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Strategic Cooperation with Differential Suppliers' Ability under Downstream Competition in Complex Products Systems

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Abstract. This paper investigates the strategic cooperation of two competitive suppliers with different abilities and a weak main manufacturer in Complex Products Systems (CoPS), where a main manufacturer signs a revenue-sharing contract based on a relationship-specific investment with the stronger supplier. The stronger supplier provides one key element to the main manufacturer and encroaches on the downstream market by producing substitutable final products simultaneously. We consider multi-period decisions, by building different models based on centralized, decentralized, and cooperative decisions. The equilibrium strategies are characterized under downstream competition, and optimal cooperation strategies are derived by building multi-period game models. The results show that strong cooperation can enhance the economic performance of each individual as well as the whole supply chain. The weak main manufacturer would face the risk of strong suppliers' supply interruptions when the competitive degree of suppliers and downstream competition are fierce enough under decentralized decisions. Additionally, the gap in the abilities of the two competitive suppliers reduces the main manufacturer's profitability. However, the revenue-sharing contract based on a relationship-specific investment can motivate the strong supplier to establish cooperation relationship and improve both stakeholders' profitability. Moreover, strategic cooperation is efficient to prevent the strong supplier encroaching on downstream and has a positive impact on boosting the weak main manufacturer's market share. Meanwhile, nurturing a domestic supplier is an effective measure for improving competitiveness and indigenous technological capability of the main manufacturer in CoPS. Finally, some useful management sights on cooperation strategy and optimal decisions are derived.

Keywords: Cooperation, downstream competition, CoPS, contract coordination, suppliers' ability

1. Introduction

Complex products and systems (CoPS) shape and enable modern industrial and economic progress through the introduction of new technology to the economic system. Generally, CoPS are highly costly and technology-intensive compared with commodity products because they produce as customized, one-off or small batched capital goods (Hobday 1998), such as aircraft, defense systems, high-speed trains, and ships. The components of CoPS are typically tailor-made to suit the buyer's requirements, whereas commodity products usually consist of standardized or modular components (Dedehayir et al. 2014); therefore, the production of CoPS is more likely to depend on cooperative partnership and to operate with the administration mode of "Main Manufacturer-Suppliers (MS)". In MS, regarded as the optimal administrative mode in the supply chain of CoPS, a main manufacturer integrates numerous suppliers to produce the final product. For instance, the long-term practice of global aircraft giants Boeing and Airbus has been to operate in MS mode base on the mode of their management and technical departments. The main manufacturer should be powerful in both finance and technology to operate competitively within the supply chain of CoPS. However, because production is high costs and technology-intensive, some main manufacturers as latecomers are underperforming in key technologies. Moreover, international business with suppliers from developed countries is highly volatile because substantial entry barriers in terms of technology, economics, and politics to forestall latecomers. This makes cooperation become a vital strategy for the development, profitability, competitiveness, and survival in firms of CoPS. Cooperation plays a significant role in industries and helps firms to increase economic benefits and maintain their technological competitiveness (Yu et al. 2018). A typical and practical example of such a case is the main manufacturer of large passenger aircraft in China. Even they are under developing in aircraft engine, flight control system and other crucial technologies and catching up with the pioneers like Boeing and Airbus is not easy. However, they still devote resources and finances to develop large passenger aircraft as a result of the huge economic benefits in the aviation industry. Therefore, strategic cooperation with a differential supplier is very worthy of study.

This study considers differential suppliers' ability. The ability of stakeholders is the capability of a company's creativity, innovation, problem-solving, risk-taking, and directing resources. It is claimed to have a certain amount of significance in distribution & logistics, marketing, and business (Steward et al. 2010, Chang and Wu 2015, Warren and Heywood 2016). In existing studies, some researchers have addressed a similar case with undifferentiated and competitive suppliers. However, for some practical problems of supply chain management in CoPS, the cooperative relationship is not only affected by the competitive degree of a supplier but also affected by the ability of suppliers. Besides, there have been few studies analyzing the effect of that ability on the cooperation of stakeholders in the supply chain. Therefore, based on the existing literature, we define the ability of supply chain members as the capability of technological innovation, risk-taking, marketability, and taking initiative in this paper in order to investigate its effect on strategic cooperation in CoPS. A differential ability matches well with the practice that the ability of supply chain members is different because CoPS are highly costly and technology-intensive, so we study the cooperation strategies with differential suppliers' ability whereas the existing studies ignored the differential.

We consider the effect of a weak main manufacturer and downstream competition on strategic cooperation in the supply chain of CoPS. How to realize cooperation is a strategic problem when a manufacturer is faced with the different ability of suppliers, competitors and competitive environment, it would be more particularly complicated with a weak main manufacturer and downstream competition in CoPS. Downstream competition is a situation in which more than two downstream stakeholders compete with the same upstream stakeholder for capacity. As a specific form of downstream competition, encroachment on downstream of a supplier is caused not only the competition in capacity but also the competition in a channel. For instance, the firm of Samsung Electronics not only supplies microprocessor to Apple Inc. for its iPhone, but also sells phone and competes with Apple Inc. in the smartphone market; Dell, Sony, and Pioneer Electronics have established two channels for selling products: intermediary retail stores and their own stores (Qing et al. 2017, Huang et al. 2018); telecommunication companies often purchase or rent networks from their market competitors (Weisman and Kang 2001). Some stronger suppliers encroachment on downstream for the sake of monopolizing key technology caused new problems to the main manufacturer in CoPS, thus we define this kind of situation as one in which there is a weak main manufacturer and strong suppliers. Monopoly is an authentic situation in a technology-intensive and costly industry like the aviation industry. This is mainly caused by the fluid phase of product innovation, and the firms who possess advanced technology can build substantial entry barriers in terms of technology, economics, market sharing and politics to forestall latecomers (Abegglen 1994, Davies 1997, Choung and Hwang 2007, Park 2012). Thus, the impact of the decision to cooperate is huge as the cooperation involves considerable challenges to coordinate for the weak main manufacturer who wants to improve and succeed in CoPS.

Drawing from the aforementioned challenges of a weak main manufacturer in CoPS, this paper studies strategic cooperation under downstream competition with differential suppliers' ability. The contributions of our research lie in the following: (i) We are the first to concentrate on designing feasible strategies from the perspective of a weak member, and the main purpose is making the weak member cooperate and compete effectively with a dominant member. Most of the existing studies prefer focusing on how the dominant member controls and coordinates other members' decision to make a favorable effect for themselves; however, few works of literature provide significant strategies to the development of a weak member. Therefore, to fulfill such a research gap, we study strategic cooperation in a downstream competition supply chain, which consists of two suppliers and one main manufacturer with different abilities. (ii) We demonstrate how the weak main manufacturer establishes a cooperative relationship with the strong supplier rather than from the perspective of a Stackelberg-leader. The competitive relationship is studied through multi-stage game. (iii) A key revenue-sharing contract based on a relationship-specific investment is proposed to realize the weak main manufacturer's cooperative goals, where the contract items should be reached through a Bargaining game. While the existing literature set a reserve profit of different stakeholders as zero in a Bargaining game, the paper takes the optimal profit of individuals as the reserve profit under a Stackelberg game, namely, the disagreement point in the Bargaining game. We further analyze the effect of the disagreement payoff allocation on the decision-making and coordination mechanisms. The superiority of the contract compared with other coordination strategies is preventing the stakeholders from opportunistic behavior; hence a relationship-specific investment is used as other control strategies. Relationship-specific investment has a greatly positive impact on using classical contracts, because these types of investments can decrease the operating costs and increase the joint profits of firms in vertical relationships. (iv) A key comparison between competition and cooperation is presented to illustrate the following questions: could the cooperation relationship be established successfully between a weak main manufacturer and a strong supplier? Does the weak main manufacturer benefit from the cooperative relationship? Is it possible to prevent the strong supplier encroaching on downstream through cooperation? How the abilities of different stakeholders affect the profitability of individuals and entirety of the supply chain?

The remainder of the paper proceeds as follows, we present relative works in section 2; the preliminary is illustrated in section 3 after a statement of the basic problem; the basic model and cooperative model are established in section 4, and then we characterize the equilibrium decisions under different scenarios; in section 5, comparative analysis is considered; lastly, conclusions are presented in section 6.

2. Literature Review

In this section, we concentrate on corroborating the originality and importance of our study. The study of this paper mainly related to three streams of literature: channel selection, downstream competition, and coordination.

2.1 Research on Channel Selection

Our research is related to the works regarding channel selection. There has been a growing body of literature on channel selection, in particular, the rapid development of e-commerce has prompted channel selection to be the vital practical significance. Rangan et al. (1992) presented an application from the perspective of the new industrial products, they illustrated the factors influencing channel choice and offered a method to support channel selection; Chiang et al. (2003) analyzed the effect of establishing a direct channel of a manufacturer on performance. Channel selection has a complex effect on many decisions of firms, such as pricing, ordering, production, inventory, cost and profit (e.g., Zhu et al. 2017, Salmani et al. 2018). Besides the aforementioned literature, some research takes quality into consideration in channel selection, Zhu et al. (2017) studied the recycling channel in a closed-loop supply chain (CLSC), Ji et al. (2018) studied optimal pricing and return policies in a dual-channel. Yang (2018) studied a manufacturer's channel selection under some practical conditions. Furthermore, capacity allocation is a critical problem related to channel selection and has been studied for several years in the field of operations management, e.g., Ivanov et al. (2018) reviewed the challenges in channel selection and studied the capacity allocation from a flexible concept. Generally, in these studies, a monopolistic supplier or a monopolistic manufacturer set to allocate their product to multiple retailers under different conditions, especially, most research set that the upstream members having all power to allocate quantity to the retailers or buyers, for instance, Lu and Lariviere (2012) considered one supplier selling products to different retailers where competition existed in the two retailers; Cohen and Purohit (2014) explored one manufacturer allocated capacity to retailers and the retailers also competed with each other. It is easy to conclude the related works on channel selection, none of the aforementioned studies thinks over the downstream competition effectively, they also ignored the effect of providers who have the ability to encroach on downstream competition. Furthermore, most of them concentrate on how to establish or operate an online and offline store, or how to decide direct selling and distribution. However, the challenges should not be restricted to the dominant members' channel selection in CoPS with downstream competition because of highly costly and technology-intensive. It is crucial to a weak chain member to improve in abilities through cooperating with a dominant effectively. To fulfill such research gap, the paper studies a supply chain under downstream competition and takes a strong supplier encroachment into consideration; we also explore two competitive suppliers where one of them has no ability to encroach on downstream in CoPS.

2.2 Research on Downstream Competition

A stream of literature focused on downstream competition, which is similar to channel selection but not the same. Arya et al. (2007) defined the activities as a supplier encroachment which supplier devotes itself to invest its own channel and sale product to costumers directly, Qing et al. (2017) and Sandonís and López (2018) further took consideration of downstream competition where the supplier not only sells raw material or other resources to the manufacturer but also produce final product to compete with the manufacturer in downstream. Supplier encroachment as a specific form of downstream competition caused so many common challenges that firms have to face with (Guan et al. 2018). As a specific form of a dual channel, downstream competition usually requires the existing element capacity to be allocated appropriately between different firms. Sandonís and López (2018) studied how upstream members encourage downstream competition in a vertically separated industry, and they designed a two-part tariff contract to study the decisions of downstream competition. Most of this literature focused on competition in capacity and channel coordination, however, it should not be only limited in competition and coordination in capacity. Thus, this paper aims to design strategies to realize cooperative relationship for the development of a weak main manufacturer. Moreover, we consider the cooperation strategy through both cooperative and non-cooperative game simultaneously so that can investigate strategic cooperation in the supply chain of CoPS.

2.3 Research on Coordination

Another stream of literature has focused on coordination of supply chain, which is more similar but not the same as our research on cooperation strategy in CoPS. The contract is a classical strategy to coordinate supply chain and be widely used to solve different problems in management and economics (e.g., Govindan and Popiuc 2014, Heydari et al. 2017, Lu et al. 2018). From the perspective of competition, contract coordination works on firms through sharing profit, allocating risk and cost, as well as coping with uncertain, for example, revenue sharing contract (Liang et al. 2017) and wholesale price contract (Nouri et al. 2018). Most of the studies on coordination refer to the dominant member to control the operation of a supply chain and coordinate other members' decision to make a favorable effect for themselves (Hsu et al. 2016), however, few works of literature provide significant strategies to the development of a weak member. Therefore, to fulfill such a research gap, we concentrate on providing some feasible strategies for a weak member to cooperate and compete effectively with a dominant member. We not only illustrate the competition between downstream members with a different ability, but also demonstrate the effect of competitive upstream members on cooperation strategies from the perspective of a weak chain member rather than the allocation of a dominant member in CoPS.

3. Preliminary

Firstly, in subsection 3.1, we analyze the channel structure of the supply chain in a large-scale and complex product manufacturing industry. The setting is two competitive suppliers and one main manufacturer. Furthermore, in subsection 3.2 we illustrate a cooperative strategy which is defined as a revenue-sharing contract based on relationship-specific investment and designed by the weak main manufacture. Moreover, the sequences of events under different scenarios are discussed in subsection 3.2 in order to demonstrate the competitive and cooperative rules among different stakeholders.

3.1 Channel Structure and Parameters

Taking into consideration the characteristics of CoPS, this paper sets two competitive suppliers and one weak main manufacturer. Let $s_x (x \in \{a, b\})$ and m denote supplier x and the main manufacturer respectively. The main manufacturer gets ready for all elements to produce the final product, except the key component provided by the two heterogeneous and competitive suppliers. However, the two competitive suppliers are in different abilities which mainly caused by technology, cost, financial, management experience, and some other factors; the main manufacturer's ability is also lower than the stronger supplier because of underdeveloped key technology. The lower or the stronger supplier can be either of the two suppliers, it will not influence the analysis of the decision problem; therefore, we define s_a as a strong supplier. Let τ_x denotes the ability of supplier x and τ_m denotes the ability of the main manufacturer. According to the exiting research, company's abilities could be measured numerically and compared meaningfully; expert evaluation and empirical study are used as common methods to measure the ability. Without loss of generality, the paper assumes that $0 > \tau_a > \tau_b > 1$ and $0 > \tau_a > \tau_m > 1$. According to Kato et al. (2018) and Yang (2018), it is definite that $\tau_a = 1 - \tau_m$ in a Bargaining game because τ_a and τ_m are set based on the power balance between the strong supplier and main manufacturer. Furthermore, the supplier s_a who has strong ability also can use the key component to produce final product, and compete with the main manufacturer by encroaching on downstream; supplier s_b only provides the key component to the main manufacturer. The channel structure is shown in Figure 1.

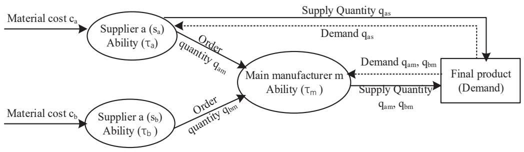


Figure 1 Channel Structure

The unit material cost of supplier x is denoted by c_x, we assume $c_a > c_b$ because the ability of s_a is stronger than s_b. Let c_s and c_m represent the production cost of s_a and the main manufacturer m respectively. The paper takes the loss cost of the main manufacturer into consideration, where the loss cost is caused by using the component of s_b to produce final product because of $\tau_a > \tau_b$. Let c_l represents the unit loss cost and defined as $c_l = \theta\left(\tau_a - \tau_b\right)^2$, θ represents a coefficient of unit loss cost; such a cost function is commonly adopted to model the cost in operation of a supply chain and logistics (e.g. Cooper and Ross 1995, Gurnani and Erkoc 2008, Kaya and Özer 2009, it means that the ability gap of s_b from s_a would cause a loss cost to the main manufacturer. Let w_x represents the wholesale price of s_x, q_{xi} represents the demand quantity of i who uses the material from s_x to produce final product, where $i \in \{s, m\}$, i.e., if $i = s$, the demand of final product is produced by the stronger supplier s_a, otherwise, it is produced by the main manufacturer m. We use p_{xi} to represent the price. The market demand is assumed to be deterministic and dependent on price. The inverse-demand functions are assumed to be

$$p_{xi}(q) = p - \beta\left(q_{xi} + \eta q_{xj}\right) - \beta\left(\gamma q_{yi} + \gamma\eta q_{yj}\right) \quad (1)$$

where $x, y \in \{a, b\}, i, j \in \{s, m\}$, $x \neq y$, $i \neq j$. In addition, $\beta > 0$ represents the price sensitivity of products; η $(0 < \eta < 1)$ represents the competitive degree of the two suppliers, it is the degree of material substitutability; γ $(0 < \gamma < 1)$ represents the competitive degree of the main manufacturer and s_a, it is the substitutable degree of final products within the main manufacturer and s_a. $\gamma\eta$ $(0 < \gamma\eta < 1)$ represents the substitutable degree of the two different products sold by the main manufacturer. It is necessary to consider vertical or horizontal substitutability in competition. Such demand functions have been commonly used in economics and marketing literature to capture the competition between multiproduct (e.g., Ziss 1995, Trivedi 1998, Feng and Lu 2013). It deserves to emphasize that $p_{bs} = 0$, $q_{bs} = 0$. All the notations are shown in 1.

3.2 Cooperation Strategy and Sequence of Events

3.2.1 Cooperation Strategy

Latecomers face special challenges as the learning process of new entrants is a steep curve because of technologically intensive and complex industries in CoPS (Frischtak 1994, Smith and Tranfield 2005). As the study of Lee and Yoon (2015) shows that latecomers in developing CoPS need attain indigenous technological capability, and this process can be accomplished by the technology for "make" or production for "buy" and resulted in co-production or co-development arrangement. In order to improve indigenous technological capabilities, establishing a cross-border technological alliance is feasible and effective. There-

Table 1 Parameters and Notations

Notations	Explanation	Notations	Explanation
x	subscript x is used to denote supplier x, $x \in \{a, b\}$	m	subscript m, m refers to the main manufacturer
s_x	supplier x	τ_x	the ability of s_x
c_x	the unit material cost of s_x	τ_m	the ability of main manufacturer m
c_s	the unit production cost of s_a	p_{xi}^t	the unit price of product q_{xi}^t
c_m	the unit production cost of the main manufacturer m	w_x^t	the unit wholesale price of s_x under scenario t
c_l	the unit loss cost of the main manufacturer	θ	the coefficient of unit loss cost
t	superscript $t, t \in \{c, d, w, b\}$ where c, d, w, b refer the scenario of centralized, decentralized, weak cooperation and bargaining respectively	$\Delta\tau$ φ	the gap of ability between the two suppliers, $\Delta\tau = \tau_a - \tau_b$ the unit revenue-sharing proportion
q_{xi}^t	the demand quantity of i who uses the material of s_x to produce final product under scenario t	π_j^t	the profit of decision maker $j (j \in \{s_x, m\})$ under scenario t
r_m	the fixed unit relationship investment of the main manufacturer to the strong supplier s_a	π_T^t	The total profit of the supply chain under scenario t

fore, the weak main manufacturer can select to cooperate with the strong supplier s_a in order to improve indigenous technological capability. One key problem of how to realize cooperation is that s_a can benefit from the cooperative relationship. Because a long-term relationship is normally governed by a sequence of short-term contract (Crawford 1990), therefore, a viable solution is revenue-sharing. However, to prevent the stakeholders from opportunistic behavior, it may be necessary to use other governance strategies. Hence the paper designs a cooperation strategy which is a revenue-sharing contract based on a relationship-specific investment. A relationship-specific investment is an investment made by one or both parties to an ongoing trading relationship, and the investment generates a lower value in alternative uses than it generates in an intended use on supporting this specific bilateral trading relationship (Vasconcelos 2014, Vázquez 2017). Relationship-specific investment has a greatly positive impact on using classical contracts, and these types of investments can decrease the operating costs and increase the joint profits of firms in vertical relationships.

In this paper, we denoted the revenue-sharing contract based on a relationship-specific investment by $c_t\left(r_m, \varphi\right)$, where r_m is a fixed unit relationship investment of the main manufacturer to strong supplier s_a, and φ is a unit revenue-sharing proportion to s_a. To cooperate with s_a, the main manufacturer offers a fixed relationship-specific investment to s_a, the relational asset is helpful to s_a to reserve capacity and then provide key component to the main manufacturer. Furthermore, in order to motivate s_a cooperating with the main manufacturer, the main manufacturer promises to share a proportion of the unit revenue, noted as φ $(0 < \varphi < 1)$, with the supplier. Thus, the contract works through two aspects in which the supplier can benefit from: one is a fixed relationship-specific investment, and another is sharing a variable proportion of the sales revenue.

3.2.2 Sequence of Events

According to the study, when there is no cooperation relationship between the main manufacturer and s_a, the sequence of the events is shown as follows:

Step1 The two competitive suppliers decide their own wholesale price w_x independently at the same time in pursuit of self-interest maximization;

Step2 The strong supplier s_a and the main manufacture decide the quantity of final product through Cournot competition.

However, if the main manufacture provides $c_t\left(r_m,\varphi\right)$, the sequence of the events would be multi-stage and show as follows:

Step1 The two competitive suppliers decide their own wholesale price w_x independently at the same time in pursuit of self-interest maximization;

Step2 The main manufacturer offers $c_t\left(r_m,\varphi\right)$, and then the strong supplier decides whether to accept c_t;

Step3 If c_t is accepted: the cooperative relationship will be established, subsequently, s_a and the main manufacture decide r_m , φ, and the quantity of final product through Bargaining game; Otherwise, the sequence will be skipped to step 4;

Step4 The strong supplier s_a and the main manufacture decide the quantity of final product through Cournot competition.

The cooperation relationship would be established if they reach an agreement on c_t, otherwise, all players will go back to the state of competition; thus, the profit under competition can be used as a disagreement point in Bargaining game. Let π_j^t denotes the profit of decision maker j $\left(j\in\{s_x,m\}\right)$ under scenario t $(t\in\{c,d,w,b\})$, where c, d, w, and b are the abbreviations of different scenarios under centralized, decentralized, weak cooperation and bargaining respectively. w_x^t stands for the wholesale price of s_x under scenario t, q_{xi}^t and p_{xi}^t represent the quantity and price of xi under scenario t. Hereafter, as shown in Figure 2, we define centralized decision as the scenario of all stakeholders work together to maximize the whole profit of the supply chain; In addition, we define decentralized decision as the scenario where the main manufacturer and s_x make decision independently to maximize individual profit; Moreover, the scenario of weak cooperation is defined as the main manufacturer and weak supplier s_b work together to compete with the strong supplier s_a; Lastly, the scenario of strong cooperation is the scenario existing a contract c_t.

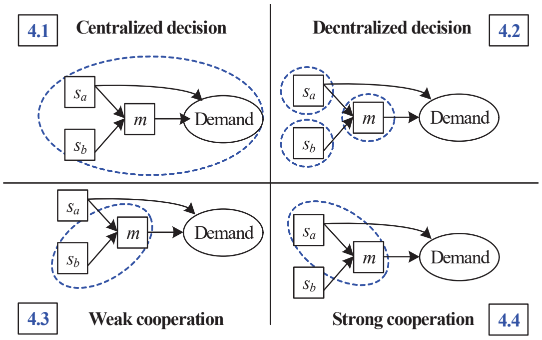


Figure 2 Scenarios and the Map of Section 4

4. Model and Equilibrium Analysis

As shown in Figure 2, section 4 aims to analyze how cooperative strategies designed by the weak main manufacturer work on improving performance and the equilibrium decisions under different scenarios. Subsection 4.1 presents the model and equilibrium decisions under centralized decisions as a benchmark; subsection 4.2 aims to study a more common case in which all stakeholders take part in decentralized decisions. We develop a two-stage game model to reveal the optimal strategies of each stakeholder, and then comparing with the benchmark model in order to illustrate the superiority of cooperation; therefore, subsection 4.3 and subsection 4.4 explore strategic cooperation which is defined as weak cooperation and strong cooperation respectively, furthermore, illustrate the superiority of cooperating with strong supplier s_a. A revenue-sharing contract based on relationship-specific investment is designed in subsection 4.4.

4.1 Centralized Decision

In order to serve as a benchmark case, we first develop a model for centralized decision. In the case of a centralized decision, all the stakeholders of the supply chain in CoPS work together to determine the quantity to maximize the total profit of the supply chain. Let π_T^C denotes the total profit of the supply chain under a centralized scenario, the decision problem of the supply chain is given as follows:

$$\max \pi_T^c\left(q_{am}^c, q_{bm}^c, q_{as}^c\right) = \textstyle\sum_{i=m,s}\left(p_{ai}^c - c_a\right) q_{ai}^c + \left[p_{bm}^c - c_b - \theta\left(\tau_a - \tau_b\right)^2\right] q_{bm}^c \quad (2)$$

Under the scenario of the centralized decision, the optimal decisions of the whole supply chain can be summarized into Proposition 1. Hereafter, proofs of all propositions and lemmas are presented in Appendix A.

Proposition 1 *(Equilibrium under centralized decision)*

When the main manufacturer and the two suppliers devote in centralized decision, the optimal decisions are denoted by $q_{am}^{c*}, q_{bm}^{c*}, q_{as}^{c*}, \pi_T^{c*}$ and given as follows.

$$\begin{cases} q_{am}^{c*} = \dfrac{(\gamma^2\eta^2-1)\left[(\eta-1)(p-c_a)+c_m-\eta c_S\right]}{2\beta(1-\gamma^2)(1-\eta^2)} - \dfrac{\gamma(\eta^2-1)\left[-p+c_b+c_m+\gamma\eta(p-c_a-c_S)+\theta(\tau_a-\tau_b)\right]}{2\beta(1-\gamma^2)(1-\eta^2)} \\ q_{bm}^{c*} = \dfrac{p(1-\gamma)+\gamma(c_a+c_m)-(c_b+c_m)-\theta(\tau_a-\tau_b)^2}{2\beta(1-\gamma^2)} \\ q_{as}^{c*} = \dfrac{p(1-\eta)+\eta(c_a+c_m)-(c_a+c_s)}{2\beta(1-\eta^2)} \\ \pi_T^{c*} = \pi_T^c\left(q_{am}^{c*}, q_{bm}^{c*}, q_{as}^{c*}\right) \end{cases}$$

4.2 Decentralized Decisions

We examine the supply chain when supplier s_x and main manufacturer are devoted to a decentralized decision. Figure 3 illustrates the decisions of the decentralized supply chain. The decision problem is a two-stage game, we first consider the optimal quantity for the main manufacturer and supplier s_a using backward induction, it is a function of wholesale price and can be derived from their payoff functions, and then the optimal wholesale price for all suppliers can be derived from suppliers' payoff functions.

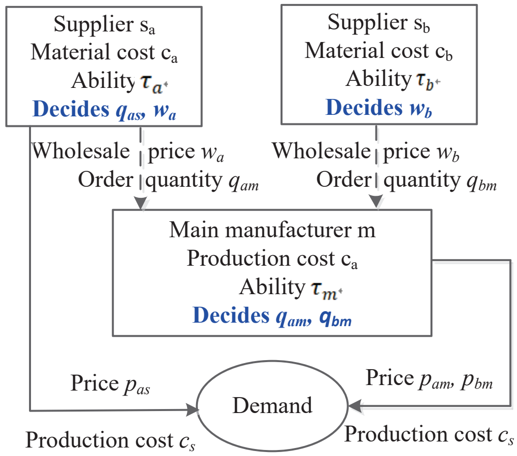


Figure 3 Decisions under Decentralized Supply

The sequence of events under decentralized decision is shown as follows, the two competitive suppliers decided their own wholesale price independently at the same time, and then production quantities are decided by supplier s_a and the main manufacturer through Cournot competition. Let π_m^d and $\pi_{s_a}^d$ be the profit of supplier s_a and the main manufacturer in the last stage respectively, thus, the payoff functions and decision model are described as follows.

$$\max \pi_m^d\left(q_{am}^d, q_{bm}^d\right) = -\theta\left(\tau_a - \tau_b\right)^2 q_{bm}^d + \sum_{x=a,b}\left(p_{xm}^d - w_m^d - c_m\right) q_{xm}^d \quad (3)$$

$$\max \pi_{s_a}^d\left(q_{as}^d\right) = \left(w_a^d - c_a\right) q_{am}^d + \left(p_{as}^d - c_a - c_s\right) q_{as}^d \quad (4)$$

The wholesale prices of the two suppliers at the first stage are the reaction functions with respect to the optimal quantities of the strong supplier s_a and the main manufacturer, thus, the profit of s_a and s_b in the first stage after production deciding are given as Eq. (5) and

Eq. (6) as follows:

$$\max \pi_{s_a}^d \left(w_a^d\right) = \left(w_a^d - c_a\right) q_{am}^d + \left(p_{as}^d - c_a - c_s\right) q_{as}^d \quad (5)$$

$$\max \pi_{s_b}^d \left(w_b^d\right) = \left(w_b^d - c_b\right) q_{bm}^d \quad (6)$$

Using backward deduction solve the decision problem, the optimal decisions can be summarized into Proposition 2.

Proposition 2 *(Equilibrium under decentralized decision)*

When the main manufacturer and the two competitive suppliers devote in a decentralized decision, the optimal decisions of the stakeholders are denoted by $q_{xi}^{d^*}$ and $w_{xi}^{d^*}$, as follows:

$$\begin{cases} w_a^{d^*} = \dfrac{32-8\eta^2(\gamma^2+1)+4\eta^3(\gamma^2-1)+2\gamma^2\eta^4}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_a + \dfrac{\gamma(\eta^2-4)^2}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_b + \dfrac{4\eta^3(\gamma^2-1)}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_s \\ \quad + \dfrac{\gamma(\eta^2-4)^2+16(\eta^2-2)-\gamma^2(\eta^4+8\eta^2-16)}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_m + \dfrac{\gamma\theta(\eta^2-4)^2(\tau_a-\tau_b)^2}{\gamma^2(3\eta^4-16)-24\eta^2+64} + k_1 \\ w_b^{d^*} = \dfrac{\gamma^3\eta^4-4\gamma\eta^2(1+\gamma^2)+2\gamma\eta^3(\gamma^2-1)+16\gamma}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_a + \dfrac{2\gamma^2\eta^4-4\eta^2(3+\gamma^2)+32}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_b + \dfrac{2\gamma\eta^3(\gamma^2-1)}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_s \\ \quad + \dfrac{(\gamma^3\eta^2-4\gamma)(\eta^2-4)+4(3\eta^2-8)-\gamma^2(\eta^4+4\eta^2-16)}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_m - \dfrac{\theta[32-12\eta^2+\gamma^2(\eta^4+4\eta^2-16)](\tau_a-\tau_b)^2}{\gamma^2(3\eta^4-16)-24\eta^2+64} + k_2 \\ q_{am}^{d^*} = \dfrac{-\beta^3(4-\gamma^2\eta^2)[\eta(p-c_a-c_s)-2(p-c_m-w_a^{d^*})]+\beta^3\gamma(4-\eta^2)[\gamma\eta(p-c_a-c_s)-2(p-c_m-w_b^{d^*}-\theta\tau_a^2+2\theta\tau_a\tau_b-\theta\tau_b^2)]}{4\beta^4(\gamma^2-1)(\eta^2-4)} \\ q_{bm}^{d^*} = \dfrac{(p-c_m)(1-\gamma)-\theta(\tau_a-\tau_b)^2+\gamma\mathbf{w}_a^{d^*}-\mathbf{w}_b^{d^*}}{2\beta(1-\gamma^2)} \\ q_{as}^{d^*} = \dfrac{p(2-\eta)+\eta(c_m+w_a^{d^*})-2(c_a+c_s)}{\beta(4-\eta^2)} \end{cases}$$

where

$$k_1 = \frac{p\left[(32-16\eta^2+4\eta^3)-\gamma(\eta^2-4)^2+\gamma^2(\eta^4-4\eta^3+8\eta^2-16)\right]}{\gamma^2(3\eta^4-16)-24\eta^2+64}$$

$$k_2 = \frac{p[32-12\eta^2-\gamma^3\eta^2(\eta^2+2\eta-4)+2\gamma(\eta^3+2\eta^2-8)+\gamma^2(\eta^4+4\eta^2-16)]}{\gamma^2(3\eta^4-16)-24\eta^2+64}$$

Lemma 1 *(Equilibrium profits under decentralized decision)*

Let $\pi_m^{d^*}$ and $\pi_{s_x}^{d^*}$ denote the optimal profit of the main manufacturer and supplier s_x under the scenario of decentralized decision, respectively, $\pi_T^{d^*}$ denotes the optimal total profit of the supply chain, therefore, the optimal profits can be summarized as follows:

$$\pi_m^{d^*} = \pi_m^d\left(q_{am}^{d^*}, q_{bm}^{d^*}\right),\ \pi_{s_a}^{d^*} = \pi_{s_a}^d\left(w_a^{d^*}, q_{as}^{d^*}\right),$$
$$\pi_{s_b}^{d^*} = \pi_{s_b}^d\left(w_b^{d^*}\right),\ \pi_T^{d^*} = \pi_m^{d^*} + \pi_{s_a}^{d^*} + \pi_{s_b}^{d^*}$$

Lemma 1 hints that the optimal profits of each stakeholder are determined by their optimal equilibrium decisions, the optimal total profit of the supply chain is the sum of all stakeholders' optimal profit.

Lemma 2 *(Impact of cost on wholesale price)*

Supposing that $\Delta\tau = \tau_a - \tau_b$ denotes the ability gap between the two suppliers,

(i) Impact of material cost. $\frac{\partial w_a^{d^*}}{\partial c_a} > 0$, $\frac{\partial w_a^{d^*}}{\partial c_b} > 0$, $\frac{\partial w_b^{d^*}}{\partial c_a} > 0$, $\frac{\partial w_b^{d^*}}{\partial c_b} > 0$;

(ii) Impact of production cost. $\frac{\partial w_a^{d^*}}{\partial c_s} < 0$, $\frac{\partial w_a^{d^*}}{\partial c_m} < 0$, $\frac{\partial w_b^{d^*}}{\partial c_s} < 0$, $\frac{\partial w_b^{d^*}}{\partial c_m} < 0$;

(iii) Impact of suppliers' ability. $\frac{\partial w_a^{d^*}}{\partial \Delta\tau} > 0$, $\frac{\partial w_b^{d^*}}{\partial \Delta\tau} < 0$.

Lemma 2 hints both the optimal wholesale prices of supplier increase with material cost and decrease with production cost in case of a decentralized decision, however, the optimal wholesale price of supplier s_a who has strong ability increases with suppliers' ability gap while it decreases with suppliers' ability gap.

4.3 Cooperation with the Weak Supplier (Weak Cooperation)

This subsection studies how the profitability of each stakeholder would be affected in the case of the main manufacturer and the weak supplier working together. We define such case as weak cooperation, and moreover, we employ superscript w to denote the variables under the scenario of weak cooperation. It is obvious that the profit of the main manufacturer and supplier s_b will perform best if their decision is centrally controlled. Since the wholesale price of supplier s_x works on dividing the profit between itself and the main manufacturer, the sequence of events under weak cooperation can be described as follows. Firstly, the two competitive suppliers decide their own wholesale price w_x independently at the same time in pursuit of self-interest maximization; and then production quantities are decided by s_a and the main manufacturer through Cournot competition. Let π_m^w and $\pi_{s_a}^w$ be the profits of supplier s_a and the main manufacturer in the last stage respectively, hence, the profits and decision models are described as follows:

$$\max \pi_m^w \left(q_{am}^w, q_{bm}^w\right) = -\left[c_b + \theta\left(\tau_a - \tau_b\right)^2\right] q_{bm}^w + \sum_{x=a,b}\left(p_{xm}^w - c_m\right) q_{xm}^w - w_a^w q_{am}^w \quad (7)$$

$$\max \pi_{s_a}^w \left(q_{as}^w\right) = \left(w_a^w - c_a\right) q_{am}^w + \left(p_{as}^w - c_a - c_s\right) q_{as}^w \quad (8)$$

p_{xi} is given as Eq. (1), s_a and the main manufacturer choose quantities to maximize their profit respectively. The wholesale prices of s_a in the first stage are the functions with respect to the optimal quantities of strong supplier s_a and the main manufacturer, thus, the profit of supplier s_a in the first stage given as Eq. (9) and the optimal wholesale price of strong supplier s_a is determined.

$$\max \pi_{s_a}^w \left(w_a^w\right) = \left(w_a^w - c_a\right) q_{am}^w + \left(p_{as}^w - c_a - c_S\right) q_{as}^w \quad (9)$$

Using backward deduction to solve the problem and the optimal decisions can be summarized into Proposition 3.

Proposition 3 *(Equilibrium under weak cooperation)*

When the main manufacturer and s_b devote to weak cooperation, the optimal decisions of the main manufacturer and the competitive suppliers are denoted by $q_{xi}^{w^*}$ and $w_x^{w^*}$, as follows:

$$\begin{cases} w_a^{w^*} = \dfrac{2\eta^3\left(\gamma^2-1\right)}{32+2\eta^2\left(\gamma^2\eta^2-2\gamma^2-6\right)}c_s + \dfrac{\gamma^2\eta^4-4\left(1+\gamma^2\right)\eta^2+2\left(\gamma^2-1\right)\eta^3+16}{32+2\eta^2\left(\gamma^2\eta^2-2\gamma^2-6\right)}c_a + \dfrac{\gamma\left(\eta^2-4\right)^2+8\left(\eta^2-2\right)-\gamma^2\eta^4}{32+2\eta^2\left(\gamma^2\eta^2-2\gamma^2-6\right)}c_m \\ \qquad + \dfrac{\gamma\left(\eta^2-4\right)^2}{32+2\eta^2\left(\gamma^2\eta^2-2\gamma^2-6\right)}c_b + \dfrac{\left(16p-8p\eta^2\right)(1-\gamma)+2p\eta^3\left(1-\gamma^2\right)-p\gamma\eta^4(1+\gamma)+\theta\gamma\left(\eta^2-4\right)^2(\tau_a-\tau_b)^2}{32+2\eta^2\left(\gamma^2\eta^2-2\gamma^2-6\right)} \\ q_{am}^{w^*} = \dfrac{-\beta^3\left(4-\gamma^2\eta^2\right)\left[\eta\left(p-c_a-c_s\right)-2\left(p-c_m-w_a^{w^*}\right)\right]+\beta^3\gamma\left(4-\eta^2\right)\left[\gamma\eta\left(p-c_a-c_s\right)-2\left(p-c_b-c_m-\theta\tau_a^2+2\theta\tau_a\tau_b-\theta\tau_b^2\right)\right]}{4\beta^4\left(\gamma^2-1\right)\left(\eta^2-4\right)} \\ q_{bm}^{w^*} = \dfrac{\left(p-c_m\right)(1-\gamma)-\theta\left(\tau_a-\tau_b\right)^2+\gamma w_a^{w^*}-c_b}{2\beta\left(1-\gamma^2\right)} \\ q_{as}^{w^*} = \dfrac{p(2-\eta)-2(c_a+c_s)+\eta\left(c_m+w_a^{w^*}\right)}{\beta\left(4-\eta^2\right)} \end{cases}$$

Lemma 3 *(Equilibrium profits under weak cooperation)*

Let $\pi_m^{w^*}$ and $\pi_{s_a}^{w^*}$ denote the optimal profits of the supplier s_a and main manufacturer under the scenario of weak cooperation, respectively, let $\pi_T^{w^*}$ denotes the optimal total profit of the supply chain, the optimal profit of supplier s_a and main manufacturer are illustrated as follows:

$$\pi_m^{w^*} = \pi_m^w\left(q_{am}^{w^*}, q_{bm}^{w^*}\right), \pi_{s_a}^{w^*} = \pi_{s_a}^w\left(q_{as}^{w^*}\right),$$
$$\pi_T^{w^*} = \pi_m^{w^*} + \pi_{S_a}^{w^*}.$$

By substituting $q_{xi}^{w^*}$ and $w_a^{w^*}$ into Eq. (7) and Eq. (8), it is easily to obtain the optimal profits of supplier s_a and main manufacturer.

Lemma 4 *(Impact of cost on wholesale price)*

(i) Impact of material cost. The wholesale price under centralized decision increases with c_a and c_b;

(ii) Impact of production cost. The wholesale price under centralized decision decreases with c_m and c_s;

(iii) Impact of suppliers' ability. The wholesale price under centralized decision increases with $\Delta\tau$.

Lemma 4 hints that the optimal wholesale price of supplier s_a increases with the material cost of both the competitive suppliers and decreases with its production cost when encroaching on downstream, counter intuitively, it would decrease with the main manufacturer's production cost in the case of weak cooperation. This result is caused by the supplier's dual role that supplier s_a benefits both from supply and self-production, on the one hand, supplier s_a can provide component to the main manufacturer with a high wholesale price to improve profitability when the material cost is high, on the other hand, a low wholesale price can gain the probability of increasing in order quantity of the main manufacturer. Moreover, the optimal wholesale price of supplier s_a increases with the gap in ability of the two suppliers, this result is generated by the advantage in technology.

4.4 Cooperation with the Strong Supplier (Strong Cooperation)

In this subsection, the main manufacturer aims to improve in indigenous technological capability through cooperating with the strong supplier s_a, therefore, the main manufacturer designs a revenue-sharing contract based on relationship-specific investment so that can induce s_a to cooperate and co-production. As mentioned in subsection 3.2, the two competitive suppliers decide the wholesale price independently at the same time and then the main manufacturer bargains with s_a to decide the contract items and quantity. The cooperation relationship would be established only in case of the profit of s_a and the main manufacturer are not less than their reserve profit, if the bargaining game fails to reach an agreement, they would trade under competition, hence, the disagreement point is the profit under decentralized supply chain. As shown in Figure 4, we first derive the optimal decisions of s_a and the main manufacturer, i.e., the optimal contract items and quantities.

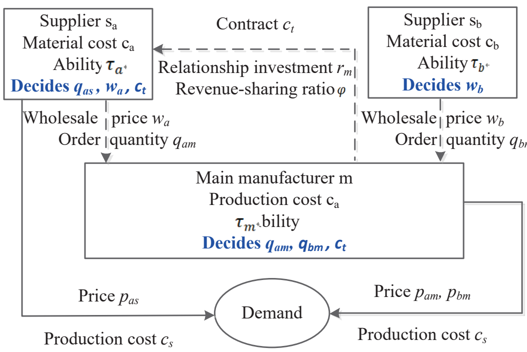


Figure 4 Decisions under Strong Cooperation

The reserve profit of s_a and the main manufacturer are given as $\pi_{s_a}^{d^*}$ and $\pi_m^{d^*}$ in Lemma 1, the two competitive suppliers decide wholesale price w_x^b in the first stage, then the main manufacturer provides the unit relationship-specific investment r_m to s_a, they bargain with each other in order to decide quantities and revenue-sharing proportion. The profit under cooperation can be illustrated as follows:

$$\pi_m^b\left(q_{am}^b, q_{bm}^b, \varphi\right) = \sum_{x=a,b}\left(p_{xm}^b - w_x^b - c_x\right) q_{xm}^b - \left(r_m + \varphi p_{am}^b\right) q_{am}^b - \theta\left(\tau_a - \tau_b\right)^2 q_{bm}^b \quad (10)$$

$$\pi_{s_a}^b\left(q_{as}^b, \varphi\right) = \left(w_a^b - c_a + r_m + \varphi p_{am}^b\right) q_{am}^b + \left(p_{as}^b - c_a - c_s\right) q_{as}^b \quad (11)$$

In our research, they bargain to decide the quantity and revenue-sharing proportion, Nash bargaining is a common and valid way to realize profit allocation (Qing et al. 2017, Kraft 2018). Hence, the decision problem is maximizing the following Nash product:

$$\max \Phi\left(q_{am}^b, q_{bm}^b, q_{as}^b, \varphi\right) = \left(\pi_m^b - \pi_m^{d^*}\right)^{\tau_m}\left(\pi_a^b - \pi_a^{d^*}\right)^{\tau_a} \quad (12)$$

where $\pi_m^b - \pi_m^{d^*}$ and $\pi_a^b - \pi_a^{d^*}$ are respectively the incremental profits of the main manufacturer and s_a. $\pi_m^{d^*}$ and $\pi_a^{d^*}$ are given in Lemma 1, supplier s_a and the main manufacturer bargain to reach agreement on contract items and production quantities given as a fixed r_m in order to maximize their profit respectively. Therefore, the decision problem in the first stage is maximizing the profit of weak supplier s_x with reaction of the optimal decisions of s_b and the main manufacturer. The profits of the two competitive suppliers in the first stage are given as Eq. (13) and Eq. (14).

$$\max \pi_{s_a}^b\left(q_{as}^b, \varphi\right) = \left(w_a^b - c_a + r_m + \varphi p_{am}^b\right) q_{am}^b + \left(p_{as}^b - c_a - c_s\right) q_{as}^b \quad (13)$$

$$\max \pi_{s_b}^b\left(w_b^b\right) = \left(w_b^b - c_b\right) q_{bm}^b \quad (14)$$

The optimal decisions under strong cooperation can be summarized into Proposition 4.

Proposition 4 *(Optimal decisions under strong cooperation)*

The optimal quantities are denoted by $q_{am}^{b^*}, q_{bm}^{b^*}$ and $q_{as}^{b^*}$, the optimal revenue-sharing proportion is denoted by φ^*, and let $w_x^{b^*}$ denote the optimal wholesale price under strong cooperation, therefore, the optimal decisions can be summarized as follows:

$$\begin{cases} w_b^{b^*} = \dfrac{(p-c_m)(1-\gamma)-\theta(\tau_a-\tau_b)^2+\gamma c_a+c_b}{2} \\ \mathbf{w}_a^{b^*} = F^{-1}\left(\dfrac{d\pi_{S_a}^d}{dw_a^b}\right) \\ q_{am}^{b^*} = \dfrac{8\beta^3\eta\gamma\left(1-\gamma^2\right)\left[\eta(p-c_a-c_m)-(p-c_a-c_s)\right]}{16\beta^4\gamma(1-\gamma^2)(1-\eta^2)} \\ \qquad + \dfrac{8\beta^3\gamma\left(1-\eta^2\right)\left[(p-c_a-c_m)-\gamma\left(p-c_m-w_b^{b^*}-\theta\tau_a^2+2\theta\tau_a\tau_b-\theta\tau_b^2\right)\right]}{16\beta^4\gamma(1-\gamma^2)(1-\eta^2)} \\ q_{bm}^{b^*} = \dfrac{(p-c_m)(1-\gamma)-\theta(\tau_a-\tau_b)^2+\gamma c_a-w_b^{b^*}}{2\beta(1-\gamma^2)} \\ q_{as}^{b*} = \dfrac{p(1-\eta)+\eta(c_a+c_m)-c_a-c_s}{2\beta(1-\eta^2)} \\ \varphi^* = F^{-1}\left(\dfrac{\pi_m^b-\pi_m^{d^*}}{\pi_a^b-\pi_a^{d^*}} - \dfrac{\tau_m}{\tau_a}\right) \end{cases}$$

Lemma 5 *(Equilibrium profits under strong cooperation)*

Let $\pi_m^{b^*}$, $\pi_{S_a}^{b^*}$ and $\pi_{S_b}^{b^*}$ denote the optimal profits of the main manufacturer and the two suppliers under the scenario of strong cooperation respectively, let $\pi_T^{b^*}$ denotes the optimal total profit of the supply chain, the optimal equilibrium profits under strong cooperation are illustrated as follows:

$$\pi_m^{b^*} = \pi_m^b\left(q_{am}^{b^*}, q_{bm}^{b^*}, \varphi^*\right), \pi_{S_a}^{b^*} = \pi_{S_a}^b\left(q_{as}^{b^*}, \varphi^*\right),$$
$$\pi_{S_b}^{b^*} = \pi_{S_b}^d\left(w_b^{b^*}\right), \pi_T^{b^*} = \pi_m^{b^*} + \pi_{S_a}^{b^*} + \pi_{S_b}^{b^*}.$$

Lemma 6 *(The effect of ability on cooperation strategy)*

The cooperation relationship would be established only if the ratio of the supplier's profit increment to the main manufacturer's profit increment is equal to the ratio of the supplier's ability to the main manufacturer's ability.

Lemma 6 hints that the profit increment from a cooperation relationship is decided by their abilities, a higher ability leads to high profitability.

Lemma 7 *(The effect of the relationship-specific investment on cooperation strategies)*

$$\frac{\partial w_b^{b^*}}{\partial r_m} = 0, \frac{\partial q_{am}^{b^*}}{\partial r_m} = 0, \frac{\partial q_{bm}^{b^*}}{\partial r_m} = 0, \quad \frac{\partial q_{as}^{b^*}}{\partial r_m} = 0$$

Lemma 7 hints that the relationship-specific investment will not affect the optimal quantities and the optimal wholesale price of the weak supplier s_b. This is determined by that the relationship-specific investment aims to recombine the profits between the strong supplier and the main manufacturer. The effect of relationship-specific investment on cooperation strategies will be analyzed in detail in section 5.

5. Comparative Analysis

In this section, some numerical experiments are presented to illustrate the effectiveness and advantage of the cooperation strategy. It is technically challenging to come up with analytical results about the comparison of different scenarios, hence numerical experiments are referenced in the case of KLX Inc. and one main manufacturer of China's large passenger aircraft. KLX Inc. is a leading provider of aerospace fasteners, consumables, and logistics services as KLX Aerospace Solutions. It also provides oilfield services and associated rental equipment across North America as KLX Energy Services. Boeing announced in 2018, that it has completed its acquisition of KLX Aerospace Solutions to enhance its growing services business and deliver greater value to its customers. The acquisition positions Boeing to compete and win in the \$2.8 trillion, 10-year aerospace services market. Simultaneously, KXL Inc. also does business with one main manufacturer of China's large passenger aircraft, however, Boeing is one global aircraft giant and competing with the firm of China's large passenger aircraft, thus, KLX Inc. is similar to encroach on downstream competition. In order to deal with this circumstance, we investigate the cooperation strategies from the perspective of the main manufacturer of China's large passenger aircraft in this section. We collected partial data from the publication and adjusted in order to capture the setting in differential suppliers' ability and downstream competition, hereafter, we set the benchmark parameters as $p = 28$, $c_m = 2$, $c_s = 5$, $c_a = 1$, $c_b = 3$, $\theta = 1.5$, $r_m = 1$, our main results are qualitatively consistent with those in the basic setting. In subsection 5.1, we employ numerical experiments to compare the cases with a different degree of product substitutability to illustrate the profitability and cooperation strategy. In subsection 5.2, we focus on analyzing the optimal strategies in case of different scenarios. In subsection 5.3, we compare the proposed cooperation strategy with a revenue-sharing contract in order to further prove the validity and applicability of the proposed contract.

5.1 Analysis of the Profitability

5.1.1 The Effect of η on Profitability

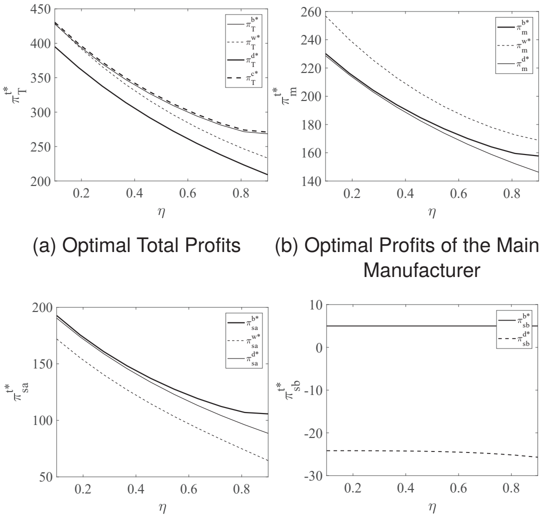
Profitability is an indispensable factor to reveal the effectiveness and advantage of cooperation strategy as well as the imperative to coordinate. Figure 5 and Figure 6 show that the optimal profits of the three stakeholders vary with the competitive degree and product substitutability.

The main results in Figure 5 can be demonstrated as follows.

(i) $\pi_T^{c*} > \pi_T^{b^*} > \pi_T^{w^*} > \pi_T^{d^*}$, $\pi_m^{w^*} > \pi_m^{b^*} > \pi_m^{d^*}$, $\pi_{s_a}^{b^*} > \pi_{s_a}^{d^*} > \pi_{s_a}^{w^*}$, $\pi_{s_b}^{b^*} > \pi_{s_b}^{d*}$;

(ii) $\frac{\partial \pi_T^{t^*}}{\partial \eta} < 0$, $\frac{\partial \pi_m^{t^*}}{\partial \eta} < 0$, $\frac{\partial \pi_{s_a}^{t^*}}{\partial \eta} < 0$, $\frac{\partial \pi_{s_b}^{d^*}}{\partial \eta} < 0$, $\frac{\partial \pi_{s_b}^{b^*}}{\partial \eta} = 0$.

From the computational results, we can find that the total profit of the supply chain under centralized decision will be the highest level compared with other scenarios despite the different competitive degree of the supplier. However, it is difficult to implement such a level in any real-life scenarios, nonetheless, Figure 5a shows that the overall profitability in the scenario of strong cooperation is very close to the total profit under the centralized decision. Meanwhile, the poorest efficiency



(a) Optimal Total Profits (b) Optimal Profits of the Main Manufacturer

(c) Optimal Profits of Supplier s_a (d) Optimal Profits of Supplier s_b

Figure 5 Optimal Profits under Different Scenarios with η

happens when all the stakeholders devote to the decentralized decision, but the overall efficiency of the supply chain can be improved whatever the weak cooperation or strong cooperation happens. Therefore, strategic cooperation is farsighted to heighten the efficiency of the whole supply chain. It deserves to illustrate that the following analysis will concentrate on the strong supplier s_a and the main manufacturer due to the cooperative relationship within the two stakeholders.

Intuitively, the total profit of the supply chain, as well as the profitability of each stakeholder, is decreasing with η, that is to say the material substitutability or the competitive degree of the two suppliers has negative impacts on the profitability. Figure 5c shows that the profitability of the strong supplier would be the lowest level under weak cooperation, so the weak cooperation between the main manufacturer and s_b can undermine the competitiveness of the strong supplier. However, it is counterintuitive from Figure 5d that the profitability of s_b is still enhancing in the scenario of strong cooperation even the cooperative relationship is established within the main manufacturer and the strong supplier. The reason for the counterintuitive conclusion mainly generated by the forward integrated effect under the scenario of weak cooperation, but an increase in the market sharing of the main manufacturer excels the integrated effect in the scenario of strong cooperation. The results in Figure 5c demonstrate that the strong supplier's profitability arrives at the highest level in case of strong cooperation despite medium profitability under decentralized.

5.1.2 The Effect of γ on Profitability

The main conclusions in Figure 6 can be directly summarized as follows.

(i) $\frac{\partial \pi_T^{t*}}{\partial \gamma} < 0$, $\frac{\partial \pi_m^{t*}}{\partial \gamma} < 0$, $\frac{\partial \pi_{sa}^{d*}}{\partial \gamma} < 0$, $\frac{\partial \pi_{s_b}^{b*}}{\partial \gamma} < 0$, $\frac{\partial \pi_{s_b}^{d*}}{\partial \gamma} > 0$

$$\frac{\partial \pi_{sa}^{w*}}{\partial \gamma} \begin{cases} > 0, & \text{if } 0 < \gamma \leq \gamma_1 \\ < 0, & \text{if } \gamma_1 < \gamma < 1 \end{cases}$$

$$\frac{\partial \pi_{sa}^{b*}}{\partial \gamma} \begin{cases} < 0, & \text{if } 0 < \gamma \leq \gamma_2 \\ > 0, & \text{if } \gamma_2 < \gamma < 1 \end{cases}$$

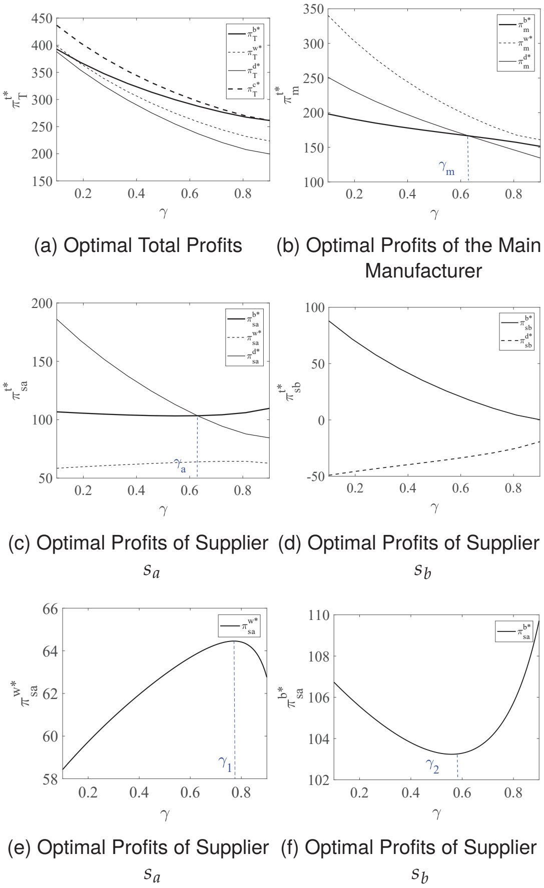
(ii) $\pi_T^{c*} > \pi_T^{b*} > \pi_T^{w*} > \pi_T^{d*}$; $\pi_{s_b}^{b*} > \pi_{s_b}^{d*}$

$$\pi_m^{w*} > \begin{cases} \pi_m^{d*} \geq \pi_m^{b*}, \text{ if } 0 < \gamma \leq \gamma_m \\ \pi_m^{b*} > \pi_m^{d*}, \text{ if } \gamma_m < \gamma \leq 1 \end{cases}$$

$$\pi_{s_a}^{w*} < \begin{cases} \pi_{s_a}^{b*} \leq \pi_{s_a}^{d*}, \text{ if } 0 < \gamma \leq \gamma_a \\ \pi_{s_a}^{d*} < \pi_{s_a}^{b*}, \text{ if } \gamma_a < \gamma \leq 1 \end{cases}$$

Even though the effect of γ on the overall profitability of the supply chain presents similar effectiveness with η, the profitability of each stakeholder is actually more comprehensive with γ. Figure 6a shows that the total profit of the supply chain decreases with γ, it means that the product substitutability of the final product has negative impacts on the profitability of the supply chain. However, the results in Figure 6b, 6c, 6d, and 6f show that the profitability of each stakeholder is also decreasing with the competitive degree of final product under different scenario, except the strong supplier's profitability under both scenarios in cooperation and the weak supplier's profitability under decentralized decision. Counter-intuitively, a decreasing trend of the strong supplier's profitability with γ is presented at the first and then displacing to increase in case of strong cooperation, but totally adverse under weak cooperation. It is also counterintuitive from Figure 6c and Figure 6d that the profitability of s_b is still ameliorating under the scenario of strong cooperation even the cooperative relationship is established within the main manufacturer and the strong supplier. Overall, the optimal profits of the main manufacturer and the strong supplier under the scenario of strong cooperation would be greater than the scenario of decentralized decision, unless γ is above a given threshold. It doesn't mean the strong cooperation relationship will not come true while γ is below the threshold value, once weak cooperation enters into business relations, the strong supplier's profitability would be far below any other situations. Therefore, the cooperative relationship would be established regardless of the competitive degree of the final product between the weak main manufacturer and the strong supplier.

Through the above computational results and comparison study, the following inspiration can be obtained: (i) the revenue-sharing contract based on relationship-specific investment is a feasible strategy for a weak main manufacturer to establish cooperation with a strong supplier in CoPS; (ii) the encroachment of a strong supplier would be weakened as a cooperative relationship; (iii) the weak cooperation would generate a forward integrated effect whereas the strong cooperation can intensify both the profitability of the supply chain and individuals; (iv) either fierce competition in upstream or downstream would reduce the integral and individual profitability; (v) nurturing domestic supplier is a possible solution to improve competitiveness and indigenous technological capability for the weak main manufacturer.



(a) Optimal Total Profits (b) Optimal Profits of the Main Manufacturer (c) Optimal Profits of Supplier s_a (d) Optimal Profits of Supplier s_b (e) Optimal Profits of Supplier s_a (f) Optimal Profits of Supplier s_b

Figure 6 Optimal Profits under Different Scenarios with η

5.2 Analysis of Optimal Strategies

We investigate the optimal strategies in this subsection with following the numerical study in subsection 5.1. Through analyzing the optimal quantities, wholesale prices, and contract items, this subsection aims to illustrate how the market share and profit allocation of individuals change under distinct scenarios. We emphasize on demonstrating the optimal decisions of the weak main manufacturer and the strong supplier.

5.2.1 Optimal Quantities

Figure 7 shows the optimal quantities of each individual. The main results can be summarized as follows.

(i) $\frac{\partial q_{as}^{t*}}{\partial \eta} < 0$, $\frac{\partial q_{am}^{t*}}{\partial \eta} < 0$ except that

$$\frac{\partial q_{am}^{b*}}{\partial \eta}\begin{cases} <0, & \text{if } 0<\eta\le\eta_1 \\ >0, & \text{if } \eta_1<\eta<1 \end{cases}$$

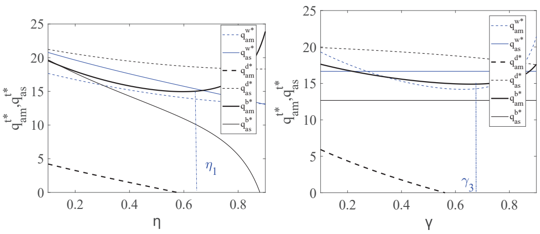
$\frac{\partial q_{as}^{t*}}{\partial \gamma}<0$, $\frac{\partial q_{am}^{t*}}{\partial \gamma}<0$ except that

$$\frac{\partial q_{am}^{b*}}{\partial \gamma}\begin{cases} <0, & \text{if } 0<\gamma\le\gamma_3 \\ >0, & \text{if } \gamma_3<\eta<1 \end{cases}$$

$$\frac{\partial q_{am}^{w*}}{\partial \gamma}\begin{cases} <0, & \text{if } 0<\gamma\le\gamma_3 \\ <0, & \text{if } \gamma_3<\gamma<1 \end{cases}$$

(ii) the optimal quantities satisfy the inequations where $q_{am}^{b*} > q_{as}^{b*}$, $q_{am}^{d*} < q_{as}^{d*}$, and $q_{am}^{w*} < q_{as}^{w*}$ with changing in η;

(iii) the optimal quantities satisfy the inequations where $q_{am}^{b*} > q_{as}^{b*}$, and $q_{am}^{d*} < q_{as}^{d*}$ with changing in γ.



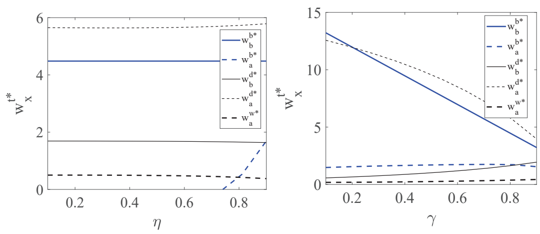
(a) With Changing in η (b) With Changing in γ

Figure 7 Optimal Quantities

Figure 7a shows that the optimal quantities of the main manufacturer and the strong supplier decrease first and rise later with η under the scenario of strong cooperation whereas they always decrease with η under any other scenario. This mainly caused by the contract items in the case of strong cooperation, the most profitable activity for the strong supplier is supplying component rather than encroaching on downstream, thus most demand constantly met by the main manufacturer while a cooperation relationship is ensured. More importantly, the main manufacturer's optimal quantity under decentralized decision would be zero when faced with the decentralized decision and a high degree of material substitutability, however, the strong supplier's optimal quantity would close to zero under the circumstance of strong cooperation and a high degree of material substitutability. The reason for the counterintuitive results lies on the profitability of the strong supplier, the strong supplier would rather interrupt providing material to the main manufacturer under decentralized decision so that can encroach on downstream competitively, nevertheless, the strong supplier still prefers to benefit from the contract and reduce the quantity of the final product. Figure 7b demonstrates similar results with Figure 7a except that the optimal quantity of the main manufacturer in the circumstance of weak cooperation also decreases first and increases over a threshold of γ. The reason is that the advantage of the weak alliance could display actively as a highly competitive degree between the main manufacturer and the strong supplier.

The comparative results in Figure 7 allow for the following comments. (i) The weak main manufacturer would suffer a risk of supply interruption from the strong suppliers under decentralized decision when faced with fierce competition both in upstream and downstream; (ii) Strategic cooperation with the strong supplier can against the strong supplier encroaching on downstream effectively; (iii) Cooperation relationship has a positive impact on boosting the weak main manufacturer's market share.

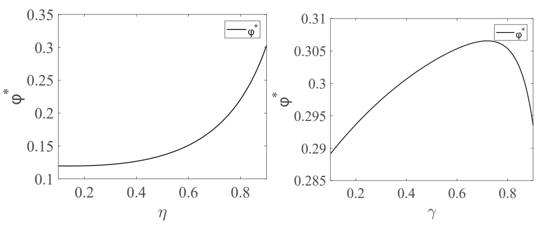
5.2.2 Optimal Wholesale Prices and Revenue-Sharing Proportion



(a) With Changing in η (b) With Changing in γ

Figure 8 Optimal Wholesale Prices

Wholesale prices and revenue-sharing proportion are critical factors in influencing profit allocation among chain members. Figure 8 demonstrates the tendencies in the wholesale prices and the competitive degree. Intuitively, the optimal wholesale prices of the two competitive suppliers have no significant change with η except the optimal wholesale price of strong supplier s_a increases obviously in the case of strong cooperation. In combination with Figure 9a, we can find that the reason for the counterintuitive results is caused by the strong supplier reduced the production of final product, because the main sources of profitability are from supplying and revenue-sharing, thus a high wholesale price and revenue-sharing proportion can ensure the profit in circumstance of facing fierce competition between the two suppliers. Figure 8b illustrates that the optimal wholesale prices of the two suppliers decrease with γ in the decentralized decision and strong cooperation whereas it increases slightly with γ in the decentralized decision and weak cooperation. It can be attributed to the contract coordination in combination with Figure 9b, the cooperative relationship is more likely to realize for the sake of profit when facing with a fierce downstream competition, therefore, the strong supplier must decide wholesale price and revenue-sharing proportion depending on the competitive degree of downstream, hence the optimal revenue-sharing proportion increases at first and decreases later with the competitive degree of downstream.



(a) With Changing in η (b) With Changing in γ

Figure 9 Revenue-Sharing Proportion

5.2.3 The Effect of Suppliers' Abilities on Cooperation

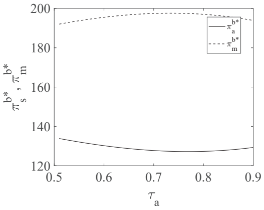
The stakeholder's ability is one of the decisive factors to affect the cooperative strategy in a cooperation relationship. The main features of Figure 10, Figure 11, and Figure 12 can be concluded as follows.

(i) $\frac{\partial \pi_{s_a}^{b^*}}{\partial \tau_b} < 0$; $\frac{\partial \pi_{m}^{b^*}}{\partial \tau_b} > 0$; $\frac{\partial \pi_{s_a}^{d^*}}{\partial \tau_b} < 0$; $\frac{\partial \pi_{m}^{d^*}}{\partial \tau_b} > 0$; $\frac{\partial q_{am}^{b^*}}{\partial \tau_a} < 0$; $\frac{\partial \varphi^*}{\partial \tau_b} < 0$; $\frac{\partial \varphi^*}{\partial \tau_m} < 0$

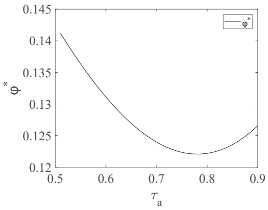
(ii) $\pi_T^{c^*} > \pi_T^{b^*} > \pi_T^{w^*} > \pi_T^{d^*}$; $\pi_m^{w^*} > \pi_m^{b^*} > \pi_m^{d^*}$; $\pi_{s_a}^{b^*} > \pi_{s_a}^{d*} > \pi_{s_a}^{w^*}$; $\pi_{s_b}^{b^*} > \pi_{s_b}^{d^*}$.

Figure 10 shows how the optimal decisions in cooperation relationship change with τ_a. The optimal quantity of the main manufacturer produced by the component from the strong supplier s_a increases with τ_a while the strong supplier's optimal quantity of final product is no relevance with τ_a, however, the optimal total quantity of the main manufacturer has a slightly decreasing tendency with τ_a, this is mainly caused by decreasing in optimal quantity from supplier s_b. Figure 10a shows the optimal profit of supplier s_a goes up first but then fall down with τ_a while the optimal profit of the main manufacturer falls down first and then rise with τ_a. Combine with Figure 10b and 10c, the main reasons for the change of optimal profit are caused by the optimal revenue-sharing proportion and quantities. Figure 10b shows that the optimal revenue-sharing proportion has the same varying tendency with the optimal profit of supplier s_a, because of the optimal revenue-sharing proportion determines the strong supplier' revenue under circumstance of cooperation, however, the main manufacturer's revenue decreases with φ, thus, its optimal profit presents an opposite character.

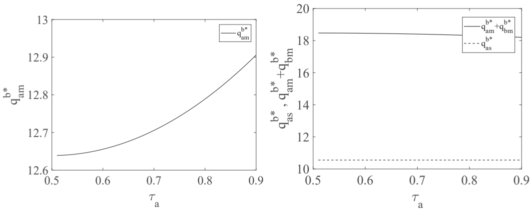
In Figure 11, we set the ability of the strong supplier s_a as $\tau_a = 0.6$, and then let the ability of the weak supplier s_b range from 0.1 to 0.59 because of $\tau_a > \tau_b$, it means that the gap of the two suppliers' abilities has been gradually narrowing over the increasing of τ_b. After comparing the profitability of each scenario, we can find that the main manufacturer and strong supplier's profitability showing an increasing gap, meanwhile, the profitability of the main manufacturer is increasing with τ_b while the strong supplier's profitability shows the op-



(a) The Effect of τ_a on π_m^{b*} and π_a^{b*}



(b) The Effect of τ_a on the Revenue-Sharing Proportion



(c) The Effect of τ_a on q_{am}^{b*} and q_{as}^{b*}

Figure 10 The Effect of Suppliers' Abilities on Cooperation

posite trend. In Figure 12, the profitability of the main manufacturer and the strong supplier are sharing the same trend with the improvement of the main manufacturer's ability. Moreover, the optimal revenue-sharing proportion presents a decreasing trend both with the abilities of weak supplier and main manufacturer. The main reasons lie on the increasing of weak supplier's ability can shut down the cost loss of the main manufacturer using the material of weak supplier, as well as increasing the competitiveness of the weak supplier so that perform well in competing with strong supplier, on the other hand, a high level of the main manufacturer's ability can enhance its bargaining power and cause well positioned in cooperation.

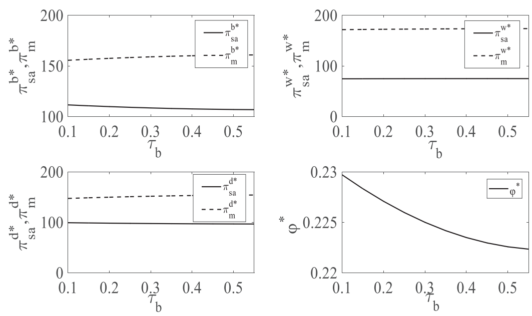


Figure 11 Different Suppliers' Abilities on Cooperation

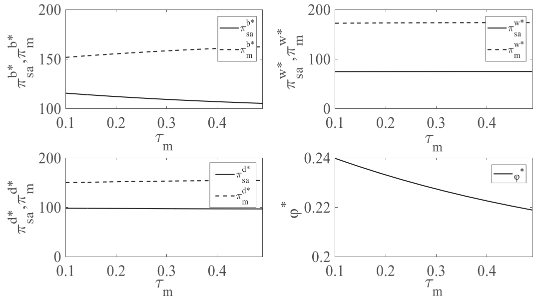


Figure 12 The Effect of the Main Manufacturer's Abilities on Cooperation

The results in Figure 10, Figure 11 and Figure 12 allow for the following insights, (i) it is better to establish a cooperative relationship for the main manufacturer when the strong supplier's ability is at a high level; (ii) the revenue-sharing contract based on relationship-specific investment can enhance the main manufacturer's profitability and marketing share when the ability of the strong supplier is relatively high; (iii) nurturing domestics suppliers and improvement of indigenous technological capability are necessary to the main manufacturer to keep strong competitiveness.

5.3 Comparing with Revenue-Sharing Contract

In order to further illustrate the validity and superiority of the proposed revenue-sharing contract based on relationship-specific investment, we next compare the proposed cooperation strategy with a conventional revenue-sharing contract. Subsection 5.3 omits a detailed decision process of the revenue-sharing contract because it is not the emphasis of this study, but we present it in Appendix B in detail. The computational results are reported in Table 2. In Table 2, π_k^{r*} denotes the optimal profit of decision maker k ($k \in \{s_x, m\}$) under scenario r where superscript r stands for the main manufacturer provides a revenue-sharing contract to the strong supplier s_a. In addition, π_T^{r*} denotes the optimal total profit of the supply chain. We use the symbols of "↑" or "↓" to clarify the variation of π_j^{b*} compared with π_k^{r*}

Table 2 Comparing with Revenue-Sharing Contract

	τ_m (0.1–0.49)							η (0.1–0.9)					
	$\pi_T^{r^*}$	$\pi_T^{b^*}(\uparrow\downarrow)$	$\pi_{s_a}^{r^*}$	$\pi_{s_a}^{b^*}(\uparrow\downarrow)$	$\pi_m^{r^*}$	$\pi_m^{b^*}(\uparrow\downarrow)$		$\pi_T^{r^*}$	$\pi_T^{b^*}(\uparrow\downarrow)$	$\pi_{s_a}^{r^*}$	$\pi_{s_a}^{b^*}(\uparrow\downarrow)$	$\pi_m^{r^*}$	$\pi_m^{b^*}(\uparrow\downarrow)$
$\varphi^* = 0.2398$	256.59	271.66 (↑)	144.11	115.55 (↓)	84.74	151.70(↑)	$\varphi^* = 0.1207$	426.2169	427.9577(↑)	243.2466	192.7544(↓)	157.1565	230.2012(↑)
$\varphi^* = 0.2339$	257.19	272.11 (↑)	143.58	112.53 (↓)	85.33	154.87(↑)	$\varphi^* = 0.1230$	362.0938	364.1881(↑)	205.4345	157.5327(↓)	130.5967	201.6533(↑)
$\varphi^* = 0.2288$	257.65	272.46(↑)	143.18	109.97(↓)	85.78	157.55(↑)	$\varphi^* = 0.1372$	312.729	318.0587(↑)	176.1583	132.2104(↓)	110.0736	180.8462(↑)
$\varphi^* = 0.2244$	257.96	272.71(↑)	142.92	107.82(↓)	86.09	159.78(↑)	$\varphi^* = 0.1789$	273.958	284.4639(↑)	152.9816	113.9042(↓)	93.40414	165.5576(↑)
$\varphi^* = 0.2206$	258.10	272.84(↑)	142.78	106.03(↓)	86.25	161.62(↑)	$\varphi^* = 0.3053$	243.1772	268.468(↑)	134.0609	105.7354(↓)	78.10971	157.7305(↑)

where "↑" and "↓" symbolize increase and decrease respectively.

As it is shown in Table 2, the optimal profit of the main manufacturer under the scenario of strong cooperation is higher than it in a simple revenue-sharing contract while the optimal profit of the strong supplier is exact inverse. Above all, the optimal total profit of the supply chain under strong cooperation is always higher than it under a simple revenue-sharing contract. That is to say, a revenue-sharing contract based on relationship-specific investment performs well than a simple revenue-sharing contract regarding total performance. The reason lies in the relationship-specific investment can improve the cooperation to more efficient performance. For instance, the main manufacturer should design a revenue-sharing contract based on relationship-specific investment to KLX Inc. rather than a simple revenue-sharing proportion. Relationship-specific investment is also common in many other firms who want to break through in knowledge and technology. Besides, relationship-specific investment is an effective strategy to avoid moral hazard in combination with a revenue-sharing contract. Therefore, the cooperative strategy proposed in this study is validity.

6. Conclusions and Future Research

In this paper, we aim to study strategic cooperation under two competitive suppliers with different abilities and a weak main manufacturer in CoPS, therefore, four models are developed under different scenarios. The channel structure is one main manufacturer trades with two competitive suppliers where the strong supplier can encroach on the downstream market through producing substitutable final products simultaneously. One benchmark model is set to illustrate the most effective scenario under the centralized decision, and then developing a more common scenario under the decentralized decision. Moreover, in order to improve the efficiency of each stakeholder, especially the developing purpose of the main manufacturer, the paper studies cooperation strategies and establishes two cooperative models under weak cooperation and strong cooperation. Different from the existing works of literature which study how the strong members allocate and control the supply chain, this paper observes how the weak individual improves the competitive environment through establishing a cooperative relationship inversely.

We characterize the equilibria and optimal decisions of each individual and develop the comparative analysis. The results show that strategic cooperation can enhance the profitability of the whole supply chain as well as individuals' profitability, especially strong cooperation can coordinate each stakeholder to well economic performance. Under the scenario of strong cooperation, the main manufacturer signs a revenue-sharing contract based on a relationship-specific investment with the strong supplier who provides a key element to the main manufacture and encroaches on the downstream market. We attempt to further understand how the weak main manufacturer realizes cooperation and grasp the opportunity to develop competitiveness and indigenous technological capability. The equilibrium decisions under different scenarios and the conditions for the cooperation strategies are characterized. We find that the revenue-sharing contract based on the relationship-specific investment which is designed by the main manufacturer can generate cooperation and coordination. Several insights are obtained.

The weak main manufacturer would face the risk of supply interruptions from the strong supplier when materials or final product are in high production substitutability under decentralized decision. A high competitive degree of suppliers and downstream competition would impair all chain members' profitability, as well as a high material cost, is harmful to the main manufacturer. Moreover, a high production cost against the suppliers' profitability whereas a high gap in ability of the two suppliers can benefit strong supplier a lot. Meanwhile, decentralized decision and high substitutability of material can generate an advantage to the strong supplier's profitability. However, the revenue-sharing contract based on a relationship investment has a positive impact on boosting the main manufacturer's profitability and market share, strategic cooperation is a feasible strategy to against the strong supplier encroaching on downstream.

In this work, we design a revenue-sharing contract based on a relationship-specific investment. The weak main manufacturer can realize cooperation with the strong supplier, however, it is worth to study how to establish cooperation relationship when a competitive main manufacturer exists in an MS mode. Moreover, for the weak main manufacturer in CoPS, how to nurture domestic supplier is worth considering for improving competitiveness and indigenous technological capability.

Appendix A Proofs

Proof of Proposition 1

By substituting Eq. (1) into Eq. (2), Eq. (A1) holds,

$$
\begin{aligned}
&\max \pi_T^c\left(q_{am}^c, q_{bm}^c, q_{as}^c\right) \\
&= \left[p - \beta q_{bm}^c - \beta\left(\gamma q_{am}^c + \gamma\eta q_{as}^c\right) - c_b - \theta\left(\tau_a - \tau_b\right)^2\right] q_{bm}^c \\
&\quad + \textstyle\sum_{i=m,s}\left[p - \beta\left(q_{ai}^c + \eta q_{aj}^c\right) - \beta\left(\gamma q_{bi}^c + \gamma\eta q_{bj}^c\right) - c_a\right] q_{ai}^c
\end{aligned}
\tag{A1}
$$

For any given quantity q_{xi}^c, we take the first partial derivative of $\pi_T^c(q_{am}^c, q_{bm}^c, q_{as}^c)$ with respect to q_{am}^c,q_{bm}^c, q_{as}^c. From $\frac{\partial\pi_T^c}{\partial q_{am}^c} = 0$, $\frac{\partial\pi_T^c}{\partial q_{bm}^c} = 0$, and $\frac{\partial\pi_T^c}{\partial q_{as}^c} = 0$ where

$$
\begin{cases}
\frac{\partial\pi_T^c}{\partial q_{am}^c} = p - c_a - c_m - \beta q_{am}^c - \beta\eta q_{as}^c - \beta\left(q_{am}^c + \eta q_{as}^c\right) \\
\qquad -2\beta\gamma q_{bm}^c \\
\frac{\partial\pi_T^c}{\partial q_{bm}^c} = p - c_b - c_m - \beta\gamma q_{am} - \beta\gamma\eta q_{as} - \beta\left(\gamma q_{am} + \gamma\eta q_{as}\right) \\
\qquad -2\beta q_{bm} - \theta\left(\tau_a - \tau_b\right)^2 \\
\frac{\partial\pi_T^c}{\partial q_{as}^c} = p - c_a - c_s - \beta\eta q_{am} - \beta q_{as} - \beta\left(\eta q_{am} + q_{as}\right) \\
\qquad -2\beta\gamma\eta q_{bm}
\end{cases}
$$

we obtain q_{am}^c, q_{bm}^c and q_{as}^c

Taking the second partial derivative of $\pi_T^c\left(q_{am}^c, q_{bm}^c, q_{as}^c\right)$ with respect to q_{am}^c, q_{bm}^c and q_{as}^c, the Hessian matrix holds as $H_{\pi_T^c}$.

$$
H_{\pi_T^c} = \begin{pmatrix}
\frac{\partial^2\pi_T^c}{\partial q_{am}^{c2}} & \frac{\partial^2\pi_T^c}{\partial q_{am}^c q_{bm}^c} & \frac{\partial^2\pi_T^c}{\partial q_{am}^c q_{as}^c} \\
\frac{\partial^2\pi_T^c}{\partial q_{bm}^c q_{am}^c} & \frac{\partial^2\pi_T^c}{\partial q_{bm}^{c2}} & \frac{\partial^2\pi_T^c}{\partial q_{bm}^c q_{as}^c} \\
\frac{\partial^2\pi_T^c}{\partial q_{as}^c q_{am}^c} & \frac{\partial^2\pi_T^c}{\partial q_{as}^c q_{bm}^c} & \frac{\partial^2\pi_T^c}{\partial q_{as}^{c2}}
\end{pmatrix}
$$

where $\frac{\partial^2\pi_T^C}{\partial q_{am}^{c2}} = -2\beta < 0$, $\frac{\partial^2\pi_T^C}{\partial q_{bm}^{c2}} = -2\beta < 0$, $\frac{\partial^2\pi_T^c}{\partial q_{as}^{c2}} = -2\beta < 0$, $\frac{\partial^2\pi_T^c}{\partial q_{am}^c q_{bm}^c} = \frac{\partial^2\pi_T^c}{\partial q_{bm}^c q_{am}^c} = -2\beta\gamma$, $\frac{\partial^2\pi_T^c}{\partial q_{am}^c q_{as}^c} = \frac{\partial^2\pi_T^c}{\partial q_{as}^c q_{am}^c} = -2\beta\eta$. Then, we have $\left|H_{\pi_{T_1}^c}\right| = -2\beta < 0$, $\left|H_{\pi_{T2}^c}\right| = 4\beta^2\left(1 + \gamma^2\right) > 0$, $\left|H_{\pi T3}\right| = -8\beta^3\left(\gamma^2 - 1\right)\left(\eta^2 - 1\right) < 0$.

Thus, the Hessian matrix $H_{\pi_T^c}$ is negative, it means that $\pi_T^c\left(q_{am}^c, q_{bm}^c, q_{as}^c\right)$ is a joint concave function of q_{am}^{c}, q_{bm}^{c} and q_{as}^{c}, therefore, we obtain the optimal production quantity as $q_{am}^{c^*}$, $q_{bm}^{c^*}$ and $q_{as}^{c^*}$ where

$$\begin{cases} q_{am}^{c^*} = q_{am}^{c} \\ \quad = \dfrac{-\gamma\left(\eta^2-1\right)\left[-p+c_b+c_m+\gamma\eta\left(p-c_a-c_s\right)+\theta\left(\tau_a-\tau_b\right)^2\right]}{2\beta\left(1-\gamma^2\right)\left(1-\eta^2\right)} \\ \quad + \dfrac{\left(\gamma^2\eta^2-1\right)\left[(\eta-1)\left(p-c_a\right)+c_m-\eta c_s\right]}{2\beta\left(1-\gamma^2\right)\left(1-\eta^2\right)} \\ q_{bm}^{c^*} = q_{bm}^{c} = \dfrac{p(1-\gamma)+\gamma(c_a+c_m)-(c_b+c_m)-\theta(\tau_a-\tau_b)^2}{2\beta\left(1-\gamma^2\right)} \\ q_{as}^{c^*} = q_{as}^{c} = \dfrac{p(1-\eta)+\eta(c_a+c_m)-(c_a+c_s)}{2\beta\left(1-\eta^2\right)} \end{cases}$$

Substituting $q_{am}^{c^*}$, $q_{bm}^{c^*}$,$q_{as}^{c^*}$ into Eq. (A1), we can obtain $\pi_T^{c^*} = \pi_T^{c}\left(q_{am}^{c^*}, q_{bm}^{c^*}, q_{as}^{c^*}\right)$

The proof of Proposition 1 is finished.

Proof of Proposition 2

By substituting Eq. (1) into Eq. (3) and Eq. (4), Eq. (A2) and Eq. (A3) hold,

$$\max \pi_m^d\left(q_{am}^d, q_{bm}^d\right) = \sum_{x=a,b}\left[p_{xm}^d - w_x^d - c_x\right]q_{xm}^d - \theta\left(\tau_a-\tau_b\right)^2 q_{bm}^d \tag{A2}$$

$$\max \pi_{s_a}^d\left(q_{as}^d\right) = \left(w_a^d - c_a\right)q_{am}^d + \left[p_{as}^d - c_a - c_s\right]q_{as}^d \tag{A3}$$

We first investigate the response functions of supplier for any given wholesale price. According to Eq. (A2) and Eq. (A3), we can easily obtain q_{am}^d, q_{bm}^d and q_{as}^d as shown in Eq. (A4) from the first partial derivative of $\pi_m^d\left(q_{am}^d, q_{bm}^d\right)$ and $\pi_{s_a}^d\left(q_{as}^d\right)$ which are $\frac{\partial\pi_m^d}{\partial q_{am}^d} = 0$, $\frac{\partial\pi_m^d}{\partial q_{bm}^d} = 0$ and $\frac{\partial\pi_m^d}{\partial q_{as}^d} = 0$, where

$$\begin{cases} q_{am}^d = \dfrac{\beta^3\gamma\left(4-\eta^2\right)\left[\gamma\eta(p-c_a-c_s)-2\left(p-c_m-w_b^d-\theta\tau_a^2+2\theta\tau_a\tau_b-\theta\tau_b^2\right)\right]}{4\beta^4(\gamma^2-1)(\eta^2-4)} \\ \qquad - \dfrac{\beta^3\left(4-\gamma^2\eta^2\right)\left[\eta\left(p-c_a-c_s\right)-2\left(p-c_m-w_a^d\right)\right]}{4\beta^4\left(\gamma^2-1\right)\left(\eta^2-4\right)} \\ q_{bm}^d = \dfrac{\left(p-c_m\right)(1-\gamma)-\theta\left(\tau_a-\tau_b\right)^2+\gamma w_a^d-w_b^d}{2\beta\left(1-\gamma^2\right)} \\ q_{as}^d = \dfrac{p(2-\eta)+\eta\left(c_m+w_a^d\right)-2(c_a+c_s)}{\beta\left(4-\eta^2\right)} \end{cases} \tag{A4}$$

Taking the second partial derivative of $\pi_m^d\left(q_{am}^d, q_{bm}^d\right)$ and $\pi_{s_a}^d\left(q_{as}^d\right)$ into consideration, because $\frac{\partial^2\pi_m^d}{\partial q_{xm}^{d2}} = -2\beta < 0$, $\frac{d^2\pi_{sa}^d}{dq_{as}^{d2}} = -2\beta < 0$, so $\pi_m^d\left(q_{am}^d, q_{bm}^d\right)$ and $\pi_{s_a}^d\left(q_{as}^d\right)$ are concave functions of q_{am}^d, q_{bm}^d and q_{as}^d, thus the optimal production quantities denoted as $q_{am}^{c^*}$, $q_{bm}^{c^*}$ and $q_{as}^{c^*}$ are holding as $q_{am}^{c^*} = q_{am}^{c}$, $q_{bm}^{c^*} = q_{bm}^{c}$ and $q_{as}^{c^*} = q_{as}^{c}$.

We continue to investigate the profits of supplier s_x in the first stage. By substituting Eq. (1) and Eq. (A4) into Eq. (5) and Eq. (6), the profits of supplier s_x hold as follows.

$$\max \pi_{s_a}^d\left(w_a^d\right) = (w_a^d - c_a)q_{am}^d + [p_{as}^d - c_a - c_s]q_{as}^d \tag{A5}$$

$$\max \pi_{s_b}^d(w_b^d) = (w_b^d - c_b)\frac{(p-c_m)(1-\gamma)-\theta(\tau_a-\tau_b)^2+\gamma w_a^d-w_b^d}{2\beta(1-\gamma^2)} \tag{A6}$$

Therefore, w_a^d and w_b^d can be obtained from the first partial derivative of $\pi_m^d(w_a^d)$ and $\pi_{s_a}^d(w_b^d)$ with respect to w_a^d and w_b^d respectively. From $\frac{\mathrm{d}\pi_{s_a}^d}{\mathrm{d}w_a^d} = 0$ and $\frac{\mathrm{d}\pi_{s_b}^d}{\mathrm{d}w_b^d} = 0$ where w_a^d and w_b^d can be derived into Eq. (A7).

$$\begin{cases} w_a^d = \dfrac{32-8\eta^2(\gamma^2+1)+4\eta^3(\gamma^2-1)+2\gamma^2\eta^4}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_a + \dfrac{\gamma(\eta^2-4)^2}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_b + \dfrac{4\eta^3(\gamma^2-1)}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_s \\ \qquad + \dfrac{\gamma(\eta^2-4)^2+16(\eta^2-2)-\gamma^2(\eta^4+8\eta^2-16)}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_m + \dfrac{\gamma\theta(\eta^2-4)^2(\tau_a-\tau_b)^2}{\gamma^2(3\eta^4-16)-24\eta^2+64} + k_1 \\ w_a^d = \dfrac{\gamma^3\eta^4-4\gamma\eta^2(1+\gamma^2)+2\gamma\eta^3(\gamma^2-1)+16\gamma}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_a + \dfrac{2\gamma^2\eta^4-4\eta^2(3+\gamma^2)+32}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_b + \dfrac{2\gamma\eta^3(\gamma^2-1)}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_s \\ \qquad + \dfrac{(\gamma^3\eta^2-4\gamma)(\eta^2-4)+4(3\eta^2-8)-\gamma^2(\eta^4+4\eta^2-16)}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_m - \dfrac{\theta[32-12\eta^2+\gamma^2(\eta^4+4\eta^2-16)](\tau_a-\tau_b)^2}{\gamma^2(3\eta^4-16)-24\eta^2+64} + k_2 \end{cases} \tag{A7}$$

where
$k_1 = \frac{p[(32-16\eta^2+4\eta^3)-\gamma(\eta^2-4)^2+\gamma^2(\eta^4-4\eta^3+8\eta^2-16)]}{\gamma^2(3\eta^4-16)-24\eta^2+64}$,
$k_2 = \frac{p[32-12\eta^2-\gamma^3\eta^2(\eta^2+2\eta-4)+2\gamma(\eta^3+2\eta^2-8)+\gamma^2(\eta^4+4\eta^2-16)]}{\gamma^2(3\eta^4-16)-24\eta^2+64}$
are constants.

Taking the second partial derivative of $\pi_m^d(w_a^d)$ and $\pi_{s_a}^d(w_b^d)$ with respect to w_a^d and w_b^d respectively, we obtain $\frac{d^2\pi_{s_a}^d}{dw_a^{d2}} = \frac{16-2(3+\gamma^2)\eta^2+\gamma^2\eta^4}{\beta(\gamma^2-1)(\eta^2-4)^2} < 0$, $\frac{d^2\pi_{s_b}^d}{dw_b^{d2}} = \frac{1}{\beta(\gamma^2-1)} < 0$, thus, $\pi_m^d(w_a^d)$ and $\pi_{s_a}^d(w_b^d)$ are concave and max imized at $w_a^d = w_a^{d^*}$ and $w_b^d = w_b^{d^*}$ respectively, therefore, we obtain $w_a^{d^*} = w_a^d$ and $w_b^{d^*} = w_b^d$.

By substituting $w_a^{d^*}$ and $w_b^{d^*}$ into Eq. (A4), we can easily summarize equilibrium decisions under decentralized supply chain into Eq. (A8).

$$\begin{cases} w_a^{d^*} = \frac{32-8\eta^2(\gamma^2+1)+4\eta^3(\gamma^2-1)+2\gamma^2\eta^4}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_a + \frac{\gamma(\eta^2-4)^2}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_b + \frac{4\eta^3(\gamma^2-1)}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_s \\ \quad + \frac{\gamma(\eta^2-4)^2+16(\eta^2-2)-\gamma^2(\eta^4+8\eta^2-16)}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_m + \frac{\gamma\theta(\eta^2-4)^2(\tau_a-\tau_b)^2}{\gamma^2(3\eta^4-16)-24\eta^2+64} + k_1 \\ w_b^{d^*} = \frac{\gamma^3\eta^4-4\gamma\eta^2(1+\gamma^2)+2\gamma\eta^3(\gamma^2-1)+16\gamma}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_a + \frac{2\gamma^2\eta^4-4\eta^2(3+\gamma^2)+32}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_b + \frac{2\gamma\eta^3(\gamma^2-1)}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_s \\ \quad + \frac{(\gamma^3\eta^2-4\gamma)(\eta^2-4)+4(3\eta^2-8)-\gamma^2(\eta^4+4\eta^2-16)}{\gamma^2(3\eta^4-16)-24\eta^2+64}c_m - \frac{\theta[32-12\eta^2+\gamma^2(\eta^4+4\eta^2-16)](\tau_a-\tau_b)^2}{\gamma^2(3\eta^4-16)-24\eta^2+64} + k_2 \\ q_{am}^{d^*} = \frac{-\beta^3(4-\gamma^2\eta^2)[\eta(p-c_a-c_s)-2(p-c_m-w_a^{d^*})]+\beta^3\gamma(4-\eta^2)[\gamma\eta(p-c_a-c_s)-2(p-c_m-w_b^{d^*}-\theta\tau_a^2+2\theta\tau_a\tau_b-\theta\tau_b^2)]}{4\beta^4(\gamma^2-1)(\eta^2-4)} \\ q_{bm}^{d^*} = \frac{(p-c_m)(1-\gamma)-\theta(\tau_a-\tau_b)^2+\gamma w_a^{d^*}-w_b^{d^*}}{2\beta(1-\gamma^2)} \\ q_{as}^{d^*} = \frac{p(2-\eta)+\eta(c_m+w_a^{d^*})-2(c_a+c_s)}{\beta(4-\eta^2)} \end{cases} \quad \text{(A8)}$$

The proof of Proposition 2 has finished.

Proof of Lemma 1

Lemma 1 can be easily obtained by substituting Eq. (A8) into Eq. (A2), Eq. (A3) and Eq. (A6), that are $\pi_m^{d^*} = \pi_m^d(q_{am}^{d^*}, q_{bm}^{d^*})$, $\pi_{s_a}^{d^*} = \pi_{s_a}^d(w_a^{d^*}, q_{as}^{d^*})$, $\pi_{s_b}^{d^*} = \pi_{s_b}^d(w_b^{d^*})$, the optimal total profit of the supply chain is the sum of stakeholders' optimal profit, therefore, $\pi_T^{d^*} = \pi_m^{d^*} + \pi_{s_a}^{d^*} + \pi_{s_b}^{d^*}$ holds.

Proof of Lemma 2

According to Eq. (A8), because $\eta \in (0,1)$, $\gamma \in (0,1)$ and $0 > \tau_a > \tau_b > 1$, the following inequations hold:

$$\frac{\partial w_a^{d^*}}{\partial c_a} = \frac{32-8\eta^2(\gamma^2+1)+4\eta^3(\gamma^2-1)+2\gamma^2\eta^4}{\gamma^2(3\eta^4-16)-24\eta^2+64} > 0$$

$$\frac{\partial w_a^{d^*}}{\partial c_b} = \frac{\gamma(\eta^2-4)^2}{\gamma^2(3\eta^4-16)-24\eta^2+64} > 0$$

$$\frac{\partial w_b^{d^*}}{\partial c_a} = \frac{\gamma^3\eta^4-4\gamma\eta^2(1+\gamma^2)+2\gamma\eta^3(\gamma^2-1)+16\gamma}{\gamma^2(3\eta^4-16)-24\eta^2+64} > 0$$

$$\frac{\partial w_b^{d^*}}{\partial c_b} = \frac{2\gamma^2\eta^4-4\eta^2(3+\gamma^2)+32}{\gamma^2(3\eta^4-16)-24\eta^2+64} > 0$$

$$\frac{\partial w_a^{d^*}}{\partial c_s} = \frac{4\eta^3(\gamma^2-1)}{\gamma^2(3\eta^4-16)-24\eta^2+64} < 0$$

$$\frac{\partial w_a^{d^*}}{\partial c_m} = \frac{\gamma(\eta^2-4)^2+16(\eta^2-2)-\gamma^2(\eta^4+8\eta^2-16)}{\gamma^2(3\eta^4-16)-24\eta^2+64} < 0$$

$$\frac{\partial w_b^{d^*}}{\partial c_s} = \frac{2\gamma\eta^3(\gamma^2-1)}{\gamma^2(3\eta^4-16)-24\eta^2+64} < 0$$

$$\frac{\partial w_b^{d^*}}{\partial c_m} = \frac{(\gamma^3\eta^2-4\gamma)(\eta^2-4)+4(3\eta^2-8)-\gamma^2(\eta^4+4\eta^2-16)}{\gamma^2(3\eta^4-16)-24\eta^2+64} < 0$$

$$\frac{\partial w_a^{d^*}}{\partial \Delta\tau} = \frac{2\gamma\theta(\eta^2-4)^2(\tau_a-\tau_b)}{\gamma^2(3\eta^4-16)-24\eta^2+64} > 0$$

$$\frac{\partial w_b^{d^*}}{\partial \Delta\tau} = \frac{2\theta[32-12\eta^2+\gamma^2(\eta^4+4\eta^2-16)](\tau_a-\tau_b)}{\gamma^2(3\eta^4-16)-24\eta^2+64} < 0$$

Proof of Lemma 2 has finished.

Proof of Proposition 3

By substituting Eq. (1) into Eq. (7) and Eq. (8), the following equations are holding,

$$\max \pi_m^w(q_{am}^w, q_{bm}^w) = \sum_{x=a,b}[p_{xm}^w - c_m]q_{xm}^w - w_a^w q_{am}^w - [c_b + \theta(\tau_a - \tau_b)^2]q_{bm}^w \tag{A9}$$

$$\max \pi_{s_a}^w(q_{as}^w) = (w_a^w - c_a)q_{am}^w + [p_{as}^w + c_a - c_s]q_{as}^w \tag{A10}$$

Denote $q_{am}^w = q_{am}^{w^*}$, $q_{bm}^w = q_{bm}^{w^*}$ and $q_{as}^w = q_{as}^{w^*}$ as the solution of the equation $\frac{\partial \pi_m^w}{\partial q_{am}^w} = 0$, $\frac{\partial \pi_m^w}{\partial q_{bm}^w} = 0$ and $\frac{d\pi_{s_a}^w}{dq_{as}^w} = 0$ respectively.

Taking the second partial derivative of $\pi_m^w(q_{am}^w, q_{bm}^w)$ and $\pi_{s_a}^w(q_{as}^w)$ into consideration, because $\frac{\partial^2 \pi_m^w}{\partial q_{xm}^{w2}} = -2\beta < 0$, $\frac{\partial^2 \pi_{s_a}^w}{\partial q_{as}^{w2}} = -2\beta < 0$, so $\pi_m^w(q_{am}^w, q_{bm}^w)$ and $\pi_{s_a}^w(q_{as}^w)$ are concave functions of q_{am}^w, q_{bm}^w and q_{as}^w, thus the optimal production quantities denoting as $q_{am}^{w^*}, q_{bm}^{w^*}$ and $q_{as}^{w^*}$ are max imized at $q_{am}^{w^*} = q_{am}^w, q_{bm}^{w^*} = q_{bm}^w$ and $q_{as}^{w^*} = q_{as}^w$ respectively. By solving simultaneous equations $\frac{\partial \pi_m^w}{\partial q_{am}^w} = 0$, $\frac{\partial \pi_m^w}{\partial q_{bm}^w} = 0$ and $\frac{\partial \pi_{s_a}^w}{\partial q_{as}^w} = 0$, we obtain q_{am}^w, q_{bm}^w and q_{as}^w as follows:

$$\begin{cases} q_{am}^w = \frac{-\beta^3(4-\gamma^2\eta^2)[\eta(p-c_a-c_s)-2(p-c_m-w_a^w)]+\beta^3\gamma(4-\eta^2)[\gamma\eta(p-c_a-c_s)-2(p-c_b-c_m-\theta\tau_a^2+2\theta\tau_a\tau_b-\theta\tau_b^2)]}{4\beta^4(\gamma^2-1)(\eta^2-4)} \\ q_{bm}^w = \frac{(p-c_m)(1-\gamma)-\theta(\tau_a-\tau_b)^2+\gamma w_a^w - c_b}{2\beta(1-\gamma^2)} \\ q_{as}^w = \frac{p(2-\eta)-2(c_a+c_s)+\eta(c_m+w_a^w)}{\beta(4-\eta^2)} \end{cases} \tag{A11}$$

Hence the profit of supplier s_a in the first stage after they decided quantities can be obtained by substituting Eq. (A11) into Eq. (8), denote $w_a^d = w_a^{d^*}$ as the solution of the equation $\frac{\partial \pi_{s_a}^w}{\partial w_a^w} = 0$, we obtain $\frac{\partial^2 \pi_{s_a}^w}{\partial w_a^{w2}} = \frac{16-2(3+\gamma^2)\eta^2+\gamma^2\eta^4}{\beta(\gamma^2-1)(\eta^2-4)^2} < 0$, thus, $\pi_{s_a}^w(w_a^w)$ is maximized at $w_a^w = w_a^{w^*}$, by solving $\frac{\partial \pi_{s_a}^w}{\partial w_a^w} = 0$, we obtain $w_a^w = w_a^{w^*}$ as follows:

$$\begin{cases} w_a^{w^*} = \frac{2\eta^3(\gamma^2-1)}{32+2\eta^2(\gamma^2\eta^2-2\gamma^2-6)}c_s + \frac{\gamma^2\eta^4-4(1+\gamma^2)\eta^2+2(\gamma^2-1)\eta^3+16}{32+2\eta^2(\gamma^2\eta^2-2\gamma^2-6)}c_a + \frac{\gamma(\eta^2-4)^2+8(\eta^2-2)-\gamma^2\eta^4}{32+2\eta^2(\gamma^2\eta^2-2\gamma^2-6)}c_m \\ \qquad + \frac{\gamma(\eta^2-4)^2}{32+2\eta^2(\gamma^2\eta^2-2\gamma^2-6)}c_b + \frac{(16p-8p\eta^2)(1-\gamma)+2p\eta^3(1-\gamma^2)-p\gamma\eta^4(1+\gamma)+\theta\gamma(\eta^2-4)^2(\tau_a-\tau_b)^2}{32+2\eta^2(\gamma^2\eta^2-2\gamma^2-6)} \end{cases}$$

By substituting $w_a^{w^*}$ into Eq. (A11), the following equations hold

$$\begin{cases} q_{am}^{w^*} = \frac{-\beta^3(4-\gamma^2\eta^2)[\eta(p-c_a-c_s)-2(p-c_m-w_a^{w^*})]+\beta^3\gamma(4-\eta^2)[\gamma\eta(p-c_a-c_s)-2(p-c_b-c_m-\theta\tau_a^2+2\theta\tau_a\tau_b-\theta\tau_b^2)]}{4\beta^4(\gamma^2-1)(\eta^2-4)} \\ q_{bm}^{w^*} = \frac{(p-c_m)(1-\gamma)-\theta(\tau_a-\tau_b)^2+\gamma w_a^{w^*} - c_b}{2\beta(1-\gamma^2)} \\ q_{as}^{w^*} = \frac{p(2-\eta)-2(c_a+c_s)+\eta(c_m+w_a^{w^*})}{\beta(4-\eta^2)} \end{cases}$$

Proposition 3 is proved.

Proof of Lemma 3

Lemma 3 can be easily obtained by substituting $q_{xi}^{w^*}$ and $w_a^{w^*}$ into Eq. (7) and Eq. (8), that are $\pi_m^{w^*} = \pi_m^w(q_{am}^{w^*}, q_{bm}^{w^*})$, $\pi_{s_a}^{w^*} = \pi_{s_a}^w(q_{as}^{w^*})$, the optimal total profit of the supply chain is the sum of stakeholders' optimal profit, therefore, $\pi_T^{w^*} = \pi_m^{w^*} + \pi_{s_a}^{w^*}$ holds.

The proof of Lemma 3 has finished.

Proof of Lemma 4

It can be easily derived from Proposition 3 that

$$\frac{\partial w_a^{c^*}}{\partial c_a} = \frac{\gamma^2\eta^4 - 4(1+\gamma^2)\eta^2 + 2(\gamma^2-1)\eta^3 + 16}{32 + 2\eta^2(\gamma^2\eta^2 - 2\gamma^2 - 6)} > 0$$
$$\frac{\partial w_a^{c^*}}{\partial c_b} = \frac{\gamma(\eta^2-4)^2}{32 + 2\eta^2(\gamma^2\eta^2 - 2\gamma^2 - 6)} > 0$$
$$\frac{\partial w_a^{c^*}}{\partial c_m} = \frac{\gamma(\eta^2-4)^2 + 8(\eta^2-2) - \gamma^2\eta^4}{32 + 2\eta^2(\gamma^2\eta^2 - 2\gamma^2 - 6)} < 0$$
$$\frac{\partial w_a^{c^*}}{\partial c_s} = \frac{2\eta^3(\gamma^2-1)}{32 + 2\eta^2(\gamma^2\eta^2 - 2\gamma^2 - 6)} < 0$$
$$\frac{\partial w_a^{c^*}}{\partial \Delta\tau} = \frac{2\theta\gamma(\eta^2-4)^2(\tau_a-\tau_b)}{32 + 2\eta^2(\gamma^2\eta^2 - 2\gamma^2 - 6)} > 0$$

Proof of Proposition 4

By substituting Eq. (1) into Eq. (7) and Eq. (8), the following equations are holding,

$$\pi_m^b(q_{am}^b, q_{bm}^b, \varphi) = \sum_{x=a,b}[q_{bx}^m - w_x^b - c_x]q_{xm}^b - r_m q_{am}^b - \theta(\tau_a-\tau_b)^2 q_{bm}^b - \varphi p_{am}^b q_{am}^b \tag{A12}$$

$$\pi_{s_a}^b(q_{as}^b, \varphi) = w_a^b - c_a + r_m + \varphi p_{am}^b q_{am}^b + (p_{as} - c_a - c_s)q_{as}^b \tag{A13}$$

According to Eq. (A12) and Eq. (A13), the decision problem in the last stage can be presented as follows,

$$\begin{aligned} &\max \Phi(q_{am}^b, q_{bm}^b, q_{as}^b, \varphi) \\ &= \left\{ \textstyle\sum_{x=a,b}(p_{xm}^b - w_x^b - c_x)q_{xm}^b - r_m q_{am}^b \right. \\ &\left. -\theta(\tau_a-\tau_b)^2 q_{bm}^b - \varphi p_{am}^b q_{am}^b - \pi_m^{d^*} \right\}^{\tau_m} \\ &\left\{(w_a^b - c_a + r_m + \varphi p_{am}^b)q_{am}^b \right. \\ &\left. +(p_{as} - c_a - c_s)q_{as}^b - \pi_a^{d^*} \right\}^{\tau_a} \end{aligned} \tag{A14}$$

Following straightforward algebra, by using second-order condition we derive that the Hessian matrix of function Φ is negative, hence we can derive the optimal decisions by first-order conditions, $\frac{\partial\Phi}{\partial q_{am}^b} = 0$, $\frac{\partial\Phi}{\partial q_{bm}^b} = 0$, $\frac{\partial\Phi}{\partial q_{as}^b} = 0$, $\frac{\partial\Phi}{\partial\varphi} = 0$. Thus, we obtain $q_{am}^b, q_{bm}^b, q_{as}^b$ and φ as follows:

$$\begin{cases} q_{am}^b &= \frac{8\beta^3\eta\gamma(1-\gamma^2)[\eta(p-c_a-c_m)-(p-c_a-c_s)]}{16\beta^4\gamma(1-\gamma^2)(1-\eta^2)} \\ &\quad + \frac{8\beta^3\gamma(1-\eta^2)[(p-c_a-c_m)-\gamma(p-c_m-w_b-\theta\tau_a^2+2\theta\tau_a\tau_b-\theta\tau_b^2)]}{16\beta^4\gamma(1-\gamma^2)(1-\eta^2)} \\ q_{bm}^b &= \frac{(p-c_m)(1-\gamma)-\theta(\tau_a-\tau_b)^2+\gamma c_a-w_b}{2\beta(1-\gamma^2)} \\ q_{as}^b &= \frac{p(1-\eta)+\eta(c_a+c_m)-c_a-c_s}{2\beta(1-\eta^2)} \\ \varphi &= F^{-1}\left(\frac{\pi_m^b-\pi_m^{d^*}}{\pi_a^b-\pi_a^{d^*}} - \frac{\tau_m}{\tau_a}\right) \end{cases} \tag{A15}$$

Therefore, by substituting Eq. (A15) into Eq. (13) and Eq. (14), the supplier's profit in stage 1 after negotiation and contract items is given as follows:

$$\max \pi_{s_a}^b(w_a^b) = \frac{8\beta^3\eta\gamma(1-\gamma^2)[\eta(p-c_a-c_m)-(p-c_a-c_s)]+8\beta^3\gamma(1-\eta^2)[(p-c_a-c_m)-\gamma(p-c_m-w_b-\theta\tau_a^2+2\theta\tau_a\tau_b-\theta\tau_b^2)]}{16\beta^4\gamma(1-\gamma^2)(1-\eta^2)}$$
$$(w_a^b - c_a + r_m + \varphi p_{am}^b)q_{am}^b + (p_{as}^b - c_a - c_s)\frac{p(1-\eta)+\eta(c_a+c_m)-c_a-c_s}{2\beta(1-\eta^2)} \tag{A16}$$

$$\max \pi_{s_b}^d(w_b^b) = (w_b^b - c_b)\frac{(p-c_m)(1-\gamma)-\theta(\tau_a-\tau_b)^2+\gamma c_a - w_b}{2\beta(1-\gamma^2)} \tag{A17}$$

The decision problem in the first stage is deciding wholesale price by supplier s_b to maximize its profit, therefore, w_b^b can be obtained from the first partial derivative of $\pi_{s_b}^d(w_b^b)$ with respect to w_b^b. From $\frac{\mathrm{d}\pi_{s_a}^d}{\mathrm{d}w_a^b} = 0$ and $\frac{\mathrm{d}\pi_{s_b}^d}{\mathrm{d}w_b^b} = 0$, w_a^b and w_b^b can be derived into Eq. (A18).

$$w_b^b = \frac{(p-c_m)(1-\gamma)-\theta(\tau_a-\tau_b)^2+\gamma c_a + c_b}{2}$$
$$w_a^b = F^{-1}\left(\frac{\mathrm{d}\pi_{s_a}^d}{\mathrm{d}w_a^b}\right) \tag{A18}$$

Taking the second partial derivative of $\pi^d_{s_x}(w^b_{bx})$ with respect to w^b_x, we obtain $\frac{\mathrm{d}^2\pi^d_{s_b}}{\mathrm{d}w^{d2}_b} = \frac{1}{\beta(\gamma^2-1)} < 0$, $\frac{\mathrm{d}^2\pi^d_{s_a}}{\mathrm{d}w^{d2}_a} < 0$ it means that $\pi^d_{s_x}(w^b_x)$ is concave and maximized at $w^{b^*}_a$ and $w^{b^*}_b$. By substituting $w^{b^*}_b$ into Eq. (A15), we can easily summarize equilibrium decisions under strong cooperation into Eq. (A19). $w^{b^*}_b = w^b_b = \frac{(p-c_m)(1-\gamma)-\theta(\tau_a-\tau_b)^2+\gamma c_a+c_b}{2}$, $w^{b^*}_a = f(w^{b^*}_b)$. By substituting $w^{b^*}_b$ into Eq. (A15), we can easily summarize equilibrium decisions under strong cooperation into Eq. (A19).

$$\begin{cases} w^{b^*}_b &= \frac{(p-c_m)(1-\gamma)-\theta(\tau_a-\tau_b)^2+\gamma c_a+c_b}{2} \\ w^{b^*}_a &= F^{-1}\left(\frac{\mathrm{d}\pi^d_{s_a}}{\mathrm{d}w^b_a}\right) \\ q^{b^*}_{am} &= \frac{8\beta^3\eta\gamma(1-\gamma^2)[\eta(p-c_a-c_m)-(p-c_a-c_s)]}{16\beta^4\gamma(1-\gamma^2)(1-\eta^2)} \\ &\quad + \frac{8\beta^3\gamma(1-\eta^2)[(p-c_a-c_m)-\gamma(p-c_m-w^{b^*}_b-\theta\tau_a^2+2\theta\tau_a\tau_b-\theta\tau_b^2)]}{16\beta^4\gamma(1-\gamma^2)(1-\eta^2)} \\ q^{b^*}_{bm} &= \frac{(p-c_m)(1-\gamma)-\theta(\tau_a-\tau_b)^2+\gamma c_a-w^{b^*}_b}{2\beta(1-\gamma^2)} \\ q^{b^*}_{as} &= \frac{p(1-\eta)+\eta(c_a+c_m)-c_a-c_s}{2\beta(1-\eta^2)} \\ \varphi^* &= F^{-1}\left(\frac{\pi^b_m-\pi^{d^*}_m}{\pi^b_a-\pi^{d^*}_a} - \frac{\tau_m}{\tau_a}\right) \end{cases} \tag{A19}$$

Proof of Proposition 4 has finished.

Proof of Lemma 5

By substituting Eq. (A19) into and Eq. (A12), Eq. (A13) and Eq. (A16), it is easily obtained the optimal profits of each stakeholder and the total profit of the supply chain as follows

$$\pi^{b^*}_m = \pi^b_m(q^{b^*}_{am}, q^{b^*}_{bm}, \varphi^*),\ \pi^{b^*}_{s_a} = \pi^b_{s_a}(q^{b^*}_{as}, \varphi^*),$$
$$\pi^{b^*}_{s_b} = \pi^d_{s_b}(w^{b^*}_b),\ \pi^{b^*}_T = \pi^{b^*}_m + \pi^{b^*}_{s_a} + \pi^{b^*}_{s_b}$$

Proof of Lemma 6

According to Eq. (A14), it can be derived from $\frac{\partial\Phi}{\partial\varphi} = 0$ that the profit increment of the two players are satisfied with the equation where $\frac{\pi^b_m-\pi^{d^*}_m}{\pi^b_a-\pi^{d^*}_a} = \frac{\tau_m}{\tau_a}$, combining with proposition 4 we can prove that the equation $\frac{\pi^{b^*}_m-\pi^{d^*}_m}{\pi^{b^*}_a-\pi^{d^*}_a} = \frac{\tau_m}{\tau_a}$ holds.

Appendix B

In order to further illustrate the validity and superiority of the proposed revenue-sharing contract based on relationship-specific investment, we compare the proposed cooperation strategy with a conventional revenue-sharing contract. Generally, the existing literature uses a classical revenue-sharing contract to coordinate a supply chain, and they didn't take cooperation into consideration. Thus, following this study, we demonstrate the optimal decision under a revenue-sharing contract. The main manufacturer provides a revenue-sharing contract to s_a with a revenue-sharing proportion φ. Let superscript r denote the decision under a revenue-sharing contract. The sequence of the events is shown as follows,

Step 1: given a revenue-sharing proportion φ, the two competitive suppliers decide their own wholesale price w^r_x independently at the same time in pursuit of self-interest maximization;

Step 2: given a revenue-sharing proportion φ, the strong supplier s_a and the main manufacture decide the quantity of final product through Cournot competition.

Let π^r_m and $\pi^r_{s_a}$ be the profit of supplier s_a and the main manufacturer in the last stage respectively, thus, the payoff functions and decision model are described as follows.

$$\begin{aligned} &\max \pi^r_m(q^r_{am}, q^r_{bm}) \\ &= [(1-\varphi)p^r_{am} - w^r_a - c_m]q^r_{am} \\ &\quad + [p^r_{bm} - c_m - w^r_b - \theta(\tau_a-\tau_b)^2]q^r_{bm} \end{aligned} \tag{B1}$$

$$\begin{aligned} \max \pi^r_{s_a}(q^r_{as}) &= (w^r_a - c_a + \varphi p^r_{am})q^r_{am} \\ &\quad + (p^r_{as} - c_a - c_s)q^r_{as} \end{aligned} \tag{B2}$$

The wholesale prices of the two suppliers at the first stage are the reaction functions with respect to the optimal quantities of the strong supplier s_a and the main manufacturer, thus, the profit of s_a and s_b in the first stage after production deciding are given as (B3) and (B4) as follows:

$$\max \pi^r_{s_a}(w^r_a) = [(1-\varphi)p^r_{am} - w^r_a - c_m]q^r_{am} + [p^r_{bm} - c_m - w^r_b - \theta(\tau_a - \tau_b)^2]q^r_{bm} \quad \text{(B3)}$$

$$\max \pi^r_{s_b}(w^r_b) = (w^r_b - c_b)q^r_{bm} \quad \text{(B4)}$$

Using backward deduction solve the decision problem, the optimal quantities are denoted by $q^{r^*}_{am}$, $q^{r^*}_{bm}$ and $q^{r^*}_{as}$, and let $w^{r^*}_x$ denote the optimal wholesale price under the revenue-sharing contract, therefore, the optimal decisions can be summarized as follows:

$$w^{r^*}_a = F^{-1}(\pi^r_{s_a}), w^{r^*}_b = F^{-1}(\pi^r_{s_b})$$

$$q^{r^*}_{am} = \frac{\beta(\gamma^2\eta^2-4)[(2-\varphi-\eta+\varphi\eta)p + (\varphi-2)(c_a+c_s) + (c_m + w^{r^*}_a)\eta]}{2\beta^2\eta[4-4\varphi-(1-\varphi^2)\eta^2 - \gamma^2(4-4\varphi+\varphi^2-\eta^2)]} - \frac{[\eta^2-4-\varphi(\eta^2-2)][2\beta(p-c_a-c_s) - \beta\gamma\eta(p-c_m-w^{r^*}_b - \theta(\tau_a-\tau_b)^2)]}{2\beta^2\eta[4-4\varphi-(1-\varphi^2)\eta^2-\gamma^2(4-4\varphi+\varphi^2-\eta^2)]}$$

$$q^{r^*}_{bm} = \frac{\gamma[\varphi(2+\eta^2)-4+\eta^2](\gamma^2\eta^2-4)[(p\varphi+w_a+c_m-p)\eta + (\varphi-2)(c_s+c_a-p)]}{2\beta\eta(\gamma^2\eta^2-4)[\eta^2-4+4\varphi-\varphi^2\eta^2+\gamma^2(4-4\varphi+\varphi^2-\eta^2)]} + \frac{\gamma[\varphi(2+\eta^2)-4+\eta^2]^2[2\beta(p-c_a-c_s) - \beta\gamma\eta(p-c_m-w_b-\theta(\tau_a-\tau_b)^2)]}{2\beta^2\eta(\gamma^2\eta^2-4)[\eta^2-4+4\varphi-\varphi^2\eta^2+\gamma^2(4-4\varphi+\varphi^2-\eta^2)]} + \frac{2\beta[-2p+p\gamma\eta-\gamma\eta c_a+2c_m-\gamma\eta c_s+2w_b+2\theta(\tau_a-\tau_b)^2]}{2\beta^2(\gamma^2\eta^2-4)}$$

$$q^{r^*}_{bm} = \frac{p[\gamma^2(\varphi-2)(\varphi\eta-\varphi-\eta+2) - \varphi\eta\gamma(\varphi-3) + 2(\varphi-1)(\varphi\eta+\eta-2)]}{2\beta[\varphi^2(\eta^2-\gamma^2)+(1-\gamma^2)(4-4\varphi-\eta^2)]} + \frac{\gamma^2(\varphi-2)^2+4(\varphi-1)}{2\beta[\varphi^2(\eta^2-\gamma^2)+(1-\gamma^2)(4-4\varphi-\eta^2)]}c_a + \frac{[\gamma^2(\varphi-2)+\gamma\varphi(\varphi-3)+2(1+\varphi)]\eta}{2\beta[\varphi^2(\eta^2-\gamma^2)+(1-\gamma^2)(4-4\varphi-\eta^2)]}c_m + \frac{[2\eta(1+\varphi)+\gamma^2\eta(\varphi-2)]w^{r*}_a}{2\beta[\varphi^2(\eta^2-\gamma^2)+(1-\gamma^2)(4-4\varphi-\eta^2)]} + \frac{\gamma\varphi\eta(\varphi-3)w^{r*}_b}{2\beta[\varphi^2(\eta^2-\gamma^2)+(1-\gamma^2)(4-4\varphi-\eta^2)]} + \frac{\gamma^2\varphi^2+4(\gamma^2-1)(1-\varphi)}{2\beta[\varphi^2(\eta^2-\gamma^2)+(1-\gamma^2)(4-4\varphi-\eta^2)]}c_s + \frac{\gamma\varphi\eta\theta(\varphi-3)(\tau_a-\tau_b)^2}{2\beta[\varphi^2(\eta^2-\gamma^2)+(1-\gamma^2)(4-4\varphi-\eta^2)]}$$

$\pi^{r^*}_m$, $\pi^{r^*}_{s_a}$, and $\pi^{r^*}_{s_b}$ can be easily obtained by substituting $q^{r^*}_{xi}$ and $w^{r^*}_a$ into (B1), (B2), (B3), and (B4), that are $\pi^{r^*}_m = \pi^r_m(q^{r^*}_{am}, q^{r^*}_{bm})$, $\pi^{r^*}_{s_a} = \pi^r_{s_a}(q^{r^*}_{as})$, and $\pi^{r*}_{s_b} = \pi^r_{s_b}(w^{r^*}_b)$. The optimal total profit of the supply chain is the sum of stakeholders' optimal profit, therefore, $\pi^{r^*}_T = \pi^{r^*}_m + \pi^{r^*}_{s_a} + \pi^{r*}_{s_b}$ holds.

The proof is similar to Proposition 2 and Proposition 4, we do not present it again to avoid complex.

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