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COST-SHARING INCENTIVE FOR COLLABORATIVE INNOVATION BETWEEN MAIN MANUFACTURER-CORE SUPPLIER BASED ON RISK FACTORS

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Abstract. This paper considers the "main manufacturer-supplier" model in collaborative cooperation among firms which requires the leader to invest significant resources and bear huge risks. However, few scholars simultaneously consider innovation risks and incentive issues under the model. We construct a Stackelberg game incentive model with different cost-sharing ratios under the risk of technological innovation. We characterize the equilibrium of the model and highlight the key role played by the main manufacturer and supplier. The results are as follows: (a) Main manufacturer can implement the cost-sharing incentive strategy under certain conditions, which is, its profit coefficient is greater than 0.75 times that of supplier and the cost-sharing ratios expected coefficient is greater than the minimum threshold. (b) The optimal cost-sharing ratio is directly proportional to the profit coefficient of the main manufacturer, inversely proportional to that of the supplier, and shows an inverted U-shape function with the probability of successful technological innovation. (c)This strategy can motivate suppliers to invest more resources, reduce the investment of the main manufacturer, simultaneously increase the profits of the main manufacturer and supplier in the certain ranges of innovation success probability and profit coefficients, with significant incentive effects.

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1. Introduction and literature review

1.1. Introduction

The "main manufacturer-supplier" model composed of one main manufacturer and multiple suppliers is mainly applicable to complex products production and innovation. Complex products have high quality, knowledge intensity, and technology requirements [10], which increases the difficulty of manufacturers in innovation. As a result, the innovation of a complex product requires the participation of numerous enterprises. The manufacturer is responsible for integration serves as the core enterprise, coordinating the resources of other suppliers from the perspective of the supply chain, and arranging task nodes and time nodes reasonably to achieve maximum profit of the entire supply chain. This is the management model of "main manufacturer-supplier".

Keywords. Collaborative innovation, stackelberg game, cost-sharing, decision analysis, main manufacturer-supplier.

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In the model, suppliers can be classified into core suppliers, cooperative suppliers, and general suppliers. Cooperative supplier is mainly responsible for the production of components, general supplier is a raw material supplier. The core supplier is the most important component and is mainly responsible for complex subsystems and equipment. The technological level of system components determines the innovation level of the entire supply chain. When the main manufacturer collaborates with core suppliers on innovation for a particular system component, huge cost limits the core supplier's resources invested in innovation, thereby affecting collaborative innovation performance [34].

The first motivation of our paper is to find an incentive strategy, which can encourage core suppliers to invest more resources in collaborative innovation. Exiting research on incentive issues in the supply chain shows that financial incentives can often achieve good results [11, 44]. Therefore, this paper considers that the main manufacturer shares the innovation costs of suppliers to enhance suppliers enthusiasm. However, complex products are different from general supply chain products. Under the innovation costs-sharing, suppliers will bear huge losses once their innovation fails. Complex products have multiple inducible risk factors and high innovation risk. Under the influence of risk factors, suppliers may still choose to retain their investment in innovation resources [23].

The second motivation of this paper is to incorporate risk factors into the incentive strategy. Regarding the issue of innovation risk and incentives, most scholars only focus on one aspect and neglect to combine the two to motivate suppliers to actively innovate from a risk perspective. As a result, we refer to [44] and [24], allow the main manufacturer to share the innovation investment costs of suppliers even in the event of suppliers innovation failure, and maintain orders with suppliers. We want to incorporate the elasticity of innovation failure probability into the model, which enables the main manufacturer to provide different cost-sharing ratios [30] for innovation success and failure [22]. This design can provide greater incentives of cost-sharing contracts while maintaining the profits of the main manufacturer.

This paper's contribution is threefold. At first, there are scare researches on the "main manufacturer-supplier" model for complex products. This paper further categorizes complex product suppliers and considers the cooperation relationship between the main manufacturer and the core supplier under this mode. Second, this is the first paper to incorporate risk factors into the design of cost-sharing contracts for complex product supply chains. Third, in previous literature models, the level of unobservable effort was used to characterize the innovation enthusiasm of suppliers. In this paper, resource investment is used to measure the level of supplier enthusiasm, making it traceable and observable. In addition, when considering collaborative innovation issues, few scholars have considered the effort investment of the main manufacturer. This paper incorporates the resources invested by the main manufacturer into the model and observes the changes of it.

Therefore, this paper focuses on addressing the following issues:

(1) As a main manufacturer with advantages such as information and rights, What incentive strategy can the main manufacturer adopt to achieve better innovation performance in the collaborative innovation process between the main manufacturer and core supplier?
(2) Due to suppliers preference for low risk, they tend to choose conservative innovation or directly abandon innovative solutions that have high risks and high returns for the main manufacturer. What measures should the main manufacturer take to incentivize suppliers to implement such innovative solutions?
(3) When the profit functions of the main manufacturer and supplier change, what changes will occur in the optimal decision and outcome of the main manufacturer and supplier?

The structure of this paper is as follows: Section 1 is the introduction and literature review, Section 2 provides the basic assumptions of model construction, Section 3 constructs and solve game models under cost-sharing and no cost-sharing, Section 4 conducts equilibrium analysis on the cost-sharing model, Section 5 verifies the effectiveness of the incentive model through case studies, and analyzes the impact of cost-sharing on the optimal results through dynamic changes in parameters. Finally, we provide suggestions for the main manufacturer to adopt the cost-sharing strategy.

1.2. Literature review

1.2.1. Collaborative innovation

Collaborative innovation in the supply chain refers to the joint investment of knowledge and technology by members, such as manufacturers, suppliers, and retailers, for the purpose of planning and carrying out product research [26]. Numerous scholars have applied various methods to solve problems in collaborative innovation, such as game theory, mathematical modeling, and empirical research [17, 29, 47]. The common supply chain model is a network chain structure formed by upstream and downstream enterprises. All levels of enterprises have equal status and a single enterprise has no prominent advantages in terms of rights and information compared to other enterprises [18]. In this model, Wang *et al.* [36] find that collaborative innovation activities have a positive impact on corporate innovation performance, and knowledge sharing plays a mediating role in it. Xie and Lei [40] analyze the impact of collaborative innovation ability of participants on collaborative innovation motivation through evolutionary game theory. They found that when the innovation ability becomes strong, the enthusiasm for collaborative innovation will become higher. Zhou *et al.* [50] research the impact of government subsidies on collaborative innovation strategies of enterprises. The research indicate that government subsidies have a positive impact on both technology transfer and joint innovation. The complexity of supply chain products determines the members positions in collaborative innovation [21]. Due to the characteristics of high knowledge intensity and high technological difficulty, some products have formed a production mode, which is centered around a few integrated or downstream enterprises with supporting enterprises surrounding them. In this model, Mondragon *et al.* [28] conclude that system integrators play an essential role in low technological uncertainty and have an edge role in high technological uncertainty. Furthermore, Complex product manufacturers can select suitable suppliers and develop into a production model of "main manufacturer-supplier" [11]. Yi *et al.* [44] formulate a dynamic game model with incomplete information based on the "main manufacturer-supplier" model. It is found that the profit distribution coefficient and order quantity will affect the cooperative equilibrium strategy. Cheng *et al.* [13] construct the optimal resource integration strategy model under the intervention and non-intervention conditions of the main manufacturer. It suggested that when the main manufacturer integrates resources, the resource value-added benefits of the supplier collaboration group significantly increase. Cao *et al.* [8] construct a game model between the main manufacturer and different types of suppliers and comprehensively considered various entities inside and outside the supply chain.

1.2.2. Incentive issues in the supply chain

Incentive issue is also a hot topic in the supply chain, and incentive measures on the supply chain can promote the members to achieve their goals. Low cooperation enthusiasm will lead to low supply chain performance [39]. Therefore, it is crucial to adopt different incentive measures to enhance the enthusiasm for cooperation between enterprises. Many scholars have studied the impact of financial incentives on supply chain performance, such as government, individual supply chain members, and supply chain [16]. To be specific, tax incentives can reduce the carbon emissions of suppliers [38]. Moreover, retailers can motivate manufacturers to reduce emissions through financial incentives as well [43]. To incentive supply chain members, manufacturers provide retailers with customer satisfaction index bonuses and assistance, which could improve customer satisfaction [37]. By establishing an optimal incentive plan system, enterprises can improve supply chain performance and obtain high-quality products at lower costs [20]. Financial incentives may also have side effects. When there is a long-term relationship incentive under the punishment, financial incentives will decrease supply chain performance. But financial incentives can supplement relationship incentives to achieve good incentive effects [15]. In the "main manufacturer-supplier" model, incentives imposed by the main manufacturer can simultaneously improve their interests. For example, relationship incentives can promote the establishment of cooperation between strong suppliers and weak manufacturers. Moreover, it can incentivize collaborative innovation between suppliers and manufacturers through linear partitioning, thereby improving their profitability and competitiveness [49].

1.2.3. Stackelberg game

Stackelberg game is a leadership model [5] used to study asymmetric competition among enterprises [31]. Yoo *et al.* [45] find that the driving force of buyers as leaders can motivate suppliers as followers to achieve cooperation goals. Leaders and followers are differentiated by the differences in power and information available to enterprises at all levels in the supply chain [12]. Therefore, many scholars have applied the Stackelberg model to investigate the incentive problem of supply chain collaborative innovation with leaders and followers. For example, Liu *et al.* [25] construct a Stackelberg game model consisting of main manufacturers, retailers, and third-party recyclers to investigate green innovation in the supply chain. Stackelberg game is also frequently used in the "main manufacturer-supplier" model. Zhao *et al.* [48] use Stackelberg game to construct a cooperative incentive model for main manufacturer and supplier based on cost-sharing. Chen *et al.* [11] employ a benefits planning model based on the individual effort and cooperation level of suppliers to identify the optimal profit distribution ratio between the main manufacturer and suppliers.

1.2.4. Coat-sharing contract

Our work builds on the cost-sharing contract in a supply chain. As a common way of supply chain coordination and motivation, Scholars often analyze the impact of cost-sharing contract on different types of supply chains. Xu *et al.* [42] analyze the impact of cost-sharing contract on competitive green supply chains, which shows that the advantage of cost-sharing strategy is gradually weakened with the intensification of supply chain greenness competition. Sun *et al.* [32] find that cost-sharing reduces the overall profit of supplier led supply chains, but increases the overall profit of retailer led and equal power supply chains. Scholars conduct research on the design of cost-sharing contracts as well. Lin *et al.* [24] design risk-free and risk-taking strategies based on cost-sharing. Xie and Dai *et al.* [41] design and compared the effects of fixed-rate cost-sharing, linear cost-sharing, and threshold-based cost-sharing. Regarding the design of cost-sharing in centralized and decentralized decision-making, Cao *et al.* [7] set up two types of the cost-sharing contract: one way for retailers to provide separate cost-sharing contracts, the other for the provision suppliers and retailers to develop the game of cost-sharing contract approach. Similarly, Bai and Wang *et al.* [2] consider cost-sharing contract under the bargaining game between two parties considering the bargaining power. Both research results indicate that, the expected utility under centralized decision-making is higher than that in the general cost-sharing contract under decentralized decision-making.

Based on the above literature, it can be seen that,

(1) Under supply chain collaborative innovation, there is a wealth of research on the influencing factors of innovation performance and supply chain coordination. However, there are many types of complex product suppliers, and research on collaborative innovation in the complex product supply chain is only superficial, lacking in-depth exploration of collaborative innovation strategies between main manufacturers and classified suppliers.
(2) Scholars typically choose to address incentive issues in the supply chain from a financial and relational perspective, and in the 'main manufacturer-supplier' model, Stackelberg game is commonly used as an analytical tool. However, the innovation risk of complex products is high, and incentivizing suppliers solely from cost and relationship perspectives cannot meet the demand for investing a large amount of resources in innovation. Therefore, it is necessary to increase research on incentivizing suppliers from the perspective of main manufacturers' risk sharing.
(3) In the literature on cost-sharing design, most cost-sharing contracts with better expected effects are targeted. However, existing literature only considers the impact of general cost-sharing contracts on collaborative innovation under the "main manufacturer-supplier" model, and lacks research on cost-sharing contract design for this model.

To explore the cost-sharing incentive problem in the "main manufacturer-supplier" model in depth, this paper focuses on the core suppliers in complex product and designs a risk cost-sharing contract. Then, we compare the optimal result with no cost-sharing and conduct parameter change analysis, and propose strategic suggestions for the main manufacturer.

2. Basic assumptions

For the cost-sharing incentive model, there are relevant assumptions and symbols as follows:

Model assumption 1 We assume that the main manufacturer is in a dominant position and the supply chain is a secondary supply chain composed of a main manufacturer and several core suppliers. Each core supplier is independent and it can be seen as an incentive issue for a main manufacturer to a core supplier.

Model assumption 2 The main manufacturer will provide certain knowledge [33] and technology to the core suppliers, which can be considered as the investment resources of the main manufacturer [26].

Model assumption 3 The innovation results of core suppliers include success and failure. Success refers to the innovative products meeting the requirements of main manufacturer, while failure refers to the products not meeting the requirements of main manufacturer [9]. The failure of innovation will not affect the cooperative relationship between the main manufacturer and supplier. We assume that is the probability of successful technological innovation determined by main manufacturer based on experience and risk.

Model assumption 4 For the main manufacturer, product innovation will reduce its cost, improve competitiveness and customer satisfaction, and thus increase profits. In addition, successful innovation will also bring an increase in sales volume and sales price [6] to suppliers. For the sake of comparison, we consider these increases as the impact coefficient of innovation on the profits of main manufacturer and the core supplier, which is defined as profit coefficient. It should be noted that the profit coefficient of the main manufacturer is the comprehensive profit coefficient after deducting the purchase price. Notations mentioned in this paper are provided in Table 1.

In Table 1, we define the resources invested by main manufacturer as a_M; a_{S_i} represents the resources invested by supplier; C_{oM} indicates the investment cost of main manufacturer for innovation; C_{oS_i} is the production cost when the core supplier's technological innovation fails; G_{eS_i} is the cost of core supplier for successful technological innovation. Then we can obtain the functions of cost:

$$C_{oM} = \frac{1}{2}\mu_M a_M^2 \tag{2.1}$$

$$C_{oS_i} = \frac{1}{2}\mu_{S_i} a_{S_i}^2. \tag{2.2}$$

When the main manufacturer and core supplier increase their investment resources in collaborative innovation, their incomes are increasing and the marginal revenue is decreasing. Moreover, as the main manufacturer and core supplier both invest resources into collaboration, we set the elasticity of their investment for innovation to be 0.5. Based on resource-based theory [3], the income functions of main manufacturer and core supplier under successful technological innovation are defined as follows:

$$G_{oM} = 2r_M a_M^{\frac{1}{2}} a_{S_i}^{\frac{1}{2}} \tag{2.3}$$

$$G_{oS_i} = 2r_{S_i} a_M^{\frac{1}{2}} a_{S_i}^{\frac{1}{2}}. \tag{2.4}$$

We define the main manufacturers cost-sharing ratio as when innovation is successful; When innovation fails, we refer to the practice of [24], allow the main manufacturer to bear the risk cost. Considering incentive effect, we define the cost-sharing ratio as $(1-\rho)^k \alpha$ [44], where K is the elasticity of innovation failure probability, provided by the main manufacturer, $k \in [0,1]$, $\alpha \in [0,1]$. The purpose of K is to control the cost-sharing to ensure the profit of the main manufacturer and incentive effect. The main manufacturer only shares the cost of core supplier's technological innovation part, that is C_{eS_i}.

TABLE 1. Notations mentioned in the paper.

Parameters	
ρ	the probability of successful innovation
k	the elasticity of innovation failure probability
r_M	the profit coefficient of main manufacturer under successful innovation
r_{S_i}	the profit coefficient of core supplier under successful innovation
b_M	the fixed revenue of main manufacturer from the original products
b_{S_i}	the fixed revenue of core supplier from the original products
μ_M	the cost coefficients of main manufacturer
μ_{S_i}	the cost coefficients of core supplier
C_{oM}	the investment cost of main manufacturer for innovation
C_{oS_i}	the fixed production costs for core suppliers under failed innovation
C_{eS_i}	the investment cost of core supplier for successful innovation
G_{eM}	the revenue of main manufacturer under successful innovation
G_{eS_i}	the revenue of core supplier under successful innovation
R'_M	the profits of main manufacturer under successful innovation
R'_{S_i}	the profits of core supplier under successful innovation
R''_M	the profits of main manufacturer under failed innovation
R''_{S_i}	the profits of core supplier under failed innovation
Decision variables	
α	the cost-sharing ratio
a_M	invested resources of main manufacturer for innovation
a_{S_i}	invested resources of core supplier for innovation
Profit functions	
π_M	expected profits of main manufacturer
π_{S_i}	expected profits of core supplier

When innovation is successful, the profits of main manufacturer and core supplier are:

$$R'_M = 2r_M a_M^{\frac{1}{2}} a_{S_i}^{\frac{1}{2}} - \frac{1}{2}\mu_M a_M^2 - \frac{1}{2}\alpha\mu_{S_i} a_{S_i}^2 \tag{2.5}$$

$$R'_{S_i} = 2r_{S_i} a_M^{\frac{1}{2}} a_{S_i}^{\frac{1}{2}} - \frac{1}{2}(1-\alpha)\mu_{S_i} a_{S_i}^2. \tag{2.6}$$

When innovation fails, both main manufacturer and core supplier will be punished, and the profits of main manufacturer and core supplier are:

$$R''_M = b_M - \frac{1}{2}\mu_M a_M^2 - \frac{1}{2}(1-\rho)^k \alpha\mu_{S_i} a_{S_i}^2 \tag{2.7}$$

$$R''_{S_i} = b_{S_i} - \frac{1}{2}(1-(1-\rho)^k\alpha))\mu_{S_i} a_{S_i}^2 - C_{oS_i}. \tag{2.8}$$

The expected profits obtained from equations (2.5), (2.6), (2.7), and (2.8) for collaborative innovation between the main manufacturer and core supplier are as follows:

$$\begin{aligned} E(R_M) &= \rho R'_M + (1-\rho)R''_M \\ &= 2\rho r_M a_M^{\frac{1}{2}} a_{S_i}^{\frac{1}{2}} + (1-\rho)b_M - \frac{1}{2}\mu_M a_M^2 - \frac{1}{2}(\rho + (1-\rho)^{k+1})\alpha\mu_{S_i} a_{S_i}^2 \end{aligned} \tag{2.9}$$

$$E(R_{S_i}) = \rho R'_{S_i} + (1-\rho)R''_{S_i} = 2\rho r_{S_i} a_M^{\frac{1}{2}} a_{S_i}^{\frac{1}{2}} + (1-\rho)b_{S_i} - \frac{1}{2}(1-\rho\alpha-(1-\rho)^{k+1}\alpha)\mu_{S_i}a_{S_i}^2 - (1-\rho)C_{oS_i}. \tag{2.10}$$

b_M and b_{S_i} are fixed revenue that main manufacturer and core supplier obtained from original products due to innovation failure.

3. Model building

(1) Construction of Cost-Sharing Model based on Stackelberg

In the model of "main manufacturer-supplier" for complex products, the main manufacturer provides its investment resources and cost-sharing ratio first. Core supplier decides its invested resources according to the investment resources of main manufacture and cost-sharing ratio. Therefore, the game between main manufacturer and supplier satisfies the Stackelberg game [1, 46]:

$$\pi_M = \max(E(R_M)) = \max\left(2\rho r_M a_M^{\frac{1}{2}} a_{S_i}^{\frac{1}{2}} + (1-\rho)b_M - \frac{1}{2}\mu_M a_M^2 - \frac{1}{2}(\rho+(1-\rho)^{k+1})\alpha\mu_{S_i}a_{S_i}^2\right) \tag{3.1}$$

$$\pi_{S_i} = \max(E(R_{S_i})) = \max\left(2\rho r_{S_i} a_M^{\frac{1}{2}} a_{S_i}^{\frac{1}{2}} + (1-\rho)b_{S_i} - \frac{1}{2}(1-\rho\alpha-(1-\rho)^{k+1}\alpha)\mu_{S_i}a_{S_i}^2 - (1-\rho)C_{oS_i}\right). \tag{3.2}$$

We use the backward induction to solve the model. As the Hessian matrix of π_M on α and a_M is a negative definite matrix and the second-order partial derivative of π_{S_i} on a_{S_i} being negative, it can be concluded that π_M and π_{S_i} have unique optimal solutions for α, a_M and a_{S_i}.

First, we take the partial derivative of a_{S_i} and obtain the equation for a_{S_i} with respect to α and a_M as follows:

$$\frac{\partial \pi_M}{\partial \pi_{S_i}} = 0 \Rightarrow a_{S_i} = \left(\frac{\rho r_{S_i} a_M^{\frac{1}{2}}}{(1-(1-\rho)^{k+1}\alpha-\rho\alpha)\mu_{S_i}}\right)^{\frac{2}{3}}. \tag{3.3}$$

Bringing equation (3.3) into equation (3.1), then we take the partial derivative of α and a_M to obtain the following equations.

$$\frac{\partial \pi_M}{\partial a_M} = 0 \Rightarrow a_M = \left(\frac{\rho^{\frac{4}{3}} r_{S_i}^{\frac{1}{3}}}{3\mu_M \mu_{S_i}^{\frac{1}{3}}(1-\rho\alpha-(1-\rho)^{k+1}\alpha)^{\frac{1}{3}}}\right)^{\frac{3}{4}} \left(4r_M - r_{S_i}\frac{\rho\alpha+(1-\rho)^{k+1}\alpha}{(1-\rho\alpha-(1-\rho)^{k+1}\alpha)}\right)^{\frac{3}{4}} \tag{3.4}$$

$$\frac{\partial \pi_M}{\partial \alpha} = 0 \Rightarrow \alpha^* = \frac{4r_M - 3r_{S_i}}{(\rho+(1-\rho)^{k+1})(4r_M + r_{S_i})}. \tag{3.5}$$

We substitute equation (3.5) into equation (3.4), and obtain the equation of a_M^* as follows.

$$a_M^* = \frac{\rho(4r_M + r_{S_i})^{\frac{1}{4}}(3r_M + \frac{3}{4}r_{S_i})^{\frac{3}{4}}}{3^{\frac{3}{4}}\mu_M^{\frac{3}{4}}\mu_{S_i}^{\frac{1}{4}}4^{\frac{1}{4}}}. \tag{3.6}$$

Then, we substitute equation (3.5) and (3.6) into equation (3.4), and obtain the equation of $a_{S_i}^*$

$$a_{S_i}^* = \frac{\rho(4r_M + r_{S_i})^{\frac{3}{4}}(3r_M + \frac{3}{4}r_{S_i})^{\frac{1}{4}}}{3^{\frac{1}{4}}\mu_M^{\frac{1}{4}}\mu_{S_i}^{\frac{3}{4}}4^{\frac{3}{4}}}. \tag{3.7}$$

Finally, we obtain the optimal solution of the game as shown in equations (3.5), (3.6) and (3.7).

(2) Construction of Costless-Sharing Model based on Stackelberg

Under the premise of no cost-sharing, the main manufacturer only needs to invest in knowledge and technology, and the core supplier determines the most favorable amount of resource investment based on the investment of main manufacturer [35]. Taking the risk of failure, losses, and costs into account, core suppliers will control their resource investment [14].

Based on the above premises, we give the expected profits of main manufacturer and core supplier without cost-sharing as follows:

$$E(R_M^{'}) = 2\rho r_M a_M^{\frac{1}{2}} a_{S_i}^{\frac{1}{2}} + (1-\rho)b_M - \frac{1}{2}\mu_M a_M^2 \tag{3.8}$$

$$E(R_{S_i}^{'}) = 2\rho r_{S_i} a_M^{\frac{1}{2}} a_{S_i}^{\frac{1}{2}} + (1-\rho)b_{S_i} - \frac{1}{2}\mu_{S_i} a_{S_i}^2 - (1-\rho)C_{oS_i}. \tag{3.9}$$

Correspondingly, we can obtain the Stackelberg game between the main manufacturer and core supplier without cost-sharing:

$$\pi_M^{'} = \max(2\rho r_M a_M^{\frac{1}{2}} a_{S_i}^{\frac{1}{2}} + (1-\rho)b_M - \frac{1}{2}\mu_M a_M^2) \tag{3.10}$$

$$\pi_{S_i}^{'} = \max(2\rho r_{S_i} a_M^{\frac{1}{2}} a_{S_i}^{\frac{1}{2}} + (1-\rho)b_{S_i} - \frac{1}{2}\mu_{S_i} a_{S_i}^2 - (1-\rho)C_{oS_i}). \tag{3.11}$$

Similarly, we obtain $a_M^{*'}$ from equation (3.10) first.

$$a_M^{*'} = \left(\frac{4}{3\mu_M}\right)^{\frac{3}{4}} \frac{\rho r_M}{\mu_{S_i}^{\frac{1}{4}}}. \tag{3.12}$$

Then, we take equation (3.12) into (3.11) and obtain $a_{S_i}^{*'}$ as follow.

$$a_{S_i}^{*'} = \frac{2^{\frac{1}{2}} r_M \rho}{3^{\frac{1}{4}} {\mu_M}^{\frac{3}{4}} {\mu_{S_i}}^{\frac{1}{4}}}. \tag{3.13}$$

By bringing equations (3.13) and (3.12) into equations (3.10) and (3.11), we can obtain the maximum profits of main manufacturer and core supplier without cost-sharing.

4. Equilibrium analysis

Analyzing the optimal solution under cost-sharing, we can obtain the following theorems.

Theorem 4.1. *In the collaborative innovation of "main manufacturer-supplier", when* $\frac{r_M}{r_{S_i}} \geq \frac{3}{4}$ *and* $\rho + (1-\rho)^{k+1} \geq \frac{4r_M - 3r_{S_i}}{4r_M + 3r_{S_i}}$, *the main manufacturer can implement the cost-sharing incentive strategy.*

Proof. From $0 \leq \alpha \leq 1$ and the equation (3.5), it can be obtained that $0 \leq \frac{4r_M - 3r_{S_i}}{(\rho + (1-\rho)^{k+1})(4r_M + r_{S_i})} \leq 1$, that is, $4r_M \geq 3r_{S_i}$ and $\rho + (1-\rho)^{k+1} \geq \frac{4r_M - 3r_{S_i}}{4r_M + 3r_{S_i}}$. □

In the above theorem, $\rho + (1-\rho)^{k+1}$ refers to the cost-sharing expectation coefficient under the incentive strategy. From the proof, it can be seen that there is a minimum threshold for the expected coefficient. The possible reason is that if the cost-sharing expectation coefficient is less than the minimum threshold, and the core supplier invests more resources, its negative effect dominates. Based on Expectancy theory, core supplier will not accept this incentive strategy. For the main manufacturer, when it adopts the cost-sharing incentive strategy, it will have the investment costs and share a portion of the core supplier's innovation costs. If technological innovation is unable to bring sufficient gain to the main manufacturer, it should not adopt this strategy neither.

Analyzing from another perspective, if the innovation has a significant effect on the core suppliers profits, the main manufacturer can shift incentive strategy, and core suppliers will spontaneously invest more resources. When main manufacturer still adopts the incentive strategy, its loss is larger than its profits. If technological innovation can bring huge benefits to main manufacturer but has minor impact on core suppliers, the cost-sharing incentive strategy will lose its incentive effect. In this case, main manufacturer needs to encourage core suppliers to engage in technological innovation with other measures, such as commission employment, order incentives, and so on. Therefore, the cost-sharing incentive strategy is feasible only when the profit coefficient of main manufacturer and core supplier meets certain conditions.

Theorem 4.2. *Under the collaborative innovation of "main manufacturer-supplier", the incentive strategy is effective when the cost-sharing incentive strategy is implemented. The incentive strategy influences the invested resources by core supplier. The ratio of cost-sharing becomes larger, the invested resources will increase.*

Proof. From equation (3.3), it can be obtained that if $\frac{\partial a_{S_i}}{\partial \alpha} = \frac{2a_M^{\frac{1}{3}}\rho^{\frac{2}{3}}r_{S_i}^{\frac{2}{3}}(\rho+(1-\rho)^{k+1})}{3\mu_{S_i}^{\frac{2}{3}}(1-\rho)^{k+1}\alpha-\rho\alpha)^{\frac{5}{3}}} > 0$, the invested resources by core suppliers will increase as the cost-sharing ratio increases. $\square$

When conducting collaborative innovation, the obstacles faced by core suppliers mainly come from high costs and huge risks. The cost-sharing strategy provides different cost-sharing ratios in various cases of innovation, so core suppliers can gain higher benefits with the cost-sharing ratio rising. Under the dual incentives of risk protection and cost-sharing, the benefits brought by innovative products to core suppliers will attract them to invest more resources in collaborative innovation, striving to improve innovation performance.

Theorem 4.3. *Under the collaborative innovation of "main manufacturer-supplier", when the cost-sharing incentive strategy can be implemented, the cost-sharing ratio shows an inverted U-shape relationship as the probability of successful innovation increases. The maximum value is taken at $\rho = 1 - (\frac{1}{k+1})^{\frac{1}{k}}$. When technological innovation is successful, the cost-sharing ratio is directly proportional to the profit coefficient of main manufacturer, and inversely proportional to that of the core supplier.*

Proof. From equation (3.5), it can be obtained that $\frac{\partial \alpha^*}{\partial \rho} = \frac{((k+1)(1-\rho)^k-1)4r_M-3r_{S_i}}{(\rho+(1-\rho)^{k+1})^2(4r_M+r_{S_i})}$, and because of $4r_M \geq 3r_{S_i}$, when $\frac{\partial \alpha^*}{\partial \rho} = 0$, $\rho = 1 - (\frac{1}{k+1})^{\frac{1}{k}}$. Therefore, when $0 < \rho < 1 - (\frac{1}{k+1})^{\frac{1}{k}}$, $\frac{\partial \alpha^*}{\partial \rho} > 0$, α^* increases as ρ increases; when $1 - (\frac{1}{k+1})^{\frac{1}{k}} < \rho < 1$, $\frac{\partial \alpha^*}{\partial \rho} < 0$, α^* decreases as ρ increases. Moreover, $\frac{\partial \alpha^*}{\partial r_{S_i}} = \frac{-24r_M}{(\rho+(1-\rho)^{k+1})(4r_M+r_{S_i})^2} < 0$, α^* decreases as $r_{S_{\mathrm{i}}}$ increases. $\square$

When the probability of successful technological innovation is low, the core supplier is willing to invest less resources in innovation due to risk considerations. According to Theorem 4.2, the main manufacturer should increase the cost-sharing ratio and motivate the core supplier to invest more resources. When the probability gradually increases to $1 - (\frac{1}{k+1})^{\frac{1}{k}}$, the risk of technological innovation is relatively small for the core supplier. Therefore, the benefits brought by successful innovation to the core supplier will motivate it to invest more resources. If main manufacturer provides a higher cost-sharing ratio as well, it will reduce its profits. Similarly, when innovation can bring high profits to the core supplier, it will spontaneously invest more resources, and the main manufacturer could provide a low cost-sharing ratio.

TABLE 2. Parameter value.

ρ	r_M	r_{S_i}	b_M	b_{S_i}	μ_M	μ_{S_i}	C_{oS_i}	k
0.7	15	18	150	180	0.4	0.7	80	0.2

TABLE 3. Stackelberg equilibrium solution values.

Equilibrium conditions	Enterprise	Cost-sharing ratio	Resources invested	Maximum profit	Supply chain profit
Cost-sharing	Main manufacturer	0.56573	19.5528	312.618	531.525
	Core supplier	0.56573	25.86589	218.907	
Without cost-sharing	Main manufacturer	0	21.407	302.96	487.341
	Core supplier	0	18.539	184.381	

5. Simulation examples

5.1. Model validation

The aircraft manufacturing industry has formed a multi-level structure composed of complete machine manufacturers and many suppliers. The structure can be generally divided into three levels. The first level is represented by complete machine manufacturers such as Boeing and Airbus, the second level is mainly composed of a relatively small number of subsystem suppliers, and the third level is composed of a large number of component suppliers and service providers [4]. As a high-tech-intensive and complex product, the level of technology aircraft manufacturing determines the profit of the aircraft value chain [19]. Therefore, the main manufacturer carries out collaborative innovation with suppliers, thereby increasing the value of various aspects of aircraft manufacturing.

We take a certain model of commercial aircraft and its hydraulic system supplier as the research object to verify the models correctness. The hydraulic system is extremely important for the safe flight and landing of aircraft [27], which is mainly used for the retraction of landing gears, speed brakes, front wheel turning control, etc. Manufacturers take measures to solve the high noise and high fault efficiency in the hydraulic system. To incentivize hydraulic system suppliers innovation, the main manufacturer adopts the cost-sharing incentive strategy among hydraulic system suppliers. Based on risk assessment and experience, the probability of successful technological innovation is determined to be 0.7, the profit coefficient of main manufacturers is 15, and the profit coefficient of the core supplier is 8 [37], more parameter values are shown in Table 2.

To verify the correctness of the model and the various patterns of variables, we allow $\rho \in [0, 1]$, $r_M \in [10, 20]$, $r_{S_i} \in [1, 10]$ to verify changes in the optimal investment resources, maximum profits, and the optimal cost-sharing ratio when ρ supports the maximum profit at an interval of 0.01, r_M at an interval of 0.1, and r_{S_i} at an interval of 0.1, respectively. To verify the incentive effect of the model, we compare the optimal investment resources and profits with and without cost-sharing. When verifying the results separately, ρ, r_M and r_{S_i} select fixed values of 0.7, 15, and 8. The parameters are set as follows:

Firstly, we use MATLAB R2022b to solve the equilibrium solution of the Stackelberg game under cost-sharing and no cost-sharing with values of 0.7, 15, and 8 for ρ, r_M and r_{S_i}. The specific results are shown in Table 3.

From Table 3, the resources invested by the core supplier under cost-sharing are more than those without cost-sharing, indicating that the cost-sharing incentive strategy plays a motivating role. We anticipate that the investment resources of main manufacturer will increase under the cost-sharing strategy. But Table 3 shows that the main manufacturer will invest more resources without cost-sharing. The possible reason is that the cost-sharing strategy increases the marginal cost of the main manufacturer and increases the investment resources of the core suppliers. Under the balance of technological innovation level and self-interest, the main manufacturer will reduce resource investment. For the main manufacturer and core supplier, the maximum profit with cost-sharing is greater than the equilibrium solution without cost-sharing. This indicates that the innovation incentive strategy is effective and beneficial for those parties involved in collaborative innovation. Therefore, it can be concluded that when the main manufacturer and core supplier engage in collaborative innovation, the cost-sharing strategy is beneficial to achieving greater benefits for them. Moreover, it can maximize the benefits of the supply chain.

5.2. Impact analysis of cost-sharing

To further investigate the impact of technological innovation and the profit coefficient on collaborative innovation, we plot the changes in the optimal solution combination when variables change. Simultaneously, the relationship between optimal investment resources and maximum profits is investigated and the specific results are shown in Figures 1 to 8.

(1) The impact of ρ on optimal results

We observe the variation of the optimal strategy combination by keeping the probability of successful innovation within the range of [0,1], and obtain the results as shown in the Figures 1–3.

From Figure 1, it can be seen that the optimal cost-sharing ratio shows an inverted U-shape function with the probability of successful innovation. It verifies the correctness of Theorem 4.3, which is in line with the collaborative innovation model of "main manufacturer-supplier". The low probability means high risk. Therefore, the main manufacturer should keep the cost-sharing ratio at a low level to achieve incentive effects for the core supplier. When the probability is high, it stimulates core suppliers to engage in technological innovation. Therefore, a high cost-sharing ratio will reduce the main manufacturers interests. This indicates that the main manufacturer should adjust the cost-sharing ratio with the probability while maintaining the incentive effect on the core supplier and maximizing its interests.

Figure 2 shows that, invested resources are increasing with the probability of successful technological innovation increasing, and maximum profits also keep increasing trend. This is because when the probability reaches a high level, the risk of collaborative innovation is relatively small, and their marginal profits increase.

From Figure 3, in addition to the resource investment of main manufacturer, the results with cost-sharing are superior to that without cost-sharing. Moreover, as the probability increases, the gaps between costless-sharing and cost-sharing of the invested resources and profits increase. This indicates that the strategy is beneficial for the main manufacturer and core supplier. The main manufacturer's benefit increases with the probability

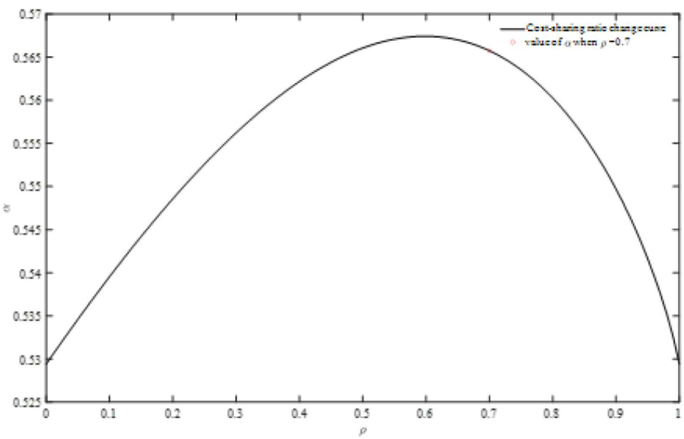

FIGURE 1. Impact curve of ρ to α.

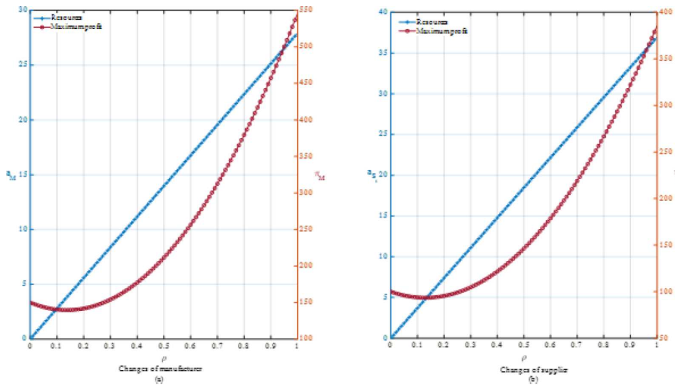

FIGURE 2. Impact curve of ρ to a_M, a_{S_i}, π_M and π_{S_i}.

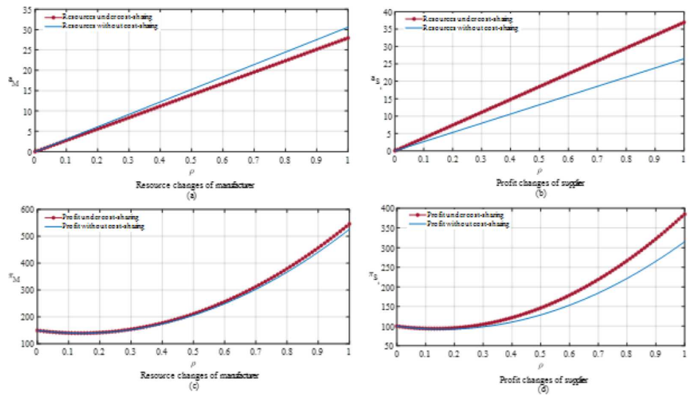

FIGURE 3. Comparison of results with and without cost-sharing under different values of ρ.

when adopting the cost-sharing incentive strategy. The investment resources of the main manufacturer under cost-sharing are still lower than those without cost-sharing. This indicates that when main manufacturer adopts the incentive strategy, it can bring greater profits and save more resources.

(2) The impact of r_M on optimal results

Figures 4 to 6 show the variation of the optimal strategy combination as the profit coefficient of main manufacturer varies within the range of [10,20].

Figure 4 shows that the optimal cost-sharing ratio is increasing with the profit coefficient of main manufacturer. The main manufacturer can derive greater benefits from innovation success with higher coefficients. Therefore, the main manufacturer provides a higher cost-sharing ratio to incentivize core suppliers for technological innovation.

In Figure 5, the investment resources and maximum profit show a linear upward trend with the profit coefficient of main manufacturer. The possible reason is that the main manufacturer will give higher cost-sharing ratios with the coefficient increasing. This also verifies the correctness of Theorem 4.3. At the same time, the investment resources and maximum profits of the core supplier are linear with the coefficient. That is because, a high coefficient attracts the main manufacturer to give a high cost-sharing ratio, thereby causing core suppliers high investment resources and profits.

In Figure 6, the invested resources and maximum profit of the core supplier under cost-sharing are also higher than those without cost-sharing. For the main manufacturer, the optimal investment resources under

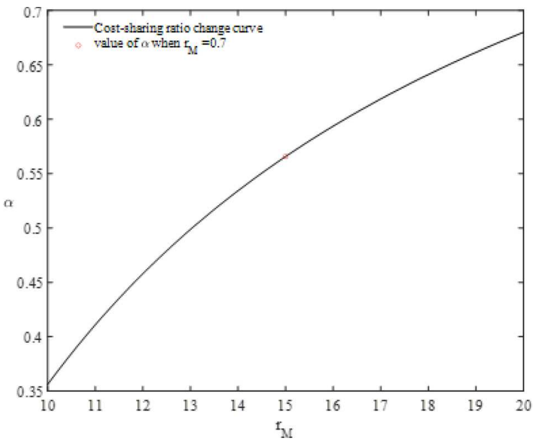

FIGURE 4. Impact curve of r_M to α.

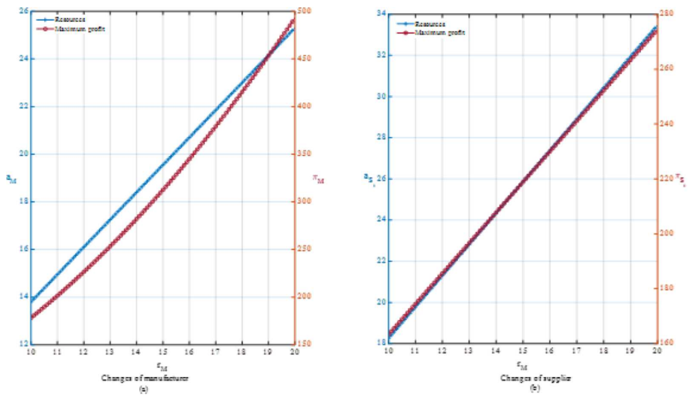

FIGURE 5. Impact curve of r_M to $a_{M,}a_{S_i}, \pi_M$ and π_{S_i}.

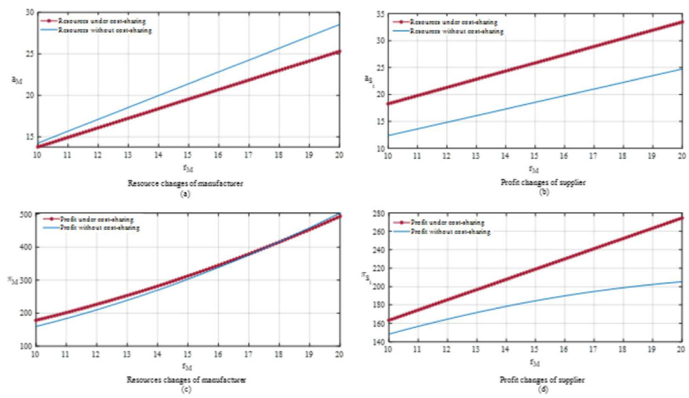

FIGURE 6. Comparison of results with and without cost-sharing under different values of r_M.

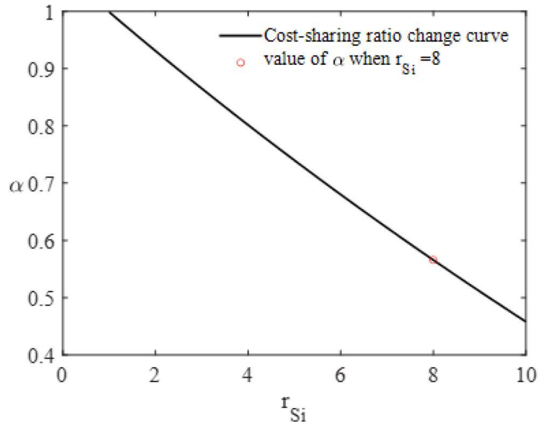

FIGURE 7. Impact curve of r_{S_i} to α.

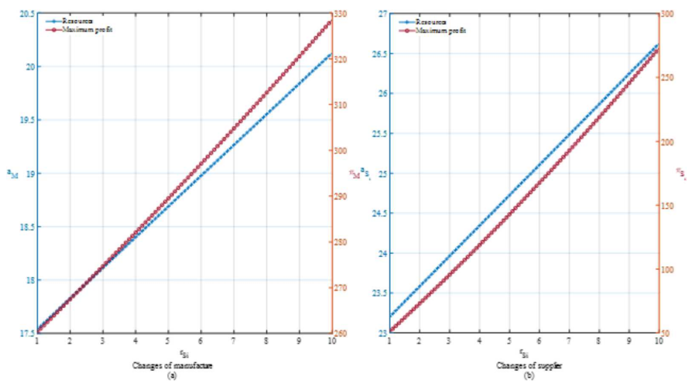

FIGURE 8. Impact curve of r_{S_i} toa_M,a_{S_i}, π_M and π_{S_i}.

cost-sharing are still smaller than those without cost-sharing. Moreover, as the coefficient increases, the maximum profit without cost-sharing gradually catches up and surpasses the maximum profit under cost-sharing. The possible reason is that the cost-sharing ratio and the core suppliers investment resources increase with the coefficient. The main manufacturer will share higher costs and obtain smaller profits with the coefficient increasing. Therefore, the main manufacturer should choose whether to adopt the incentive strategy based on the impact of innovation on their profits. When the profit without cost-sharing is greater than that under cost-sharing, the main manufacturer is supposed to choose another appropriate collaborative innovation strategy based on the balance of interests.

(3) The impact of r_{S_i} on optimal results

In order to observe the impact of the profit coefficient of core supplier on the optimal strategy combination, we varied r_{S_i} within the range of [1,10], and the results are shown in Figures 7 to 10.

The optimal cost-sharing ratio in Figure 7 decreases as the profit coefficient of core supplier increases. This situation arises because when the coefficient is high, the core supplier may spontaneously invest resources in innovation. Therefore, the main manufacturer can provide a low cost-sharing ratio to incentivize core suppliers to invest.

In Figure 8, the resources invested by the main manufacturer and the maximum profit increase with the profit coefficient of the core supplier. This is mainly because when the coefficient is high, the core supplier will invest

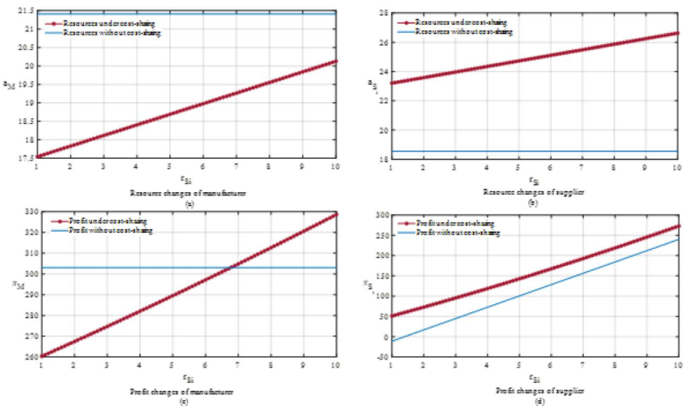

FIGURE 9. Comparison of results with and without cost-sharing under different values of rsi.

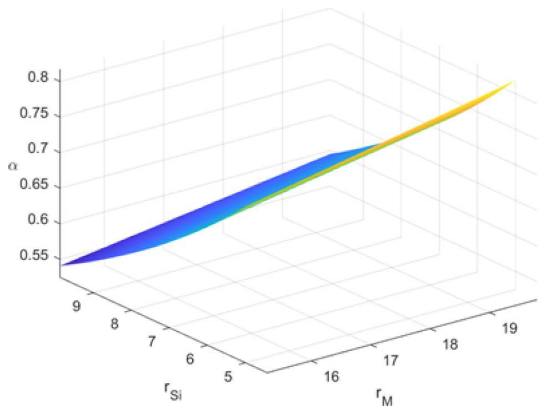

FIGURE 10. The change of when r_M and r_{S_i}change simultaneously.

more resources, thereby providing more profits for the main manufacturers. Under the positive response of the core supplier, the main manufacturer will invest more resources in collaborative innovation for their interests. The invested resources by core supplier and their profits increase with the coefficient, which is in line with the production and operation mode of core suppliers.

In Figure 9, without cost-sharing, the optimal investment resources and profits of the main manufacturer are not affected by the core supplier's profit coefficient. However, under cost-sharing, the combination of main manufacturing increases with the coefficient. It indicates that under the strategy, the main manufacturer can also improve their maximum profit with the increase of core supplier's profit coefficient. The main manufacturer can choose an appropriate collaborative innovation strategy by comparing the difference between the additional benefits and saving resources. The combination of results under cost-sharing of core suppliers is still higher than that without cost-sharing. Without cost-sharing, the optimal investment resources of core suppliers are not affected by the profit coefficient. This indicates that the cost-sharing incentive strategy will increase core suppliers investment resources. The difference in maximum profit of core supplier between the two scenarios decreases with the coefficient. The possible reason is that when the impact coefficient is high, the core supplier invests more resources under cost-sharing, but the marginal benefit decreases. As a result, the total profit continuously approaches the total profit without cost-sharing.

(4) The impact of r_M and r_{S_i} change simultaneously on optimal results.

Figure 10 reflects the relationship between α and r_M, r_{S_i}. To meet the conditions for implementing the cost-sharing incentive strategy, we set $r_M \in [15, 20]$, $r_{S_i} \in [4, 10]$ on the image, and observe the change in the optimal cost-sharing ratio.

From the above picture, we can see that when the profit coefficient of core supplier decreases and the main manufacturers increases, the optimal cost-sharing ratio will rise. This is because, in this situation, the core supplier's technological innovation has little benefit. The core supplier will be willing to invest more resources when the main manufacturer provides a high cost-sharing ratio. Similarly, if the profit coefficient of core supplier is relatively high and the profit coefficient of main manufacturer is low, the optimal cost-sharing ratio is also low. At this point, the core supplier will actively invest more resources in technological innovation for their interests.

5.3. Suggestions for main manufacturer

Based on the above simulation analysis, we can conclude that when the main manufacturer adopts the cost-sharing incentive strategy for core suppliers, the following points need to be noted:

(1) When the probability of successful technological innovation varies within the range of [0,1], the main manufacturer can adopt the cost-sharing incentive strategy. Although the cost-sharing strategy does not bring significant incentive effects under low probability, it can help the main manufacturer and supplier establish a good cooperative relationship. The higher the probability of successful technological innovation, the more significant the incentive effect of cost-sharing strategy, which is more conducive to improving profits and establishing and maintaining a close cooperative relationship between the two.
(2) The main manufacturer should choose the cost-sharing incentive strategy when the impact of innovative products on their own profits is not high. At this point, the incentive effect is obvious, and the profit increase of the main manufacturer is significant. When innovative products have a high impact on its profits, although the cost-sharing strategy have obvious incentive effects, the main manufacturer needs to bear a high proportion of cost-sharing, and the final profit is lower than the profit level without cost-sharing.
(3) The main manufacturer should adopt the cost-sharing strategy when innovative products have a high impact on the profits of core suppliers. Under low impact, although the cost-sharing strategy has a significant incentive effect, the final profit of the main manufacturer is lower than that without cost-sharing. Therefore, in this situation, the main manufacturer abandoning the cost-sharing strategy can avoid more marginal profits being consumed internally.

6. Conclusions

Collaborative innovation under the "main manufacturer-supplier" model involves games among various stakeholders, ultimately achieving a stable and balanced state. Referring to the cost-sharing strategy, we construct a master-follower Stackelberg game incentive model with the main manufacturer as the dominant position and the core supplier as the follower. Considering technological innovation risks, we divide technological innovation into two cases: success and failure. The probability of technological innovation allows the main manufacturer to provide different cost-sharing ratios to incentivize the core supplier. The conclusions are drawn as follows:

(1) The expected coefficient of cost-sharing ratio should be greater than the minimum threshold based on the profit coefficient equation. Moreover, when the ratio of profit coefficient between the main manufacturer and core supplier is greater than 0.75, the main manufacturer can adopt the optimal cost-sharing ratio to incentivize the supplier. The optimal cost-sharing ratio shows an inverted U-shape relationship, optimal investment resources and profits of both show an upward trend as the probability of successful technological innovation increases. Under the cost-sharing incentive strategy, the optimal investment resources of the main manufacturer are always smaller than that without cost-sharing, and the optimal profits gradually increase and surpass that without cost-sharing with probability increases. Moreover, the optimal profit gap

between cost-sharing and costless-sharing is expanding with the probability, and the incentive effect is more significant as well.

(2) The optimal cost-sharing ratio increases with the main manufacturer's profit coefficient, and the upward trend gradually flattens out. The increase in the coefficient has a positive impact on the optimal investment resources and profits. Under the cost-sharing incentive strategy, the optimal investment resources of main manufacturer are always smaller than those without cost-sharing. However, only when the profit coefficient of main manufacturer is within a certain range, the optimal profit under cost-sharing is greater than that without cost-sharing.

(3) The profit coefficient of core supplier varies in the opposite direction to the optimal cost-sharing ratio. Under costless-sharing, the optimal resource investment and profit of the main manufacturer keep stable with coefficient. However, the cost-sharing strategy ensures that the profit of main manufacturer increases with the coefficient. The cost-sharing strategy also plays a motivating role on the core supplier. The optimal investment resources and profit of core supplier are greater than those without cost-sharing. As the coefficient increases, the optimal profit gap of core supplier between cost-sharing and costless-sharing continues to decrease. The main manufacturer and core supplier need to choose whether to share costs based on the profit coefficient of core supplier.

This paper studies the cost-sharing incentive strategy of the main manufacturer for core suppliers. As we only focus on financial incentives, what other kinds of incentives can we use for better incentive effects? What is the incentive effect of combining financial incentives with other kinds of incentives? These are the research directions that we need to continue to delve into.

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