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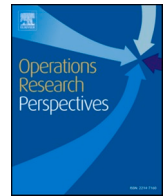
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How to improve the key component's quality: the impact of overconfident manufacturer's R&D investment

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ABSTRACT

In the EV supply chain, R&D cooperation for key components between the manufacturer and tier 2 supplier is common. This paper primarily explores the effects of cross-echelon R&D cooperation and overconfidence on the quality and price of key components, as well as the profits of the manufacturer and suppliers. We assume that the supply chain consists of one tier 2 supplier, one tier 1 supplier, and one overconfident manufacturer. We first present the wholesale price contract as a benchmark, followed by the two-part contract and the equity contract between the tier 2 supplier and the manufacturer. Additionally, we compare above three contracts and provide numerical examples. We find that (1) the manufacturer's overconfidence level and the contract type jointly affect the quality of the key component and the profit of the tier 1 supplier. When the overconfidence level is low or the manufacturer's shareholding ratio is low, the two-part contract is more effective in improving the key component's quality and the tier 1 supplier's profit. Or else, the equity cooperation contract is more effective in improving the key component's quality and the tier 1 supplier's profit. (2) Under the equity contract, the tier 2 supplier can obtain higher profit, while the manufacturer may achieve higher overestimated expected profit under the two-part contract. (3) Under the two-part contract, the manufacturer's overconfidence increases the component's quality and the profit of the tier 1 supplier, but decreases the profit of the tier 2 supplier. In the other two contracts, the manufacturer's overconfidence leads to a decline in the key component's quality and the profits of both the tier 1 and tier 2 suppliers.

1. Introduction

As the intelligence and electrification levels of electric vehicles continue to improve, EV manufacturers are placing increasingly demand on high-quality of key components, such as chips. In 2022, there was a direct decrease in EV production due to the low supply of high-quality chips.¹ To ensure the supply of high-quality components, suppliers must continuously invest in key component R&D. However, supplier's financial constraint limits the investment in key components R&D, which has resulted in delays in the delivery, leading to the supply uncertainty of key components [1].

To ensure timely delivery of high-quality components, some manufacturers have begun investing in their suppliers [2]. Unlike previous manufacturers who invested in tier 1 suppliers, in the EV supply chain, the manufacturer now invests in key component suppliers, who are

typically tier 2 or tier 3 supplier.² For example, the chip supplier sells chips to the battery supplier, then the battery supplier provides the EV manufacturer with the battery and chips. Here, the chip supplier is a tier 2 supplier. Manufacturers' investment in multi-level suppliers is common in automotive supply chains. Driven by the realities of the EV supply chain, this paper explores the effects of the manufacturer's investment in tier 2 supplier on the decisions of supply chain members.

Two-part contract and equity investment are two strategies commonly used by manufacturers. In the two-part contract, the manufacturer proposes the requirements that the component needs to meet for the supplier and provides a fixed investment to the supplier. In turn, the supplier needs to provide the manufacturer with components that meet the quality requirements on schedule. For example, the Panasonic EV Energy Company, a joint venture established by Toyota and Panasonic, supplies batteries for Toyota's Prius. Panasonic invested

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¹ See: <https://www.eetrend.com/content/2023/100567785.html>.

² See: China's Electric Vehicle Supply Chain and Its Future Prospects

approximately \$4 billion in the long-term development, including automotive batteries and air conditioning equipment.³

In the equity investment contract, the manufacturer may share a portion of the supplier's equity, with the share depending mainly on the quality of new products. For example, in 2012, Intel Corp. announced its investment of \$4.1 billion in its technology supplier, ASML, and Intel could acquire 15 % of ASML's equity [1].

In 2019, Ford initially invested in Solid Power and further increased its investment in 2021 through a \$130 million Series B round co-led with BMW. These investments aim to advance the testing, piloting, and scaling of solid-state battery technology to expedite its integration into future Ford electric vehicles.⁴

The incentives inherent in the two cooperation contracts require manufacturers to carefully evaluate their investment and partnership strategies.

Additionally, new technologies often introduce uncertainty in demand. Upstream innovating suppliers coupled with overconfident downstream manufacturers may lead to an overestimation of the influence that the innovation exerts on the demand [3]. Thus, we assume the manufacturer is overconfident in consumer demand, causing overestimation of the demand.

Therefore, considering the manufacturer's overconfidence behavior, in this paper we mainly discuss the following research questions:

- (1) How will manufacturer's investment in tier 2 supplier affect supply chain members' decision-making, including tier 2 supplier, tier 1 supplier and the manufacturer?
- (2) What are the different impacts of the two cooperation contracts on tier 2 supplier's R&D decisions?
- (3) How does the manufacturer's overconfidence affect his investment strategy and tier 2 supplier's decisions?

Considering that the supply chain is composed of a tier 2 supplier, a tier 1 supplier and a manufacturer, and the manufacturer is overconfident in demand. We first consider the wholesale price contract as a benchmark, then construct two-part contract and equity contract. We then explore the optimal quality and price for the key component under the three contracts, respectively. Additionally, we compare the equilibrium strategies with the overconfident manufacturer and rational suppliers under above three different contracts, ultimately deriving the analytical results.

Our study has two main contributions: (1) we study the cross-echelon R&D investment cooperation between the manufacturer and tier 2 supplier, while most previous studies focused on the investment cooperation between manufacturers and tier 1 suppliers [1,2]; (2) We comprehensively analyze the impact of overconfidence on manufacturer's investment contract selection and supplier's R&D level, while previous studies only focus on upstream supplier's decision-making when there is overconfidence behavior [4,5].

The main findings are (1) when the manufacturer invests in the tier 2 supplier, both the quality of the key component and the profits of the two suppliers are higher compared to when there is no investment; (2) If the manufacturer's shareholding ratio or overconfidence level is low, the two-part contract is more conducive to improving the quality of the core component; otherwise, the equity contract is more effective; (3) Among the three contract types, the equity contract provides more profit for the tier 2 supplier. Tier 1 supplier's profit depends on the manufacturer's shareholding ratio and overconfidence level. If either the shareholding ratio or overconfidence level is low, the tier 1 supplier will prefer the two-part contract; otherwise, the equity contract is a better

choice for the tier 1 supplier; (4) the manufacturer may be more willing to choose two-part contract, especially when there is a high degree of overconfidence. Under the other two contracts, the manufacturer's overconfidence leads to a decrease in chip quality and supplier profits, while the manufacturer's own profit increases.

The remainder sections are structured as follows: literature review is shown in Section 2. The basic assumptions and definitions are present in Section 3. Section 4 introduces the three types of contract models. Section 5 explores the difference between the three models by a comparative analysis. Section 6 details sensitivity analysis and numerical examples. Section 7 concludes the paper, summarizing key findings and proposing future research directions.

2. Literature review

In this section, we mainly review the two streams of literature that are closely related to our research: vertical collaboration mechanisms between supply chain members and the overconfidence behavior.

The first stream focuses on how manufacturers establish collaborative contracts to improve supply chain efficiency and resilience by aligning the interests of suppliers and manufacturers [6,7]. Common investment contracts in supply chain collaboration include wholesale price contracts [8,9], two-part contracts, rebate contracts [10], revenue-sharing contracts [11,12], equity contracts [1] and joint investment contracts [13].

The equity contract is particularly significant in the new energy vehicle supply chain. For instance, Chen et al. [14] investigated the impact of cross-shareholding contract, revealing its efficacy in reducing the double marginalization effect and improving overall supply chain performance, leading to mutual benefits. Similarly, Xia et al. [15] examined the effects of cross-shareholding on prices, carbon reduction, and profitability across two distinct supply chain power structures: the manufacturer-led and retailer-led models. Their findings indicate that cross-shareholding leads to greater reductions in carbon emissions. Zhang and Lee [1] studied how a manufacturer's loan and equity investment in suppliers affect supplier decision-making.

Two-part contract is also a popular contract used by the supply chain members. Li et al. [16] studied a cross-selling strategy implemented by two manufacturers and common retailers. Bai et al. [17] concluded that two-part tariffs outperformed revenue-sharing contracts in robustness within a two-echelon sustainable supply chain under carbon trading. Yang and Ma [18] identified the optimal two-part tariff contract to address information asymmetry in a supply chain with two unreliable suppliers and a retailer. Cao et al. [19] explored the optimal channel strategy and coordination contract in a retailer-led green supply chain, considering the channel purchasing cost. Ma et al. [20] investigated green R&D investment strategies and found that a two-part pricing contract promotes green manufacturing practices by evaluating both external and internal funding.

The reviewed literature mainly focuses on two-echelon supply chains involving suppliers and manufacturers. However, our paper discusses the optimal decision-making problem in a three-echelon supply chain consisting of a tier 2 supplier, a tier 1 supplier, and a manufacturer [21]. We also explore the influences of overconfidence on optimal decision-making.

Second, we review papers that consider overconfidence in supply chains. The term "overconfidence" was first coined by Alpert and Raiffa (1982), and it was introduced into the supply chain context by Croson et al. [22], who analyzed the decisions of overconfident news vendors. The overconfidence and optimism are known behavioral biases that affect news vendors' ordering decisions [23]. Liu and Lee [4] explored the optimal dual channel prices for manufacturers and retailers when consumers exhibit overconfidence. Amor and Kooli [24] studied the impact of the overconfidence bias on venture capital firms' investments.

Further studies investigated the influence of overconfidence on various supply chain configurations and contract types. Wang [5] found

³ See: <https://www.forbes.com/sites/alanohnsman/2022/07/13/teslas-long-time-partner-panasonic-building-4-billion-ev-battery-plant-in-kansas/>

⁴ See: <https://media.ford.com/content/fordmedia/fna/us/en/news/2021/05/03/ford-boosts-investment-in-solid-power.html>.

that overconfidence negatively affects decision-making and expected profits under wholesale price contracts for both suppliers and manufacturers in a two-echelon supply chain. Xiao et al. [25] explored the interaction of manufacturers considering fairness concerns and overconfidence, evaluating the effects on three optimal contract designs: wholesale price contracts, revenue-sharing contracts, and cost-sharing contracts. Lu et al. [26] studied how a green supplier's overconfidence affects inventory choices, considering variable demand influenced by effort and a rational retailer's behavior.

The above literature examines how overconfidence affects members' R&D decisions and profits. However, our study not only considers the influence of overconfidence on supply chain members' decisions but also accounts for the distinct influences under different manufacturer investment agreements.

Specifically, in a three-echelon supply chain composed of a tier 2 supplier, a tier 1 supplier and a manufacturer, considering the impact of the manufacturer's overestimation of R&D level on demand, we present the optimal decisions of two suppliers and manufacturer under the wholesale price contract, the two-part contract and the equity contract, and we show the influence of overconfidence level and different contracts on the supply chain members' decisions. Finally, we give some management insights.

3. Problem description and model assumptions

Consider a three-echelon supply chain composed of a tier 2 supplier, a tier 1 supplier and a manufacturer. Tier 2 supplier produces the key component with quality q and sells it to tier 1 supplier at the wholesale price w_2 . Then tier 1 supplier assembles the key component into modules, such as battery, and then sell them to the manufacturer with the wholesale price w_1 . Finally, the manufacturer assembles all the modules into finished products, then sells them to consumers at the retail price p .

Products' quality affects consumers' demand [27–29], especially the quality of the key component. For example, Xpeng Motors, Nvidia, and Desay SV have signed a strategic cooperation agreement to develop advanced driver-assistance systems (ADAS) using Nvidia's Xavier chip [30]. Desay SV, as the Tier 1 supplier, is responsible for integrating the Xavier chip into Xpeng's vehicle systems. In this case, Nvidia acts as the tier 2 supplier, providing the core chip technology to support the development of Xpeng's intelligent driving systems. Obviously, the quality of the chip is a crucial determinant of the performance and reliability of the intelligent driving system, and further affects the vehicle's demand. Consumers evaluate products based on multiple attributes, such as quality and price, which in turn influence their purchasing decisions [30,31], so we assume the demand is affected by the quality of the key component and the price, $D = a - p + \theta q$, where a represents the potential market demand, p represents the retail price, q is the quality of the key component, and $q \in [0, \bar{q}]$, where \bar{q} captures the highest quality threshold that the industry can reach. θ indicates the consumer's sensitivity coefficient to the component's quality. The unit manufacturing cost associated with the key component is denoted by c . The manufacturing costs incurred by the tier 1 supplier and the manufacturer are denoted as c_{s1} and c_m , respectively. To ensure the feasibility of the model, it is required that $a > 0$, $\theta > 0$ and $a - c - c_m - c_{s1} > 0$.

Assuming that the key component's R&D cost is related to its quality and is a convex function of the quality, that is, $c_1 = \frac{1}{2}rq^2$, where $r > 0$ is the R&D cost coefficient, and the bigger r , the greater the cost required for innovation. The unit production cost of the key component is c . To simplify the analysis, we assume other components' production costs are zero.

Assume that tier 2 and 1 suppliers, being risk-neutral, seek to maximize their expected profits. The manufacturer is overconfident, which manifests in overestimating the impact of the key component's quality on demand and overestimating the uncertainty of demand. In other words, the manufacturer believes that the sensitivity coefficient of

consumers to the component's quality is higher than the actual value. The overestimated expected demand function is:

$$\tilde{D} = a - p + \theta(1 + \gamma)q, \quad (1)$$

where $\gamma \in [0, 1]$ is the overconfidence level of the manufacturer, when $\gamma = 0$, the manufacturer is fully rational, and when $\gamma = 1$, then the manufacturer is fully overconfident. Table 1 shows the main parameters and decision variables used in this paper.

4. Model

In this section, we study how the manufacturer's investment contracts affect the R&D and pricing decisions of tier 2 supplier. Firstly, we present our benchmark contract –wholesale price contract. Then, we construct two-part contract and equity contract models, respectively. In the following analysis, superscripts $j = 1, 2, 3$ denotes the wholesale price, two-part, and equity contracts, respectively. We depict the supply chain structure in Fig. 1.

The sequence of the game is as follows: (1) tier 2 supplier determines the key component quality q and the wholesale price w_2 ; (2) tier 1 supplier determines the wholesale price w_1 ; (3) the manufacturer determines the retail price p .

Under these assumptions, we formulate the decision-making model for the three-echelon supply chain. Rational suppliers make decisions based on real market demand. However, the overconfident manufacturer makes decisions based on the overestimated expected profits resulting from overconfidence.

4.1. The wholesale price contract

In the wholesale price contract, the tier 2 supplier conducts component R&D on its own, and in this case, the tier 2 supplier bears all R&D cost. In this scenario, the profit functions for tier 2 and 1 suppliers, and the overestimated expected profit function due to overconfidence

Table 1
Model parameters and decision variables.

Parameter	Description	Decision variable	Description
D	Market demand	q^j	The key component's quality under the j -th strategy
\tilde{D}	The overestimated expected demand	w_i^j	The wholesale price of the tier i supplier under the j -th strategy
r	Supplier R&D cost coefficient	p	The manufacturer's retail price
a	Potential market demand	$E(\pi_m^j)$	The overestimated expected profit of the manufacturer under the j -th strategy
c	The fixed unit cost of the key component	π_{si}^j	Tier i suppliers' profits under the j -th strategy
c_m	The production costs of the manufacturer	F	A fixed transfer payment paid by the manufacturer
c_{s1}	The production costs of tier 1 supplier		
θ	Consumer's sensitivity coefficient to the component's quality		
γ	Manufacturer's overconfidence level		
c_1	The cost of R&D of key component		
τ	Manufacturer's shareholding ratio		
i	The i -th tier supplier, $i = 1, 2$		
j	The j -th strategy, $j = 1, 2, 3$		

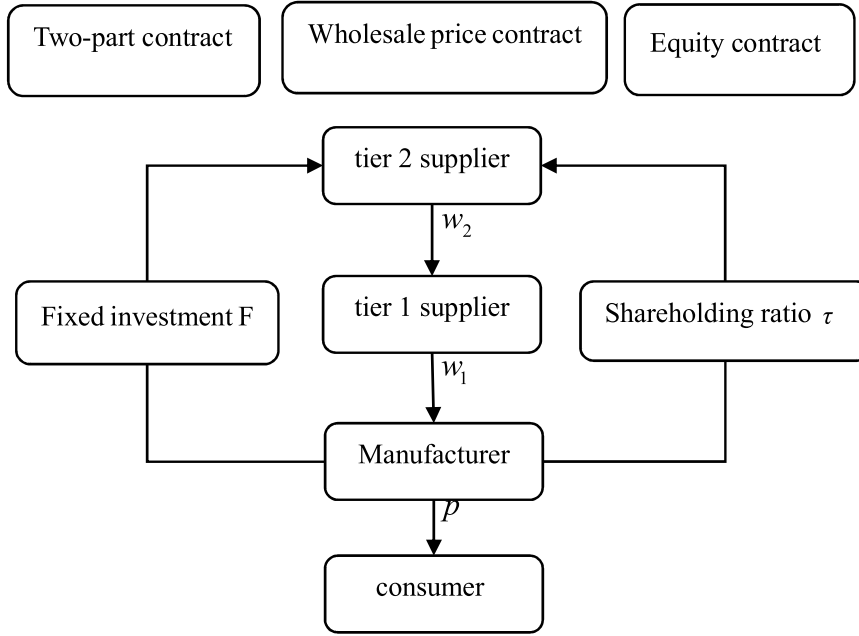


Fig. 1. Supply chain structure diagram.

are as follows:

$$\pi_{s2}^1 = D(w_2 - c) - \frac{1}{2}r(q^1)^2, \quad (2)$$

$$\pi_{s1}^1 = D(w_1 - w_2 - c_{s1}), \quad (3)$$

$$E(\pi_m^1) = \tilde{D}(p - w_1 - c_m). \quad (4)$$

Under the wholesale price contract, suppliers and the manufacturer optimize their decisions based on individual objective functions. We derive the optimal decisions in Proposition 1 using the backward induction method.

Proposition 1. Under the wholesale price contract, when $8r > (1 - \gamma)^2\theta^2$, the optimal key component's quality, the wholesale prices of tier 2 and tier 1 suppliers, the retail price, suppliers' profits, and the manufacturer's overestimated expected profit are:

$$q^{1*} = \frac{\theta(a - c - c_m - c_{s1})(1 - \gamma)}{8r - (1 - \gamma)^2\theta^2} \quad (5)$$

$$w_2^{1*} = \frac{4r(a + c - c_m - c_{s1}) - c(1 - \gamma)^2\theta^2}{8r - (1 - \gamma)^2\theta^2} \quad (6)$$

$$w_1^{1*} = \frac{2r(3a + c - 3c_m + c_{s1}) - (c + c_{s1})(1 - \gamma)^2\theta^2}{8r - (1 - \gamma)^2\theta^2} \quad (7)$$

$$p^{1*} = \frac{r(7a + c + c_m + c_{s1}) + (1 - \gamma)(a\gamma - c - c_m - c_{s1})\theta^2}{8r - (1 - \gamma)^2\theta^2} \quad (8)$$

$$\pi_{s2}^{1*} = \frac{r(a - c - c_m - c_{s1})^2}{2(8r - (1 - \gamma)^2\theta^2)} \quad (9)$$

$$\pi_{s1}^{1*} = \frac{2r^2(a - c - c_m - c_{s1})^2}{(8r - (1 - \gamma)^2\theta^2)^2} \quad (10)$$

$$E(\pi_m^1)^* = \frac{(a - c - c_m - c_{s1})^2(\gamma\theta^2 + r - \gamma^2\theta^2)^2}{(8r - (1 - \gamma)^2\theta^2)^2} \quad (11)$$

Lemma 1. $\frac{\partial q^{1*}}{\partial \gamma} < 0$; $\frac{\partial w_2^{1*}}{\partial \gamma} \leq 0$; $\frac{\partial w_1^{1*}}{\partial \gamma} \leq 0$; $\frac{\partial p^{1*}}{\partial \gamma} < 0$; $\frac{\partial \pi_{s2}^{1*}}{\partial \gamma} \leq 0$; $\frac{\partial \pi_{s1}^{1*}}{\partial \gamma} \leq 0$.

Lemma 1 shows the change trends of the optimal solutions and suppliers' profits with the manufacturer's overconfidence level. Lemma 1 suggests that the key component's quality, the wholesale prices, the profits of tier 1 and tier 2 suppliers decrease as the manufacturer's overconfidence level increases.

From lemma 1, we can conclude that when the manufacturer is overconfident, the key component's quality, wholesale prices, retail price and the tier 2 and 1 suppliers' profits are lower than the corresponding results of the manufacturer's rational situation, and are negatively correlated with manufacturer's overconfidence level. As the overconfidence's level rises, tier 2 supplier invests less in improving the quality of key component, and then wholesale prices decreases.

4.2. The two-part contract model

Under the two-part contract, the manufacturer proposes the requirements to be met for the key component's quality, q^2 , to the tier 2 supplier, and provides a part of the fixed investment F to the tier 2 supplier, that is, the manufacturer provides a two-part contract (q^2, F) to the tier 2 supplier. In the automotive industry, manufacturers often propose components' quality requirements, especially when the manufacturer invests in the supplier. Generally, manufacturers invest the strategic supplier and set the components' requirements, then suppliers conduct R&D as well as production based on these requirements. For example, Tesla has invested in Topr Group and established a long-term cooperative relationship with it. Topr Group provides a variety of components that meet the requirements, such as chassis systems, shock absorbers, and interior functional parts.

In this contract, the manufacturer determines the component's quality requirement q^2 and the fixed investment F . The fixed investment F must ensure that the tier 2 supplier's profit is greater than or equal to the profit of the supplier under the wholesale price contract, in order to guarantee that the tier 2 supplier agrees to participate in this contract.

In this scenario, the profit functions for tier 2 supplier, tier 1 supplier, and the overestimated expected profit function due to overconfidence are as follows:

$$\pi_{s2}^2 = D(w_2 - c) - \frac{1}{2}r(q^2)^2 + F, \quad (12)$$

$$\pi_{s1}^2 = D(w_1 - w_2 - c_{s1}), \quad (13)$$

$$E(\pi_m^2) = \tilde{D}(p - w_1 - c_m) - F. \quad (14)$$

The game sequence in this contract is as follows: (1) the manufacturer determines the component's quality q^2 and the fixed investment F ; (2) tier 2 supplier determines the wholesale price w_2 ; (3) tier 1 supplier determines the wholesale price w_1 ; (4) the manufacturer determines the retail price p .

Similarly, we obtain the optimal decisions under the two-part contract, as stated in Proposition 2.

Proposition 2. Under the two-part contract, when $32r > (53\gamma^2 + 6\gamma + 5)\theta^2$, the optimal key component's quality, the wholesale prices of the tier 1 and 2 suppliers, the retail price, the fixed investment F , the suppliers' profits and the manufacturer's overestimated expected profit are:

$$q^{2*} = \frac{\theta[(a - c - c_{s1} - c_m)(5 + 3\gamma)]}{32r - (53\gamma^2 + 6\gamma + 5)\theta^2} \quad (15)$$

$$w_2^{2*} = \frac{[(28(a - c_m - c_{s1}) + 25c)\gamma^2 + 2\gamma(2(a - c_m - c_{s1}) + c) + 5c]\theta^2 - 16r(a - c_m - c_{s1} + c)}{(53\gamma^2 + 6\gamma + 5)\theta^2 - 32r} \quad (16)$$

$$w_1^{2*} = \frac{[(42(a - c_m) + 11(c + c_{s1}))\gamma^2 + 6\gamma(a - c_m) + 5(c + c_{s1})]\theta^2 - 8r(3(a - c_m) + (c + c_{s1}))}{(53\gamma^2 + 6\gamma + 5)\theta^2 - 32r} \quad (17)$$

$$p^{2*} = \frac{[(46a + 7(c + c_m + c_{s1}))\gamma^2 + 2\gamma(a + 2(c + c_m + c_{s1})) + 5(c + c_m + c_{s1})]\theta^2 - 4r(7a + c + c_m + c_{s1})}{(53\gamma^2 + 6\gamma + 5)\theta^2 - 32r} \quad (18)$$

$$F_{\min} = \frac{4(a - c - c_m - c_{s1})^2(7\gamma + 1)^2(\gamma\theta^2 - \gamma^2\theta^2 + r)^2\theta^2}{(32r - (53\gamma^2 + 6\gamma + 5)\theta^2)^2(8r - (\gamma - 1)^2\theta^2)} \quad (19)$$

$$\pi_{s2}^{2*} = \frac{r(a - c - c_m - c_{s1})^2}{2(8r - (1 - \gamma)^2\theta^2)} \quad (20)$$

$$\pi_{s1}^{2*} = \frac{2(a - c - c_m - c_{s1})^2(\gamma\theta^2 + 7\gamma^2\theta^2 - 4r)^2}{(32r - (53\gamma^2 + 6\gamma + 5)\theta^2)^2} \quad (21)$$

$$E(\pi_m^2)^* = \frac{4(a - c - c_m - c_{s1})^2(\gamma\theta^2 - \gamma^2\theta^2 + r)^2}{[(53\gamma^2 - 100\gamma + 46)\gamma^2 - 4\gamma + 5]\theta^4 + (-456\gamma^2 + 16\gamma - 72)r\theta^2 + 256r^2} \quad (22)$$

Lemma 2: $\frac{\partial q^{2*}}{\partial \gamma} > 0$; $\frac{\partial w_2^{2*}}{\partial \gamma} > 0$; $\frac{\partial w_1^{2*}}{\partial \gamma} > 0$; $\frac{\partial p^{2*}}{\partial \gamma} > 0$; $\frac{\partial F_{\min}^{2*}}{\partial \gamma} < 0$; $\frac{\partial \pi_{s1}^{2*}}{\partial \gamma} > 0$.

Lemma 2 shows the change trends of the optimal solutions and suppliers' profits with the manufacturer's overconfidence level. Lemma 2 shows that the quality of key component, the wholesale prices, and tier 1 supplier profits increase with manufacturer's overconfidence, while

tier 2 supplier profit decreases in the two-part contract. This shows that manufacturer's overconfidence in demand will result in a series of blind decisions, such as the belief that the quality of the key component will increase, and the wholesale price will increase, which will lead to an increase in the sales, thereby increasing tier 1 supplier's profit. Obviously, tier 2 supplier needs to consider the manufacturer's overconfidence degree, and prefer to cooperate with a manufacturer with a lower level of overconfidence.

4.3. The equity contract

In the equity contract, the manufacturer holds tier 2 supplier's shares vertically, and the shareholding amount is τ , where $0 < \tau < 0.5$, considering a shareholding ratio of $>50\%$ will result in a transfer of control of the company. In this scenario, the profit functions for tier 2 supplier, tier 1 supplier, and the overestimated expected profit function due to overconfidence are as follows:

$$\pi_{s2}^3 = (1 - \tau) \left(D(w_2 - c) - \frac{1}{2}r(q^3)^2 \right), \quad (23)$$

$$\pi_{s1}^3 = D(w_1 - w_2 - c_{s1}), \quad (24)$$

$$E(\pi_m^3) = \tilde{D}(p - w_1 - c_m) + \tau \left(\tilde{D}(w_2 - c) - \frac{1}{2}r(q^3)^2 \right). \quad (25)$$

Similar to Proposition 1, Proposition 3 presents the optimal solutions for the equity contract scenario.

Proposition 3: Under the equity contract, when $8r(1 - \tau) > (1 - \gamma)^2\theta^2$, the optimal key component's quality, the wholesale prices of the tier 2 and 1 suppliers, the manufacturer's retail price, the suppliers' profit, and the manufacturer's overestimated expected profit

are:

$$q^{3*} = \frac{\theta(a - c - c_m - c_{s1})(1 - \gamma)}{8r(1 - \tau) - (1 - \gamma)^2\theta^2} \quad (26)$$

$$w_2^{3*} = \frac{4r(a - c_m - c_{s1}) + 4cr(1 - 2\tau) - (1 - \gamma)^2c\theta^2}{8r(1 - \tau) - (1 - \gamma)^2\theta^2} \quad (27)$$

$$w_1^{3*} = \frac{2r(3a + c + c_{s1} - 3c_m) - 2\tau r(a + 3c - c_m + 3c_{s1}) - (c + c_{s1})(1 - \gamma)^2\theta^2}{8r(1 - \tau) - (1 - \gamma)^2\theta^2} \quad (28)$$

$$p^{3*} = \frac{r(1 - \tau)(7a + c + c_m + c_{s1}) + (a\gamma - c - c_m - c_{s1})(1 - \gamma)\theta^2}{8r(1 - \tau) - (1 - \gamma)^2\theta^2} \quad (29)$$

$$\pi_{s2}^{3*} = \frac{r(a-c-c_m-c_{s1})^2(1-\tau)}{2(8r(1-\tau)-(1-\gamma)^2\theta^2)} \quad (30)$$

$$\pi_{s1}^{3*} = \frac{2r^2(a-c-c_m-c_{s1})^2(1-\tau)^2}{(8r(1-\tau)-(1-\gamma)^2\theta^2)^2} \quad (31)$$

$$E(\pi_m^{3*}) = \frac{(a-c-c_m-c_{s1})^2 \left(\frac{2(1-\gamma)^2\theta^4\gamma^2-4(1-\gamma)\gamma r\theta^2}{(1-\gamma)(1+3\gamma)\tau\theta^2+2r^2(1-\tau)^2} \right)}{2(8r(1-\tau)-(1-\gamma)^2\theta^2)^2} \quad (32)$$

Lemma 3: $\frac{\partial q^{3*}}{\partial \gamma} < 0$; $\frac{\partial w_2^{3*}}{\partial \gamma} < 0$; $\frac{\partial w_1^{3*}}{\partial \gamma} < 0$; $\frac{\partial p^{3*}}{\partial \gamma} < 0$; $\frac{\partial \pi_{s1}^{3*}}{\partial \gamma} < 0$; $\frac{\partial \pi_{s2}^{3*}}{\partial \gamma} < 0$.

Lemma 4: $\frac{\partial q^{3*}}{\partial \tau} < 0$; $\frac{\partial w_2^{3*}}{\partial \tau} < 0$; $\frac{\partial w_1^{3*}}{\partial \tau} < 0$; $\frac{\partial p^{3*}}{\partial \tau} < 0$; $\frac{\partial \pi_{s1}^{3*}}{\partial \tau} < 0$; $\frac{\partial \pi_{s2}^{3*}}{\partial \tau} < 0$;

When $0 < \gamma \leq \frac{5}{13}$, i.e. $r \geq \frac{2(29\gamma^3-27\gamma^2-\gamma-1)}{52\gamma-20}$ and $\tau < \frac{1}{2}$, $\frac{\partial E(\pi_m^{3*})}{\partial \tau} > 0$.

When $\frac{5}{13} < \gamma < 1$, i.e. $r < \frac{2(29\gamma^3-27\gamma^2-\gamma-1)}{52\gamma-20}$,

(i) If $\tau > \frac{36\gamma r-4r+(1+\gamma+27\gamma^2-29\gamma^3)}{12r+20\gamma r}$, then $\frac{\partial E(\pi_m^{3*})}{\partial \tau} < 0$;

(ii) If $\tau < \frac{36\gamma r-4r+(1+\gamma+27\gamma^2-29\gamma^3)}{12r+20\gamma r}$, then $\frac{\partial E(\pi_m^{3*})}{\partial \tau} > 0$.

Lemmas 3–4 show the changes of the optimal solutions and suppliers' profits with manufacturer's overconfidence level and shareholding ratio. Lemma 3 suggests that under the equity contract, the results are the same as those of the wholesale price contract. Under the equity contract, when the manufacturer is overconfident, the quality of the key component, the wholesale prices, and the retail price are all lower than those under the manufacturer's rational situation. Furthermore, as the level of the overconfidence increases, the quality of the key component, the wholesale prices and the retail price decline. Overall, compared to the scenario of complete rationality, overconfidence reduces profits for both tier 1 and 2 suppliers, with profits decreasing as overconfidence increases.

Lemma 4 suggests that as manufacturer's shareholding ratio increases, the key component's quality, wholesale price and retail price and the profits of the two suppliers all decrease. At low levels of manufacturer's overconfidence, the manufacturer's overestimated profits increase with the shareholding ratio. Conversely, at high levels of overconfidence and shareholding ratio, the manufacturer's overestimated profits decrease as the shareholding ratio increases. Conversely, when the level of manufacturer overconfidence is high and the shareholding ratio is low, the manufacturer's overestimated expected profit increase as the shareholding ratio increases.

The optimal equilibrium solutions and profits under different contracts are shown in Table 2.

5. Comparative analysis of cooperation contracts

Lemma 5. The key component's quality satisfies:

(1) when $\gamma < \frac{3}{11}$, then $q^{1*} < q^{3*} < q^{2*}$, $\pi_{s1}^{1*} \leq \pi_{s1}^{3*} \leq \pi_{s1}^{2*}$.

(2) When $\gamma > \frac{3}{11}$,

(i) If $0 < \tau < \frac{r(1+7\gamma)+\gamma\theta^2(1+6\gamma-7\gamma^2)}{r(5+3\gamma)}$, then $q^{1*} < q^{3*} < q^{2*}$, $\pi_{s1}^{1*} \leq \pi_{s1}^{3*} \leq \pi_{s1}^{2*}$.

(ii) If $\frac{r(1+7\gamma)+\gamma\theta^2(1+6\gamma-7\gamma^2)}{r(5+3\gamma)} < \tau < \frac{1}{2}$, then $q^{1*} < q^{2*} < q^{3*}$, $\pi_{s1}^{1*} \leq \pi_{s1}^{2*} \leq \pi_{s1}^{3*}$, the equalities hold for $\lambda = 1$.

Lemma 5 shows that when the overconfidence level is very small, i.e. $\gamma < \frac{3}{11}$, or the manufacturer's shareholding ratio is very low, then the two-part contract is more conducive to improving the quality of the key component and tier 1 supplier's profit. When the overconfidence level and the manufacturer's shareholding level are both high, the equity

Table 2

The optimal equilibrium solutions under different contracts and the profits of all parties in the supply chain.

	Wholesale price Contract	Two-part Contract	Equity contract
p^j	$\frac{r(7a+c+c_m+c_{s1})+(1-\gamma)(a\gamma-c-c_m-c_{s1})\theta^2}{8r-(1-\gamma)^2\theta^2}$	$\frac{[(46a+7(c+c_m+c_{s1}))\gamma^2+2\gamma(a+2(c+c_m+c_{s1}))+5(c+c_m+c_{s1})]\theta^2-4r(7a+c+c_m+c_{s1})}{4r(7a+c+c_m+c_{s1})}$	$\frac{r(1-\tau)(7a+c+c_m+c_{s1})+(a\gamma-c-c_m-c_{s1})(1-\gamma)\theta^2}{8r(1-\tau)-(1-\gamma)^2\theta^2}$
w_1^j	$\frac{2r(3a+c-3c_m+c_{s1})-(c+c_{s1})(1-\gamma)^2\theta^2}{8r-(1-\gamma)^2\theta^2}$	$\frac{[(42(a-c_m)+11(c+c_{s1}))\gamma^2+6\gamma(a-c_m)+5(c+c_{s1})]\theta^2-8r(3(a-c_m)+(c+c_{s1}))}{8r(3(a-c_m)+(c+c_{s1}))}$	$\frac{2r(3a+c+c_{s1}-3c_m)-(c+c_{s1})(1-\gamma)^2\theta^2}{8r(1-\tau)-(1-\gamma)^2\theta^2}$
w_2^j	$\frac{4r(a+c-c_m-c_{s1})-c(1-\gamma)^2\theta^2}{8r-(1-\gamma)^2\theta^2}$	$\frac{[(28(a-c_m-c_{s1})+25c)\gamma^2+2\gamma(2(a-c_m-c_{s1})+c)+5c]\theta^2-16r(a-c_m-c_{s1}+c)}{16r(a-c_m-c_{s1}+c)}$	$\frac{4r(a-c_m-c_{s1})+4a\tau(1-2\tau)-(1-\gamma)^2c\theta^2}{8r(1-\tau)-(1-\gamma)^2\theta^2}$
q^j	$\frac{\theta(a-c-c_m-c_{s1})(1-\gamma)}{8r-(1-\gamma)^2\theta^2}$	$\frac{\theta[(a-c-c_{s1}-c_m)(5+3\gamma)]}{32r-(53\gamma^2+6\gamma+5)\theta^2}$	$\frac{\theta(a-c-c_m-c_{s1})(1-\gamma)}{8r(1-\tau)-(1-\gamma)^2\theta^2}$
π_{s2}^j	$\frac{r(a-c-c_m-c_{s1})^2}{2(8r-(1-\gamma)^2\theta^2)}$	$\frac{r(a-c-c_m-c_{s1})^2}{2(8r-(1-\gamma)^2\theta^2)}$	$\frac{r(a-c-c_m-c_{s1})^2(1-\tau)}{2(8r(1-\tau)-(1-\gamma)^2\theta^2)}$
π_{s1}^j	$\frac{2r^2(a-c-c_m-c_{s1})^2}{(8r-(1-\gamma)^2\theta^2)^2}$	$\frac{2(a-c-c_m-c_{s1})^2(\gamma\theta^2+7\gamma^2\theta^2-4r)^2}{(32r-(53\gamma^2+6\gamma+5)\theta^2)^2}$	$\frac{2r^2(a-c-c_m-c_{s1})^2(1-\tau)^2}{(8r(1-\tau)-(1-\gamma)^2\theta^2)^2}$
$E(\pi_m^j)$	$\frac{(a-c-c_m-c_{s1})^2(\gamma\theta^2+r-\gamma^2\theta^2)^2}{(8r-(1-\gamma)^2\theta^2)^2}$	$\frac{4(a-c-c_m-c_{s1})^2(\gamma\theta^2-r)^2\theta^2+r^2}{[(53\gamma^2-100\gamma+46)\gamma^2-4\gamma+5]\theta^2+(-456\gamma^2+16\gamma-72)r\theta^2+256r^2}$	$\frac{(a-c-c_m-c_{s1})^2 \left(\frac{2(1-\gamma)^2\theta^4\gamma^2-4(1-\gamma)\gamma r\theta^2}{(1-\gamma)(1+3\gamma)\tau\theta^2+2r^2(1-\tau)^2} \right)}{2(8r(1-\tau)-(1-\gamma)^2\theta^2)^2}$

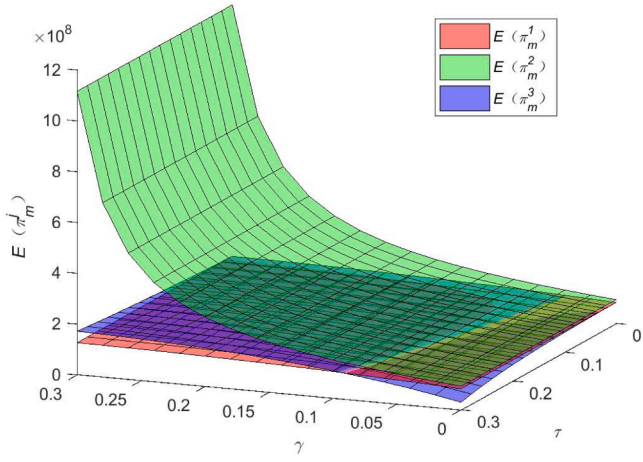


Fig. 2. Manufacturer's overestimated expected profits as functions of γ and τ .

contract is more effective in improving key component quality and tier 1 supplier's profit than the two-part contract.

Overall, both the two-part and equity contracts result in increased product quality and tier 1 supplier's profit. There is consistency between the two contracts in terms of product quality and tier 1's profit. Specifically, tier 1 supplier's profit and key component quality can reach their maximum under the same contract. In other words, high component quality will lead to higher profits for tier 1 suppliers.

Lemma 6. Tier 2 supplier's profit satisfies: $\pi_{s2}^1 = \pi_{s2}^2 \leq \pi_{s2}^3$, the equalities hold for $\gamma = 1$.

Lemma 6 presents that the tier 2 supplier can obtain more profit under the equity contract. This is because the manufacturer holds significant power in the two-part contract, minimizing the profit of the tier 2 supplier.

Lemma 7. When $\gamma = 0$ 时, the manufacturer's profit satisfies $\pi_m^{3*} \leq \pi_m^{1*} < \pi_m^{2*}$, and the manufacturer's profit under the equity contract is the smallest, while the profit under the two-part contract is the largest.

The manufacturer's overestimated expected profit satisfies $E(\pi_m^{2*}) > E(\pi_m^{1*})$.

Lemma 7 shows that the overconfident manufacturer's expected profit is higher under the two-part contract than under the wholesale price contract. Therefore, the overconfident manufacturer prefers to employ the two-part contract to improve the quality of the key component.

Since the overestimated expected profit function of the manufacturer under the equity contract is complex, we provide a comparison of the manufacturer's expected profits through numerical examples.

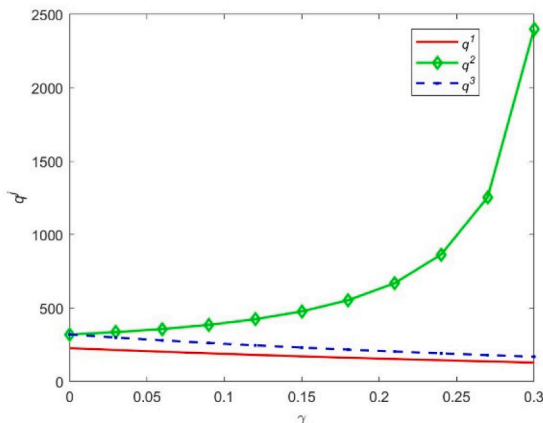


Fig. 2 shows that the manufacturer's overestimated expected profit under the two-part contract is higher than those under the wholesale price contract and equity contract. The wholesale price contract results in higher overestimated profits than equity contracts with low overconfidence. Conversely, if the overconfidence level is high, the overestimated expected profit under the wholesale price contract is lower than those under the equity contract.

6. Numerical examples

We present with numerical experiments to visually demonstrate the influence of manufacturer overconfidence, with the parameters specified as $a = 1 \times 10^5$, $c = 3 \times 10^4$, $c_m = c_{s1} = 1 \times 10^4$, $\tau = 0.2$, $r = 4 \times 10^3$, $\theta = 1 \times 10^2$.

6.1. The impact of overconfidence level on decision variables

Fig. 3 shows how the manufacturer's overconfidence level affects key component's quality, wholesale prices and retail price. We can see that under wholesale price contract and equity contract, component's quality, wholesale and retail prices decrease as manufacturer's overconfidence level increases. However, under two-part contract, the component's quality, wholesale and retail prices increase as γ increases. Additionally, the quality of the key component, as well as wholesale and

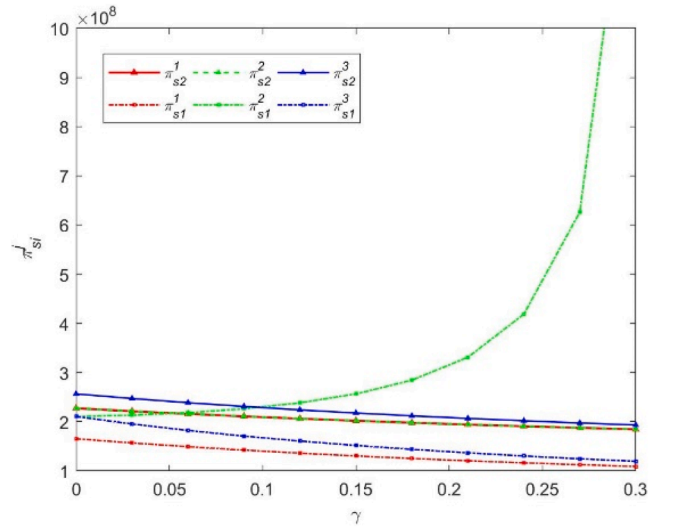


Fig. 4. Tier 1 and 2 suppliers' profits as functions of γ .

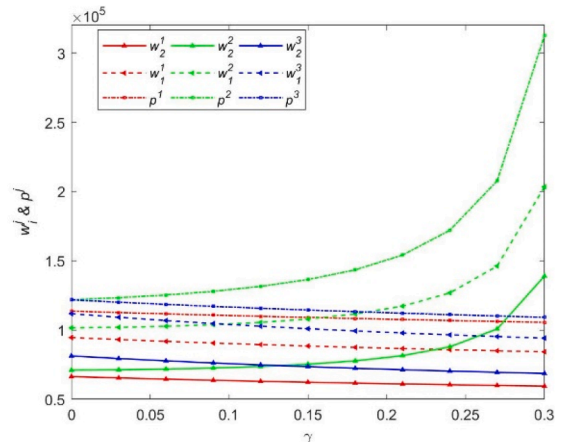


Fig. 3. The optimal key component's quality, wholesale prices and retail price as functions of γ .

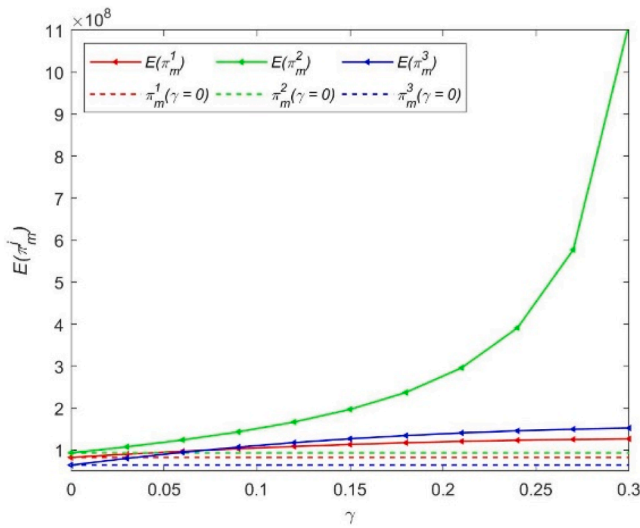


Fig. 5. Manufacturer's overestimated expected profits as functions of γ .

retail prices under both the two-part and equity contracts, exceed those under the wholesale price contract. However, under the equity contract, since the manufacturer holds a vertical stake in the tier 2 supplier, the incentive effect on the supplier's R&D is relatively weaker. These results are in accordance with Lemmas 1–3 and 5.

6.2. The impact of overconfidence on the profits of suppliers and manufacturer

Figs. 4 and 5 show the impacts of the manufacturer's overconfidence level on the profits of suppliers and manufacturer. Fig. 4 presents that under the three types of contracts, tier 2 supplier's profit reduces as γ raises. Under wholesale price contract and equity contract, tier 1 supplier's profit also reduces as γ raises. However, under the two-part contract, tier 1 supplier's profit increases as γ increases.

For the tier 2 supplier, the profit under the equity contract is always higher than under both the wholesale price and two-part contracts. For the tier 1 supplier, the profit is highest under the two-part contract because the quality of key components is highest, leading to a higher price. These results are in accordance with Lemmas 1–3 and 5–7.

Fig. 5 shows that the manufacturer's overestimated expected profit

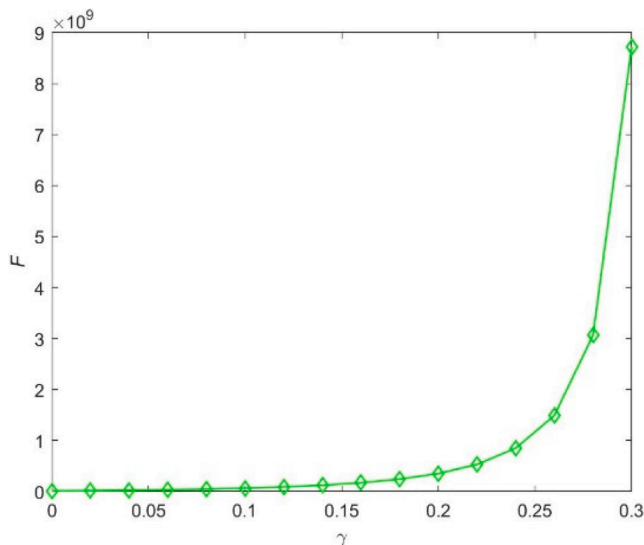


Fig. 6. The impact of γ on F .

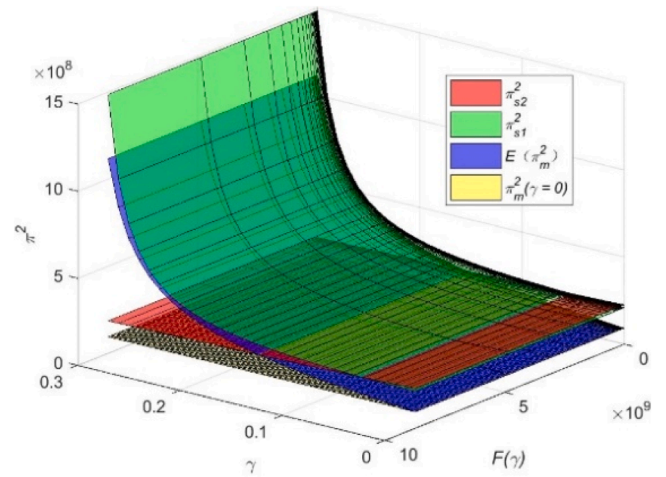


Fig. 7. The impact of γ and F on π^2 .

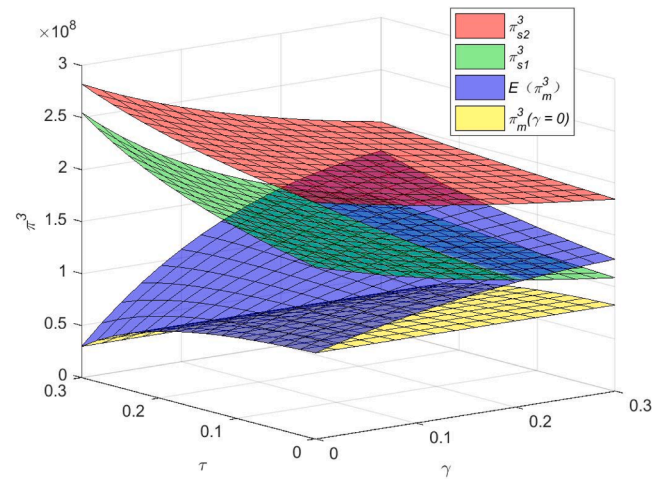


Fig. 8. The impacts of γ and τ on π^3 .

risks with γ across all three contracts, peaking with the two-part contract. Moreover, the manufacturer's actual profit is maximized under the two-part contract. We also find that the manufacturer may not obtain more profit in the equity contract than in the wholesale price contract, especially when the overconfident level is very small.

6.3. The impacts of overconfidence and shareholding ratio on supply chain members' profits

Fig. 6 shows the effect of the manufacturer's overconfidence on two-part contract. Fig. 6 shows that fixed investment increases as γ increases. When γ is high, the impact on $0.25 < \gamma < 0.3$ is more apparent. This is due to the manufacturer's overestimation of product demand, leading to continuous increases in fixed investment.

Fig. 7 shows the impact of overconfidence and fixed investment on the supply chain members' profits under two-part contract. Tier 1 supplier's increases as γ increases, while tier 2 supplier's profit decreases as γ increases. The manufacturer's overconfidence harms tier 2 supplier's profit, so the dominant manufacturer should take appropriate measures to mitigate the negative impact of overconfidence on suppliers. Otherwise, the imbalance of supply chain benefits caused by the power structure may lead to the breakdown of internal cooperation relationships within the supply chain.

Fig. 8 shows the impact of overconfidence and the shareholding ratio under equity contract. From Fig. 8, we see that when the manufacturer's

overconfidence level is low, the manufacturer's overestimated expected profit decreases with the shareholding ratio; when the overconfidence level is not very small, then the manufacturer's expected profit increases with the shareholding ratio. In other word, the impact of shareholding ratio on manufacturer's overestimated expected profit is influenced by the overconfidence level. The profits of tier 2 and 1 suppliers increase with the shareholding ratio but decrease with the manufacturer's overconfidence level, which is consistent with Figs.6 and 7. This suggests that higher overconfidence seems to be detrimental to suppliers. Therefore, the equity contract does not fundamentally eliminate the adverse effects of overconfidence on suppliers. The higher the shareholding ratio, the more profit the manufacturer takes away, leaving less profit for the tier 2 supplier to reinvest in reproduction. However, if the shareholding ratio is too low, below a certain threshold, the manufacturer will lose the motivation to invest. Thus, the shareholding ratio should be set within a reasonable range to ensure that both parties benefit.

7. Conclusion

This study examines a three-echelon supply chain comprising a tier 2 supplier, a tier 1 supplier, and a manufacturer. We study the cooperative R&D strategy between the overconfident manufacturer and rational tier 2 supplier. We derive the optimal key component's quality, wholesale prices, and retail price for the wholesale price contract, two-part contract, and equity contract. Furthermore, we present the different impacts of the overconfidence on component's quality and supply chain members' profits under the three contracts. Finally, we give the numerical examples to supplement our theoretical results.

The main conclusions are (1) when the manufacturer invests in the tier 2 supplier, the key component's quality, the profits of the tier 1 and 2 suppliers will be higher than those without investment. In addition, the manufacturer's actual profit is higher with the two-part contract than with the wholesale price contract, but lower with the equity contract; (2) among the three types of contracts, tier 2 supplier will prefer equity contract. For the tier 1 supplier, if the manufacturer's shareholding ratio or overconfidence level is low, the two-part contract is more beneficial to tier1 supplier. Otherwise, the equity contract is more

beneficial to tier1 supplier. For the manufacturer, the two-part contract is more preferred, especially when there is a high level of overconfidence; (3) under the wholesale price contract and the equity contract, manufacturer's overconfidence will lead to a decline in key component's quality and tier 1 and 2 suppliers' profits. The higher the overconfidence level, the smaller the component's quality and suppliers' profits. Under the two-part contract, manufacturer's overconfidence raises the key component's quality and tier 1 supplier's profit, but decreases tier 2 supplier's profit.

This study examines the cooperative R&D decision-making among three-echelon supply chain members. The research has several limitations, which are followed by potential directions for future research. First, the R&D of key components often faces failures, but this paper does not consider the possibility of R&D failure. Therefore, future research can explore the impact of incorporating the probability of failure in the R&D of key components on overall supply chain decision-making. Second, both the manufacturer and tier 1 supplier can invest in the tier 2 supplier to improve the quality of the components, or the manufacturer may delegate the investment decision to the tier 1 supplier. Future study could consider above scenarios. Third, in this study overconfidence is defined as the manufacturer's over-optimism in demand forecasting. Future research could extend this by considering different types of overconfidence, such as overconfidence in production capacity or market competitiveness. These different forms of overconfidence may have varying impacts on supply chain decision-making, which deserves further investigation.

CRedit authorship contribution statement

Linghong Zhang: Writing – review & editing, Supervision, Methodology, Conceptualization. **Huimin Pan:** Writing – original draft, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Proof of Proposition 1: Because $\frac{\partial^2 E(\pi_m^1)}{\partial (p^1)^2} = -2 < 0$, then let $\frac{\partial E(\pi_m^1)}{\partial (p^1)} = 0$, we can obtain the unique optimal solution $p^{1*} = \frac{a+c_m+w_1^1+q^1\theta(1+\gamma)}{2}$. Substituting p^{1*} into tier 1 supplier's profit function π_{s1}^1 , we can obtain $\frac{\partial^2 \pi_{s1}^1}{\partial (w_1^1)^2} = -1 < 0$, then we can obtain the unique optimal solution $w_1^{1*}, w_1^{1*} = \frac{a-c_m+c_{s1}+w_1^1+(1-\gamma)q^1\theta}{2}$.

$$\text{The Hessian matrix } H_1(w_2^1, q^1) \text{ of } \pi_{s2}^{1*} \text{ is } H_1(w_2^1, q^1) = \begin{bmatrix} \frac{\partial^2 \pi_{s2}^1}{\partial (w_2^1)^2} & \frac{\partial^2 \pi_{s2}^1}{\partial w_2^1 \partial q^1} \\ \frac{\partial^2 \pi_{s2}^1}{\partial q^1 \partial w_2^1} & \frac{\partial^2 \pi_{s2}^1}{\partial (q^1)^2} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{(1-\gamma)\theta}{4} \\ \frac{(1-\gamma)\theta}{4} & -r \end{bmatrix}.$$

As can be seen from $H_1(w_2^1, q^1)$, when $\frac{r}{2} - \frac{(1-\gamma)^2\theta^2}{16} > 0$, i.e., $r > \frac{(1-\gamma)^2\theta^2}{8}$, then the Hessian matrix is negative definite and the tier 2 supplier's problem has a unique optimal solution (q^{1*}, w_2^{1*}) .

$$q^{1*} = \frac{\theta(a-c-c_m-c_{s1})(1-\gamma)}{8r-(1-\gamma)^2\theta^2}$$

By solving $\frac{\partial \pi_{s2}^1}{\partial (q^1)} = 0$, we can obtain

$$w_2^{1*} = \frac{4r(a+c-c_m-c_{s1})-c(1-\gamma)^2\theta^2}{8r-(1-\gamma)^2\theta^2}$$

Plugging (q^{1*}, w_2^{1*}) into tier 1 supplier's optimal wholesale price and manufacturer's optimal retail price, we can obtain w_1^{1*} and p^{1*} as given in Proposition 1.

Substituting above optimal solutions into tier 2 and 1 suppliers' profit function and manufacturer's overestimated expected profit, thereby we can derive the equilibrium profit function as present in Proposition 1.

Proof of Proposition 2: Because $\frac{\partial^2 E(\pi_m^2)}{\partial (p^2)^2} = -2 < 0$, then let $\frac{\partial E(\pi_m^2)}{\partial (p^2)} = 0$, we can obtain the unique optimal solution $p^{2*} = \frac{a+c_m+w_1^2+q^2\theta(1+\gamma)}{2}$.

Substituting p^{2*} into tier 1 supplier's profit function π_{s1}^2 , we can obtain $\frac{\partial^2 \pi_{s1}^2}{\partial (w_1^2)^2} = -1 < 0$, then we can obtain the unique optimal solution $w_1^{2*}, w_1^{2*} = \frac{a-c_m+c_{s1}+w_2^2+(1-\gamma)q^2\theta}{2}$.

Substituting p^{2*} and w_1^{2*} into tier 2 supplier's profit function π_{s2}^2 , we can obtain $\frac{\partial^2 \pi_{s2}^2}{\partial (w_2^2)^2} = -\frac{1}{2} < 0$, then we can obtain the unique optimal solution $w_2^{2*}, w_2^{2*} = \frac{a+c-c_m-c_{s1}+(1-\gamma)q^2\theta}{2}$.

Substituting p^{2*}, w_1^{2*} and w_2^{2*} into tier 2 supplier's profit function π_{s2}^2 and π_{s1}^2 . we can obtain We can obtain the minimum $F = \pi_{s2}^1 - \pi_{s2}^2 = \frac{4(a-c-c_m-c_{s1})^2(7\gamma+1)^2(\gamma\theta^2-\gamma^2\theta^2+r)^2\theta^2}{(32r-(53\gamma^2+6\gamma+5)\theta^2)^2(8r-(\gamma-1)^2\theta^2)}$. Substituting $p^{2*}, w_1^{2*}, w_2^{2*}$ and Finto manufacturer's overestimated expected profit function $E(\pi_m^2)$, then let $\frac{\partial E(\pi_m^2)}{\partial (q^2)} = 0$, we can obtain the unique optimal solution $q^{2*}, q^{2*} = \frac{\theta((a-c-c_{s1}-c_m)(5+3\gamma))}{32r-(53\gamma^2+6\gamma+5)\theta^2}$.

$$\text{The Hessian matrix } H_2(p^2, q^2) \text{ of } E(\pi_m^2)^* \text{ is } H_2(p^2, q^2) = \begin{bmatrix} \frac{\partial^2 E(\pi_m^2)}{\partial (p^2)^2} & \frac{\partial^2 E(\pi_m^2)}{\partial p^2 \partial q^2} \\ \frac{\partial^2 E(\pi_m^2)}{\partial q^2 \partial p^2} & \frac{\partial^2 E(\pi_m^2)}{\partial (q^2)^2} \end{bmatrix} = \begin{bmatrix} -2 & \frac{(7+\gamma)\theta}{4} \\ \frac{(7+\gamma)\theta}{4} & \frac{(13\gamma^2-2\gamma-11)\theta^2}{8} - r \end{bmatrix}.$$

As can be seen from $H_2(p^2, q^2)$, when $2r - \frac{(53\gamma^2+6\gamma+5)\theta^2}{16} > 0$, i.e., $32r > (53\gamma^2 + 6\gamma + 5)\theta^2$, then the Hessian matrix is negative definite and the manufacturer's problem has a unique optimal solution (p^{2*}, q^{2*}) .

Plugging q^{2*} into F , tier 2 and 1 suppliers' optimal wholesale prices and manufacturer's optimal retail price, we can obtain F, w_2^{2*}, w_1^{2*} and p^{2*} as given in Proposition 2.

Substituting above optimal solutions into tier 2 and 1 suppliers' profit function and manufacturer's overestimated expected profit, thereby we can derive the equilibrium profit function as present in Proposition 2.

Proof of Proposition 3: Because $\frac{\partial^2 E(\pi_m^3)}{\partial (p^3)^2} = -2$, then let $\frac{\partial E(\pi_m^3)}{\partial (p^3)} = 0$, we can obtain the unique optimal solution $p^{3*} = \frac{a+c_m+w_1^3+q^3\theta(1+\gamma)+\tau(c-w_2^3)}{2}$.

Substituting p^{3*} into tier 1 supplier's profit function π_{s1}^3 , we can obtain $\frac{\partial^2 \pi_{s1}^3}{\partial (w_1^3)^2} = -1 < 0$, then we can obtain the unique optimal solution $w_1^{3*}, w_1^{3*} = \frac{a-c_m+c_{s1}+w_2^3-(1+\gamma)q^3\theta-\tau(c-w_2^3)}{2}$.

$$\text{The Hessian matrix } H_3(w_2^3, q^3) \text{ of } \pi_{s2}^3 \text{ is } H_3(w_2^3, q^3) = \begin{bmatrix} \frac{\partial^2 \pi_{s2}^3}{\partial (w_2^3)^2} & \frac{\partial^2 \pi_{s2}^3}{\partial w_2^3 \partial q^3} \\ \frac{\partial^2 \pi_{s2}^3}{\partial q^3 \partial w_2^3} & \frac{\partial^2 \pi_{s2}^3}{\partial (q^3)^2} \end{bmatrix} = \begin{bmatrix} -\frac{1}{2}(1-\tau)^2 & (1-\tau)\frac{(1-\gamma)\theta}{4} \\ (1-\tau)\frac{(1-\gamma)\theta}{4} & r(\tau-1) \end{bmatrix}.$$

As can be seen from $H_3(w_2^3, q^3)$, when $\frac{r}{2}(1-\tau) - \frac{(1-\gamma)^2\theta^2}{16} > 0$, i.e., $8r(1-\tau) > (1-\gamma)^2\theta^2$, then the Hessian matrix is negative definite and the tier 2's problem has a unique optimal solution (w_2^{3*}, q^{3*}) .

$$q^{3*} = \frac{\theta(a-c-c_m-c_{s1})(1-\gamma)}{8r(1-\tau) - (1-\gamma)^2\theta^2}$$

By solving $\frac{\partial \pi_{s2}^3}{\partial (q^3)} = 0, \frac{\partial \pi_{s2}^3}{\partial (w_2^3)} = 0$, we can obtain

$$w_2^{3*} = \frac{4r(a-c-c_m-c_{s1}) + 4cr(1-2\tau) - (1-\gamma)^2c\theta^2}{8r(1-\tau) - (1-\gamma)^2\theta^2}$$

Plugging (w_2^{3*}, q^{3*}) into tier 1 supplier's optimal wholesale price and manufacturer's optimal retail price, we can obtain w_1^{3*} and p^{3*} as given in Proposition 3.

Substituting above optimal solutions into tier 2 and 1 suppliers' profit function and manufacturer's overestimated expected profit, thereby we can derive the equilibrium profit function as present in Proposition 3.

Appendix B

Proof of Lemma 1.

When $\gamma = 0$, then $q^{1*}, w_2^{1*}, w_1^{1*}$, and p^{1*} are the optimal decisions when the manufacturer is completely rational.

From Eqs. (6), (7, 8, 9, 10) and (11), we can obtain

$$\frac{\partial q^{1*}}{\partial \gamma} = -\frac{\theta(a-c-c_m-c_{s1})(\theta^2(\gamma-1)^2+8r)}{(8r-\theta^2(\gamma-1)^2)^2} < 0$$

$$\frac{\partial p^{1*}}{\partial \gamma} = -\frac{\theta^2(a-c-c_m-c_{s1})(\theta^2(\gamma-1)^2+6r+2r\gamma)}{(8r-\theta^2(\gamma-1)^2)^2} < 0$$

$$\frac{\partial w_2^{1*}}{\partial \gamma} = \frac{8r\theta^2(a-c-c_m-c_{s1})(\gamma-1)}{(8r-\theta^2(\gamma-1)^2)^2} \leq 0; \quad \frac{\partial w_1^{1*}}{\partial \gamma} = \frac{12r\theta^2(a-c-c_m-c_{s1})(\gamma-1)}{(8r-\theta^2(\gamma-1)^2)^2} \leq 0;$$

$$\frac{\partial \pi_{s2}^{1*}}{\partial \gamma} = \frac{r\theta^2(a-c-c_m-c_{s1})^2(\gamma-1)}{(8r-\theta^2(\gamma-1)^2)^2} \leq 0; \quad \frac{\partial \pi_{s1}^{1*}}{\partial \gamma} = \frac{8r^2\theta^2(a-c-c_m-c_{s1})^2(\gamma-1)}{(8r-\theta^2(\gamma-1)^2)^2} \leq 0.$$

Only when the manufacturer is completely overconfident, i.e. $\gamma = 1$, then $\frac{\partial w_2^{1*}}{\partial \gamma} = \frac{\partial w_1^{1*}}{\partial \gamma} = \frac{\partial \pi_{s2}^{1*}}{\partial \gamma} = \frac{\partial \pi_{s1}^{1*}}{\partial \gamma} = 0$, so lemma 1 is proven.

Proof of Lemmas 2–4. The proofs of Lemmas 2–4 are similar to Lemma 1.

Proof of Lemma 5.

$$q^{2*} - q^{1*} = \frac{8\theta(7\gamma + 1)(a - c - c_m - c_{s1})(r + \gamma\theta^2(1 - \gamma))}{(8r - (1 - \gamma)^2\theta^2)(32r - (53\gamma^2 + 6\gamma + 5)\theta^2)} > 0, q^{2*} > q^{1*}.$$

$$q^{3*} - q^{1*} = \frac{8\tau\theta(a - c - c_m - c_{s1})(1 - \gamma)}{(8r(1 - \tau) - (1 - \gamma)^2\theta^2)(8r - (1 - \gamma)^2\theta^2)} > 0, q^{3*} > q^{1*}.$$

$$q^{2*} - q^{3*} = \frac{8\theta(a - c - c_m - c_{s1})(r(1 - 5\tau + 7\gamma - 3\tau\gamma) + \gamma\theta^2(1 + 6\gamma - 7\gamma^2))}{(8r(1 - \tau) - (1 - \gamma)^2\theta^2)(32r - (53\gamma^2 + 6\gamma + 5)\theta^2)}, \text{ where the denominator is greater than 0. So let } r(1 - 5\tau + 7\gamma - 3\tau\gamma) + \gamma\theta^2(1 + 6\gamma - 7\gamma^2) = 0, \\ \text{then } \tau = \frac{r(1 + 7\gamma) + \gamma\theta^2(1 + 6\gamma - 7\gamma^2)}{r(5 + 3\gamma)}.$$

$$\text{Given } \frac{r(1 + 7\gamma) + \gamma\theta^2(1 + 6\gamma - 7\gamma^2)}{r(5 + 3\gamma)} > \frac{1}{2}, \text{ solving for } r \text{ yields } r = \frac{14\gamma^3\theta^2 - 12\gamma^2\theta^2 - 2\gamma\theta^2}{11\gamma - 3}.$$

$$(1) \text{ When } \gamma < \frac{3}{11}, \frac{r(1 + 7\gamma) + \gamma\theta^2(1 + 6\gamma - 7\gamma^2)}{r(5 + 3\gamma)} \geq \frac{1}{2}, q^{1*} < q^{3*} < q^{2*}.$$

$$(2) \text{ When } \gamma > \frac{3}{11}, \frac{r(1 + 7\gamma) + \gamma\theta^2(1 + 6\gamma - 7\gamma^2)}{r(5 + 3\gamma)} < \frac{1}{2}.$$

$$(i) \text{ If } 0 < \tau < \frac{r(1 + 7\gamma) + \gamma\theta^2(1 + 6\gamma - 7\gamma^2)}{r(5 + 3\gamma)}, \text{ then } q^{1*} < q^{3*} < q^{2*}.$$

$$(ii) \text{ If } \frac{r(1 + 7\gamma) + \gamma\theta^2(1 + 6\gamma - 7\gamma^2)}{r(5 + 3\gamma)} < \tau < \frac{1}{2}, \text{ then } q^{1*} < q^{2*} < q^{3*}.$$

$$\pi_{s1}^3 - \pi_{s1}^1 = \frac{2\tau\theta^2r^2(a - c - c_m - c_{s1})^2(1 - \gamma)^2(16r(1 - \tau) + (\tau - 2)(1 - \gamma)^2\theta^2)}{(8r - (1 - \gamma)^2\theta^2)^2(8r(1 - \tau) - (1 - \gamma)^2\theta^2)^2} > 0.$$

$$\sqrt{\frac{\pi_{s1}^2}{2(a - c - c_m - c_{s1})^2}} = \frac{4r - \gamma\theta^2 - 7\gamma^2\theta^2}{32r - (53\gamma^2 + 6\gamma + 5)\theta^2}, \sqrt{\frac{\pi_{s1}^1}{2(a - c - c_m - c_{s1})^2}} = \frac{r}{8r - (1 - \gamma)^2\theta^2}, \sqrt{\frac{\pi_{s1}^2}{2(a - c - c_m - c_{s1})^2}} - \sqrt{\frac{\pi_{s1}^1}{2(a - c - c_m - c_{s1})^2}} \\ = \frac{\gamma\theta^4(\gamma - 1)^2(7\gamma + 1) + r\theta^2(7\gamma + 1)(1 - \gamma)}{(32r - (53\gamma^2 + 6\gamma + 5)\theta^2)(8r - (1 - \gamma)^2\theta^2)} > 0.$$

Therefore $\pi_{s1}^2 \geq \pi_{s1}^1$, if and only if $\lambda = 1$, the equation holds.

$$\sqrt{\frac{\pi_{s1}^3}{2(a - c - c_m - c_{s1})^2}} - \sqrt{\frac{\pi_{s1}^2}{2(a - c - c_m - c_{s1})^2}} = \frac{-\gamma\theta^4(\gamma - 1)^2(7\gamma + 1) + r\theta^2(7\gamma + 1)(\gamma - 1) + \tau\theta^2(3\gamma + 5)(1 - \gamma)}{(32r - (53\gamma^2 + 6\gamma + 5)\theta^2)(8r - (1 - \gamma)^2\theta^2)}$$

Let the numerator be equal to 0, then $\tau = \frac{\gamma\theta^2(7\gamma + 1)(1 - \gamma) + r(7\gamma + 1)}{r(5 + 3\gamma)}$. Given $\frac{\gamma\theta^2(7\gamma + 1)(1 - \gamma) + r(7\gamma + 1)}{r(5 + 3\gamma)} = \frac{1}{2}$, we can obtain $r = \frac{14\gamma^3\theta^2 - 12\gamma^2\theta^2 - 2\gamma\theta^2}{11\gamma - 3}$.

$$(1) \text{ when } r \geq \frac{3}{11}, \frac{\gamma\theta^2(7\gamma + 1)(1 - \gamma) + r(7\gamma + 1)}{r(5 + 3\gamma)} \geq \frac{1}{2}, \sqrt{\frac{\pi_{s1}^3}{2(a - c - c_m - c_{s1})^2}} - \sqrt{\frac{\pi_{s1}^2}{2(a - c - c_m - c_{s1})^2}} < 0, \text{ then } \pi_{s1}^1 \leq \pi_{s1}^3 \leq \pi_{s1}^2.$$

$$(2) \text{ when } r < \frac{3}{11}, \text{ then } \frac{r(1 + 7\gamma) + \gamma\theta^2(1 + 6\gamma - 7\gamma^2)}{r(5 + 3\gamma)} < \frac{1}{2}.$$

$$(i) 0 < \tau < \frac{\gamma\theta^2(7\gamma + 1)(1 - \gamma) + r(7\gamma + 1)}{r(5 + 3\gamma)}, \sqrt{\frac{\pi_{s1}^3}{2(a - c - c_m - c_{s1})^2}} - \sqrt{\frac{\pi_{s1}^2}{2(a - c - c_m - c_{s1})^2}} < 0, \text{ then } \pi_{s1}^1 \leq \pi_{s1}^3 \leq \pi_{s1}^2.$$

$$(ii) \text{ If } \tau < \frac{\gamma\theta^2(7\gamma + 1)(1 - \gamma) + r(7\gamma + 1)}{r(5 + 3\gamma)} < \frac{1}{2}, \sqrt{\frac{\pi_{s1}^3}{2(a - c - c_m - c_{s1})^2}} - \sqrt{\frac{\pi_{s1}^2}{2(a - c - c_m - c_{s1})^2}} > 0, \text{ then } \pi_{s1}^1 \leq \pi_{s1}^2 \leq \pi_{s1}^3, \text{ the equalities hold for } \lambda = 1.$$

Proof of Lemma 6.

$$\pi_{s2}^{3*} - \pi_{s2}^{1*} = \frac{\tau\theta^2r(a - c - c_m - c_{s1})^2(1 - \gamma)^2}{2(8r - (1 - \gamma)^2\theta^2)(8r(1 - \tau) - (1 - \gamma)^2\theta^2)} \geq 0, \text{ therefore } \pi_{s1}^{3*} \geq \pi_{s2}^{1*}$$

Proof of Lemma 7.

$$\pi_m^{1*} = \frac{(a - c - c_m - c_{s1})^2r^2}{(8r - \theta^2)^2}, \pi_m^{2*} = \frac{4(a - c - c_m - c_{s1})^2r^2}{256r^2 - 72r\theta^2 + 5\theta^4},$$

$$\pi_m^{3*} = \frac{r(a - c - c_m - c_{s1})^2(2r\tau^2 - \tau\theta^2 - 4r\tau + 2r)}{2(8r(1 - \tau) - \theta^2)^2}.$$

$$\frac{\pi_m^{2*} - \pi_m^{1*}}{(a - c - c_m - c_{s1})^2r^2} = \frac{\theta^2}{(8r - \theta^2)^2(32r - 5\theta^2)} > 0$$

$$\frac{\pi_m^{3*} - \pi_m^{1*}}{(a - c - c_m - c_{s1})^2 r} = \frac{-\tau\theta^2(32\tau r^2 - 12r\theta^2 + 32r^2 + \theta^4 - 2\tau r\theta^2)}{2(8r - \theta^2)^2(8r(1 - \tau) - \theta^2)^2}$$

The equation is given as: $-\tau\theta^2(32\tau r^2 - 12r\theta^2 + 32r^2 + \theta^4 - 2\tau r\theta^2) = 0$, which leads to the solutions $\tau_1 = 0$ or $\tau_2 = \frac{32r^2 - 12r\theta^2 + \theta^4}{2r\theta^2 - 32r}$. Since $\tau_2 < 0$, it follows that $0 \leq \tau < \frac{1}{2}$, $-\tau\theta^2(32\tau r^2 - 12r\theta^2 + 32r^2 + \theta^4 - 2\tau r\theta^2) \leq 0$, which implies that $\pi_m^{3*} \leq \pi_m^{1*}$, and when $\tau = 0$, equality holds.

Because

$$\begin{aligned} & [(53\gamma^2 - 100\gamma + 46)\gamma^2\theta^4 + (-456\gamma^2 + 16\gamma - 72)r\theta^2 + 5\theta^4 - 4\gamma\theta^4 + 256r^2] - 4(8r - (1 - \gamma)^2\theta^2)^2 \\ & = -\theta^2(7\gamma + 1)^2((8r - (1 - \gamma)^2\theta^2)) < 0, \text{ then } E(\pi_m^{2*}) > E(\pi_m^{1*}) \end{aligned}$$

Data availability

No data was used for the research described in the article.

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