]  

\[ \max_{w_{m2}^N} \pi_{s2}^N = (w_{m2}^N - c_2)q_{m2}^N - (1 - \varphi_N) \frac{1}{2} k_i q_{m2}^N \]

\[ + (1 - \delta_m) k_1 q_{m2}^N \]  

**Stage 2:** The weak main manufacturer decides production and order quantities based on the given wholesale prices. Let \( \pi_{s1}^N \) denote the profit of the weak main manufacturer under the NL scenario. Then, \( \pi_{s1}^N \) and the decision problem in the second stage are

\[ \max_{q_{m1}^N, q_{m2}^N} \pi_{s1}^N = \sum_{i=1,2} (p_{mi}^N - w_{mi}^N - c_m)q_{mi}^N \]

\[ + \delta_m k_1 q_{m2}^N - (\delta_1 - \delta_2) k_i q_{m2}^N \]

\[ - \varphi_N \frac{1}{2} k_1^2 q_{m2}^N \]  

**Stage 3:** The weak main manufacturer provides an NL contract that is dependent on its production and establishes a cost-sharing rate. The goal of the NL contract is to encourage the domestic supplier to develop technology before \( s_2 \) makes a decision concerning investing in R&D. The decision problem in the third stage is

\[ \max_{p_{mi}^N, q_{mi}^N} \pi_{s1}^N = \sum_{i=1,2} (p_{mi}^N - w_{mi}^N - c_m)q_{mi}^N \]

\[ + \delta_m k_1 q_{m2}^N - (\delta_1 - \delta_2) k_i q_{m2}^N \]

\[ - \varphi_N \frac{1}{2} k_1^2 q_{m2}^N \]  

**Stage 4:** \( s_2 \) determines the degree of technology effort that will maximize individual profit while also including consideration of other stakeholders’ decisions. The decision problem in the fourth stage is

\[ \max_{p_{mi}^N, q_{mi}^N} \pi_{s2}^N = (w_{m2}^N - c_2)q_{m2}^N - (1 - \varphi_N) \frac{1}{2} k_i^2 q_{m2}^N \]

\[ + (1 - \delta_m) k_1 q_{m2}^N \]  

Such a decision sequence is practical because a powerful firm acts first to garner a first-mover advantage.
Using backward induction for solving the multistage game, we can summarize the equilibrium strategies and outcomes as Proposition 3.

**Proposition 3:** Under the NL scenario, let \( w_{ni}^{NL} \) denote the optimal wholesale price of supplier \( s_i \), \( t_{NL}^* \) represent the optimal degree of technology effort for \( s_2 \), \( q_{ni}^{NL} \) designate the optimal cost-sharing rate, and \( q_{ni}^{NL} \) indicate the optimal production quantity of the main manufacturer. The optimal decisions under the NL scenario are then given as follows \( w_{ni}^{NL} \), as shown at the bottom of the page, where

\[
l_1 = k_1^4 \alpha^2 + k_0 k_2^2 (7 \alpha \beta^2 - 12 \alpha^3) + 8k_0^3 (4 \alpha \beta^2 - 5 \alpha^2 \beta^2 + \beta^4)
\]

\[
l_2 = k_2^4 \alpha^2 + 32k_0^2 \alpha (\alpha^2 - \beta^2) + 4k_0 k_2^2 (\beta^2 - 3 \alpha^2)
\]

\[
l_3 = k_2^2 \alpha + 8k_0 (\beta^2 - \alpha^2) + 2k_2^2 \alpha \delta_m + 2k_2^2 \alpha_m
\]

\[
l_4 = k_2^2 \alpha - 4k_0 P \alpha + 2k_0 P \beta + 2k_0 P \beta^2
\]

\[
l_5 = k_2^2 \alpha + 8k_0 k_2^2 (7 \alpha \beta^2 - 12 \alpha^3) + 8k_0^3 (4 \alpha \beta^2 - 5 \alpha^2 \beta^2 + \beta^4)
\]

\[
l_6 = 3k_2^4 \alpha + 64k_0^2 \alpha (\alpha^2 - \beta^2) + 8k_0 k_2^2 (\beta^2 - 4 \alpha^2)
\]

\[
l_7 = k_2^4 \alpha + 64k_0^2 \alpha (\alpha^2 - \beta^2) + 8k_0 k_2^2 (\beta^2 - 2 \alpha^2)
\]

and \( l_8 = k_2^2 \alpha (3 + 2 \delta_m - \delta_m^2) - 8k_0 (\alpha^2 - \beta^2) \) are used for saving notations.

**Proposition 4:** Let \( \pi_{ni}^{NL}^* \), \( \pi_{ni}^{NL}^* \), and \( \pi_{ni}^{NL}^* \) denote the optimal total profit of supplier \( s_i \), the main manufacturer, and the entire supply chain, respectively. The optimal profits under the NL scenario can then be summarized as follows:

\[
\pi_{ni}^{NL}^* = \sum_{i=1,2} \left( (P_{ni}^{NL}^* - w_{ni}^{NL}^* - c_m)q_{ni}^{NL}^* + \delta_m k_1 t_{NL}^* q_{ni}^{NL}^* - (\delta_1 - \delta_2) k_1 q_{ni}^{NL}^* - \varphi_{NL}^* \right) \frac{1}{2} k_0 t_{NL}^2
\]

\[
\pi_{s2}^{NL}^* = (w_{m2}^{NL}^* - c_2)q_{m2}^{NL}^* - (1 - \varphi_{NL}^*) \frac{1}{2} k_0 t_{NL}^2 + (1 - \delta_m) k_1 q_{ni}^{NL}^* q_{ni}^{NL}^*
\]

\[
\pi_{s1}^{NL} = (w_{ni}^{NL} - c_1)q_{m1}^{NL} + \pi_{ni}^{NL}^*
\]

The optimal decisions under the NL scenario are considerably different from those with the BM scenario. Analysis of the optimal decisions under NL shows that the investment of the domestic supplier in R&D and the cost-sharing rate vastly change the optimal decisions and level of performance. The weak main manufacturer determines a beneficial cost-sharing rate dependent only on its ability. However, the degree of technology effort of the domestic supplier is complex, since the R&D revenue, the optimal quantity, and the optimal cost-sharing rate are all unstable. Section 5 provides a detailed explanation of how the performance of a different individual and an entire supply chain vary according to the cost-sharing contract and the degree of technology effort.
B. TECHNOLOGY LICENSING CONTRACT AND EQUILIBRIUM (TL)

TL is a crucial cooperative strategy for technology development, especially in the high-tech industry. In a TL scenario, the three stakeholders must reach an agreement about TL when a TL contract is provided by the weak main manufacturer. The TL contract is a joint contract that combines cost-sharing and revenue-sharing. Because the domestic supplier pays for TL, it is subject to greater financial pressure. Cost-sharing can therefore reduce the risks faced by the domestic supplier with respect to technology and finance. To improve supplier cultivation and indigenous technological capability and as an integrator of an MS mode, the weak main manufacturer commits to expediting the TL process and investing in R&D. A revenue-sharing rate is provided as motivation for s1 to license its technology, and a cost-sharing rate encourages s2 to invest in R&D. The multistage game is developed with the following sequence:

Stage 1: The wholesale prices are first given by the two competitive suppliers, with \( w_{m1}^T \) denoting the wholesale price given by supplier s1. The subsequent game is thus a multistage game based on the given wholesale prices, i.e., \( w_{m1}^T \) and \( w_{m2}^T \).

Stage 2: Depending on the given wholesale prices, the weak main manufacturer determines the production and order quantity. \( \pi_{m1}^T \) is employed for designating the profit for the weak main manufacturer under the TL scenario so that \( \pi_{m1}^T \) and the decision problem in the second stage are then

\[
\max_{q_{m1},q_{m2}} \pi_{m1}^T = \sum_{i=1,2} (p_{m1}^T - w_{m1} - c_{mi})q_{mi}^T + r_{m1}k_{1TL}q_{m2}^T
\]

\[
- (\delta_1 - \delta_2)k_{1TL}q_{m2} - \varphi_{TL}(1 - \theta\eta) \frac{1}{2} k_{1TL}^2 \tag{10}
\]

Stage 3: With consideration of the TL contract, powerful supplier s1 determines whether to license technology and what the optimal royalty rate \( \eta \) should be to maximize its profit. The decision problem in the third stage is

\[
\max_{\eta} \pi_{s1}^T = (w_{m1}^T - c_{1})q_{m1}^T + (1 - r)\delta_{m1}k_{1TL}q_{m2}^T + F + \nu \eta \tag{11}
\]

Stage 4: Based on knowledge of the royalty rate, the weak main manufacturer decides on cost-sharing rate \( \varphi_{TL} \). The objective of the main manufacturer is to maximize its individual profit. The optimization decision in the fourth stage is

\[
\max_{\varphi_{TL}} \pi_{m2}^T = \min_{\eta} \sum_{i=1,2} (p_{m1}^T - w_{m1} - c_{mi})q_{mi}^T + r_{m2}k_{2TL}q_{m2}^T
\]

\[
- (\delta_1 - \delta_2)k_{2TL}q_{m2} - \varphi_{TL}(1 - \theta\eta) \frac{1}{2} k_{2TL}^2 \tag{12}
\]

Stage 5: According to information from the previous stage, the domestic supplier s2 establishes the degree of technology effort \( t_{TL} \). The goal of s2 is to maximize its individual profit. The optimization decision in the fifth stage is

\[
\max_{t_{TL}} \pi_{s2}^T = (w_{m2}^T - c_{2})q_{m2}^T - (1 - \varphi_{TL}(1 - \theta\eta)) \frac{1}{2} k_{2TL}^2
\]

\[
+ (1 - \delta_{m})k_{tTL}q_{m2}^T - F - \nu \eta \tag{13}
\]

This type of decision sequence is commonly based on the ability of the different stakeholders. Although the objective function of powerful members should consider competition as well as incentives, a member can still make an earlier decision to obtain a first-mover advantage. Backward induction is used for solving the multistage game. The equilibrium strategies and outcomes are summarized as Proposition 5.

Proposition 5: Under the TL scenario, let \( t_{TL}^* \) represent the optimal degree of technology effort for s2. \( \varphi_{TL}^* \) designates the optimal cost-sharing rate, and \( q_{m1}^T^* \) denote the optimal production quantity of the main manufacturer. The optimal decisions under the TL scenario are then given as follows \( q_{m1}^T^* \), as shown at the bottom of the next page.

Proposition 6: Let \( \pi_{m1}^T^*, \pi_{s1}^T^*, \) and \( \pi_{s2}^T^* \) denote optimal total profit under the TL scenario for supplier s1, the main manufacturer, and the entire supply chain, respectively. The optimal profits can then be summarized as follows:

\[
\pi_{m1}^T^* = \sum_{i=1,2} (p_{m1}^T - w_{m1} - c_{mi})q_{mi}^T + r_{m1}k_{1TL}q_{m2}^T
\]

\[
- (\delta_1 - \delta_2)k_{1TL}q_{m2} - \varphi_{TL}^*(1 - \theta\eta^*) \frac{1}{2} k_{1TL}^2 \tag{14}
\]

\[
\pi_{s1}^T^* = (w_{m1}^T - c_{1})q_{m1}^T + (1 - r)\delta_{m1}k_{1TL}q_{m2}^T + F + \nu \eta^* \tag{15}
\]

\[
\pi_{s2}^T^* = (w_{m2}^T - c_{2})q_{m2}^T - (1 - \varphi_{TL}^*)(1 - \theta\eta^*) \frac{1}{2} k_{2TL}^2
\]

\[
+ (1 - \delta_{m})k_{tTL}q_{m2}^T - F - \nu \eta^* \tag{16}
\]

\[
\pi_{m2}^T^* = \pi_{m1}^T^* + \pi_{s1}^T^* + \pi_{s2}^T^* \tag{17}
\]

Conclusion 2 (The Effect of the Ability of the Weak Main Manufacturer on the Cost-Sharing Rate):

\[
\frac{\partial \pi_{m1}^*}{\partial \delta_{m}} > 0, \quad \frac{\partial \pi_{m1}^*}{\partial \delta_{m}} > 0. \tag{18}
\]

It is found that the optimal decisions and performance of the supply chain change dramatically because of TL. The licensor, namely, the powerful supplier, benefits from TL; the profit structure of the licensee, i.e., the domestic supplier, also exhibits a tremendous difference. These outcomes occur mainly because TL changes the costs and revenues of the stakeholders. Optimal performance is enhanced by the TL contract. In addition, the royalty fee, cost-sharing rate, and revenue-sharing rate have significant effects on the optimal royalty rate for the powerful supplier and the optimal technology effort of the domestic supplier. In other words, the TL contract of the weak main manufacturer can coordinate the supply chain and the two competitive suppliers such that they become more effective. Conclusion 2 suggests that no matter what the incentive strategy is, the optimal cost-sharing rate of the main manufacturer will increase in line with its ability; therefore, the weak main manufacturer could invest a
stakeholders, and contractual items.

In regard to technology transfer (\(\eta\)), the abilities of different suppliers, such as the degree of supplier competition (\(\beta\)), the capability of the domestic supplier with regard to technology transfer (\(\theta\)), the abilities of different stakeholders, and contractual items.

V. COMPARATIVE ANALYSIS

We provide numerical examples based on the BM to illustrate the performance of the contracts with respect to TL and supplier cultivation, as well as the effect of key parameters on the optimal decisions. The works in [44] and [45] are taken as a reference, and we then set the parameters as \(P = 20\), \(\alpha = 1\), \(c_1 = 2\), \(c_2 = 3\), \(c_m = 4\), \(\delta_m = 0.4\), \(\delta_1 = 0.6\), \(\delta_2 = 0.4\), \(v = 1\), \(r = 0.4\), and \(\theta = 0.5\). A broad range of key parameters is used to ensure the validity of the comparative analysis. Subsection A is focused on revealing the validity and preference of the contracts; the effect of a given wholesale price on TL is explored. Subsection B describes our investigation of the effect on the optimal decisions and TL with respect to key parameters, such as the degree of supplier competition (\(\beta\)), the ability of the domestic supplier with regard to technology transfer (\(\theta\)), the abilities of different stakeholders, and contractual items.

A. ANALYSIS OF CONTRACT VALIDITY AND PREFERENCE

Since the optimal decisions in scenario TL are the decision-making problem with respect to the given wholesale prices under TL, we first compared the optimal wholesale prices under NL and BM such that those values can set a reference point for the wholesale prices. Figure 2 shows the optimal wholesale prices under NL and BM when the degree of competition between the two suppliers is increasing. It can be seen that wholesale prices under the cost-sharing contract exhibit three main characteristics depending on the degree of competition.

First, optimal wholesale prices decrease in line with the degree of supplier competition. This means that upstream competition can reduce the main manufacturer’s material cost. The reason for this effect lies in the fact that horizontal competition can benefit downstream members by reducing the wholesale price. Second, regardless of supplier cultivation, the powerful supplier’s optimal wholesale price is always below that of the domestic supplier. In other words, the powerful supplier always retains a cost advantage. This advantage is observed primarily because of the advantage enjoyed by the powerful supplier with respect to cost and ability, which enables it to compete effectively with the domestic supplier at preponderant trade prices. Third, the wholesale prices under NL are less than those in the case of BM. Clearly, the cost-sharing contract changes the optimal decisions. In other words, the cultivation of the domestic supplier in regard to R&D not only alleviates the cost of trading with the domestic supplier but can also reduce the trading cost with the powerful supplier. In general, coordination strategies can work to enhance the performance of a supply chain by indirectly reducing the cost of trading with upstream members. Therefore, we take into consideration all three of the above characteristics in setting the given wholesale prices under TL. The purpose is to illustrate how a TL contract operates with respect to technology cooperation and supplier cultivation.

\[
q^{TL*}_{m1} = \frac{[(2r - 1) \delta_m + 1] (\alpha - \beta) (P - c_m) + \beta k_1 (\delta_1 - \delta_2) - \alpha w_{m1}^{TL} + \beta w_{m2}^{TL}}{2 (\alpha^2 - \beta^2) [(2r - 1) \delta_m + 1] + \sqrt{2} \beta k_1 \sqrt{k_0 v \delta_m} (r - 1) [(2r - 1) \delta_m + 1]^5}
\]

\[
q^{TL*}_{m2} = \frac{[\delta_m (2r - 1) + 1] [\alpha - \beta] (P - c_m) - \alpha k_1 (\delta_1 - \delta_2) + \beta w_{m1}^{TL} - \alpha w_{m2}^{TL}}{2 (\alpha^2 - \beta^2) [(2r - 1) \delta_m + 1] - \sqrt{2} \alpha k_1 \sqrt{\theta \delta_m v k_0} (r - 1) [(2r - 1) \delta_m + 1]^5}
\]

\[
\eta^* = \frac{1}{\theta} + \sqrt{\frac{k_1^2 (r - 1) q^{TL*}_{m2} \delta_m [(2r - 1) \delta_m + 1]}{2 k_0 v \theta}}
\]

\[
\psi_{TL}^* = \frac{(2r + 1) \delta_m - 1}{(2r - 1) \delta_m + 1}
\]

\[
t_{TL}^* = \frac{k_1 q^{TL*}_{m2} (1 - \delta_m)}{k_0 (\theta \eta^* - 1) (\psi_{TL}^* - 1)}
\]
Figure 3 shows the effect of the contracts on the optimal performance of the entire supply chain. The key findings shown in Figure 3 can be summarized in two parts.

First, \( \frac{\partial \pi}{\partial \beta} < 0 \), i.e., the optimal total profit of the whole supply chain decreases with the degree of supplier competition. Intuitively, upstream competition weakens total performance. Second, when \( w_{TL}^{m1} = w_{NL}^{m1} \) and \( w_{TL}^{m2} = w_{NL}^{m2} \) hold, we have \( \pi_{TL}^{NL} > \pi_{TL}^{BM} > \pi_{BM}^{NL} \); for the scenarios \( \{w_{m1}^{TL} < w_{m1}^{NL}, w_{m2}^{TL} = w_{m2}^{NL}\} \) and \( \{w_{m1}^{TL} < w_{m1}^{NL}, w_{m2}^{TL} < w_{m2}^{NL}\} \), \( \pi_{TL}^{NL} > \pi_{NL}^{NL} > \pi_{BM}^{NL} \) is strictly true. It is worth noting that optimal performance is greatly improved in scenario TL when \( w_{TL}^{m1} < w_{m1}^{NL} \) and \( w_{TL}^{m2} < w_{m2}^{NL} \). These results can be analyzed in two ways. On the one hand, the two designed contracts can promote the total performance of at least one wholesale price in scenario TL that is less than it is in scenario NL. On the other hand, the most efficient performance occurs when both of the wholesale prices in scenario TL are less than those in scenario NL. The above results indicate that the two contracts are significant in improving supply chain performance. Next, we analyze contract preference from optimal individual performance.

Table 2 illustrates how the performance of each individual varies with the degree of supplier competition for the given wholesale prices. As the trends of each individual’s performance are similar, to avoid trivial findings, we focus our analysis on the benchmark model and the effective scenarios. The main findings are analyzed as follows.

(i) The effect of the degree of supplier competition on optimal performance is shown as \( \frac{\partial \pi}{\partial \beta} > 0 \), \( \frac{\partial \pi}{\partial \beta} < 0 \), \( \frac{\partial \pi}{\partial \beta} < 0 \). That is, the two competitive suppliers’ optimal profits decrease with \( \beta \) no matter which scenario is chosen. However, the weak main manufacturer’s optimal profit increases with \( \beta \). The main reason for this effect is the competition between the...
two suppliers. Competition between the two suppliers becomes fiercer with increased product substitutability, which means that they must thus trade with the main manufacturer at a concessional wholesale price to remain competitive. Such a situation gives the weak main manufacturer a chance for cost savings when purchasing materials. Therefore, it is clear that supplier competition damages their individual profits but substantially benefits the weak main manufacturer.

(ii) The main manufacturer and the powerful supplier prefer the TL contract. The evidence stems from Table 2. It can be easily summarized that $\pi_{s1}^{NL} > \pi_{s1}^{BM}$ and $\pi_{m}^{NL} > \pi_{m}^{BM}$ are always true regardless of the wholesale prices. Most importantly, we find that the powerful supplier’s level of performance is inferior to that achieved under the BM. That is, the NL contract is not only good for cultivating the domestic supplier but can also make sense with respect to preventing the powerful supplier from increasing its profitability. Therefore, technology cooperation and domestic supplier cultivation is a pivotal method of strengthening the international competitiveness of a domestic industry.

(iii) The domestic supplier prefers to share costs. It can be easily obtained from Table 2 that $\pi_{s2}^{NL} > \pi_{s2}^{BM} > \pi_{s2}^{TL}$ is always true. This result indicates that the cost-sharing contract is valid to enhance the performance of the entire supply chain as well as that of the domestic supplier. Surprisingly, compared with the BM, the optimal profit of the powerful supplier is diminished under TL. This is mainly because the revenue-sharing contract generates more advantage for the powerful supplier. Therefore, the domestic supplier can be cultivated by increasing its profitability with an NL contract. The advantage of the NL contract lies in its facilitation of the efficiency of the domestic supplier’s technological innovation. The domestic supplier can be motivated to increase R&D investment and to yield additional revenue. Additionally, because the NL contract is ultimately aimed at cultivating the domestic supplier through sharing the cost and risk associated with R&D, the NL contract is also effective for improving technology.

The above results suggest that TL benefits all parties for a number of reasons. First, the licensor, i.e., the powerful supplier, licenses its technology to the domestic supplier based on the following considerations: a) the licensor benefits from the royalty fee, and TL is likely to generate greater profit; b) the weak main manufacturer pays a specific portion of its revenue to stimulate TL so that once the powerful supplier licenses the technology, the powerful supplier shares in the revenue of the weak main manufacturer. Second, the benefit to the licensee, i.e., the domestic supplier, is greater with TL because TL is helpful for enhancing the domestic supplier’s efficiency with respect to technological innovation.

The final point arising from the analysis is that the weak main manufacturer acquires further indirect advantages from TL: reduced purchase costs and additional innovation revenue. Enhanced performance of the supply chain is therefore attributed to technology cooperation among stakeholders and an effective supplier cultivation strategy. TL thus benefits both the licensee and the licensor and further improves the performance of the supply chain.

### B. ANALYSIS OF OPTIMAL DECISIONS

#### 1) EFFECT OF $\beta$, $\delta_1$, AND $\delta_m$ ON OPTIMAL QUANTITY AND WHOLESALE PRICE

The topic of disputes is usually whether the licensor should be the first-tier supplier. To confirm that the licensor is preferable as a first-tier supplier, we take the optimal quantity to be a criterion because the first-tier supplier should provide advanced components directly to the main manufacturer. Figure 4 shows the effect of the degree of supplier competition and the stakeholders’ abilities on the optimal quantity and wholesale price decisions. The key results shown in Figure 4 can be summarized as follows:

1. $\frac{\partial q_{m1}^{*}}{\partial \beta} > 0$, $0 < \beta < \beta_1$, $\frac{\partial q_{m1}^{*}}{\partial \delta_1} < 0$; $\frac{\partial q_{m1}^{*}}{\partial \delta_m} < 0$,

2. $\frac{\partial q_{m1}^{*}}{\partial \delta_1} > 0$, $\frac{\partial q_{m1}^{*}}{\partial \delta_1} > 0$, $\frac{\partial q_{m1}^{*}}{\partial \delta_m} < 0$.
FIGURE 4. Optimal quantities and wholesale prices under different scenarios.

3) $q_{m1}^{BM^*} > q_{m2}^{BM^*} > q_{m1}^{NL^*} > q_{m2}^{NL^*} > q_{m2}^{TL^*}$

Figure 4(a) shows that the optimal quantity of product $q_{m1}$ decreases with $\beta$ while $0 < \beta < \beta_1$, but it increases with $\beta$ while $\beta_1 < \beta < 1$, and the optimal quantity of product $q_{m2}$ always decreases with $\beta$. This effect is attributable mainly to the competitive and substitutable degree of the two suppliers.
When the substitutable degree of the two suppliers is greater than $\beta_1$, the cost advantage of the powerful supplier becomes significant, and the main manufacturer prefers to obtain material from the powerful supplier. In particular, when $\beta < \beta_0$ under TL, the optimal quantity from the domestic supplier is ranked second to the optimal quantity from the powerful supplier. This ranking strongly suggests that the TL contract is highly effective for cultivating a domestic supplier when the degree of substitution of materials is significantly different, especially when the substitutability of the material is lower.

Figures 4(b) and 4(c) illustrate that the optimal quantity of product $q_{m2}$ increases with $\delta_m$ but decreases with $\delta_1$, while $q_{m1}$ exhibits completely opposite behavior. The optimal whole price shows the same trend. These results are caused by the differing abilities of the three stakeholders: the higher the weak main manufacturer’s ability is, the greater the advantage associated with any domestic supplier cultivation. However, the gap between the levels of ability of the two competitive suppliers hurts the domestic supplier. The advantages of the powerful supplier with respect to technology and cost is increasingly prominent as the gap in ability continues to widen. This result also reveals that the optimal quantity $q_{m1}$ is always greater than $q_{m2}$ under the same scenario and especially shows that the optimal profit under TL is the highest for all of the scenarios.

In particular, based on some important results indicated in Figure 4(c), when each independent scenario is evaluated, there exists a specific $S^*_m$ that makes the optimal wholesale price of the powerful supplier greater than the domestic supplier’s wholesale price. This effect is created as the ability gap between the suppliers becomes substantially larger. At that point, the powerful party no longer needs a concessional wholesale price to maintain a cost advantage since it dominates the upstream market. An examination of the results demonstrates that the licensor, i.e., the powerful supplier, maintains its role as the primary supplier of material to the weak main manufacturer. Being a first-tier supplier helps the powerful supplier directly enhance its economic performance. Therefore, taking all of the benefits into consideration, the powerful supplier is better off being a first-tier supplier and simultaneously licensing technology to the domestic supplier.

2) EFFECT OF $\beta$, $\theta$, $\delta_i$, AND $\delta_m$ ON THE OPTIMAL COST-SHARING RATE AND DEGREE OF TECHNOLOGY EFFORT

The degree of technology effort on the part of the domestic supplier is one main standard for assessing the effect of different strategies and supplier cultivation. We analyze the effect of the suppliers’ competitive degree, the ability of different stakeholders, and the technology transfer capability of the domestic supplier with respect to the optimal cost-sharing rate and the degree of technology effort. Figure 5 shows the relations. The results illustrated in Figure 5 can be expressed as follows:

1) $\frac{\partial r_{NL}^*}{\partial \theta} < 0$, $\frac{\partial r_{TL}^*}{\partial \theta} > 0$, $\frac{\partial r_{NL}^*}{\partial \delta_m} < 0$;
2) $\frac{\partial r_{NL}^*}{\partial \delta_i} > 0$, $\frac{\partial r_{TL}^*}{\partial \delta_i} < 0$, $\frac{\partial r_{NL}^*}{\partial \delta_1} < 0$, $\frac{\partial r_{TL}^*}{\partial \delta_1} > 0$;
3) $\frac{\partial \varphi_{NL}^*}{\partial \delta_m} > 0$.

Figure 5(a) demonstrates that the degree of technology effort on the part of the domestic supplier decreases with $\beta$ when the NL contract is used but increases with $\beta$ when TL is employed. This outcome occurs because a high degree of competition indicates a small gap between the two suppliers so that the optimal cost-sharing rate on the part of the domestic supplier reduces its investment in R&D. However, rather than reducing its R&D investment, the domestic supplier prefers to increase its investment when the powerful supplier licenses its technology to the domestic supplier. This preference stems mainly from the fact that under TL, most of the weak main manufacturer’s material comes from the powerful supplier, so the domestic supplier must invest more in order to reduce the gap between itself and the powerful supplier.

In addition, Figure 5(b) indicates that the optimal degree of technology effort increases with a weaker ability on the part of the main manufacturer under the NL contract but decreases when TL occurs. However, Figure 5(c) reveals the complete opposite with respect to the powerful supplier’s ability. Under both scenarios, the optimal cost-sharing rate decreases with the main manufacturer’s ability. This result arises from the main manufacturer’s goal of supplier cultivation, and a powerful main manufacturer shares a substantial amount of the domestic supplier’s R&D cost to improve its indigenous technological capability.

Figure 5(d) illustrates that under TL, the degree of optimal technology effort on the part of the domestic supplier decreases with its technology transfer capability. The reason for this effect is that TL advances the domestic supplier’s technological ability so that it invests a small amount to save on R&D costs. On the other hand, a high level of technology transfer ability indicates that the domestic supplier improves with regard to technological innovation and stable R&D investment. Most importantly, under NL, both the optimal degree of technology effort and the cost-sharing rate are greater than in the case of TL. This discrepancy occurs because TL from the powerful supplier alleviates the domestic supplier’s R&D pressures, and the improvement in the weak main manufacturer’s performance makes it possible for it to share additional R&D costs and risks.

3) EFFECT OF $\beta$, $\theta$, $\delta_i$, AND $\delta_m$ ON THE OPTIMAL TECHNOLOGY LICENSING STRATEGY

Considering the performance of both individual members and the entire supply chain, when the given wholesale prices under TL are less than the optimal wholesale prices under NL, the most efficient scenario is clearly the one under TL. The impact of key parameters on the optimal TL strategy should...
Figure 6 demonstrates how the degree of supplier competition, technology transfer capability, and ability of different stakeholders affect the optimal TL strategy. The results shown in Figure 6 can be expressed as follows:

1) \( \frac{\partial \eta^*}{\partial \delta_m} > 0, \frac{\partial \eta^*}{\partial \delta} > 0, \frac{\partial \eta^*}{\partial r} > 0, \frac{\partial \eta^*}{\partial \theta} < 0; \)

2) \( \frac{\partial q^*_m}{\partial r} = 0, \frac{\partial q^*_m}{\partial \theta} = 0, \frac{\partial q^*_m}{\partial r} = 0, \frac{\partial q^*_m}{\partial \theta} = 0. \)

It is intuitively evident from Figure 6(a) that the optimal royalty rate increases with the degree of supplier competition and that most importantly, the royalty rate increases sharply with a higher degree of supplier competition. This result is attributable to the very high degree of product substitution when supplier competition is fierce. At that point, the difference with respect to technology between the two suppliers is insignificant, so a high royalty rate therefore be taken into consideration. Figure 6 demonstrates how the degree of supplier competition, technology transfer capability, and ability of different stakeholders affect the optimal TL strategy.
represents only a small threat to the powerful supplier. However, the powerful supplier can generate additional revenue from TL and therefore prefers to license its technology to enhance its economic performance. A high degree of supplier competition indicates a narrow difference with respect to material substitutability. In this case, the technological advantage of the powerful supplier is substantially diminished, thus further reducing the competitiveness of the powerful supplier with respect to selling the material.

TL therefore becomes another arrangement for making a profit.

As demonstrated in Figures 6(b) and 6(c), an additional consideration is that the optimal royalty rate increases with weaker ability on the part of the main manufacturer and with a higher revenue-sharing rate. This relationship exists because a high revenue-sharing rate and a weak ability on the part of the main manufacturer mean that TL would generate additional benefit for the licensor. The powerful supplier is...
attracted to the prospect of sharing revenue from the weak main manufacturer, so it licenses more technology in an effort to cooperate with both the domestic supplier and the main manufacturer.

Figures 6(c) and 6(d) also illustrate that the optimal quantity seldom changes with either the revenue-sharing rate or the technology transfer capability. This finding means that the optimal quantity is independent of both the revenue-sharing rate and the domestic supplier’s technology transfer capability, since the technology contract operates primarily to reallocate the revenue of the stakeholders rather than to change demand, and the technology transfer capability affects the technology effort of the domestic supplier.

However, a notable effect revealed in Figure 6(d) is that the optimal royalty rate decreases with the domestic supplier’s technology transfer capability. In particular, the optimal technology royalty rate radically decreases when the technology transfer capability of the domestic supplier is quite feeble and ultimately tends to be stable and maintain a low level with increased technology transfer capability.

These complex results suggest that the technology transfer capability of the domestic supplier is a key signal for the licensor when deciding on the optimal royalty rate. The reason for this conclusion lies in the fact that the technology transfer capability of the domestic supplier hurts the powerful supplier in two ways. First, a high level of technology transfer capability implies that the domestic supplier has strong independent innovation abilities, which can threaten the powerful supplier’s hold on its leading technology status. Second, improvement in the technological capability of the domestic supplier could heighten its relationship with downstream members; once the relationship is consolidated, the role of the domestic supplier in business with downstream members would be advanced, which would operate against the powerful supplier’s interest in maintaining its status as the technology leader. Therefore, when its technology transfer capability is weak, the powerful supplier should license additional technology to the domestic supplier, and the higher the royalty rate is, the greater the profit that will be generated. Nevertheless, in the case of a greater level of technology transfer capability, the royalty rate would be slashed since the powerful supplier would wish to reduce the royalty rate to avoid possible risk.

Overall, however, TL represents the optimal strategy for the powerful supplier regardless of the characteristics of the rival, and the optimal royalty rate is highly dependent on the degree of supplier competition, the ability of the weak main manufacturer, the revenue-sharing rate, and the technology transfer capability of the domestic supplier.

VI. CONCLUSION

The goal of the main manufacturer is to improve indigenous technological capabilities. We have designed a cost-sharing contract and a technology licensing contract for realizing technology cooperation and supplier cultivation. Two multistage games have been developed as a means of revealing the decision-making mechanisms of the three stakeholders. After characterizing the optimal decisions under two different scenarios, we compared the findings with those from a benchmark model to study possible strategies that may enable a weak main manufacturer to improve its indigenous technological capability.

While cooperation is always beneficial for supply chain members, we show the magnitude of cooperation in improving the capabilities of a weak main manufacturer in CoPS. It is important for the weak main manufacturer to cultivate suppliers and stimulate technology cooperation. Our study provides several insights regarding this question. While both cost-sharing and joint contracts are effective, the technology licensing strategy is the most efficient strategy for enhancing both individual performance and the performance of the entire supply chain. However, the contract preferences of different stakeholders vary depending on several factors. Although the three stakeholders’ contract preferences are different, the technology licensing contract is the optimal strategy in the long term, and the cost-sharing contract is the optimal strategy for technology licensing in the short term. Technology licensing must be generated when cooperative contracts are provided by the weak main manufacturer. The royalty rate increases with the powerful supplier’s ability in scenario TL, while it has an opposite character in NL. The powerful supplier is the first-tier supplier regardless of any differences in the scenarios so that greater economic benefits can be derived. The powerful supplier reduces the risk-avoidance royalty rate for a domestic supplier that has a proven technology transfer capability.

Finally, there are a number of ways to extend this research. One key question is whether other strategies can be effective for improving capabilities under asymmetric information regarding supplier volume. On the other hand, some key competitive factors should be taken into consideration, such as trade disputes, entry barriers, and competitive upstream or downstream members.

APPENDIX

Proof of Proposition 1: From Eq. (1), we can get

\[ p_{m1}^{BM} = P - \alpha q_{m1}^{BM} - \beta q_{m2}^{BM} \quad (A1) \]
\[ p_{m2}^{BM} = P - \alpha q_{m2}^{BM} - \beta q_{m1}^{BM} \quad (A2) \]

Backward induction is used for solving the problems, so we first solve for the weak main manufacturer’s decisions in the second stage. When we substitute Eq. (A1) and Eq. (A2) into Eq. (4), the profit of the main manufacturer under the BM scenario would be as expressed in Eq. (A3):

\[ \max_{q_{mi1}, q_{mi2}} \pi_{m}^{BM} = \sum_{i=1,2} (P - \alpha q_{mi}^{BM} - \beta q_{mj}^{BM} - w_{mi}^{BM} - c_{m}) q_{mi}^{BM} \]
\[ - (\delta_{1} - \delta_{2})k_{i} q_{mi2}^{BM} \quad (A3) \]
The partial derivative of $\pi_m^{BM}$ with respect to $q_{m1}^{BM}$ and $q_{m2}^{BM}$ is as follows:

$$\frac{\partial \pi_m^{BM}}{\partial q_{m1}^{BM}} = P - c_m - 2\alpha q_{m1}^{BM} - 2\beta q_{m2}^{BM} - w_{m1}$$

$$\frac{\partial \pi_m^{BM}}{\partial q_{m2}^{BM}} = P - c_m - 2\beta q_{m1}^{BM} - 2\alpha q_{m2}^{BM} - w_{m2} - k_1(\delta_1 - \delta_2)$$

Using the first-order condition, we obtain $q_{m1}^{BM}$ and $q_{m2}^{BM}$ in Eq. (A4) and Eq. (A5), by solving the simultaneous equations

\[
\frac{\partial \pi_m^{BM}}{\partial q_{m1}^{BM}} = 0, \quad \frac{\partial \pi_m^{BM}}{\partial q_{m2}^{BM}} = 0.
\]

\[
q_{m1}^{BM} = \frac{P - \beta - \alpha c_m + \beta c_m - \alpha w_{m1} + \beta w_{m2} + \beta k_1 \delta_1 - \beta k_2 \delta_2}{2(\alpha^2 - \beta^2)} \tag{A4}
\]

\[
q_{m2}^{BM} = \frac{P - \beta - \alpha c_m + \beta c_m + \alpha w_{m1} + \beta w_{m2} - \alpha k_1 \delta_1 + \alpha k_2 \delta_2}{2(\alpha^2 - \beta^2)} \tag{A5}
\]

Taking the second partial derivative of $\pi_m^{BM}$ into consideration, because $\frac{\partial^2 \pi_m^{BM}}{\partial q_{m1}^{BM}^2} = 2\alpha < 0$, then $\pi_m^{BM}$ is a concave function of $q_{m1}^{BM}$ and $q_{m2}^{BM}$; thus the optimal production quantities denoted as $q_{m1}^{BM}$ and $q_{m2}^{BM}$ hold as $d_{m1}^{BM} = q_{m1}^{BM}$ and $d_{m2}^{BM} = q_{m2}^{BM}$.

Taking Eq. (A4) and Eq. (A5) into account, we then solve for the suppliers' decisions in the first stage. When we substitute Eq. (A4) and Eq. (A5) into Eq. (2) and Eq. (3), the profits of supplier $s_1$ hold as follows:

\[
\max_{w_{m1}} \pi_{m1}^{BM} = \left\{ \begin{array}{c}
\frac{(w_{m1}^{BM} - c_1)(P - \beta - \alpha c_m + \beta c_m - \alpha w_{m1})}{2(\alpha^2 - \beta^2)} + \frac{(w_{m1}^{BM} - c_1)(\beta w_{m2} + \beta k_1 \delta_1 - \beta k_2 \delta_2)}{2(\alpha^2 - \beta^2)} \\
\frac{(w_{m1}^{BM} - c_1)(\beta w_{m2} + \beta k_1 \delta_1 - \beta k_2 \delta_2)}{2(\alpha^2 - \beta^2)}
\end{array} \right. \tag{A6}
\]

\[
\max_{w_{m2}} \pi_{m2}^{BM} = \left\{ \begin{array}{c}
\frac{(w_{m2}^{BM} - c_2)(P - \beta - \alpha c_m + \beta c_m + \beta w_{m1})}{2(\alpha^2 - \beta^2)} + \frac{(w_{m2}^{BM} - c_2)(\alpha w_{m1} + \alpha k_1 \delta_1 - \alpha k_2 \delta_2)}{2(\alpha^2 - \beta^2)} \\
\frac{(w_{m2}^{BM} - c_2)(\alpha w_{m1} + \alpha k_1 \delta_1 - \alpha k_2 \delta_2)}{2(\alpha^2 - \beta^2)}
\end{array} \right. \tag{A7}
\]

Taking the second partial derivative of $\pi_{s_1}^{BM}$ and $\pi_{s_2}^{BM}$ into consideration, we get

$$\frac{\partial^2 \pi_{s_1}^{BM}}{\partial d_{m1}^{BM}^2} = \frac{\partial^2 \pi_{s_2}^{BM}}{\partial d_{m2}^{BM}^2} = -\frac{\alpha - \beta}{\alpha^2 - \beta^2} < 0;$$

therefore, $\pi_{s_1}^{BM}$ is a concave function of $w_{m1}$, and $\pi_{s_2}^{BM}$ is a concave function of $w_{m2}$. Thus, the optimal wholesale prices can be denoted as $w_{m1}^{BM*}$ and $w_{m2}^{BM*}$, where $w_{m1}^{BM*}$ and $w_{m2}^{BM*}$ can be obtained from the first-order condition.

\[
w_{m1}^{BM*} = \frac{2\alpha^2(p + c_1) - \alpha \beta(p - c_2) - p \beta^2}{4\alpha^2 - \beta^2} + \frac{\beta^2 - 2\alpha^2 + \alpha \beta c_1 + \alpha \beta k_1(\delta_1 - \delta_2)}{4\alpha^2 - \beta^2}
\]

\[
w_{m2}^{BM*} = \frac{2\alpha^2(p + c_2) - \alpha \beta(p - c_1) - p \beta^2 + (\beta^2 - 2\alpha^2 + \alpha \beta)c_2}{4\alpha^2 - \beta^2} - \frac{2\alpha^2 k_1 - \beta \delta_1 k_1(\delta_1 - \delta_2)}{4\alpha^2 - \beta^2}
\]

When we substitute $w_{m1}^{BM*}$ and $w_{m2}^{BM*}$ into Eq. (A4) and Eq. (A5), $q_{m1}^{BM}$ and $q_{m2}^{BM}$ hold as

\[
d_{m1}^{BM} = \frac{(\alpha - \beta)(p - c_m) + \beta k_1(\delta_1 - \delta_2) - \alpha w_{m1}^{BM*} + \beta w_{m2}^{BM*}}{2(\alpha^2 - \beta^2)} \tag{A8}
\]

\[
d_{m2}^{BM} = \frac{(\alpha - \beta)(p - c_m) - \alpha k_1(\delta_1 - \delta_2) + \beta w_{m1}^{BM*} - \alpha w_{m2}^{BM*}}{2(\alpha^2 - \beta^2)} \tag{A9}
\]

When we substitute $w_{m1}^{BM*}$, $w_{m2}^{BM*}$, $q_{m1}^{BM}$, and $q_{m2}^{BM}$ into Eq. (2), Eq. (3), and Eq. (4), the optimal profits hold as

\[
\pi_{s_1}^{BM*} = (w_{m1}^{BM*} - c_1)q_{m1}^{BM}, \quad \pi_{s_2}^{BM*} = (w_{m2}^{BM*} - c_2)q_{m2}^{BM*}
\]

\[
\pi_T^{BM*} = \pi_{s_1}^{BM*} + \pi_{s_2}^{BM*} + \pi_m^{BM*}
\]

The proofs of Proposition 1 and Proposition 2 are completed.

Proof of Proposition 1: Based on Proposition 1, conclusion 1 can be easily proved as follows:

1) $\frac{\partial \omega_{m1}^{BM*}}{\partial c_1} = \frac{2\alpha^2}{4\alpha^2 - \beta^2} > 0, \quad \frac{\partial \omega_{m1}^{BM*}}{\partial c_2} = \frac{4\alpha^2 - \beta^2}{4\alpha^2 - \beta^2} > 0$;

2) $\frac{\partial \omega_{m2}^{BM*}}{\partial c_1} = \frac{\alpha \beta}{4\alpha^2 - \beta^2} > 0, \quad \frac{\partial \omega_{m2}^{BM*}}{\partial c_2} = \frac{4\alpha^2 - \beta^2}{4\alpha^2 - \beta^2} > 0$;

3) $\frac{\partial \omega_{s}^{BM*}}{\partial \delta_1} = \frac{\alpha k_1}{4\alpha^2 - \beta^2} > 0, \quad \frac{\partial \omega_{s}^{BM*}}{\partial \delta_2} = \frac{4\alpha^2 - \beta^2}{4\alpha^2 - \beta^2} > 0$.

Proof of Proposition 3: From Eq. (1), we can get

\[
p_{NL, m1} = P - \alpha q_{m1}^{NL} - \beta, \quad p_{NL, m2} = P - \alpha q_{m2}^{NL} - \beta q_{m1}^{NL} \tag{B1}
\]

Backward induction is used for solving the problems, so we first solve for the domestic supplier's decisions in the last stage.

When we substitute Eq. (B1) and Eq. (B2) into Eq. (9), the profit of $s_2$ under the NL scenario would be as expressed in Eq. (B3):

\[
\max_{\pi_{s_2}^{NL}} = (w_{m2}^{NL} - c_2)q_{m2}^{NL} - (1 - \varphi_{NL})k_0 t_{NL}^{SL} \tag{B3}
\]

The partial derivative of $\pi_{s_2}^{NL}$ with respect to $t_{NL}$ holds as

\[
d\pi_{s_2}^{NL}/dt_{NL} = k_0 q_{NL}^{SL}(1 - \delta_1) - k_0 q_{NL}^{SL}(1 - \varphi_{NL}) \tag{B4}
\]

Taking the second partial derivative of $\pi_{s_2}^{NL}$ into consideration, because $\frac{\partial^2 \pi_{s_2}^{NL}}{\partial t_{NL}^2} = -k_0(1 - \varphi_{NL}) < 0$, then $\pi_{s_2}^{NL}$ is a concave function of $t_{NL}$; thus, the optimal degree of technology effort denoted as $t_{NL}^*$ holds as $\pi_{s_2}^{NL} = I_{NL}$. Taking Eq. (B4) into account, we then solve for the main manufacturer's decision
In the third stage. When we substitute Eq. (B4) into Eq. (2) and Eq. (8), the profit of the main manufacturer holds as follows:

\[
\max_{\varphi_{NL}^{m}} \pi_{NL}^{m} = \sum_{i=1,2} \left( (P_{NL}^{m} - w_{NL}^{m} - c_{m}) q_{NL}^{m} \right) + \delta_{m} k_{i} q_{NL}^{m} \left( \frac{(\delta_{m} - 1)}{k_{0}(\varphi_{NL}^{m} - 1)} \right) - (\delta_{1} - \delta_{2}) k_{i} q_{NL}^{m} - \varphi_{NL}^{m} \frac{1}{2} k_{0} \left( \frac{k_{i} q_{NL}^{m} (\delta_{m} - 1)}{k_{0}(\varphi_{NL}^{m} - 1)} \right)^{2} \tag{B5}
\]

Because

\[
\frac{d\pi_{NL}^{m}}{d\varphi_{NL}^{m}} = -k_{i} q_{NL}^{m} \left( \frac{(\delta_{m} - 1)}{k_{0}(\varphi_{NL}^{m} - 1)} \right) - \frac{k_{i} q_{NL}^{m} (\delta_{m} - 1)}{k_{0}(\varphi_{NL}^{m} - 1)} \frac{k_{i} q_{NL}^{m} (\delta_{m} - 1)}{k_{0}(\varphi_{NL}^{m} - 1)} = 0
\]

so \(\frac{d\pi_{NL}^{m}}{d\varphi_{NL}^{m}} < 0\), we can obtain the optimal cost-sharing rate, which is denoted as \(\varphi_{NL}^{n}\) holding as \(\varphi_{NL}^{n} = \varphi_{NL}^{m}\).

\[
\varphi_{NL}^{m} = \frac{3\delta_{m} - 1}{\delta_{m} + 1} \tag{B6}
\]

Taking Eq. (B6) into account, we then solve for the main manufacturer’s decision in the second stage. When we substitute Eq. (B6) into Eq. (B5), the profit of the main manufacturer holds as follows:

\[
\max_{q_{m1}^{NL}, q_{m2}^{NL}} \pi_{NL}^{m} = \sum_{i=1,2} \left( (P_{NL}^{m} - w_{NL}^{m} - c_{m}) q_{NL}^{m} \right) + \delta_{m} k_{i} q_{NL}^{m} \left( \frac{(\delta_{m} - 1)}{k_{0}(\varphi_{NL}^{m} - 1)} \right) - (\delta_{1} - \delta_{2}) k_{i} q_{NL}^{m} - \varphi_{NL}^{m} \frac{1}{2} k_{0} \left( \frac{k_{i} q_{NL}^{m} (\delta_{m} - 1)}{k_{0}(\varphi_{NL}^{m} - 1)} \right)^{2} \tag{B7}
\]

Using the first-order condition, we obtain \(q_{m1}^{NL}\) and \(q_{m2}^{NL}\) in Eq. (B8) and Eq. (B9), as shown at the bottom of the next page, by solving the simultaneous equations \(\frac{\partial \pi_{NL}^{m}}{\partial q_{m1}^{NL}} = 0, \frac{\partial \pi_{NL}^{m}}{\partial q_{m2}^{NL}} = 0\).

Because \(\frac{d^{2} \pi_{NL}^{m}}{d q_{m1}^{NL}} < 0\) and \(\frac{d^{2} \pi_{NL}^{m}}{d q_{m2}^{NL}} < 0\), we can then obtain the optimal quantities in the second stage, which are denoted as \(q_{m1}^{NL}\) and \(q_{m2}^{NL}\) holding as \(q_{m1}^{NL} = q_{m1}^{NL}\) and \(q_{m2}^{NL} = q_{m2}^{NL}\). Taking Eq. (B8) and Eq. (B9) into account, we then solve for the suppliers’ decisions in the first stage. When we substitute Eq. (B8) and Eq. (B9) into Eq. (5) and Eq. (6), the profits of supplier \(s_{1}\) hold as follows Eq. (B10) and Eq. (B11), as shown at the bottom of the next page.

Because \(\frac{d^{2} \pi_{NL}^{m}}{d w_{NL}^{m1}} < 0\) and \(\frac{d^{2} \pi_{NL}^{m}}{d w_{NL}^{m2}} < 0\), we can then obtain the optimal wholesale prices in the first stage, which are denoted as \(w_{NL}^{m1}\) and \(w_{NL}^{m2}\) holding as \(w_{NL}^{m1} = w_{NL}^{m1}\) and \(w_{NL}^{m2} = w_{NL}^{m2}\). We then obtain the suppliers’ decisions in the first stage by solving the simultaneous equations \(\frac{d \pi_{NL}^{m}}{d w_{m1}^{NL}} = 0, \frac{d \pi_{NL}^{m}}{d w_{m2}^{NL}} = 0\), as shown at the bottom of the next page, where \(l_{e} (e = 1, 2, 3, \ldots, 8)\) are used for saving notations, and

\[
l_{1} = k_{i}^{*} \alpha_{1}^{2} + k_{i}^{*} (7 \alpha_{2} \beta_{1}^{2} - 12 \alpha_{3}) + 8k_{i}^{*} (4 \alpha_{4}^{2} - 5 \alpha_{2}^{2} \beta_{2}^{2} + \beta_{4})
\]

By substituting \(w_{NL}^{m1}\) into Eq. (B8) and Eq. (B9), we get \(q_{m1}^{NL}\); by substituting \(q_{m1}^{NL}\) into Eq. (B4) and Eq. (B9), we get \(q_{m2}^{NL}\). The results for Proposition 3 are then obtained.

**Proof of Proposition 4:** Proposition 4 can be easily proved if Proposition 3 is substituted into Eq. (C7), Eq. (C10), and Eq. (C11).

**Proof of Proposition 5:** From Eq. (1), we can get

\[
P_{TL}^{m1} = P - \alpha q_{m1} - \beta q_{m2} \tag{C1}
\]

\[
P_{TL}^{m2} = P - \alpha q_{m1} - \beta q_{m2} \tag{C2}
\]

Backward induction is used for solving the problems, so we first solve for the domestic supplier’s decisions in the last stage.

When we substitute Eq. (C1) and Eq. (C2) into Eq. (13), the profit of \(s_{2}\) under the TL scenario would be as expressed in Eq. (C3):

\[
\max_{\pi_{TL}^{s2}} = (w_{TL}^{m1} - c_{2}) q_{m1}^{NL} - (1 - \varphi_{TL})(1 - \theta) \frac{1}{2} k_{i} q_{TL}^{m1} - (1 - \delta_{m}) k_{i} q_{m2}^{NL} - F - \eta \varphi_{TL} \tag{C3}
\]

The first partial derivative of \(\pi_{TL}^{s2}\) with respect to \(q_{m2}^{NL}\) holds as

\[
\frac{d \pi_{TL}^{s2}}{d q_{m2}^{NL}} = k_{i} q_{m2}^{NL} (1 - \delta_{m}) - k_{i} q_{m2}^{NL} (1 - \theta) - (1 - \varphi_{TL}) \tag{C4}
\]

Taking the second partial derivative of \(\pi_{TL}^{s2}\) into consideration, because

\[
\frac{d^{2} \pi_{TL}^{s2}}{d q_{m2}^{NL}} = -k_{i}(1 - \theta)(1 - \varphi_{NL}) < 0, \text{ then } \pi_{TL}^{s2}\text{ is a concave function of } q_{m2}^{NL}\text{. Using the optimal degree of technology effort is then denoted as } r^{*}_{TL}\text{ holding as } r^{*}_{TL} = t_{NL}^{*}.
\]

Taking Eq. (C4) into account, we then solve for the main manufacturer’s decision in the third stage. When we substitute Eq. (C4) into Eq. (12), the profit of the main manufacturer holds as follows:

\[
\max_{\pi_{m}^{NL}} = \sum_{i=1,2} (P_{TL}^{m} - w_{m1}^{m} - c_{m}) q_{m1}^{NL} + r_{m1} k_{i} q_{m2}^{NL} - (\delta_{1} - \delta_{2}) k_{i} q_{m2}^{NL} - \varphi_{TL}(1 - \theta) \frac{1}{2} k_{i} q_{TL}^{m1} \tag{C5}
\]

Because

\[
\frac{d \pi_{m}^{NL}}{d q_{m2}^{NL}} = k_{i} q_{m2}^{NL} (1 + \varphi_{TL} + \delta_{m}(2 r - 1) \varphi_{TL} - 1 - 2 r) \frac{1}{2} k_{i} q_{TL}^{m1} - \varphi_{TL} (1 - 3)^{3}
\]
so \( \frac{d^2 \pi_{TL}}{d \varphi_{TL}^2} < 0 \), we can then obtain the optimal cost-sharing rate, which is denoted as \( \varphi_{TL}^* \) holding as \( \varphi_{TL} = \varphi_{TL}^* \).

\[
\varphi_{TL} = \frac{(2r + 1) \delta_m - 1}{(2r - 1) \delta_m + 1}
\]  
(C6)

Taking Eq. (C6) into account, we then solve for the powerful supplier’s decision in the third stage. When we substitute Eq. (C4) and Eq. (C6) into Eq. (11), the profit of \( s_1 \) holds as follows:

\[
\max_{\pi_{TL}^*} \pi_{TL}^{s_1} = (w_{m1}^T - c_1)q_{m1}^T + (1 - r)\delta_m k_T q_{m2}^T F + \eta
\]  
(C7)

Because \( \frac{d^2 \pi_{TL}^*}{d \varphi_{TL}^*} < 0 \), we can then obtain the optimal royalty rate, which is denoted as \( \eta^* \). \( \eta^* \) holds as \( \eta^* = \eta \). By solving

\[
q_{m1}^T = \begin{bmatrix} -8k\beta w_{m2}^N - w_{m1}^T \left[k_1^2 (1 + \delta_m)^2 - 8k_3(\beta - \alpha)\right] - c_m k_1^2 (1 + \delta_m)^2 + 8k_0(\beta - \alpha) \\
+ k_1^2 P (1 + \delta_m)^2 + 8k_0P(\beta - \alpha) - 8k_0k_1k_1(\delta_1 - \delta_2) \\
2 \left[8k_0(\beta - \alpha)^2 + k_1^2 \alpha^2(1 + \delta_m)^2\right]
\end{bmatrix}
\]  
(B8)

\[
q_{m2}^T = \begin{bmatrix} 4k_0[(\alpha - \beta)(P - c_m) - \alpha k_1(\delta_1 - \delta_2) + \beta w_{m1}^N - \alpha w_{m2}^N] \\
8k_0(\alpha^2 - \beta^2) - k_1^2 \alpha^2(1 + \delta_m)^2
\end{bmatrix}
\]  
(B9)

\[
\max_{w_{m1}^T} \pi_{NL}^{s_1} = \left\{ \begin{array}{l}
\frac{-8k_0\beta w_{m2}^N - w_{m1}^T \left[k_1^2 (1 + \delta_m)^2 - 8k_0(\alpha)\right] - c_m [k_1^2 (1 + \delta_m)^2 + 8k_0(\beta - \alpha)]}{2 \left[8k_0(\beta - \alpha)^2 + k_1^2 \alpha(1 + \delta_m)^2\right]}
+ k_1^2 P (1 + \delta_m)^2 + 8k_0P(\beta - \alpha) - 8k_0k_1k_1(\delta_1 - \delta_2)
+ 2 \left[8k_0(\beta - \alpha)^2 + k_1^2 \alpha^2(1 + \delta_m)^2\right]
\end{array} \right\}
\]  
(B10)

\[
\max_{w_{m2}^T} \pi_{NL}^{s_2} = \left\{ \begin{array}{l}
\frac{4k_0[(\alpha - \beta)(P - c_m) - \alpha k_1(\delta_1 - \delta_2) + \beta w_{m1}^N - \alpha w_{m2}^N]}{8k_0(\alpha^2 - \beta^2) - k_1^2 \alpha^2(1 + \delta_m)^2}
+ (1 - \varphi_{NL}) \frac{3}{2} k_0^2 w_{NL}^T + (1 - \delta_m) k_T w_{NL}^T
\end{array} \right\}
\]  
(B11)

\[
w_{m1}^T = \begin{bmatrix}
\alpha c_1 \left[l_2 + k_1^2 \left(3k_1^2(\alpha^2 + \alpha k_1^2 + 8k_0k_1^2 - 16k_0k_1^2)\right) d_m + k_1^2 \left(3k_1^2 \alpha + 4k_0k_1^2 - 4k_0\alpha^2\right) \delta_m^2 + k_1^4 \delta_m^4
\end{bmatrix}
\]  
(B10)

\[
w_{m2}^T = \begin{bmatrix}
\alpha c_2 \left[l_2 + k_1^2 \left(3k_1^2(\alpha^2 + \alpha k_1^2 + 8k_0k_1^2 - 16k_0k_1^2)\right) d_m + k_1^2 \left(3k_1^2 \alpha + 4k_0k_1^2 - 4k_0\alpha^2\right) \delta_m^2 + k_1^4 \delta_m^4
\end{bmatrix}
\]  
(B11)

\[
q_{m1}^T = \begin{bmatrix}
\frac{(2r - 1) \delta_m + 1}{2 \left(\alpha^2 - \beta^2\right) \delta_m + 1}
\end{bmatrix}
\]  
(C10)

\[
q_{m2}^T = \begin{bmatrix}
\frac{(2r - 1) \delta_m + 1}{2 \left(\alpha^2 - \beta^2\right) \delta_m + 1}
\end{bmatrix}
\]  
(C11)
\[ \frac{d\eta_1}{d\eta_2} = 0, \text{ we can get} \]
\[ \eta = \frac{1}{\theta} + \frac{k_0 k_r^2 (t - 1) \delta^2 q_{m2}^2 - \delta_{m1} [1 + (2r - 1) \delta_{m1}]}{2k_0 \theta^2} \quad (C8) \]

Taking Eq. (C8) into account, we then solve for the main manufacturer’s decision in the second stage. When we substitute Eq. (C8) into Eq. (C5), the profit of the main manufacturer holds as follows:

\[ \max_{q_{m1}, q_{m2}} \pi_m^{TL} = \sum_{i=1,2} (q_{m1} - w_{mi} - c_m) q_{m1} + \partial q_{m1} k_1 q_{m1}^2 - \partial q_{m2} q_{m2}^2 - \partial q_{m2} \eta(1 - \eta) \frac{h_0^2}{2} - \eta^2 \eta_m \quad (C9) \]

Using the first-order condition, we obtain \( q_{m1}^{TL} \) and \( q_{m2}^{TL} \) in Eq. (C10) and Eq. (C11), as shown at the bottom of the previous page, by solving the simultaneous equations

\[ \frac{d\eta_1}{d\eta_2} = \frac{d\eta_1}{d\eta_2} = 0. \]

Because

\[ \eta_1^{NL} = \frac{\alpha a_{m1}}{\alpha a_{m2}} \approx -2 \alpha < 0, \text{ we can then} \]

obtain the optimal quantities in the second stage, which are denoted as \( q_{m1}^{NL} \) and \( q_{m2}^{NL} \) holding as \( \eta_1^{NL} = \eta_2^{NL} = 0 \) and \( \eta_1^{TL} = \eta_2^{TL} = \eta_2^{NL} \) by substituting Eq. (C10) and Eq. (C11) into Eq. (C8) and Eq. (C4), we then obtain the optimal decisions for Proposition 5.

Proof of Proposition 6: Proposition 6 can be easily proved if Proposition 5 is substituted into Eq. (C3), Eq. (C7), and Eq. (C9).

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