

# Research on Core technology R&D Investment and Outcome Transformation Strategy of Single Manufacturer Based on Multi-factor Influences

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**Abstract:** This study examines the impact of uncertainty in core technology R&D innovation on a second-tier supply chain comprising two rival final product manufacturers and a key component supplier. It investigates a single manufacturer's decision-making regarding R&D investment and outcome transformation. Four scenarios are identified based on different investment and transformation strategies: no investment, individual investment with self-use of outcomes, individual investment with outcome transfer, and cooperative investment with outcome sharing. The study analyzes how these strategies affect the supply chain and considers the influence of R&D success rate and competition intensity. Findings suggest that a manufacturer's strategic choices are influenced by competition intensity, R&D success rate, and investment costs. Specifically, high R&D investment costs become crucial under significant R&D uncertainty, while under low uncertainty, optimistic R&D success expectations reduce the importance of investment costs. Manufacturers can increase overall supply chain profit when investment costs are low and success rates are high. Moreover, as competition intensifies, self-use of R&D outcomes by the manufacturer becomes more advantageous for the supply chain. This research contributes theoretical insights into single manufacturer R&D investment decisions and offers valuable insights for further exploration in core technology R&D investment and outcome transformation strategies.

**Keywords:** R&D Investment, Outcome Transformation, Supply Chain Management, Game Theory.

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## 1. Introduction

In today's volatile and uncertain environment, every supply chain enterprise is susceptible to disruptive events [1]. A common approach to mitigating risks is through enterprise investment in the research and development (R&D) of core technology. Enterprises typically control the R&D process by allocating resources accordingly. Long-term investment in core technology development enables enterprises to mitigate the impact of external risks [2]. Furthermore, the performance of R&D affects the overall performance of the company [3]. The influence of enterprise R&D in core technology on supply chain risks is increasingly apparent. Firms are continuously seeking ways of consolidating competitive advantages in times of drastic business environment changes, with investment in technology innovation being essential in acquiring a unique advantage. However, despite the critical importance of core technology, many enterprises struggle to make the right decisions regarding investments in core technology R&D.

When manufacturers contemplate investing in core technology R&D, they encounter four key practical dilemmas. Firstly, they must decide whether to undertake such investments. Investing in core technology entails long-term risks due to R&D uncertainty, potentially leading to substantial investment loss and market exit if unsuccessful. Yet, success can yield significant benefits like cost reduction and increased market demand, enhancing competitiveness by enabling independent key component production.

Secondly, determining the investment level poses a challenge. Higher investments may boost R&D success rates but also escalate costs. Excessive investment, however, risks enterprise performance if R&D fails, necessitating prudent

investment management.

Thirdly, manufacturers grapple with the decision to share R&D costs through collaborative investments. Risk-averse approaches may lead to non-investment or risk transfer to competitors via technical cooperation. Collaborative investments mitigate R&D uncertainty effects and counter monopolistic suppliers, yet require competitor consensus and may not always yield mutually beneficial outcomes.

Fourthly, upon technological innovation success, manufacturers must strategize R&D result utilization. They typically opt for independent self-use, transferring results through supply contracts, or cooperative sharing. Self-use maintains core competitiveness, while result transfer diversifies revenue streams. Cooperative sharing, involving mutual investment and result sharing among competitors, aims to circumvent supply restrictions from monopolistic suppliers.

These strategies epitomize common practices in R&D result transformation, with the paper scrutinizing their benefits, hurdles, and implications for manufacturers aiming to optimize technological innovation utilization. Generally, analyzing any enterprise activity from a supply chain viewpoint is feasible, albeit with varying degrees and forms. In industrial production, where manufacturers oversee final product production, breakthroughs in core technology profoundly impact manufacturing, heightening the urgency for such advancements. Employing a game theory framework, this paper delves into manufacturers' behaviors within the supply chain regarding R&D intentions. It meticulously assesses how competition and R&D uncertainty influence outcomes in a scenario of symmetric information. Additionally, the study investigates manufacturers' strategies for R&D investment and outcome transformation, addressing four pivotal decision-making issues. By doing so, the paper

aims to furnish manufacturers with invaluable insights and guidance for navigating the intricacies of R&D within the supply chain.

## 2. Literature Review

From a research perspective, this paper primarily delves into the realm of technological innovation, specifically emphasizing investments in core technology R&D and its subsequent outcome transformation. Core technology is a systemic concept encompassing fundamental processes, essential components, significant machinery and equipment, as well as the technologies related to system architecture [4]. The significance of core technology for enterprises is clearly evident, particularly in critical sectors where core technology often entails significant R&D challenges but offer substantial returns upon successful development [5]. Typically, enterprises aim to maintain control over their operations by indirectly influencing the R&D innovation process and expectations regarding core technology through the allocation of resources, often in accordance with the amount invested. In terms of investment in technology R&D, the main focus lies on identifying the specific factors influencing such investments and devising concrete strategies for technology R&D investment.

Regarding the influencing factors, most closely related to our work is the literature addressing investment in core technology R&D in the fields of economics, supply chain and operations management. Essentially, the extant research can be categorized into four groups, depending on whether competition, R&D investment cost, and R&D uncertainty are taken into account. Competition, a frequently discussed topic in operations management, has dual effects. On one hand, it has the potential to bring about positive impacts. For instance, introducing upstream competition and specifying suitable contracts can enhance the overall profitability of the entire functional supply chain [6]. However, in some cases, competition from different directions can yield different effects. For instance, the presence of vertical competition may hinder a company's ability to improve product sustainability levels, but under certain conditions, it can enhance the performance of the supply chain system [7]. On the other hand, competition often leads to a winner-takes-all scenario. While competition among products can drive up their quality standards, the varying quality levels set by different manufacturers typically result in a winner-takes-all situation, which may be detrimental to the entire supply chain [8]. Downstream competition may diminish upstream technology R&D. Additionally, when consumer preferences fall below a certain threshold, the market size for new technology products will shrink due to competition. Moreover, downstream competition may impair the profitability of suppliers [9]. During the R&D process, competitive factors are indeed paramount. However, research costs also occupy a pivotal position in numerous studies. It is widely acknowledged that technological innovation has the potential to significantly reduce production costs for businesses, and the application of many emerging technologies in reality has proven this point [10]. Vernon et al have explored the impact of R&D costs on future research investment decisions of enterprises [11]. They propose that R&D often manifest in financial indicators and suggest that these financial signals exert significant influence on enterprise research investment decisions. Furthermore, as long as the R&D costs are sufficiently low, manufacturers will definitely invest in

technology. However, when R&D costs are high, whether manufacturers will invest in technology depends on the influence of other factors [12]. Due to the possibility of R&D failure in reality, there is also some discussion in existing research about R&D uncertainty. There is considerable discussion on how businesses can mitigate the impact of R&D uncertainty. For example, by comparing two representative cost-based transfer pricing methods: full cost pricing and variable cost pricing, different cost pricing approaches can be found to effectively address R&D uncertainty in different situations [13]. Wang and Zhang approach the issue from the government's perspective, researching how governments should subsidize companies actively engaged in technological R&D in the event of potential R&D failures, thereby reducing the impact of R&D uncertainty [14]. Some scholars also start from the mechanism of uncertainty to explore how uncertainty affects companies' R&D investments [15]. Niu and Shen go further by not only considering the uncertainty of R&D but also taking into account the absorptive capacity of enterprises and considering knowledge spillover effects [16]. They explore how these factors affect manufacturers' R&D decisions.

In the realm of technology innovation strategy research, a preponderance of studies is focused on technology investment decisions and the strategies for transforming R&D outcomes into practical applications. Within the subset of research pertaining to technology investment strategy, the primary emphasis lies in exploring investment methodologies and quantifying the optimal level of investment. Chen et al compared the cooperative and non-cooperative patterns of green R&D among enterprises [17]. Furthermore, other scholars have further elaborated and refined the cooperative patterns of enterprise technological R&D. This work has provided valuable insights into how various enterprises cooperate and collaborate in the pursuit of technological advancements. Hu et al consider a supply chain involving a manufacturer and a retailer, and they identify four investment modes for the manufacturer: manufacturer sole investment, retailer sole investment, or collaboration or independent investment by both companies [18]. The aim of these investment modes is to decrease the manufacturer's production costs. Furthermore, they find that different investment modes exhibit varying performances under different circumstances. Among these three investment modes, there is a greater focus on collaborative investment in research. Wu and Zhang have studied the collaborative R&D between suppliers and manufacturers, and have similarly categorized the collaborative investment modes into three types: non-collaboration between suppliers and manufacturers, sole collaboration of suppliers with manufacturers, and collaboration between both suppliers and manufacturers [19]. Furthermore, they have found that the investment level of suppliers increases with the increase in the rate of technological spillover, while the investment level of manufacturers relative to the rate of technological spillover depends on their R&D efficiency and competitive level. By using the concept of contribution levels to measure the technical contributions of enterprises to supply chain R&D cooperation, investigations into the R&D cooperation behavior of enterprises within the supply chain indicate that only when the contribution levels of two enterprises match Pareto, meaning when each enterprise's contribution level is equal, can they achieve a win-win situation with their partners through cartelization at the level comparable to their partners

[20]. According to the direction of R&D cooperation within the supply chain, R&D cooperation can also be categorized into vertical cooperation and horizontal cooperation. Xu et al point out that R&D cooperation often ends in failure due to its inherent instability. They also suggest that vertical R&D cooperation is inherently unstable, with downstream enterprises more prone to default [21]. The level of knowledge spillover and R&D costs have different impacts on firm profits. When the level of knowledge spillover is low or the R&D costs are high, mechanisms like opportunistic punishment may be more effective in ensuring the stability of cooperation.

In terms of R&D outcome transformation, the focus is typically on how enterprises utilize R&D achievements. Specifically, common discussions revolve around outcome transformation methods aimed at the technology itself and the production of products utilizing the technology. Manufacturers typically engage in technology sharing of the technology itself through technology licensing or technology transfer, and technological efficiency can influence the choice of technology licensing [22]. Yang et al study whether and how patent-holding companies (Supplier S1) license their technological patents to potential competitors (Supplier S2), and point out how supply risk influences S1's willingness to license technology [23]. Currently, there is more discussion about licensing technology to competitors, but there is relatively less discussion about the utilization of technology for producing products. Li and Jiang have studied the situation where two competing manufacturers engage in the supply of critical components, with one manufacturer possessing unique technology to produce the critical component while the other manufacturer cannot produce it [24]. They point out that this horizontal subcontracting approach benefits both companies, enabling them to achieve a win-win situation. Hu et al have also studied the horizontal outsourcing of critical components between two competing companies engaged in Bertrand competition, emphasizing the importance of single-purchase commitments [25]. They point out that horizontal outsourcing occurs when the entrant commits to exclusive procurement, and the incumbent company has a component cost advantage or even a minor cost disadvantage compared to alternative suppliers. Specifically, if the component cost difference is small, horizontal outsourcing may soften downstream market competition and benefit both companies, albeit at the expense of raising consumer prices.

Existing research predominantly explores factors influencing technology R&D investment and outcome transfer in technological innovation, detailing specific strategies for R&D investment and outcome transfer. Notably, competition, R&D costs, and uncertainty feature prominently among influencing factors. Investment strategies primarily encompass cooperative and non-cooperative approaches, with further refinement of cooperative strategies. Outcome transfer strategies typically involve technology sharing and product transfer. However, existing research has limitations. Firstly, there's a dearth of studies on unilateral manufacturer core technology R&D investment and outcome transfer under monopolistic supply, with limited attention to outcome transfer. Secondly, most studies overlook intrinsic relationships among influencing factors. Lastly, the impact of enterprise manufacturing technology R&D investment behavior on the overall supply chain is seldom explored.

To bridge these gaps, this paper adopts a manufacturer-

centric perspective within the supply chain, employing game theory methods. It considers competition, technological R&D costs, and uncertainty as influencing factors, examining R&D investment and outcome transfer strategies among manufacturers, assuming symmetric information on research outcomes. Strategies are systematically categorized into: no investment, sole investment for self-use, sole investment for transfer, and cooperative investment for sharing outcomes. By comparing optimal solutions in each scenario, the paper seeks to address the following questions: (a) Should manufacturers invest in the R&D of core technology? And how should manufacturers choose core technology R&D investment and outcome transformation strategies?

(b) How does the R&D investment cost of core technology affect manufacturers' decisions regarding R&D investment and outcome transformation?

(c) What impact does the R&D investment behavior of manufacturers have on the overall supply chain?

(d) How do competition and research and development uncertainty influence overall supply chain profitability through the R&D investment behavior of manufacturers?

So, to answer these questions, this paper constructs a game theory model in the third section, analyzes the model in the fourth section, summarizes the conclusions in the fifth section, and provides references and proof processes in the end.

### 3. The Model

To explore the efficacy of these factors, we consider a two-echelon supply chain composed of two competing manufacturers and a monopolistic supplier. The supplier uses its unique technical advantages to produce key components, while the two manufacturers do not have the ability to produce key components. In order to break the monopoly on key components, some manufacturers try to invest in research and development (R&D) of the core technology required to produce key components. These manufacturers usually have the willingness to research and develop core technology, but whether they actually invest in the R&D of core technology depends on the actual situation. And other manufacturers may not invest in the R&D of core technology due to lack of strength, corporate strategy, etc. To better describe the above situation, we assume that manufacturer 1 has a willingness to invest in R&D, while manufacturer 2 will not invest in core technology R&D (exchanging assumptions will not change the results). The supplier has attained a breakthrough in core technology, facilitating the production of key components, which are subsequently distributed to both manufacturers. Both manufacturers employ these key components in the manufacturing processes of two distinct final products, thereby engaging in market competition, and the production of each final product requires a key component. And the notations used in this paper are described in Table 1.

**Table 1.** List of Notations

	Notations	Description
Decision variables	$Q_i^t$	Manufacturer $i$ 's order quantity under scenario $t$
	$W_S^U$	Unit wholesale price for supplier under scenario $U$ .
	$W_1^{YSB}$	Unit transfer price from Manufacturer 1 under scenario $YSB$ .
Demand parameters	$A$	Potential market size
	$P_i^t$	The selling price of final product $i$ in scenario $t$ .
	$\theta$	Competition intensity between manufacturers. $\theta \in (0,1)$
	$C$	The baseline production cost of key components. ( $A > C$ )
Cost parameters	$F$	Manufacturer 1's R&D investment cost
	$\lambda$	The likelihood of successful R&D. $\lambda \in (0,1)$
	$\Pi_{Mi}^t$	Manufacturer $M_i$ 's profit under model $t$
Profit functions	$\Pi_S^t$	supplier $S$ 's profit under model $t$
	$\Pi_T^t$	The total profit of SC under model $t$
	$t$	to represent the parameters and variables under model $t$ $t \in N, YF1, YF2, YSA, YSB, YSC$
Superscript	$U$	to represent the parameters and variables under model $t$ $U \in N, YF1, YF2, YSA$
	*	Given the uncertainty of R&D, the equilibrium parameters
	**	Given the success of R&D, the equilibrium parameters
Note: $i \in \{1, 2\}$		

For the purpose of facilitating analysis, this paper makes the following assumptions without loss of generality:

**Assumption 1:** The wholesale pricing of key components is determined through an open market approach with uniform pricing, meaning that the wholesale price for a unit of key component is the same for both manufacturers without any differentiation in pricing. Let  $W$  represent the wholesale price for each unit of key component, and  $C$  represent the supplier's production cost for unit of key components. Additionally, since we primarily focus on the impact of R&D costs for core technology on investment decisions, other costs such as product assembly are standardized to zero.

**Assumption 2:** When Manufacturer 1 decides to invest in core technology R&D, they incur a core technology investment cost represented by  $F$ . The outcomes of the technology R&D are uncertain, meaning there are two possible scenarios: success and failure. The probabilities of success and failure are represented by  $\lambda$  and  $1 - \lambda$ , respectively, where  $\lambda$  belongs to the interval  $[0, 1]$ .

**Assumption 3:** The successful development of core technology will impact the cost of key components, but will not affect the demand for the final product. Since this paper focuses on the impact of investment in R&D costs, it is necessary to exclude the effects of technological advancements on consumers. Previous studies have assumed that when R&D are successful, production costs are directly reduced to zero, neglecting the discussion of whether the success of core technology R&D affects Manufacturer 1's ability to produce key components. Therefore, this paper assumes that when R&D are successful, Manufacturer 1

possesses the core technology and can utilize it to produce key components, with the production cost per unit of key component being the same as that of the supplier, represented by  $C$ . In the event of research failure, Manufacturer 1 does not acquire the capability to produce key components and will bear the investment cost. And in this scenario, Manufacturer 1, in order to remain in the market, continues to purchase key components from the supplier for the production of final products.

**Assumption 4:** Manufacturer 1 has various strategies for investing in and utilizing core technology research. This paper primarily considers the following four scenarios:

In scenario 1, manufacturer 1 does not invest. Manufacturer 1 voluntarily abstains from technological innovation and maintains the existing market structure.

In scenario 2, manufacturer 1 invests independently for self-use. Manufacturer 1 invests independently, and upon successful technology R&D, utilizes the core technology to produce key components for its own finished product manufacturing, thus discontinuing purchases of key components from the supplier.

In scenario 3, manufacturer 1 invests independently and transfers key components. Manufacturer 1 invests independently, and upon successful technology R&D, not only meets its own production needs but also supplies key components to competitor Manufacturer 2, thereby leading to the exit of the supplier from the market.

In scenario 4, manufacturer 1 and Manufacturer 2 collaborate on investment with shared results: Manufacturer 1 and Manufacturer 2 collaborate on investment, and upon successful technology R&D, both parties can utilize the technology to produce key components at a unit cost of  $C$  and engage in final product manufacturing, resulting in the exit of the supplier from the market.

According to existing research [26] the consumer utility function can be represented as:

$$U = \alpha_1 Q_1 + \alpha_2 Q_2 - \frac{1}{2}(Q_1^2 + Q_2^2) - \theta Q_1 Q_2 - P_1 Q_1 - P_2 Q_2 \quad (1)$$

In this context,  $\alpha_1$  and  $\alpha_2$  represent the potential market demand for final product 1 and final product 2, respectively. To simplify the study, let  $\alpha_1 = \alpha_2 = A$ . Based on the first-order optimality conditions  $\frac{\partial U}{\partial Q_1} = 0$  and  $\frac{\partial U}{\partial Q_2} = 0$ , we can derive the demand functions for final product 1 and final product 2 as follows:

$$\begin{cases} Q_1 = \frac{(1-\theta)A - P_1 + \theta P_2}{1-\theta^2} \\ Q_2 = \frac{(1-\theta)A - P_2 + \theta P_1}{1-\theta^2} \end{cases} \quad (2)$$

As the production is determined independently by each manufacturer, it is necessary to derive their inverse demand functions:

$$\begin{cases} P_1 = A - Q_1 - \theta Q_2 \\ P_2 = A - Q_2 - \theta Q_1 \end{cases} \quad (3)$$

In different models, the game among supply chain members can be divided into three stages: the stage of technological R&D investment, the stage of wholesale price decision-making, and the stage of final product production decision-making. The specific game sequence can be found in the solution section of each model. Below are the model structures, profit functions of each entity in the supply chain, and corresponding equilibrium results for the scenarios.

### 3.1. Manufacturer 1 Does Not Invest in Core technology R&D (Model N)

Using the superscript N to denote this scenario, manufacturer 1 voluntarily abstains from investing in the

R&D of core technology. Similar to Manufacturer 2, Manufacturer 1 obtains the necessary key components for product manufacturing through the supplier in the open market. The model structure is illustrated as follows:

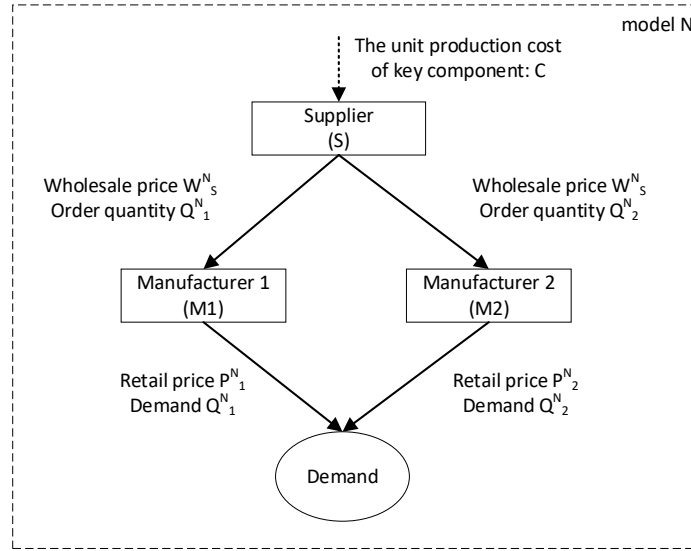


Figure 1. The supply chain structure of Model N

The profit functions of the two manufacturers and the supplier are as follows:

$$\pi_1^N = P_1^N Q_1^N - W_s^N Q_1^N \quad (4)$$

$$\pi_2^N = P_2^N Q_2^N - W_s^N Q_2^N \quad (5)$$

$$\pi_s^N = (W_s^N - C)(Q_1^N + Q_2^N) \quad (6)$$

In Model N, the decision sequence of each entity in the supply chain is as follows:

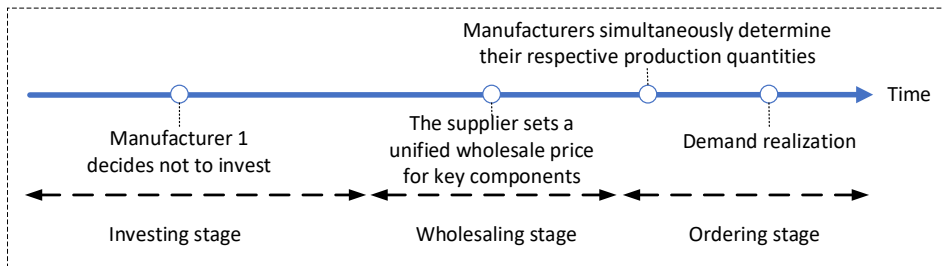


Figure 2. The decision sequence of Model N

By utilizing backward induction to solve Model N, the following propositions can be derived.

Proposition 1: When Manufacturer 1 does not invest in the R&D of core technology, the equilibriums are as follows:

$$Q_1^{N*} = \frac{A-C}{2\theta+4} \quad (7)$$

$$Q_2^{N*} = \frac{A-C}{2\theta+4} \quad (8)$$

$$P_1^{N*} = \frac{(A+C)\theta+3A+C}{2\theta+4} \quad (9)$$

$$P_2^{N*} = \frac{(A+C)\theta+3A+C}{2\theta+4} \quad (10)$$

$$W_s^{N*} = \frac{A+C}{2} \quad (11)$$

$$\pi_1^{N*} = \frac{(A-C)^2}{4(\theta+2)^2} \quad (12)$$

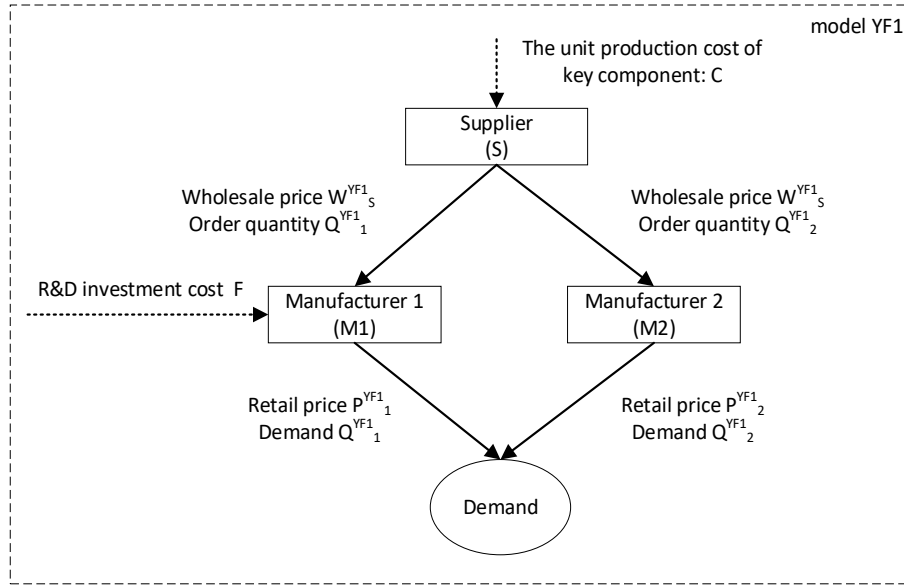
$$\pi_2^{N*} = \frac{(A-C)^2}{4(\theta+2)^2} \quad (13)$$

$$\pi_s^{N*} = \frac{(A-C)^2}{2\theta+4} \quad (14)$$

When a manufacturer chooses not to invest, it is not affected by the uncertainty of R&D. Conversely, when Manufacturer 1 chooses an investment decision, the equilibrium outcomes are affected by the uncertainty of R&D. When Manufacturer 1's R&D fails, this paper elaborates on the following two scenarios based on the different entities bearing the investment costs.

### 3.2. Manufacturer 1 Invests Solely in Core technology R&D, Research Failure and Self-Bearing Costs (Model YF1)

Using the superscript YF1 to denote the scenario where Manufacturer 1 invests solely in core technology R&D, but the research fails. On one hand, due to Manufacturer 1's sole investment and the failure of the R&D, the investment costs need to be borne independently. On the other hand, to remain in the market, Manufacturer 1 still needs to procure key components from the supplier for final product manufacturing. In this scenario, the supply chain structure is as follows:



**Figure 3.** The supply chain structure of Model YF1

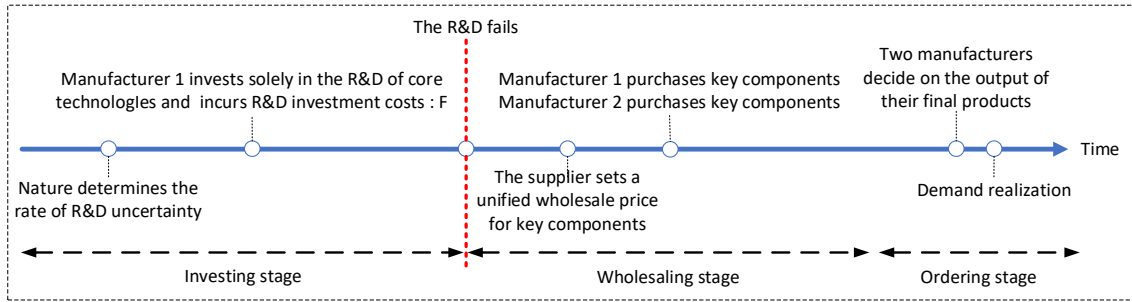
The profit functions of the two manufacturers and the supplier are as follows:

$$\pi_1^{YF1} = P_1^{YF1} Q_1^{YF1} - W_S^{YF1} Q_1^{YF1} - F \quad (15)$$

$$\pi_2^{YF1} = P_2^{YF1} Q_2^{YF1} - W_S^{YF1} Q_2^{YF1} \quad (16)$$

$$\pi_S^{YF1} = (W_S^{YF1} - C)(Q_1^{YF1} + Q_2^{YF1}) \quad (17)$$

In Model YF1, the decision sequence of each entity in the supply chain is as follows:



**Figure 4.** The decision sequence of Model YF1

By utilizing backward induction to solve Model YF1, the following proposition can be derived:

Proposition 2: When Manufacturer 1 invests solely in the R&D of core technology, and in case of research failure with costs borne independently, the equilibriums are as follows:

$$Q_1^{YF1*} = \frac{A-C}{2\theta+4} \quad (18)$$

$$Q_2^{YF1*} = \frac{A-C}{2\theta+4} \quad (19)$$

$$P_1^{YF1*} = \frac{(A+C)\theta+3A+C}{2\theta+4} \quad (20)$$

$$P_2^{YF1*} = \frac{(A+C)\theta+3A+C}{2\theta+4} \quad (21)$$

$$W_S^{YF1*} = \frac{A+C}{2} \quad (22)$$

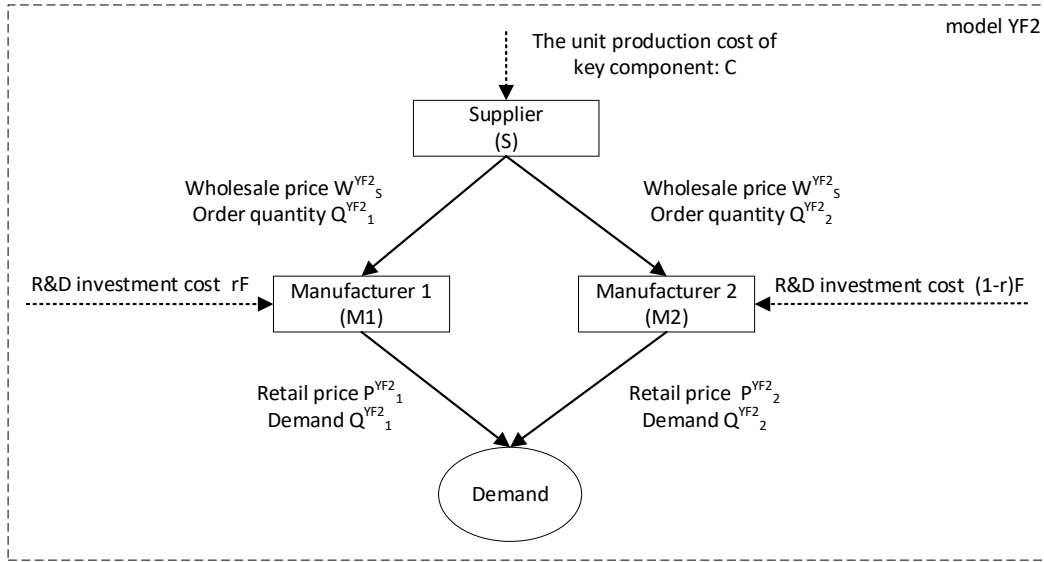
$$\pi_1^{YF1*} = \frac{(A-C)^2}{4(\theta+2)^2} - F \quad (23)$$

$$\pi_2^{YF1*} = \frac{(A-C)^2}{4(\theta+2)^2} \quad (24)$$

$$\pi_S^{YF1*} = \frac{(A-C)^2}{2\theta+4} \quad (25)$$

### 3.3. Collaborative Investment in Core technology R&D, Research Failure with Shared Costs (Model YF2)

Using the superscript YF2 to denote the scenario where Manufacturer 1 and Manufacturer 2 collaborate in investing in core technology R&D with shared costs, but the research fails. Since Manufacturer 1 and Manufacturer 2 reached an agreement on the collaborative investment in R&D of core technology prior to the R&D, Manufacturer 1 bears the proportion  $r$  of the investment costs, while Manufacturer 2 bears  $1-r$ . If the R&D is successful, both manufacturers can utilize the core technology for their own key component production. In case of research failure, each manufacturer also needs to bear the corresponding proportion of the R&D costs. The supply chain structure of Model YF2 is illustrated as follows:



**Figure 5.** The supply chain structure of Model YF1

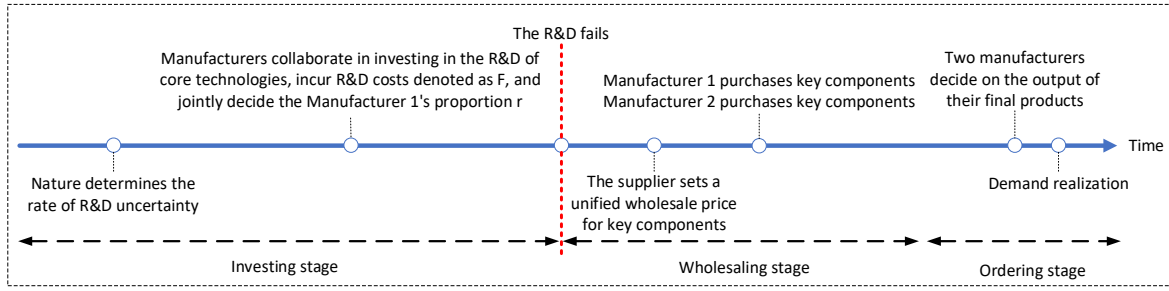
The profit functions of the two manufacturers and the supplier are as follows:

$$\pi_S^{YF2} = (W_S^{YF2} - C)(Q_1^{YF2} + Q_2^{YF2}) \quad (28)$$

$$\pi_1^{YF2} = P_1^{YF2} Q_1^{YF2} - W_S^{YF2} Q_1^{YF2} - rF \quad (26)$$

In Model YF2, the decision sequence of each entity in the supply chain is as follows:

$$\pi_2^{YF2} = P_2^{YF2} Q_2^{YF2} - W_S^{YF2} Q_2^{YF2} - (1-r)F \quad (27)$$



**Figure 6.** The decision sequence of Model YF2

By employing backward induction to solve Model YF2, the following proposition can be obtained:

**Proposition 3:** When Manufacturers collaborate in investing in the R&D of core technology, and in case of research failure with shared costs, the equilibriums are as follows:

$$Q_1^{YF2*} = \frac{A-C}{2\theta+4} \quad (29)$$

$$Q_2^{YF2*} = \frac{A-C}{2\theta+4} \quad (30)$$

$$P_1^{YF2*} = \frac{(A+C)\theta+3A+C}{2\theta+4} \quad (31)$$

$$P_2^{YF2*} = \frac{(A+C)\theta+3A+C}{2\theta+4} \quad (32)$$

$$W_S^{YF2*} = \frac{A+C}{2} \quad (33)$$

$$r^* = \frac{1}{2} \quad (34)$$

$$\pi_1^{YF2*} = \frac{(A-C)^2}{4(\theta+2)^2} - \frac{F}{2} \quad (35)$$

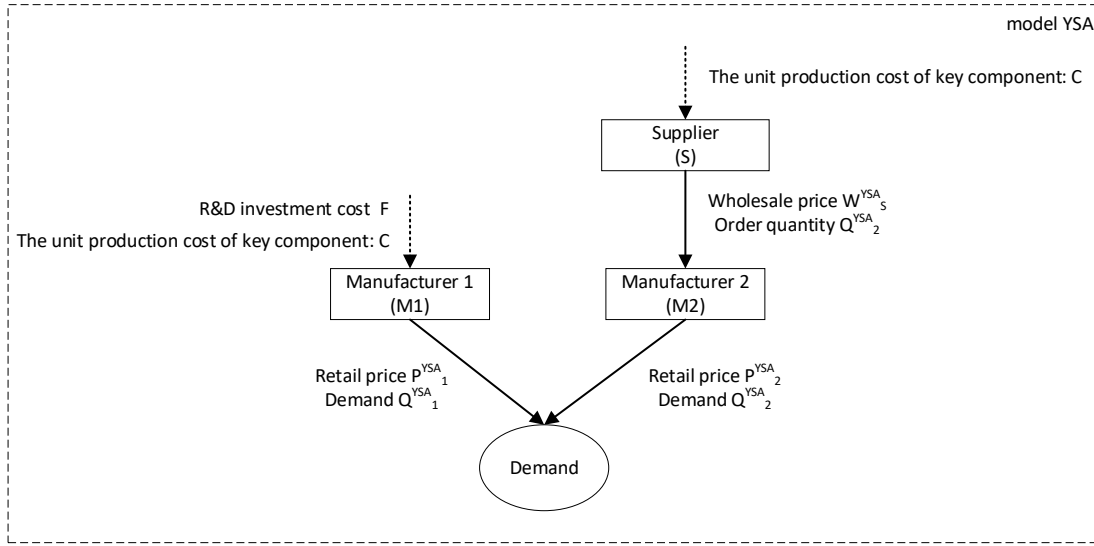
$$\pi_2^{YF2*} = \frac{(A-C)^2}{4(\theta+2)^2} - \frac{F}{2} \quad (36)$$

$$\pi_S^{YF2*} = \frac{(A-C)^2}{2\theta+4} \quad (37)$$

When Manufacturer 1 invests and the R&D is successful, this paper elaborates on the following three scenarios based on the different methods of outcome conversion.

### 3.4. Manufacturer 1 Solely Invests in Core technology R&D, Successful R&D with Self-Use of Results (Model YSA)

Using the superscript YSA to denote the scenario where Manufacturer 1 solely invests in the R&D of core technology, and upon successful R&D, utilizes the results for self-use. The supply chain structure of this model is illustrated as follows:



**Figure 7.** The supply chain structure of Model YSA

The profit functions of the two manufacturers and the supplier are as follows:

$$\pi_1^{YSA} = P_1^{YSA} Q_1^{YSA} - C Q_1^{YSA} - F \quad (38)$$

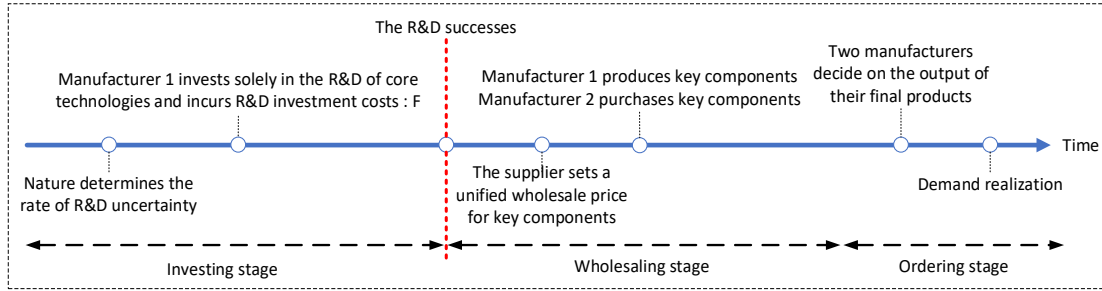
$$\pi_2^{YSA} = P_2^{YSA} Q_2^{YSA} - W_S^{YSA} Q_2^{YSA} \quad (39)$$

$$\pi_S^{YSA} = (W_S^{YSA} - C) Q_2^{YSA} \quad (40)$$

In the above scenario, due to the uncertainty surrounding the R&D results, Manufacturer 1 can calculate the expected profit before investing.

$$E(\pi_1^{YSA}) = \lambda \pi_1^{YSA} + (1 - \lambda) \pi_1^{YF1} \quad (41)$$

In Model YSA, the decision sequence of each entity in the supply chain is as follows:



**Figure 8.** The decision sequence of Model YSA

Employing backward induction to solve Model YSA yields the following proposition:

Proposition 4: When Manufacturer 1 solely invests in the R&D of core technology, and upon successful R&D, utilizes the results for self-use, the equilibriums are as follows:

$$Q_1^{YSA*} = \frac{(\theta+4)(A-C)}{4\theta+8} \quad (42)$$

$$Q_2^{YSA*} = \frac{A-C}{2\theta+4} \quad (43)$$

$$P_1^{YSA*} = \frac{(A+3C)\theta+4A+4C}{4\theta+8} \quad (44)$$

$$P_2^{YSA*} = \frac{(6-\theta)A+(\theta^2+4\theta+2)C}{4\theta+8} \quad (45)$$

$$W_S^{YFA*} = \left(\frac{1}{2} - \frac{\theta}{4}\right)A + \left(\frac{1}{2} + \frac{\theta}{4}\right)C \quad (46)$$

$$\pi_1^{YSA*} = \frac{(\theta+4)^2(A-C)^2}{16(\theta+2)^2} - F \quad (47)$$

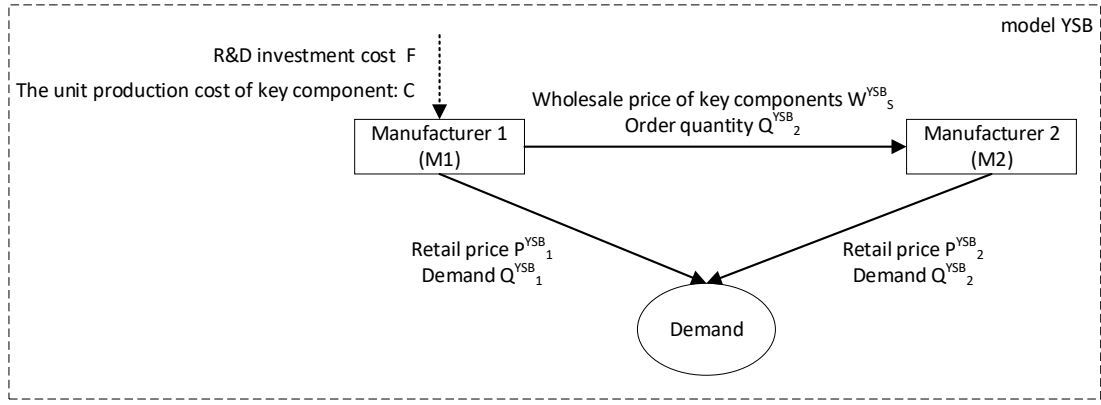
$$\pi_2^{YSA*} = \frac{(A-C)^2}{4(\theta+2)^2} \quad (48)$$

$$\pi_S^{YSA*} = \frac{(2-\theta)(A-C)^2}{8\theta+16} \quad (49)$$

$$E(\pi_1^{YSA}) = \frac{(4+(\theta^2+8\theta+12)\lambda)(A-C)^2}{16(\theta+2)^2} - F \quad (50)$$

### 3.5. Manufacturer 1 Solely Invests in Core technology R&D, Successful R&D with Outcome Transfer (Model YSB)

Using the superscript YSB to denote the scenario where Manufacturer 1 solely invests in the R&D of core technology, and upon successful R&D, transfers the outcomes. The supply chain structure of this model is illustrated as follows:



**Figure 9.** The supply chain structure of Model YSB

The profit functions of the two manufacturers and the supplier are as follows:

$$\pi_1^{YSB} = P_1^{YSB} Q_1^{YSB} + W_1^{YSB} Q_2^{YSB} - C(Q_1^{YSB} + Q_2^{YSB}) - F \quad (51)$$

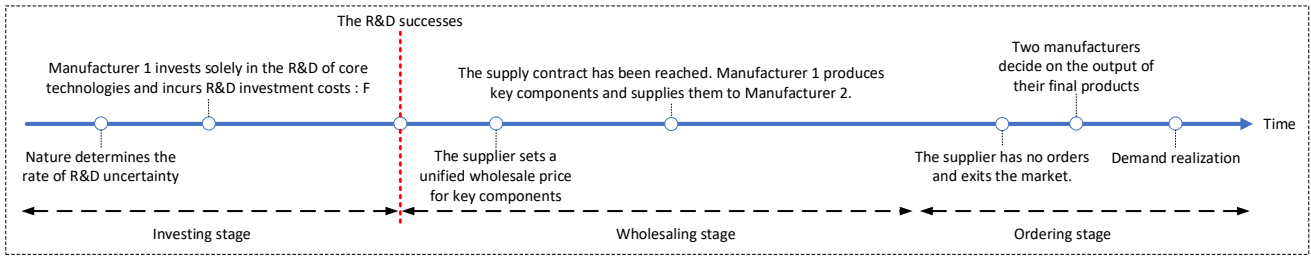
$$\pi_2^{YFB} = P_2^{YSB} Q_2^{YSB} - W_1^{YSB} Q_2^{YSB} \quad (52)$$

In the above scenario, due to the uncertainty surrounding

the R&D results, Manufacturer 1 can calculate the expected profit before investing.

$$E(\pi_1^{YSB}) = \lambda \pi_1^{YSB} + (1 - \lambda) \pi_1^{YF1} \quad (53)$$

In Model YSB, the decision sequence of each entity in the supply chain is as follows:



**Figure 10.** The decision sequence of Model YSB

By employing backward induction to solve Model YSB, the following proposition can be obtained:

**Proposition 5:** When Manufacturer 1 solely invests in the R&D of core technology, and upon successful R&D, transfers the outcomes, the equilibriums are as follows:

$$Q_1^{YSB*} = \frac{(\theta+4)(\theta-2)(A-C)}{6\theta^2-16} \quad (54)$$

$$Q_2^{YSB*} = \frac{2(\theta-1)(A-C)}{3\theta^2-8} \quad (55)$$

$$P_1^{YSB*} = \frac{(\theta^2+2\theta-8)A+(5\theta^2-2\theta-8)C}{6\theta^2-16} \quad (56)$$

$$P_2^{YSB*} = \frac{(-\theta^3+4\theta^2+4\theta-12)A+(\theta^3+2\theta^2-4\theta-4)C}{6\theta^2-16} \quad (57)$$

$$W_1^{YSB*} = \frac{(-\theta^3+4\theta^2-8)A+(\theta^3+2\theta^2-8)C}{6\theta^2-16} \quad (58)$$

$$\pi_1^{YSB*} = -\frac{(\theta-2)(\theta-6)(A-C)^2}{4(3\theta^2-8)} - F \quad (59)$$

$$\pi_2^{YSB*} = \frac{4(1-\theta)^2(A-C)^2}{(3\theta^2-8)^2} \quad (60)$$

$$\pi_s^{YSB*} = 0 \quad (61)$$

$$E(\pi_1^{YSB*}) = \frac{-((\theta^4-4\theta^3-13\theta^2+16\theta+40)\lambda-3\theta^2+8)(A-C)^2}{4(3\theta^2-8)(\theta+2)^2} - F \quad (62)$$

### 3.6. Manufacturers Collaborate in Investing in Core technology R&D, Successful R&D with Outcome Sharing (Model YSC)

Using the superscript YSC to denote the scenario where Manufacturer 1 and Manufacturer 2 collaborate in investing in core technology R&D, and upon successful R&D, share the outcomes. The supply chain structure of this model is illustrated in the following figure:

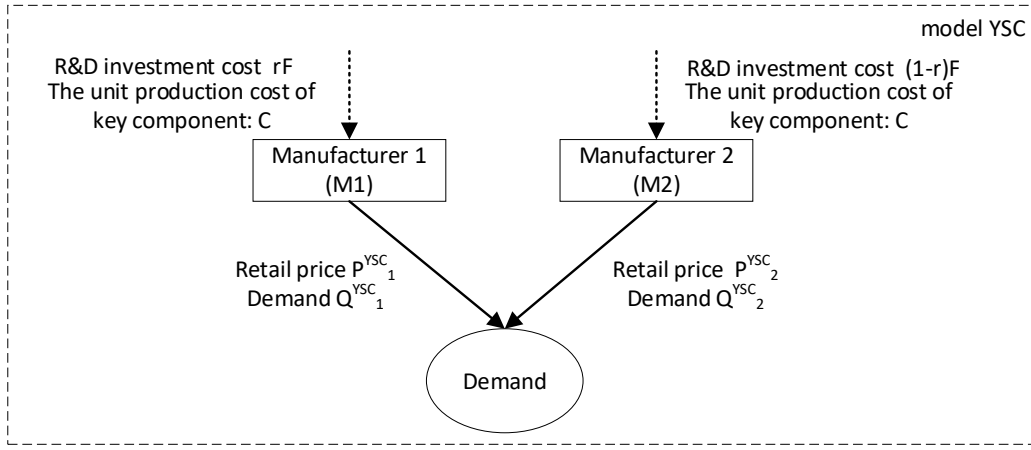


Figure 11. The supply chain structure of Model YSC

The profit functions of the two manufacturers and the supplier are as follows:

$$\pi_1^{YSC} = P_1^{YSC} Q_1^{YSC} - C Q_1^{YSC} - rF \quad (63)$$

$$\pi_2^{YSC} = P_2^{YSC} Q_2^{YSC} - C Q_2^{YSC} - (1-r)F \quad (64)$$

In the above scenario, due to the uncertainty surrounding the R&D results, Manufacturer 1 and Manufacturer 2 can

calculate the expected profit before investing.

$$E(\pi_1^{YSC}) = \lambda \pi_1^{YSC} + (1-\lambda) \pi_1^{YF2} \quad (65)$$

$$E(\pi_2^{YSC}) = \lambda \pi_2^{YSC} + (1-\lambda) \pi_2^{YF2} \quad (66)$$

In Model YSC, the decision sequence of each entity in the supply chain is as follows:

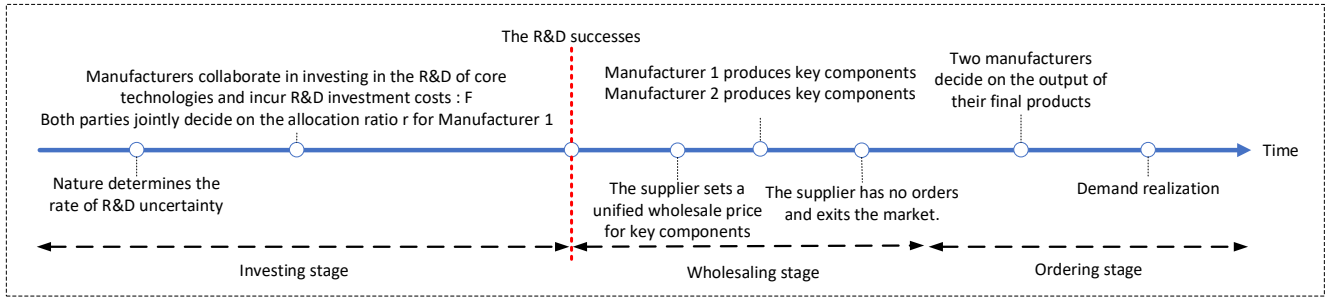


Figure 12. The decision sequence of Model YSC

By using backward induction to solve Model YSC, the following proposition can be obtained:

Proposition 6: When Manufacturer 1 and Manufacturer 2 collaborate in investing in the R&D of core technology, and upon successful R&D with outcome sharing, the equilibriums are as follows:

$$Q_1^{YSC*} = \frac{A-C}{\theta+2} \quad (67)$$

$$Q_2^{YSC*} = \frac{A-C}{\theta+2} \quad (68)$$

$$P_1^{YSC*} = \frac{A+(1+\theta)C}{\theta+2} \quad (69)$$

$$P_2^{YSC*} = \frac{A+(1+\theta)C}{\theta+2} \quad (70)$$

$$\pi_1^{YSC*} = \frac{(A-C)^2}{(\theta+2)^2} - \frac{F}{2} \quad (71)$$

$$\pi_2^{YSC*} = \frac{(A-C)^2}{(\theta+2)^2} - \frac{F}{2} \quad (72)$$

$$\pi_S^{YSC*} = 0 \quad (73)$$

$$E(\pi_1^{YSC*}) = \frac{(3\lambda+1)(A-C)^2}{4(\theta+2)^2} - \frac{F}{2} \quad (74)$$

$$E(\pi_2^{YSC*}) = \frac{(3\lambda+1)(A-C)^2}{4(\theta+2)^2} - \frac{F}{2} \quad (75)$$

#### 4. Equilibrium Analysis

In this part, we will analyze the equilibrium solutions obtained in the previous section. Firstly, we will determine the

optimal core technology R&D investment strategy for Manufacturer 1, as well as the outcome transformation method. Secondly, we will compare the impact of Manufacturer 1's optimal core technology R&D investment strategy and the optimal outcome transformation method on the overall profit of the supply chain. Finally, we will analyze the impact of the competition intensity between manufacturers and the success rate of R&D on the overall profit of the supply chain, and validate the conclusions through numerical simulations.

Theorem 1: The core technology R&D investment strategy of Manufacturer 1 is dependent on the investment cost, the success rate of R&D, and the substitutability of final products. Specifically:

(a). Manufacturers will invest in the R&D of core technology even in the presence of R&D uncertainty when  $0 < \lambda < \frac{1}{6}$  and  $0 < F < \frac{3(A-C)^2\lambda}{2(2+\theta)^2}$

(b). Manufacturers will not invest in the R&D of core technology even in the presence of R&D uncertainty when  $0 < \lambda < \frac{1}{6}$  and  $\frac{3(A-C)^2\lambda}{2(2+\theta)^2} < F$

(c). Manufacturers will invest in the R&D of core technology even in the presence of R&D uncertainty when  $\frac{1}{6} \leq \lambda < 1$  and  $0 < F < \frac{(A-C)^2}{4(2+\theta)^2}$

Theorem 1 reveals the factors influencing whether Manufacturer 1 invests in core technology, consistent with existing literature, indicating that the likelihood of R&D success affects Manufacturer 1's investment decision.

Additionally, the R&D investment cost is a crucial factor for Manufacturer 1. When the R&D success rate is relatively low, the investment cost is the primary concern for Manufacturer 1. However, when the R&D success rate is relatively high, Manufacturer 1 has higher expectations for successful technology development and is more willing to invest in core technology R&D, with the investment cost no longer hindering Manufacturer 1 from investing in technology R&D. Moreover, a higher level of competition between the two types of products leads to Manufacturer 1 being more sensitive to changes in R&D investment costs.

Theorem 2: When Manufacturer 1 invests in core technology R&D, the optimal investment strategy is also influenced by the R&D investment cost, R&D success rate, and product substitutability. Specifically:

(a). Manufacturer 1 will choose to invest independently when  $0 < \theta \leq 3\sqrt{2} - 4$  and  $0 < F < \frac{\theta(\theta+8)(A-C)^2\lambda}{8(2+\theta)^2}$ .

(b). Manufacturer 1 will choose to invest independently when  $3\sqrt{2} - 4 < \theta < 1$ ,  $0 < \lambda < \frac{2}{\theta(\theta+8)}$  and  $0 < F < \frac{\theta(\theta+8)(A-C)^2\lambda}{8(2+\theta)^2}$ .

(c). Manufacturer 1 will choose to invest independently when  $3\sqrt{2} - 4 < \theta < 1$ ,  $\frac{2}{\theta(\theta+8)} \leq \lambda < 1$  and  $0 < F < \frac{(A-C)^2}{4(2+\theta)^2}$ .

(d). Manufacturer 1 will choose to collaborate on investment when  $0 < \theta \leq 3\sqrt{2} - 4$ ,  $0 < \lambda < \frac{1}{6}$  and  $\frac{\theta(\theta+8)(A-C)^2\lambda}{8(2+\theta)^2} \leq F < \frac{3(A-C)^2\lambda}{2(2+\theta)^2}$ .

(e). Manufacturer 1 will choose to collaborate on investment when  $0 < \theta \leq 3\sqrt{2} - 4$ ,  $\frac{1}{6} \leq \lambda < 1$  and  $\frac{\theta(\theta+8)(A-C)^2\lambda}{8(2+\theta)^2} \leq F < \frac{(A-C)^2}{4(2+\theta)^2}$ .

(f). Manufacturer 1 will choose to collaborate on investment when  $3\sqrt{2} - 4 < \theta < 1$ ,  $\frac{1}{6} \leq \lambda < \frac{2}{\theta(\theta+8)}$  and  $\frac{\theta(\theta+8)(A-C)^2\lambda}{8(2+\theta)^2} < F < \frac{(A-C)^2}{4(2+\theta)^2}$ .

According to Theorem 2, when Manufacturer 1 opts for core technology R&D, the investment strategy choice is shaped by product substitutability, R&D success rate, and investment cost. Specifically, R&D cost size directly impacts Manufacturer 1's investment approach. Generally, low R&D costs favor independent investment, while high costs drive cooperation to share expenses. However, product substitutability and R&D success rate jointly affect Manufacturer 1's decision space, sometimes outweighing R&D costs. For instance, in scenario (c), intense product competition and high R&D success rate nullify R&D cost influence, leading to independent investment. Conversely, scenario (b) shows that with intense competition but low R&D success, R&D cost affects Manufacturer 1's decision. In scenario (a), low product competition primarily influences investment approach, while R&D success rate mainly affects decision scope. These findings reveal that Manufacturer 1's optimal investment method is shaped by these three factors, indicating a complex influence mechanism.

Theorem 3: When Manufacturer 1's core technology R&D is successful, the optimal outcome transformation strategy is:

(a).  $\pi_1^{YSB**} > \pi_1^{YSA**}$ ,  $\pi_2^{YSB**} < \pi_2^{YSA**}$   
(b).  $\pi_1^{YSC**} > \pi_1^{YSA**}$ ,  $\pi_2^{YSC**} > \pi_2^{YSA**}$  when  $F \in \left( \frac{\theta(\theta+8)(A-C)^2}{8(\theta+2)^2}, \frac{3(A-C)^2}{2(\theta+2)^2} \right)$

It can be deduced that compared to outcome transfer, which benefits Manufacturer 1 but disadvantages Manufacturer 2, entering into an outcome transfer contract may not be viable. Despite the advantage to Manufacturer 1, it would still prefer self-use of outcomes ultimately. This preference stems from the fact that if Manufacturer 2 agrees to a lateral supply contract with Manufacturer 1, although Manufacturer 2 obtains a lower wholesale price, Manufacturer 1 gains market share, resulting in reduced output for Manufacturer 2 and putting it at a disadvantage. Regarding self-use versus outcome sharing, whether Manufacturer 1 has an incentive to choose outcome sharing depends on product substitutability and technology R&D costs. When both factors fall within the range of (b), outcome sharing benefits both parties, fostering cooperation and leading Manufacturer 1 to ultimately choose this strategy. This also suggests that pre-existing cooperation is more stable than post hoc cooperation.

Theorem 4: The impact of Manufacturer 1's technological R&D investment behavior on the overall supply chain profit:

(a).  $\pi_T^{N*} > \pi_T^{YSA*}$ ,  $\pi_T^{N*} > \pi_T^{YSB*}$ ,  $\pi_T^{N*} > \pi_T^{YSC*}$  when  $(\theta + 6)\lambda - 2\theta - 4 < 0$ ,  $-\theta + 3\lambda - 2 < 0$ ,  $G < 0$

(b).  $\pi_T^{N*} < \pi_T^{YSA*}$ ,  $\pi_T^{N*} < \pi_T^{YSB*}$ ,  $\pi_T^{N*} < \pi_T^{YSC*}$

When  $(\theta + 6)\lambda - 2\theta - 4 > 0$ ,  $-\theta + 3\lambda - 2 > 0$ ,  $G > 0$  and  $F < \frac{(A-C)^2}{4(2+\theta)^2}$

$\min\left\{-\frac{(A-C)^2(\theta-3\lambda+2)}{2(\theta+2)^2}, \frac{(A-C)^2((\lambda-2)\theta+6\lambda-4)}{2(\theta+2)^2}, -\frac{(A-C)^2G}{4(\theta+2)^2(3\theta^2-8)^2}\right\}$

$G = -3\lambda\theta^6 + (12\lambda - 18)\theta^5 + (47\lambda - 29)\theta^4 + (-80\lambda + 128)\theta^3 + (-224\lambda + 192)\theta^2 + (128\lambda - 192)\theta + 320\lambda - 256$

$$\pi_T^{N*} = \pi_1^{N*} + \pi_2^{N*} + \pi_S^{N*} \quad (76)$$

$$\pi_T^{YSA*} = E(\pi_1^{YSA*}) + \pi_2^{YSA*} + \pi_S^{YSA*} \quad (77)$$

$$\pi_T^{YSB*} = E(\pi_1^{YSB*}) + \pi_2^{YSB*} \quad (78)$$

$$\pi_T^{YSC*} = E(\pi_1^{YSC*}) + E(\pi_2^{YSC*}) \quad (79)$$

The above equation indicates that when the intensity of competition and the success rate of R&D remain within a certain range, Manufacturer 1's technological R&D investment behavior will decrease the overall profitability of the supply chain, regardless of the investment method chosen by Manufacturer 1. Conversely, when all three equations mentioned above are greater than 0, whether Manufacturer 1's R&D investment behavior can increase the overall profit of the supply chain depends on the size of the R&D investment cost F.

Theorem 5: The impact of Manufacturer 1's R&D success rate and the intensity of competition between manufacturers on the overall profit of the supply chain:

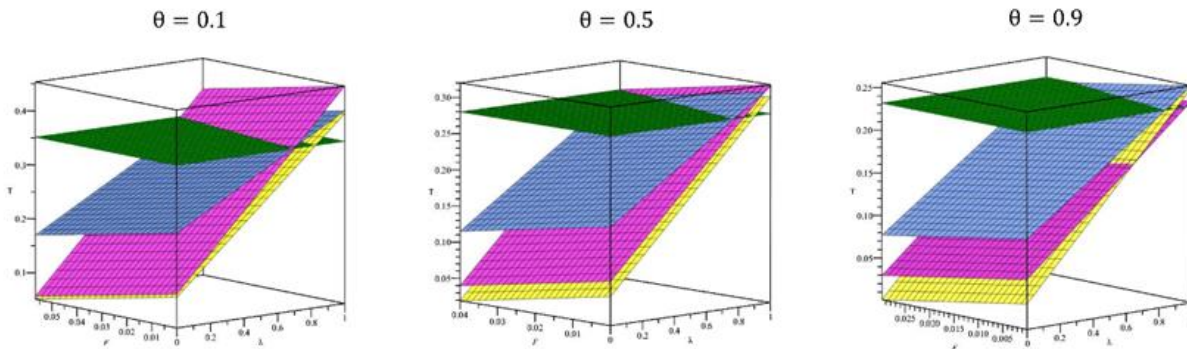
(a). Impact of R&D Success Rate: Only when the R&D investment cost F is low and the R&D success rate  $\lambda$  is high, Manufacturer 1's R&D investment behavior can increase the overall profit of the supply chain. Otherwise, Manufacturer 1's R&D investment behavior will harm the overall profit of the supply chain.

(b). Impact of Competition Intensity: When the R&D investment cost F is low and the R&D success rate  $\lambda$  is high, the effect of Manufacturer 1's different outcome transfer behaviors on the overall profit of the supply chain is influenced by the competition intensity  $\theta$ . Specifically, when  $\theta$  is low, both outcome transfer and self-use are better than outcome sharing after prior cooperation. However, as  $\theta$  increases, the advantage of outcome sharing diminishes. That is, as  $\theta$  increases, Manufacturer 1's choice of self-use or

outcome transfer can lead to greater overall profit for the supply chain.

To verify the above conclusion, let  $A = 2$  and  $C = 1$ . Let

$\theta = 0.1, 0.5, \text{ and } 0.9$  respectively. Ensure that the value of  $F$  satisfies  $F < \frac{(A-C)^2}{4(\theta+2)^2}$ .



**Figure 13.** The overall profit of the supply chain under different scenarios

The boundary between the green plane and others in the three graphs signifies the distinct impacts of Manufacturer 1's R&D investment behavior and outcome transformation strategies on overall supply chain profit, aligning with Theorem 5. The graphs indicate that when  $F$  is relatively low and  $\lambda$  is high, Manufacturer 1's R&D investment behavior is more advantageous for the supply chain. Additionally, with increasing  $\theta$ , the supply chain's overall profit decreases when Manufacturer 1 doesn't invest, reducing the space where Manufacturer 1's R&D investment and outcome transformation behaviors benefit the supply chain. Furthermore, strategies involving self-use and outcome transfer tend to benefit the supply chain, especially when competition between manufacturers is low. In such scenarios, cooperation agreements are more likely, optimizing the supply chain under favorable conditions. However, as competition intensifies, cooperation may not always enhance the supply chain. In these cases, it's optimal for Manufacturer 1 to utilize its R&D outcomes for self-use, indicating that heightened competition makes Manufacturer 1's self-use of R&D outcomes more advantageous for the supply chain.

## 5. Conclusion

In response to the competitive and uncertain R&D environment faced by manufacturers in real industrial production, this paper considers a two-tier supply chain consisting of two competing manufacturers and a supplier monopolizing a key component. In this setup, one manufacturer decides on core technology R&D investment (Manufacturer 1), while the other does not invest in core technology R&D (Manufacturer 2). Based on the different R&D investment and outcome transformation strategies of Manufacturer 1, the paper categorizes them into four scenarios: no investment, sole investment for self-use, sole investment for transfer, and collaborative investment for shared outcomes. Uncertainty in R&D is introduced to explore the optimal core technology R&D investment and outcome transformation strategies for Manufacturer 1.

By solving game models and comparing equilibriums, the paper finds that the choice of core technology R&D investment and outcome transformation strategy for a single manufacturer is influenced by the intensity of competition between manufacturers, R&D success rate, and R&D investment cost. Specifically, when R&D uncertainty is high, the R&D investment cost becomes the primary factor influencing manufacturers' R&D investment decisions. When R&D uncertainty is low, optimistic expectations regarding

R&D success render the R&D investment cost less restrictive, and the competition level between manufacturers reflects the sensitivity of manufacturers to changes in R&D investment costs. Only when R&D investment costs are low and R&D success rates are high can Manufacturer 1's R&D investment behavior increase the overall profit of the supply chain. Furthermore, intensified competition leads to Manufacturer 1's self-use of R&D results being more beneficial to the supply chain.

Through exploration of core technology R&D investment and outcome transformation strategies, this paper provides theoretical support for the R&D investment of individual manufacturers and enriches the literature for further research in related fields. However, this paper only considers the R&D investment and outcome transformation strategies of a single manufacturer under the condition of symmetric information on R&D costs, without considering situations where R&D cost information is asymmetric or multiple manufacturers engage in R&D. Such scenarios are common in reality, and for manufacturers' proactive R&D investment behavior, suppliers in a monopoly position will also have corresponding responses. Therefore, future research should supplement these aspects to provide a more comprehensive understanding.

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