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Technology outage risk and independent research and development investment decision in global supply chains

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Abstract: Under the new global situation of the world pattern, the global industrial chain and supply chain are being reconstructed, and the safe and stable operation is facing a large number of risks and challenges. As the internal driving force of the reconstruction of the global supply chain, key core technologies have become an important part of world economic competition. This paper addresses the issue that what product manufacturer should do to prevent the risk of key core technology outage in the context of international competition. This paper first constructs a duopoly Hotelling model of two competitive products from two countries and the game models under different circumstances where enterprises in the core technology outage whether or not implement the independent research and development (IR&D). We establish four scenarios: non-IR&D benchmark before and after technology outage, IR&D before and after technology outage. Furthermore, outage risk is evaluated by comparing the impact of outage initiated by the government on the profit change of the initiator country firms and the firm in which supply is cut off. When the enterprises in technology outage implement IR&D, we compare the scale of profit changes of enterprises between the two countries and analyze the effectiveness of IR&D investment of enterprises in the country suffering from technology outage to cope with the technology outage risk. Our analysis indicates that: outage maybe make the country that initiates the core technology outage lose more profits and the core technology country's profit change may be bigger than the country investing IR&D. Moreover, the enterprise's IR&D investment can establish certain game space and rights for their country. When the country can reduce technological disadvantages, IR&D strategy, to some extent, can reduce the urgency due to the technology outage risk and weaken the absolute control from the rival country that initiates the technology outage.

Keywords: supply chain security; risk prevention; technology outage; Independent research and

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development; game theory

1. Introduction

As the outgrowth of the international division of labor, the global supply chain pattern has been in dynamic change, by restructuring to participate in and promote the technological and industrial transformations [1,2]. At present, the outage risk and security issues due to trade friction, epidemic impact, and Russia-Ukraine conflict make global supply chains reconfiguration show the trend of anti-globalization, and supply chains security rises to the national security strategy and is highly concerned by many countries. The "National Security Strategy 2022" issued by the White House takes supply chains security as a key element of the national security strategy of the United States. The European Union issued the "EU Chips Act" to strengthen its semiconductor ecosystem in 2022. The State Council of China issued the "14th Five-Year Plan" for Digital Economy development in 2021, which points out that "the resilience and stability of industrial and supply chains should be improved to enhance the ability of the industrial system to resist shocks". The Chinese government has elevated supply-chain security to a national level in the 20th CPC National Congress. Moreover, the key and core technology is a drive of the global industrial chains and supply chains operations. The key and core technologies are controlled by others, which leads to a sharp rise in the risk of global supply chain. [3]. To solve this dilemma, the Chinese government issued "the Opinions on improving a new system for mobilizing the resources nationwide to achieve breakthroughs in core technologies in key fields under the socialist market economy system", which emphasizes pooling resources to carry out original and leading scientific and technological breakthroughs, accompanied by a strong determination that resolutely wins the battle for key and core technologies.

In the current situation of the global supply chain, unilateralism, and trade protectionism are prevailing. In the fields where they are technologically advanced, many countries frequently implement technical supply interruption to suppress the development of manufacturing enterprises and industries of other relevant countries. China has serious supply chain outage risks in key areas, such as chips and industrial software, due to backward IR&D capabilities, technology dependence on foreign countries, and weak industrial chain integration [4]. For example, the United States cut off the supply of chips to ZTE and Huawei to sanction and suppress the development of Chinese enterprises. The United States imposed sanctions on ZTE in 2018, banning American companies from selling components, goods, software, and technology to ZTE for the next seven years. ZTE's annual revenue in 2018 was 85.513 billion yuan, down 21.41% year-on-year, and its net profit was 6.984

billion yuan, down 252.88% year-on-year. In 2020, the United States announced that chip manufacturers using American technology all over the world were prohibited from making chips for Huawei. With the intensification of sanctions in 2021, Huawei's consumer business revenue dropped sharply by 49.6%. Huawei's share of the global market for premium phones (those with an average wholesale price above $400) fell from 13 percent to 6 percent in 2021, according to Counterpoint Research's Market Pulse Service. This event exposes the core technology weakness of China's supply chains in key fields. To avoid serious impacts on the supply chains, enterprises have to increase IR&D investment and tackle key core technologies. However, a government-initiated outage against another country may damage the interests of enterprises in both countries. For the country that initiates sanctions to cut off the supply, an effective outage means bringing a larger loss to the opponents, while the initiator country's own side is in a profitable state or has a smaller loss.

Therefore, under the scenario that the key and core technology is in outage in global supply chains, considering the country under sanctions implements independent research and development(IR&D) investment, what will be the impact on the interests of enterprises of both countries? When both sides' interests decline due to the technology outage, which side loses more interests? On preventing and tackling the technology outage risk initiated by other governments, what is the effect of independent research and development(IR&D) investment in the country being sanctioned? Related to these issues, the academia of industry chains and supply chains, governments, and related enterprises are faced with important strategic choices.

Aiming at the technology outage initiated by the government of the country where the key and core technology suppliers are located, considering the global supply chains consisting of a supplier and manufacturer of the country that initiates the core technology outage, as well as the manufacturers of the country that suffers from the core technology outage, this paper constructs the Hotelling model between the two manufacturers and constructs the game models under different circumstances where enterprises in the core technology outage whether or not implement the independent research and development(IR&D). Furthermore, when the enterprises of the country in technology outage implement IR&D, we compare the scale of profit changes of enterprises between the two countries and analyze the effectiveness of IR&D investment of enterprises in the country suffering from technology outage to cope with the technology outage risk. On the one hand, this paper theoretically fills the research gap on government-initiated technology outages in global supply chains. On the other hand, it focuses on analyzing the relationship between enterprises' independent research and development(IR&D) and coping with the technology outage risk, drawing the following conclusions: Enterprises' independent research and development(IR&D) investment can establish certain game space and rights for their country when the country is faced with technology outage risk. When a country is in the situation of reducing technological disadvantages, the independent research and development(IR&D) strategy, to some extent, can reduce the urgency due to the technology outage risk and weaken the absolute control from the rival country that initiates the technology outage.

The remainder of this paper is organized as follows. The next section reviews the related literature. Section 3 introduces the problem and basic assumptions. Section 4 provides models for each strategy and analyzes the optimal decisions under different strategies. Section 5 compare two countries' profit change to analyze outage risk and IR&D investment by numerical analysis. Section 6 concludes this study and outlines directions for future research. All proofs of this paper are in Appendix.

2. Literature review

The research closely related to this paper can be divided into the following three aspects: The connotation and characteristics of key and core technology, market competition of technical products, supply chain risk and supply chain security. We will summarize related studies from these three aspects.

Firstly, we analyze the connotation and characteristics of key and core technology. Existing research has made theoretical and empirical research on the importance of key and core technologies at the scientific construction and market development from the perspective of industry and country. Han et al. consider the key and core technology generally refers to the technical system that controls the technological heights of the same industry, and that plays irreplaceable, inaccessible, and insurmountable roles [5]. Zhang and Yuan argue that the key and core technology, consisting of core materials, components, equipment, processes, etc., serves enterprises' technological innovation, which plays a central role in production or technical system [6]. Yu and Xiong believe that the key and core technology has the dual orientation of science and market, which not only requires the innovative breakthrough of basic science but also needs to face the market to realize its commercial value [7]. Hu and Yuan, based on these theories of technological gap, sustainable development concept, and overall national security concept, define the key and core technology as 'the technologies, methods, and knowledge that can continuously maintain security in all aspects of the state and play a decisive role in the technology chains and industrial chains [8]. Zhang et al. point out that key and core technologies will affect the healthy development of the country and the ecosystem of scientific and technological innovation, and can help the country build its core competitiveness and seize a favorable position in international competition [9]. In combination with these above studies, this paper focuses on the key and core technology which plays a core role in the industrial chain and supply chain. The technology is highly dependent on and vulnerable to blockade and oppression by technology providers, posing difficulties to conducting IR&D.

The important connotation of global supply chains security research is how to cope with supply chains risk. Existing research utilizes different methods to find the causes and forms of supply chain risk, and proposes different solutions to reduce supply chain risk. Richard and Rebecca, reviewing the previous studies on the sources of global supply chains risks and the recovery path of global supply chains, propose that the risk-versus-reward framework from portfolio theory to evaluate the rationality of anti-risk policy [10]. Zhang et al. use the system dynamics method to simulate the changes caused by the disruption of any sectors in supply chain. They propose mitigation strategies for enterprises to cope with different node disruptions to improve their overall efficiency and operational capabilities [11]. Mustafa et al. study the relevance of potential risk mitigation strategies to small and medium-sized enterprises to guide them in how to configure their supply chains and mitigate the risks caused by major disruptions [12]. Arrate et al. analyze the ripple effect on supply chains, which occurs when disruption at one node spreads throughout the supply chain and impacts its performance, design, and planning parameters [13]. Saurabh et al. focus on the supply chain outage risks caused by product innovation. Based on data from 164 enterprises, they show that greater product innovation activity is associated with greater supplier dependence and increased product variety which, in turn, increases the supply chain outage risk faced by enterprises [14]. Wang et al. studied the decision evolution of the supply chains network, treated as a complex adaptive system, from both the aspects of time dynamic and spatial features, and made a reasonable explanation of the response strategies of upstream and downstream enterprises in the supply chains network [15]. Piprani et al. confirm multi-dimensional supply chain flexibility in improving supply chain resistance under a high supply chain risk environment by using the effective responses of 191 large manufacturing companies in Pakistan [16]. Huang and Fan investigate plausibly exogenous variation in geographic proximity caused by new built high-speed railway connections between suppliers and their customers in China, and find the strong evidence that supplier-customer geographic proximity reduces supplier firms risk taking [17]. The above studies focus on the traditional supply chains composed of suppliers, manufacturers, or retailers, while this paper focuses on the global supply chains composed of products using key and core technology and their core technology suppliers. Besides, the existing studies mainly focus on the risks caused by external factors of supply chains. Differently, our paper focuses on the endogenous risks triggered by members of global supply chains, that is, the governments of countries whose enterprises possess key and core technologies, according to the relative scale of profit changes between domestic enterprises and foreign enterprises using the technologies, decide whether to implement technologies outage directing at other countries.

This paper is also related to the research on technological product market competition. Technical licensing and cooperation will affect the optimal decisions of technology providers and technology recipients. Different market environments and trade policies will affect the selection strategies of market participants. Based on two competing firms with asymmetric bargaining power, Zhao et al. established a theoretical model of bilateral cross-licensing under the price competition environment, to study the offering motivation and optimal decision of each participant on technology [18]. Zhang et al. studied the optimal technology licensing contract between the technology provider and the provided under different types of mixed competition modes and discussed the influence of different supply modes on consumer decision-making [19]. Based on the optimal quantity of technology licenses of key technology owners, Chan and Phoebe established a price competition model and studied the impact of the number of technology licenses on consumers and social welfare [20]. Hou et al. established a two-stage model for incumbents and entrants of the market to study their cooperation strategies and optimal innovation input level in different market environments [21]. Feng et al., according to the product flows and the directed market, studied how cross-border trade policies (including tariffs, quotas, and subsidies) affect the competitive advantages and profits of each participant in the global supply chains [22]. Ilhang and Lee used the empirical data of listed companies in South Korea to study the impact of product market competition on enterprises' IR&D investment. They explained the practical significance that product market competition drives enterprises' technology IR&D investment [23]. Through the analysis of the data of technical cooperation of Chinese enterprises, Wu found that technical cooperation in market competition will reduce the enthusiasm of product innovation, which is also different from sectoral technology characteristics [24]. However, these above studies seldom consider the technology IR&D investment and global supply chains risk under the market competition of the same technology supply.

3. Problem statement

Consider a global supply chain comprising a manufacturer(Ma) in A country, B country's key core technology supplier(S) and manufacturer(Mb). Two manufacturers produce and sell the same and alternate products, P_a and P_b, to consumers separately. They all use the same key core technology from S. Two manufacturers form a duopoly competition and sell products to consumers at price p_a and p_b. We model this competition using a framework that is akin to the Hotelling model [25,26]. Specifically, we assume that P_a and P_b are located at two ends of the interval $[0,1]$, and consumers are uniformly distributed along a unit interval. Two products, q_a and q_b, have qualitative difference denoted as $q_\Delta(q_a - q_b)$. We assume that consumers differ in their preferences for certain attributes about two products. Consumers' location x represent ideal demand for products. The distance between consumer's location and one product reflects the level of mismatch, which measures consumers' disutility per unit deviation from the ideal product. A higher t represents that consumers feel more strongly about their preferences being matched.

Consumers compare two utility of purchasing P_a and P_b, and buy one product. Before technology outage, two products use the key core technology of supplier S. Since the two manufacturers are in perfect competition, it is assumed that they both determine the product price at the same time (see Fig. 1a). At the behest of the government in B country, the technology supplier cuts off the technology supply for Ma (see Fig. 1b). To deal with risk of technology outage, Ma invests independent research and development technology (IR&D) as a reserve. Before technology outage, two products still use the key core technology of supplier S and IR&D is not used (see Fig. 1c). After technology outage, Ma uses IR&D (see Fig. 1d).

Therefore, the technology supplier's supply strategies are supply(Y) and outage(N). Manufacturer A's technology strategies are non-IR&D benchmark(B) and IR&D(I). Based on the above, we define four scenarios in Table 1. The notations used in our models are presented in Table 2. A summary of model assumptions is as follows.

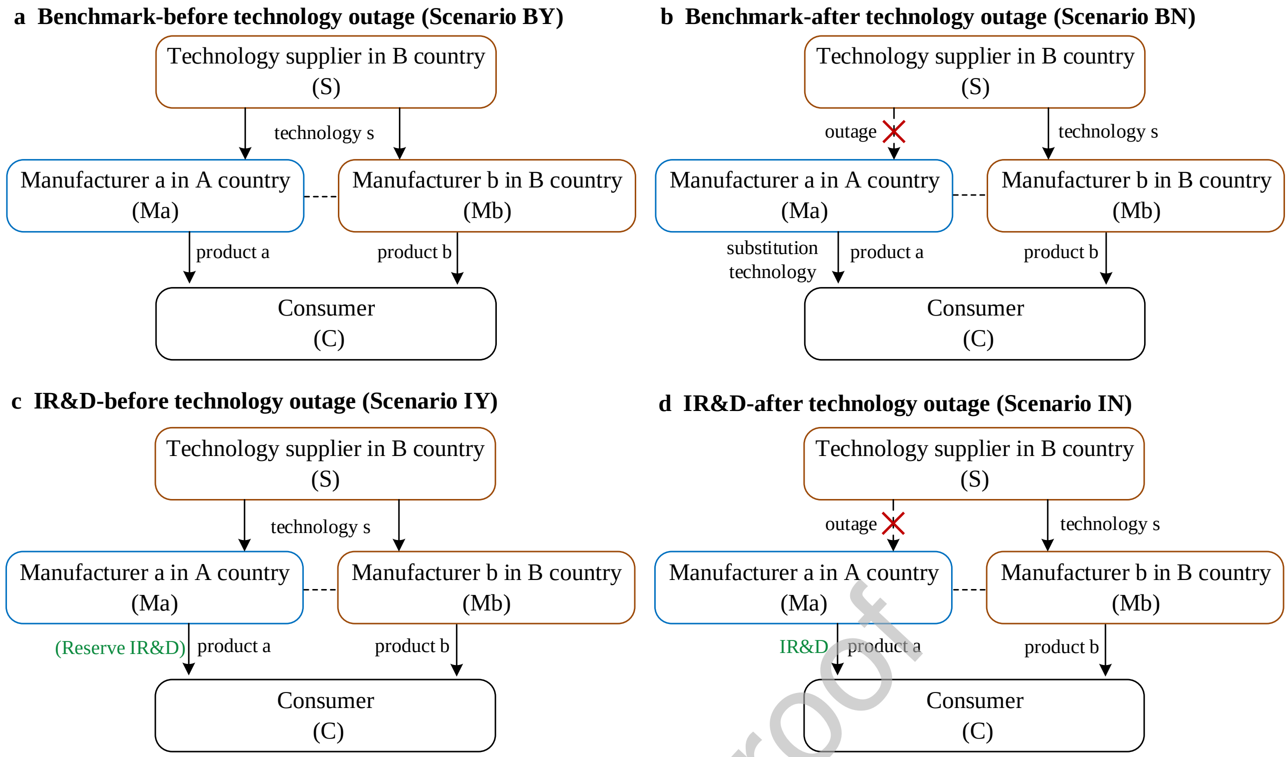

Fig. 1. Technology and products supply chain structures

Assumption 1. Two manufacturers' products are full coverage of the market, $d = 1$.

Assumption 2. The technology supply can obtain a unit profit of technology as $\beta(\beta > 0)$.

Assumption 3. The consumers' utility is non-negative at four scenarios in our research. We can get $k > \frac{1}{t}$ at Scenario IN. This means that k is not too low to ensure a non-negative utility.

Assumption 4. Other technology has disadvantage $\alpha(\alpha > 0)$ compared with original technology after outage.

Assumption 5. Consumers can gain a unit spillover r from the manufacturer A's IR&D investment [27]. The amount of this spillover affected by the IR&D level is g.

Table 1. Different strategy pairs and four scenarios.

Manufacturer A's technology Strategies \ Technology Supplier's supply strategies	**Supply（Y）**	**Outage（N）**
Benchmark （B）	Scenario BY	Scenario BN
IR&D （I）	Scenario IY	Scenario IN

Table 2. Summary of basic notations.

Parameters	
q_i	the quality of product, $i = a, b$
θ	consumer's product quality perceived coefficient
t	consumer preference
x	consumer's location
α	technology disadvantage of other technology after outage
β	a unit profit of technology
r	a spillover effect of IR&D investment
k	manufacturer A's cost per unit of IR&D level squared
Decision variables	
p_i^J	the price of product i in scenario J, where $i = a, b$ and $J = BY, BN, IY, IN$
g^J	manufacturer A's IR&D level, where $J = IY, IN$
Dependent variables	
d_i^J	the demand of product i in scenario J, where $i = a, b$ and $J = BY, BN, IY, IN$
π_{Mi}^J	manufacturer i's profit in scenario J, where $i = a, b$ and $J = BY, BN, IY, IN$
π_S^J	technology supplier's profit in scenario J, where $J = BY, BN, IY, IN$

4. Model framework and analysis

According to the manufacturer A's two technology strategies, we denote Scenario BY and BN as non-IR&D benchmark strategy, and Scenario IY and IN as IR&D investment strategy.

4.1. Non-IR&D Benchmark

Before technology outage, Ma and Mb use the same technology *s*, that is scenario BY. Consumer obtain the utility by purchasing two products are respectively

$$U_a^{BY} = \theta q_a - tx - p_a \tag{1}$$

$$U_b^{BY} = \theta q_b - t(1-x) - p_b \tag{2}$$

where θq_i is consumers' basic utility from purchasing one product. Without loss of generality, let $\theta = 1$. To ensure two products always in the market, we assume $-3t < q_\Delta < 3t$. According to Eqs. 1 and 2, we can get consumers' demand for P_a and P_b. To simplify analysis, the marginal cost of two products and fix cost of S are not considered, which does not influence the results in our research. Two manufacturers' and supplier's profit functions are respectively

$$\pi_{Ma}^{BY} = p_a^{BY}(\frac{q_\Delta + t - p_a^{BY} + p_b^{BY}}{2t}) \quad (3)$$

$$\pi_{Mb}^{BY} = p_b^{BY}(\frac{-q_\Delta + t + p_a^{BY} - p_b^{BY}}{2t}) \quad (4)$$

$$\pi_S^{BY} = \beta \quad (5)$$

Before technology outage, the equilibrium results of market competition between the two products are given in Proposition 1.

Proposition 1. In scenario BY, the optimal solutions and profits are listed in Table 3.

Next we discuss the scenario BN that the B country's government implement technology outage. After outage, consumers' utility is unchanged by purchasing P_b because Mb uses the original technology. By now consumer's utility by purchasing P_a is

$$U_a^{BN} = \theta q_a - tx - p_a - \alpha \quad (6)$$

To ensure P_a always in the market, we also assume $0 < \alpha < q_\Delta + 3t$. Two manufacturers' and supplier's profit functions are respectively

$$\pi_{Ma}^{BN} = p_a^{BN}(\frac{q_\Delta + t - \alpha - p_a^{BN} + p_b^{BN}}{2t}) \quad (7)$$

$$\pi_{Mb}^{BN} = p_b^{BN}(\frac{q_\Delta + t + \alpha + p_a^{BN} - p_b^{BN}}{2t}) \quad (8)$$

$$\pi_S^{BN} = \beta(\frac{q_\Delta + t + \alpha + p_a^{BN} - p_b^{BN}}{2t}) \quad (9)$$

Now the equilibrium results of market competition between the two products are given in Proposition 2.

Proposition 2. In scenario BN, the optimal solutions and profits are listed in Table 3.

Table 3. Optimal decisions and profits in non-IR&D benchmark

	Scenario BY	Scenario BN
Decisions	$p_a^{BY} = \frac{q_\Delta + t}{3}$, $p_b^{BY} = \frac{-q_\Delta + t}{3}$	$p_a^{BN} = \frac{q_\Delta + t - \alpha}{3}$, $p_b^{BN} = \frac{-q_\Delta + t + \alpha}{3}$
Demands	$d_a^{BY} = \frac{q_\Delta + 3t}{6t}$, $d_b^{BY} = \frac{-q_\Delta + 3t}{6t}$	$d_a^{BN} = \frac{q_\Delta + 3t - \alpha}{6t}$, $d_b^{BN} = \frac{-q_\Delta + 3t + \alpha}{6t}$
Profits	$\pi_{Ma}^{BY} = \frac{(q_\Delta + 3t)^2}{18t}$, $\pi_{Mb}^{BY} = \frac{(-q_\Delta + 3t)^2}{18t}$, $\pi_S^{BY} = \beta$	$\pi_{Ma}^{BN} = \frac{(q_\Delta + 3t - \alpha)^2}{18t}$, $\pi_{Mb}^{BN} = \frac{(-q_\Delta + 3t + \alpha)^2}{18t}$, $\pi_S^{BN} = \frac{\beta(-q_\Delta + 3t + \alpha)}{6t}$

From Proposition 1, we can see that before outage two products have the same price and divide the market when they have the same quality. If the quality is different, product with quality advantages are priced higher and their sales volume is higher. Proposition 1 describes a higher consumer preference leads a higher pricing. Now consumers focus on horizontal differences and manufacturers will have a stronger pricing right. After technology outage, Proposition 2 describes the price, demand and profit of P_a decrease with an increasing technology disadvantage. The impact of technology disadvantage on supplier and manufacturer B are the opposite. For this outage, manufacturer A can improve horizontal differences design to cover the disadvantage.

4.2. IR&D investment

To deal with risk of technology outage, the manufacturer A invests IR&D technology as a reserve. Before technology outage, Ma and Mb use the same technology s, that is scenario IY. Consumer obtain the utility by purchasing two products are respectively:

$$U_a^{IY} = \theta q_a - tx - p_a + rg \tag{10}$$

$$U_b^{IY} = \theta q_b - t(1-x) - p_b \tag{11}$$

Where g is manufacturer A's IR&D level. Without loss of generality, we assume a spillover effect of IR&D investment $r=1$. According to Eqs. 10 and 11, we can get consumers' demand for P_a and P_b. Two manufacturers' and supplier's profit functions are respectively:

$$\pi_{Ma}^{IY} = p_a^{IY} \frac{q_\Delta + t + g^{IY} - p_a^{IY} + p_b^{IY}}{2t} - k(g^{IY})^2 \tag{12}$$

$$\pi_{Mb}^{IY} = p_b^{IY} \frac{-q_\Delta + t - g^{IY} + p_a^{IY} - p_b^{IY}}{2t} \tag{13}$$

$$\pi_S^{IY} = \beta \tag{14}$$

Before technology outage, when Ma invests IR&D, the equilibrium results of market competition between the two products are given in Proposition 3.

Proposition 3. In scenario IY, the optimal solutions and profits are listed in Table 4.

Next we discuss the scenario IN that the country B's government implement technology outage and Ma uses the IR&D technology and continues this investment. After outage, consumer's utility is unchanged by purchasing P_b because Mb uses the original technology. By now consumer's utility by purchasing P_a is

$$U_a^{IN} = \theta q_a - tx - p_a + rg - (\alpha - g) \tag{15}$$

At this moment, using the IR&D technology can decrease some technology disadvantage from outage.

Two manufacturers' and supplier's profit functions are respectively

$$\pi_{Ma}^{IN} = p_a^{IN} \frac{q_\Delta + t - \alpha + 2g^{IN} - p_a^{IN} + p_b^{IN}}{2t} - k(g^{IN})^2 \tag{16}$$

$$\pi_{Mb}^{IN} = p_b^{IN} \frac{-q_\Delta + t + \alpha - 2g^{IN} + p_a^{IN} - p_b^{IN}}{2t} \tag{17}$$

$$\pi_S^{IN} = \beta \frac{-q_\Delta + t + \alpha - 2g^{IN} + p_a^{IN} - p_b^{IN}}{2t} \tag{18}$$

Now the equilibrium results of market competition between the two products are given in Proposition 4.

Proposition 4. In scenario IN, the optimal solutions and profits are listed in Table 4.

Table 4. Optimal decisions and profits in IR&D

	Scenario IY	Scenario IN
Decisions	$p_a^{IY} = \frac{4kt(q_\Delta + 3t)}{12kt - 1}$, $g^{IY} = \frac{q_\Delta + 3t}{12kt - 1}$ $p_b^{IY} = \frac{2t(-2kq_\Delta + 6kt - 1)}{12kt - 1}$	$p_a^{IN} = \frac{kt(q_\Delta + 3t - \alpha)}{3kt - 1}$, $g^{IN} = \frac{q_\Delta + 3t - \alpha}{6kt - 2}$ $p_b^{IN} = \frac{-kt(q_\Delta + 3t + \alpha) - 2t}{3kt - 1}$
Demands	$d_a^{IY} = \frac{2k(q_\Delta + 3t)}{12kt - 1}$ $d_b^{IY} = \frac{-2kq_\Delta + 6kt - 1}{12kt - 1}$	$d_a^{IN} = \frac{k(q_\Delta + 3t - \alpha)}{2(3kt - 1)}$ $d_b^{IN} = \frac{-k(q_\Delta - 3t - \alpha) - 2}{2(3kt - 1)}$
Profits	$\pi_{Ma}^{IY} = \frac{k(q_\Delta + 3t)^2(8kt - 1)}{(12kt - 1)^2}$ $\pi_{Mb}^{IY} = \frac{2t(-2kq_\Delta + 6kt - 1)^2}{(12kt - 1)^2}$ $\pi_S^{IY} = \beta$	$\pi_{Ma}^{IN} = \frac{k(2kt - 1)(q_\Delta + 3t - \alpha)^2}{4(3kt - 1)^2}$ $\pi_{Mb}^{IN} = \frac{2t(k(q_\Delta - \alpha - 3t) + 2)^2}{(3kt - 1)^2}$ $\pi_S^{IN} = \frac{\beta(-k(q_\Delta - \alpha - 3t) - 2)}{6kt - 2}$

From Proposition 3, we can see that the price and demand of P_a is higher than P_b when two products have the same quality. Consumer preference on IR&D makes Ma has a stronger pricing right. If two products have different qualities, a higher consumer preference could weaken the impact of qualitative difference. The manufacturer could outstand the character of products to make up disadvantage of qualities. After technology outage, from Proposition 4, if two products have the same quality, the pricing right of Ma is increasing with a decreasing technology disadvantage.

Manufacturer A's IR&D level is positive with an increasing consumer preference. If P_a has a quality disadvantage, technology disadvantage has the same impact of qualitative difference on IR&D level. That is IR&D level increases with a decreasing technology disadvantage and qualitative difference. If P_a has a quality advantage, IR&D level increases with a decreasing technology disadvantage and an increasing qualitative difference. By now it means that the manufacturer could counteract the effect of technology disadvantage by improving products quality.

Proposition 5. (i) If $\alpha < \frac{3(3t+q_\Delta)}{12kt-1}$, then $p_a^{IN} > p_a^{IY}$ and $p_b^{IN} < p_b^{IY}$; If $\alpha \geq \frac{3(3t+q_\Delta)}{12kt-1}$, then $p_a^{IN} \leq p_a^{IY}$ and $p_b^{IN} \geq p_b^{IY}$.

(ii) If $\alpha < \frac{(3t+q_\Delta)(6kt+1)}{12kt-1}$, then $g^{IN} > g^{IY}$; If $\alpha \geq \frac{(3t+q_\Delta)(6kt+1)}{12kt-1}$, then $g^{IN} \leq g^{IY}$.

Proposition 5 indicates that if technology disadvantage is relatively low, the manufacturer A improves the price of P_a and the manufacturer B decreases the price of P_b when the country B's government implement technology outage. If technology disadvantage is relatively high, the manufacturer A decreases the price of P_a and the manufacturer B improves the price of P_b after outage. This means that narrowing technology disadvantage could improve the pricing right of the manufacturer suffering from technology outage and weaken the pricing right of the manufacturer in the initiator country. In addition, a lower technology disadvantage makes the IR&D level improve after suffering from technology outage. A higher technology disadvantage of IR&D makes the IR&D level decrease after outage. It means that a relatively low technology disadvantage could motivate the manufacturer suffering from technology outage to improve his IR&D level to face this outage. However, if technology disadvantage of IR&D is relatively high, technology outage makes IR&D level be lower than before. In the reality, IR&D seems pointless with a higher technology disadvantage.

5. Outage risk and IR&D investment analysis

In this section, we will compare two countries' profit change to analyze outage risk and IR&D investment. B is a country that initiates the core technology outage, and A is a country that suffers from the core technology outage.

5.1. Outage risk analysis under IR&D investment strategy

Under Scenario IY and Scenario IN, A country's profit change is $\Delta\pi_A^{IN-IY} = \pi_{Ma}^{IN} - \pi_{Ma}^{IY}$. Country B's profit change is $\Delta\pi_B^{IN-IY} = \pi_{Mb}^{IN} + \pi_S^{IN} - (\pi_{Mb}^{IY} + \pi_S^{IY})$. The relationship of profit change and outage risk is as follows.

When country B cuts off the supply of technology to country A if the profit of country B increases, country A faces the highest risk of being cut off. Otherwise, the profit of B will decrease. If the profit loss of country B is less than that of country A, the risk of being cut off for country A is higher, while if the profit loss of country B is greater than that of country A, the risk of being cut off for country A is lower. If the profit of country A can be increased after being cut off, the risk of cutting off the supply of country B is also low.

We further illustrate the above results in Fig. 2 based on a set of numerical simulations. In this example, let $t = 1.5$, $\beta = 1.5$, $q_\Delta = -1$. The main outcomes are illustrated in Fig. 2.

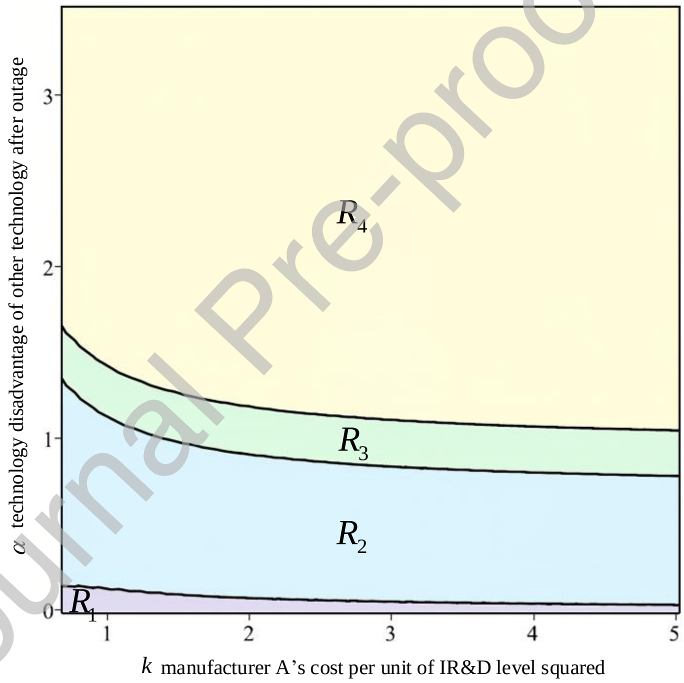

Fig. 2. Profit change and outage risk between two countries.

For country A, within R_1, the profit after the outage is increased through IR&D investment, at which time the technological disadvantage under any square unit cost k is small. For B, within R_4, the profit will increase after the outage, and the technological disadvantage will be greater at this time. In a word, in R_1, the profit of country A after the outage increases while the profit of country B decreases. At this time, the risk of being cut off is the smallest. In addition, country A has continuously reduced its technological disadvantage through IR&D investment, and achieved technological progress and risk control, which also has a certain impact on the decision-making of country B. However, within R_4, the risk of being cut off is greatest when the profit of country A is reduced and the profit of country B is increased. And country A is still unable to cope with the risk of supply cut-off due to its greater technological disadvantage of self-research. In R_2, after the outage, the profit of both countries decreased, and the profit reduction in country A was smaller than that in country B. At this time, the risk that A will be cut off is relatively low, and A reversely increases the loss of implementation of cut-off in country B by owning self-research technology. Within R_3, the profit of both countries decreased after the outage, but the decrease in profit of country A was larger than that of country B. At this time, country B may still damage country A at the expense of its interests. This is the result of losing both. Therefore, the greater the technological disadvantage, the greater the risk of being cut off. The reserve of self-research technology can establish a certain competitive advantage for the country suffering technology outage. For the above risk analysis under IR&D investment strategy, Example 2 will further explore the relationship between IR&D investment and risk control.

5.2. IR&D investment and risk control

Under non-IR&D benchmark and IR&D, A country's profit change is $\left|\Delta\pi_A^{IN-IY}\right|-\left|\Delta\pi_A^{BN-BY}\right|$. B country's profit change is $\left|\Delta\pi_B^{IN-IY}\right|-\left|\Delta\pi_B^{BN-BY}\right|$. The relationship of profit change and IR&D investment is as follows.

Facing the outage by B, when the loss of profit after the IR&D investment in country A is less than the loss of profit under non-IR&D investment, then the IR&D investment has a greater impact on A's risk response and the possibility of A's investment is greater. If the loss of profit after the IR&D investment in country A is more than the loss of profit under non-IR&D investment, then the effect of IR&D investment on the risk response of country A is small, and the probability of IR&D investment in country A is small. Looking further at the change of profit in country B, the supply cut-off is implemented under two strategies. If the loss of profit of country B under the IR&D investment strategy is greater than the loss under the non-IR&D investment strategy, then the A IR&D investment has a greater impact on the decision-making of outage. If B increases the profit under both strategies, then when the increment under the IR&D investment strategy is less than that under the non-IR&D investment strategy, it can be considered that the IR&D investment can reduce the profit increment of B.

We further illustrate the above results in Figs. 3 and 4 based on a set of numerical simulations. In this example, let $t=1.5$, $\beta=1.5$, $q_\Delta=-1$. The main outcomes are illustrated in Figs. 3 and 4. Fig. 3 shows Country A's profit change due to IR&D under outage risk. Fig. 4 shows Country B's profit change due to IR&D under outage risk. Fig. 5 shows risk control of IR&D investment.

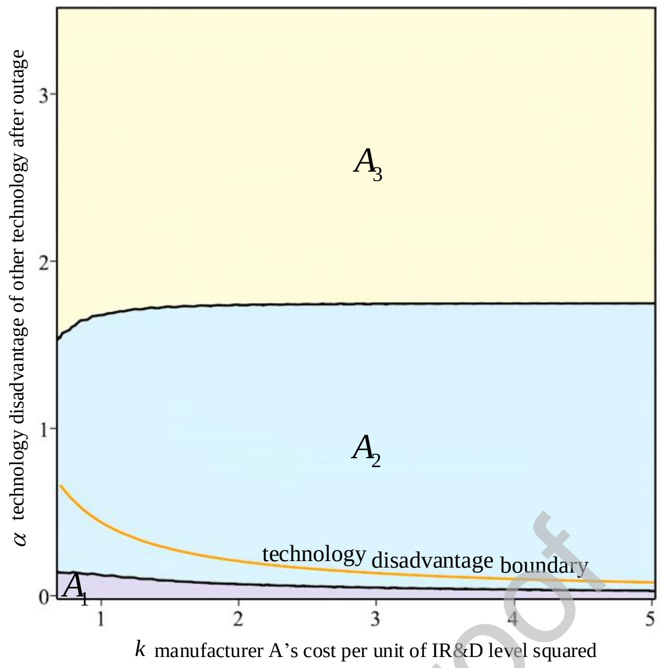

Fig. 3. Country A's profit change due to IR&D under outage risk.

In Fig. 3, for country A, region A_1 is the case where IR&D investment has the greatest impact on risk response and also has the highest requirement on the technology level. Within A_2 and A_3, A will suffer a loss of profit in both strategies under outage. Among them, within A_2, the loss of profit under the IR&D investment strategy is less than the loss under the non-IR&D investment strategy. At this time, choosing IR&D investment can reduce certain own losses. With the increase of technological disadvantage, within A_3, the loss of profit under the IR&D investment strategy is greater than the loss under non-IR&D investment. At this time, the low efficiency of IR&D investment due to the technological disadvantage will result in more losses due to self-research. In order to clearly present the profit change relationship, we present the profit changes of the two countries under the two strategies in Table 5 and Table 6 in detail.

Table 5. Country A's profit change for comparing Benchmark/IR&D due to outage

	Profit change between BN and BY $\Delta\pi_A^{BN-BY}$	Profit change between IN and IY $\Delta\pi_A^{IN-IY}$	Profit change due to IR&D under outage $\left\|\Delta\pi_A^{IN-IY}\right\|-\left\|\Delta\pi_A^{BN-BY}\right\|$	Symbols
A_1	−	+	/	$[-,+]^{/}$
A_2	−	−	−	$[-,-]^{-}$
A_3	−	−	+	$[-,-]^{+}$

Notes. "−" means a negative value. "+" means a positive value. "/" means a value without discussion.

Table 6. Country B's profit change for comparing Benchmark/IR&D due to outage

	Profit change between BN and BY $\Delta\pi_B^{BN-BY}$	Profit change between IN and IY $\Delta\pi_B^{IN-IY}$	Profit change due to IR&D under outage $\left|\Delta\pi_B^{IN-IY}\right|-\left|\Delta\pi_B^{BN-BY}\right|$	Symbols
B_1	−	−	+	$[-,-]^{+}$
B_2	+	−	/	$[+,-]^{/}$
B_3	+	+	−	$[+,+]^{-}$

Notes. "−" means a negative value. "+" means a positive value. "/" means a value without discussion.

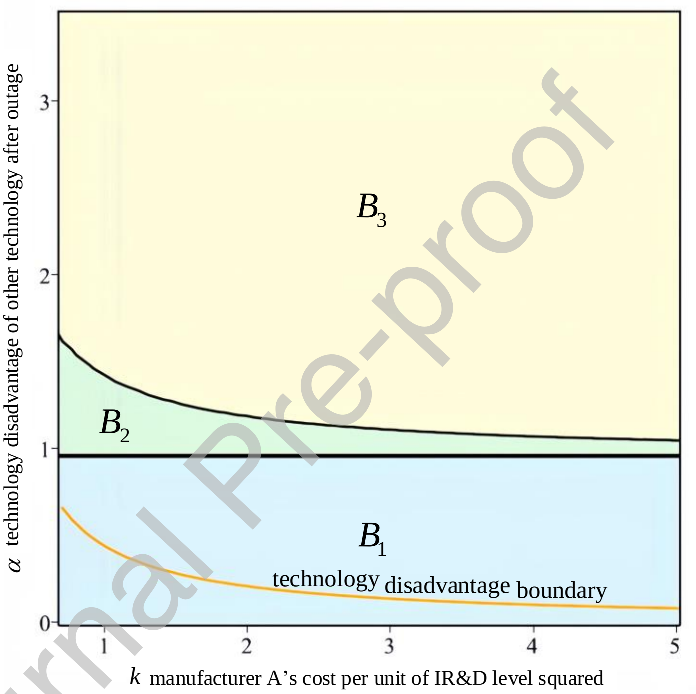

Fig. 4. Country B's profit change due to IR&D under outage risk.

In Fig. 4, for country B, within B_1, it will face the loss of profits under the two strategies, and the loss of profits under the IR&D investment strategy is more than that under the non-IR&D investment strategy. Within B_2, if the technological disadvantage is moderate, country B will lose its profit with the outage under the IR&D investment strategy, but will increase its profit if it does not. Therefore, as long as the technological disadvantage is not too great, B doesn't want A to select IR&D investment, and at the same time, it also carefully considers the decision to cut off the supply. We believe that at this time, country A's IR&D investment has relatively effectively enhanced its leading power to deal with the risk of the supply outage. By IR&D investment, country A has expanded the scope of allowable technological disadvantages and reduced the absolute right of country B to cut off the supply. This part of the improvement can be reflected in the summary Fig. 5, i.e., region C_2 and

C_3.

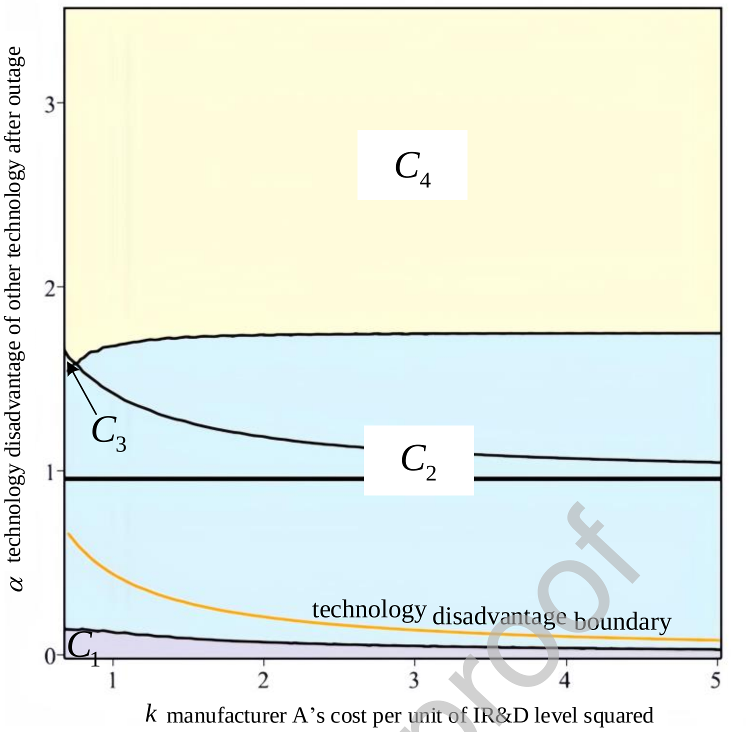

Fig. 5. Risk control of IR&D investment

Finally, at region B3, under both strategies, the profit of country B will increase with selecting to cut off, but the profit increment under the IR&D investment strategy is smaller than that under non-IR&D investment. That is to say, under the condition of greater technological disadvantage, IR&D investment cannot completely change the risk of supply outage, but IR&D investment can reduce the profit increment of the initiator country. However, considering that ineffective IR&D investment will also increase its profit loss, country A is also facing the decision of pyrrhic victory. In the above three pictures, the orange line is the technology disadvantage boundary. When the technological disadvantage falls below the threshold, we think that country A will achieve IR&D. Therefore, this line can be regarded as the goal of IR&D.

7. Conclusion

This paper investigates a global supply chain comprising a manufacturer in one country that suffers from the core technology outage, and a key core technology supplier and manufacturer in the other country that initiates the core technology outage. Aiming at the technology outage initiated by the government of the country where the key and core technology suppliers are located, we develop and compare two strategies non-IR&D and IR&D to analyze the outage risk and the influence of IR&D on risk control. This paper provides new insights into supply chain risk management facing international competition. Our findings show that technology disadvantage plays an important role in technology outage risk. For the country that initiates the core technology outage, outage maybe make him lose more profits and the core technology country's profit change may be bigger than the country investing IR&D. For the country that suffers from the core technology outage, the enterprise's independent research and development(IR&D) investment can establish certain game space and rights for their country. However, the low efficiency of IR&D investment due to the technological disadvantage will result in more losses due to self-research. Our study also might have some limitations. For strategy selections, IR&D investment might have a long way to use. How to model a dynamic change is an important issue for supply chain risk management in the future.

Declaration of competing interest

The authors declare that they have no conflicts of interest in this work.

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Appendix A

Proof of Proposition 1.

Based on Eqs. 1=2, the indifferent point is $x^* = \frac{q_\Delta + t - p_a + p_b}{2t}$. The demand for P_a and P_b are $d_a^* = \frac{q_\Delta + t - p_a + p_b}{2t}$ and $d_b^* = 1 - \frac{q_\Delta + t - p_a + p_b}{2t}$. Two manufacturers' profit functions can be rewritten as Eqs. 3 and 4. we have the first-order condition of p_a and p_b, and get $p_a(p_b) = \frac{t + q_\Delta + p_b}{2}$ and $p_b(p_a) = \frac{t - q_\Delta + p_a}{2}$. The profit functions are concave in two prices due to $\frac{\partial^2 \pi_{Ma}^{BY}}{\partial p_a^2} = -\frac{1}{t} < 0$ and $\frac{\partial^2 \pi_{Mb}^{BY}}{\partial p_b^2} = -\frac{1}{t} < 0$. Solving the simultaneous equations, we can gain the equilibrium decisions shown at table 3.

Proof of Proposition 2.

Based on Eqs. 6=2, the indifferent point is $x^* = \frac{q_\Delta + t - p_a + p_b - \alpha}{2t}$. The demand for P_a and P_b are $d_a^* = \frac{q_\Delta + t - p_a + p_b - \alpha}{2t}$ and $d_b^* = 1 - \frac{q_\Delta + t - p_a + p_b - \alpha}{2t}$. Two manufacturers' profit functions can be rewritten as Eqs. 7 and 8. we have the first-order condition of p_a and p_b, and get $p_a(p_b) = \frac{t + q_\Delta + p_b - \alpha}{2}$ and $p_b(p_a) = \frac{t - q_\Delta + p_a + \alpha}{2}$. The profit functions are concave in two prices due to $\frac{\partial^2 \pi_{Ma}^{BN}}{\partial p_a^2} = -\frac{1}{t} < 0$ and $\frac{\partial^2 \pi_{Mb}^{BN}}{\partial p_b^2} = -\frac{1}{t} < 0$. Solving the simultaneous equations, we can gain the equilibrium decisions shown at table 3.

Proof of Proposition 3.

Based on Eqs. 10=11, the indifferent point is $x^* = \frac{q_\Delta + t + g - p_a + p_b}{2t}$. The demand for P_a and P_b are $d_a^* = \frac{q_\Delta + t + g - p_a + p_b}{2t}$ and $d_b^* = 1 - \frac{q_\Delta + t + g - p_a + p_b}{2t}$. Two manufacturers' profit functions can be rewritten as Eqs. 12 and 13. we have the first-order condition of p_a, g and p_b, and get $p_a(p_b) = \frac{4kt(q_\Delta + p_b + t)}{8kt - 1}$ $g(p_b) = \frac{q_\Delta + p_b + t}{8kt - 1}$ and $p_b(p_a, g) = \frac{t - q_\Delta + p_a - g}{2}$. The profit functions are concave in two prices due to $\frac{\partial^2 \pi_{Ma}^{IY}}{\partial p_a^2} = -\frac{1}{t} < 0$, $H_1 = \begin{bmatrix} -\frac{1}{t} & \frac{1}{2t} \\ \frac{1}{2t} & -2k \end{bmatrix} = \frac{8kt - 1}{4t^2} > 0$ and $\frac{\partial^2 \pi_{Mb}^{IY}}{\partial p_b^2} = -\frac{1}{t} < 0$. Solving the simultaneous equations, we can gain the equilibrium decisions shown at table 4.

Proof of Proposition 4.

Based on Eqs. 15=1, the indifferent point is $x^* = \frac{q_\Delta + t + 2g - p_a + p_b - \alpha}{2t}$. The demand for P_a and P_b are $d_a^* = \frac{q_\Delta + t + 2g - p_a + p_b - \alpha}{2t}$ and $d_b^* = 1 - \frac{q_\Delta + t + 2g - p_a + p_b - \alpha}{2t}$. Two manufacturers' profit functions can be rewritten as Eqs. 16 and 17. we have the first-order condition of p_a, g and p_b, and get $p_a(p_b) = \frac{kt(q_\Delta + p_b + t - \alpha)}{2kt - 1}$ $g(p_b) = \frac{q_\Delta + p_b + t - \alpha}{4kt - 2}$ and $p_b(p_a, g) = \frac{t - q_\Delta + p_a - g + \alpha}{2}$. The profit functions are concave in two prices due to

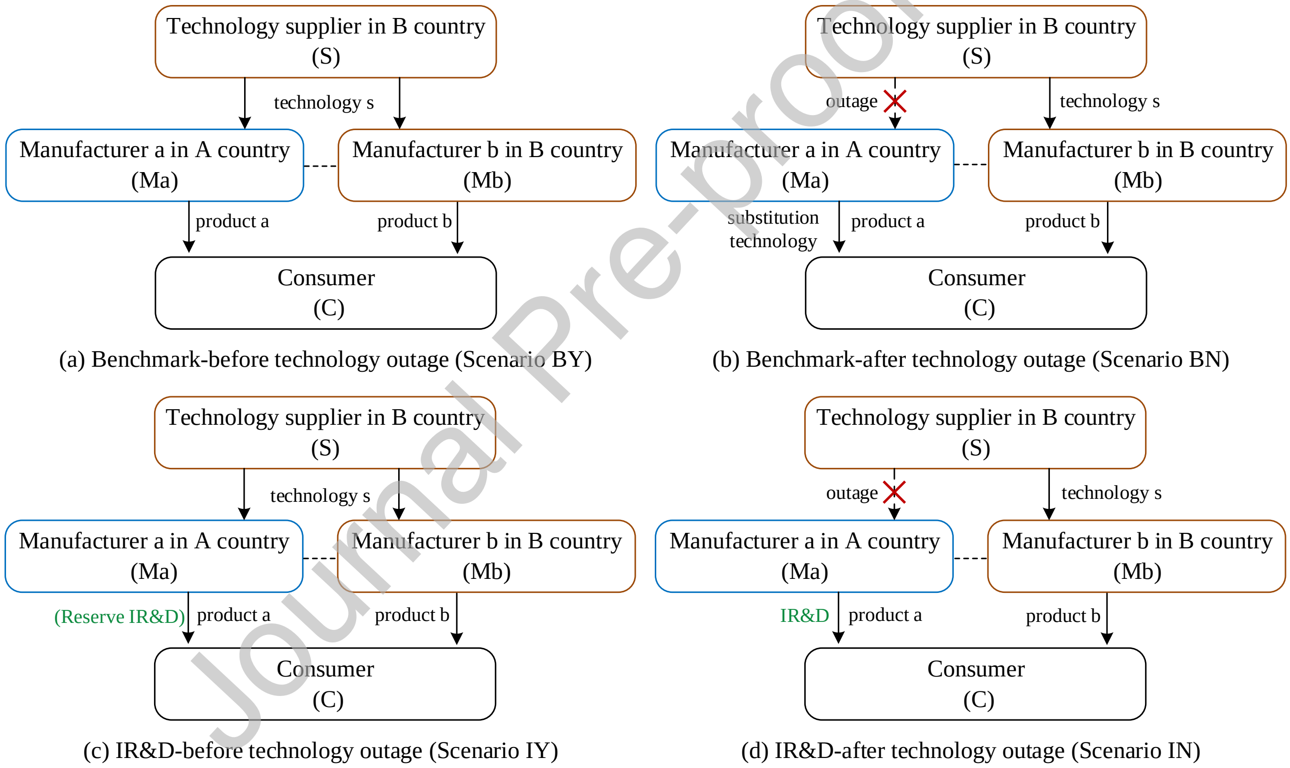
$\frac{\partial^2 \pi_{Ma}^{IN}}{\partial p_a^2} = -\frac{1}{t} < 0$, $H_2 = \begin{bmatrix} -\frac{1}{t} & \frac{1}{t} \\ \frac{1}{t} & -2k \end{bmatrix} = \frac{2kt-1}{t^2} > 0$ and $\frac{\partial^2 \pi_{Mb}^{IY}}{\partial p_b^2} = -\frac{1}{t} < 0$. Solving the simultaneous equations, we can gain the equilibrium decisions shown at table 4.

Proof of Proposition 5.

This Proposition is easily proved by comparing the results of Proposition 4, so we omit it.

Graphical Abstract

Figure 1. Technology and products supply chain structures



(a) Benchmark-before technology outage (Scenario BY) (b) Benchmark-after technology outage (Scenario BN)

(c) IR&D-before technology outage (Scenario IY) (d) IR&D-after technology outage (Scenario IN)

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Conflict of Interest

Dear editor of Fundamental Research,

No conflict of interest exists in the submission of this manuscript, and the manuscript has been approved by all authors for publication. I would like to declare on behalf of my coauthor that the work is original research that has not been published previously and is not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the enclosed manuscript.