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Blockchain adoption and mode selection strategies for remanufacturing supply chain under cap-and-trade policy

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ABSTRACT

Environmental conservation and economic advantages have propelled the swift expansion of the remanufacturing industry. Many original equipment manufacturers (OEMs) delegate remanufacturing operations to third-party remanufacturers (TPRs) through outsourcing and authorization. Furthermore, blockchain technology enhances consumers' intention to purchase remanufactured products by disclosing more product information. To investigate the impacts of blockchain on remanufacturing mode selection, this paper focuses on a competitive remanufacturing supply chain comprising an OEM and a TPR under a cap-and-trade policy. Further, four game-theoretic models are derived from whether to adopt blockchain technology and which remanufacturing mode to select. Three major findings are obtained by solving and comparing the four models: (1) Adopting blockchain does not consistently result in advantages for both the OEM and TPR, and they should adopt blockchain for information disclosure in instances where the unit blockchain adoption cost is low, and the disclosure degree of remanufactured product information is also low. (2) Compared with not adopting blockchain technology, if the unit blockchain adoption cost is low, blockchain technology will increase the remanufactured product sales, thereby fostering the advancement of remanufacturing and contributing to reducing the environmental impact. (3) Whether blockchain is adopted or not, the OEM always tends to be in the outsourcing remanufacturing mode. The TPR only opts for the outsourcing remanufacturing mode when consumers' preference for remanufactured products is high. More importantly, adopting blockchain will likely enhance consumers' preference for remanufactured products, potentially shifting the TPR's inclination for remanufacturing mode from authorization to outsourcing in some instances.

1. Introduction

In recent years, the escalating concern regarding global climate change has grown significantly, with excessive carbon emissions recognized as a major cause of climate deterioration (Taleizadeh et al., 2021). Thus, several countries and regions have enacted a range of policies to curb carbon emissions, such as cap-and-trade policies (CTPs), carbon taxes, and various subsidies (Seydanlou et al., 2022; Tiwari et al., 2021). Among them, CTPs are generally recognized as the most efficient market-based approach due to their market-oriented and economic incentive characteristics (Xu et al., 2023). Within this regulatory framework, the government establishes emission allowances for specific industries, companies, or organizations and converts these allowances into tradable carbon permits that companies can buy or sell based on their emissions (Ghosh et al., 2020; Entezaminia et al., 2021). The European Union emissions Trading Market, established in 2005, is the world's first large-scale carbon trading market and has contributed to saving approximately 50 % of the EU's carbon emissions (Shu et al., 2017). China also established its carbon emissions trading market in July 2021, now the world's largest.

Simultaneously achieving a low-carbon economy through a CTP, remanufacturing is a pivotal driving force in fostering sustainable development. As an environmentally friendly production method, remanufacturing can effectively reduce greenhouse gas emissions and energy consumption by recycling products at the end of their lifespan, offering both environmental and economic benefits (Ferguson et al., 2009). The data demonstrates that, in contrast to producing new products, remanufacturing production can result in a minimum of 50 % cost

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savings, 60 % energy conservation, and 70 % reduction in raw material usage (Matsumoto et al., 2016). In practice, numerous manufacturers, including Caterpillar, Bosch, HP, and GE, have successfully engaged in remanufacturing and derived significant benefits from it (Reimann et al., 2019). Bosch, for instance, has produced 2.5 million remanufactured parts per year since the initiation of its eXchange Project during the 1980 s, which are 40 % cheaper than new parts. However, owing to a dearth of exclusive remanufacturing technology and the inherent lower profitability of remanufactured products compared to new ones, original equipment manufacturers (OEMs) typically delegate recycling and remanufacturing operations to specialized third-party remanufacturers (TPRs) (Agrawal et al., 2015). Protected by intellectual property rights, two main modes of entrusting recycling and remanufacturing operations in the industry are outsourcing remanufacturing and authorization remanufacturing (Zhang et al., 2021). In the outsourcing remanufacturing mode, OEMs pay outsourcing fees to delegate the remanufacturing process to TPRs but retain the authority to market the remanufactured products. For example, Dell delegated the remanufacturing process to Wistron, and Land Rover has partnered with Caterpillar to outsource remanufacturing to it (Pasha et al., 2022). In the authorization remanufacturing mode, OEMs delegate the entire remanufacturing process and the right to sell remanufactured products to TPRs for licensing fees. Authorization remanufacturing is also favored by companies, with Apple licensing its remanufacturing business to Foxconn, which sells remanufactured products through its proprietary channels (Zhou et al., 2021). In conclusion, the impact mechanisms on OEM and TPR business decisions vary among different remanufacturing modes. Therefore, it holds considerable practical importance to explore the decisions of OEMs and TPRs and the selection strategies of remanufacturing mode.

In practice, given the non-transparent production process of remanufactured products and a lack of publicity, a significant portion of consumers harbors apprehensions about product quality. As a result, consumers exhibit a lower willingness to pay (WTP) for remanufactured products compared to new ones (Abbey et al., 2019; Aydin & Mansour, 2023). When consumers want to buy an Apple iPod MP3 player, they prioritize a new product over a remanufactured one. The rise of blockchain technology offers a promising solution to this issue (Babich & Hilary, 2020; Dutta et al., 2020). Blockchain is fundamentally a decentralized distributed database designed to efficiently, verifiably, and permanently record transactions between two parties, with visibility, verification, and immutability advantages (Azzi et al., 2019; Centobelli et al., 2022). It is a network of multiple computer nodes; each keeps an identical copy of the data, verifies and records transactions through consensus algorithms, and has been widely adopted in several fields (Saberi et al., 2019). Walmart partners with IBM to implement blockchain technology to trace mango origins. In just 2.2 s, blockchain users can access comprehensive details regarding the source, origin, and storage of mangoes (Kamath, 2018). Additionally, Everledger utilizes blockchain to document and authenticate the origin and identification details of gemstones and jewelry, aiming to mitigate gemstone smuggling and counterfeiting issues (Yang et al., 2022).

During the remanufacturing process, blockchain can identify and record production and inspection information for key components. By disclosing a complete and accurate history of a product to consumers, blockchain technology can build consumer trust in remanufactured products (Montecchi et al., 2019). As an illustration, Volvo Cars has partnered with Circulor to implement a blockchain traceability system to enable real-time tracking and logging of the sourcing, production, and distribution of industrial parts to ensure supply chain transparency and traceability, improving product quality and customer satisfaction (Choi et al., 2020). In addition, OEMs and TPRs can make accurate production decisions during the remanufacturing process with precise information provided by the blockchain, thereby achieving goals such as resource optimization, cost control, and sustainability. For example, Siemens has partnered with suppliers to develop a project called Digital Supply Chain, which aims to use blockchain technology to improve supply chain management and product traceability in the automotive manufacturing industry. However, although blockchain technology can enhance consumers' WTP and expand the remanufacturing market, adopting blockchain faces several challenges such as cost, privacy breaches, and legal issues (Govindan, 2022). Therefore, OEMs and TPRs should consider the advantages and disadvantages of blockchain technology before adopting it. Overall, it is necessary to evaluate two scenarios of the adoption and non-adoption of blockchain, analyze the optimal strategies made by OEMs and TPRs, and examine the conditions for adopting blockchain technology.

In summary, both CTPs and blockchain technology significantly impact the optimal decisions of both OEMs and TPRs, thereby influencing the selection of remanufacturing modes. However, few studies have thoroughly explored the effects of both CTPs and blockchain technology on the remanufacturing supply chain. To address these research gaps, the subsequent research questions are focused on: (1) Under the CTP, how do OEMs and TPRs choose between the outsourcing and authorization remanufacturing modes? (2) When will OEMs and TPRs adopt blockchain technology for information disclosure under different remanufacturing modes? (3) What are the optimal remanufacturing mode selection strategies for OEMs and TPRs when adopting blockchain technology, and how does blockchain technology impact the remanufacturing mode selection?

To answer the above issues, the present study considers a supply chain consisting of an OEM and a TPR and studies their decisions concerning whether to adopt blockchain technology and which remanufacturing mode to select. Firstly, the equilibrium solutions of the four models are determined. Following this, a comprehensive comparison ensues, delving into the OEM and TPR's optimal prices, quantities, and profits under different models. Simultaneously, a sensitivity analysis is conducted. Finally, we provide insights into the interaction between blockchain technology adoption and remanufacturing mode selection through numerical analysis.

Overall, our contributions are summarized in the following two points. (1) Although scholars have previously compared the remanufacturing modes of outsourcing and authorization, our analysis extends to examining the impact of CTP and blockchain technology on operational decisions for both the OEM and TPR under two remanufacturing modes. (2) Secondly, we combine blockchain and remanufacturing to examine the conditions for adopting blockchain in different remanufacturing modes and further analyze whether blockchain technology will affect the selection of manufacturing mode.

The subsequent sections of this paper unfold as follows: Section 2 delves into the relevant literature, while Section 3 delineates the research problem and presents the hypotheses. Moving forward, Section 4 formulates and resolves game models. Section 5 undertakes sensitivity and comparative analyses. Section 6 follows suit by conducting a numerical analysis. The paper concludes with Section 7, describing findings and future research directions.

2. Literature review

This paper identifies three primary areas of literature pertinent to the topic: the impact of cap-and-trade policy on remanufacturing, remanufacturing mode selection, and the adoption of blockchain in supply chains.

2.1. The impact of cap-and-trade policy on remanufacturing

Cap-and-trade policy, as one of the primary policy responses to the challenge of climate change, affects carbon emissions and remanufacturing activities (Ebrahimi et al., 2022; Kundu & Chakrabarti, 2018; Mishra et al., 2020). Turki et al. (2018) examined the role of CTP in reducing emissions. Results indicated that lowering the cap on carbon emissions or increasing carbon trading price would incentivize manufacturers to engage in remanufacturing, thus effectively reducing carbon emissions. Dey et al. (2023) found that CTP and green investments are crucial for both profit enhancement and carbon emissions reduction. Xia et al. (2023) studied three carbon emission reduction models under outsourced remanufacturing and found that carbon trading prices and consumer preferences are essential to manufacturers making emission reduction decisions. Based on the above studies, several scholars have undertaken in-depth research regarding the influence of this policy on remanufacturing. Chai et al. (2018) provided evidence that implementing the CTP can facilitate the expansion of the industry across both conventional and green markets. Kushwaha et al. (2020) examined manufacturers' decisions on recycling modes under the CTP. Zhao et al. (2021) studied operational decisions of competitive remanufacturing supply chain closures considering both CTP and quality uncertainty. Hong et al. (2021) found that manufacturers are more inclined to disclose information about the quality of their products to realize higher profits, especially if consumers prefer higher-quality products. Waltho et al. (2019) constructed a distributed robust optimization model to investigate the optimal production decisions within the closed-loop supply chain. Sun and Liu (2023) also consider the effects of consumer education and CTPs on OEM and IR operating decisions. They found that increasing carbon prices will effectively encourage manufacturers to move into the remanufacturing sector, thereby fostering the growth of the remanufacturing industry. Compared to the literature mentioned above, this paper focuses on operational decisions for OEM and TPR in two distinct remanufacturing modes under the CTP.

2.2. The third-party remanufacturing mode

Two third-party remanufacturing modes, outsourcing, and authorization, have been extensively studied. Regarding outsourcing remanufacturing, Zhao et al. (2021) explored how outsourcing remanufacturing influences the OEM and TPR decision-making processes. Their findings suggest that outsourcing remanufacturing allows the OEM to concentrate on essential aspects of their business, such as innovating new products, thereby boosting revenue generated from remanufacturing. On this basis, Sarkar and Bhuniya (2022) explored the optimal decisions of manufacturers and remanufacturers in international outsourced remanufacturing under tax and tariff policies. Regarding authorization remanufacturing, Reimann et al. (2019) found that manufacturers are more inclined to commission a third-party remanufacturer rather than remanufacturing themselves in the presence of low remanufacturing costs. Jin et al. (2022) discussed the OEMs' authorization strategies in the remanufacturing market, including dealer and remanufacturing authorization, by analyzing the two modes of competition, cooperation, and environmental impact. Further, some scholars have combined several remanufacturing modes and studied the selection of remanufacturing modes. Zou et al. (2016) conducted the inaugural comparative analysis between the outsourcing and authorization remanufacturing modes. They found that consumers' purchase intention for remanufactured products would affect the TPR's choice of remanufacturing mode. Considering environmental responsibility and green consumption behaviors, Feng et al. (2021) analyzed the strategic decisions made by manufacturers and third-party remanufacturers to explore their optimal remanufacturing modes. Zhang et al. (2021) explored an in-depth study of remanufacturing strategic decisions and environmental impacts of contract manufacturers under two remanufacturing modes, either an outsourcing or an authorization remanufacturing mode. Zhou et al. (2023) found that manufacturers' financial constraints impact the selection of remanufacturing modes. Although the comparative study of the two third-party remanufacturing modes is relatively in-depth. With the establishment of carbon trading markets and the rise of new technologies, further study the impacts of blockchain technology and CTP on the two remanufacturing modes.

2.3. The adoption of blockchain in supply chains

The traceability and information-sharing capabilities of blockchain technology significantly contribute to enhancing supply chain efficiency (Taylor et al., 2020; Li et al., 2022; Roushan et al., 2024). Olsen and Tomlin (2020) emphasized that blockchain technology can eliminate information intermediation, improve transparency and traceability, and help fundamentally change the supply chain structure. Babich and Hilary (2020) pointed out the primary advantages and costs associated with implementing blockchain to enhance operational performance. Given the advantages of blockchain technology, it has been implemented in numerous industries, including medicine (Jamil et al., 2019), food (Vu et al., 2023), luxury (De Boissieu et al., 2021), and finance (Tsao & Vu, 2022). Tozanlı et al. (2020) discovered that adopting blockchain can enhance the capacity of remanufacturers to ascertain the pricing and quantity aspects of recycling while benefiting both consumers and remanufacturers. Niu et al. (2022) evaluated the blockchain application preference of supply chain participants under consumer risk aversion and quality distrust. Gong et al. (2023) identified that adopting blockchain into the remanufacturing competitive supply chain can improve consumers' purchase intention and environmental benefits. However, whether to introduce blockchain should consider such factors as product value, cost, and sales channels. Similarly, Xu et al. (2023) delved into integrating blockchain and remanufacturing for a supply chain model comprising manufacturers, third-party companies, and online platforms. They found that blockchain adoption can improve productivity and coordination. Considering consumer concerns about remanufactured parts, Wang et al. (2024) examined the motivations of reverse supply chain participants to adopt blockchain. The study most closely related to ours is Yang et al. (2022), who discussed the optimal strategies for manufacturers and remanufacturers to cooperate and compete under blockchain technology by considering brand advantage and patent licensing fees. In contrast, our study focuses on the impact of blockchain adoption on the OEM's and TPR's selection of two remanufacturing modes, outsourcing and authorization.

The differences between this paper and the above literature are summarized as follows. First, although there are studies that have introduced blockchain technology into the remanufacturing supply chain and explored the optimal strategies for adopting blockchain technology. Unlike the literature Yang et al. (2022), Gong et al. (2023), and Wang et al. (2024), we further analyze the impact of the adoption of blockchain technology on the remanufacturing mode. Second, the literature on blockchain technology has fewer studies that consider the CTP context. Similar to Xu et al. (2023), we consider both CTP and blockchain. Differently, we examined the motivation of supply chain members to adopt blockchain technology and the preference for remanufacturing modes under the CTP. In conclusion, the differences between our study and other studies are shown in Table 1.

3. Model description and assumptions

3.1. Description of the problem

In this study, our focus is on examining the impact of blockchain technology on the decision-making of remanufacturing supply chain members and the selection of remanufacturing mode under the CTP. We establish a two-stage remanufacturing supply chain consisting of an OEM that produces only new products and a TPR that produces remanufactured products. In practice, consumers are concerned about the quality of products and have distrust in the quality of remanufactured products. For this reason, the OEM and TPR can use blockchain technology to provide consumers with information on remanufactured products.

To prevent competition and free-riding behavior by the TPR, the OEM outsources or authorizes remanufacturing operations to the TPR to carry out based on intellectual property protection. And the OEM serves

Table 1
The differences between existing related works and our paper.

Papers	Remanufacturing	Blockchain	Cap-and-trade policy	Environment analysis
Kushwaha et al. (2020)			✓	✓
Tozanlı et al. (2020)		✓		✓
Zhang et al. (2021)	✓			✓
Niu et al. (2022)		✓		
Yang et al. (2022)	✓	✓		
Gong et al. (2023)		✓		✓
Li et al. (2023)		✓		✓
Xu et al. (2023)		✓	✓	
Xia et al. (2023)	✓		✓	✓
Wang et al. (2024)		✓		✓
This study	✓	✓	✓	✓

as the Stackelberg leader. Under the outsourcing remanufacturing mode, the OEM decides the price of new products, the unit outsourcing fee, and whether to adopt blockchain technology. The TPR decides the recycling rate of used products based on the unit outsourcing fee. Under the authorization remanufacturing mode, the OEM decides the price of new products and unit authorization fee, and the TPR decides the price of remanufactured products and the decision to adopt blockchain technology. In summary, we establish four models based on the chosen remanufacturing mode and the adoption or non-adoption of blockchain technology: (a) outsourcing remanufacturing mode without blockchain technology (model *NW*), (b) outsourcing remanufacturing mode with blockchain technology (model *BW*), (c) authorization remanufacturing mode without blockchain technology (model *NS*), and (d) authorization remanufacturing mode with blockchain technology (model *BS*). The framework of the models is shown in Fig. 1.

3.2. Model assumptions

We first outline our fundamental assumptions below and consolidate the corresponding parameters in Table 2.

Assumption 1. Assume that the total market size is 1 and consumers' WTP for a new product is θ uniformly distributed on [0,1]. Due to consumers' limited understanding of the remanufacturing process and their perception of remanufactured products as inferior to new ones, we assume that consumers' WTP for a remanufactured product is $\delta\theta$. Here, δ is the consumer preference, and $0 < \delta < 1$ (Niu et al., 2022).

Assumption 2. Consumers pay more attention to the quality of remanufactured products in the market. In traditional circumstances, OEMs and TPRs typically disclose some product information. However, the lack of a robust verification system makes it difficult for consumers to trust this information entirely. When adopting blockchain technology, OEMs and TPRs can record information about various stages of products and efficiently deliver it to consumers in real time. Referring to

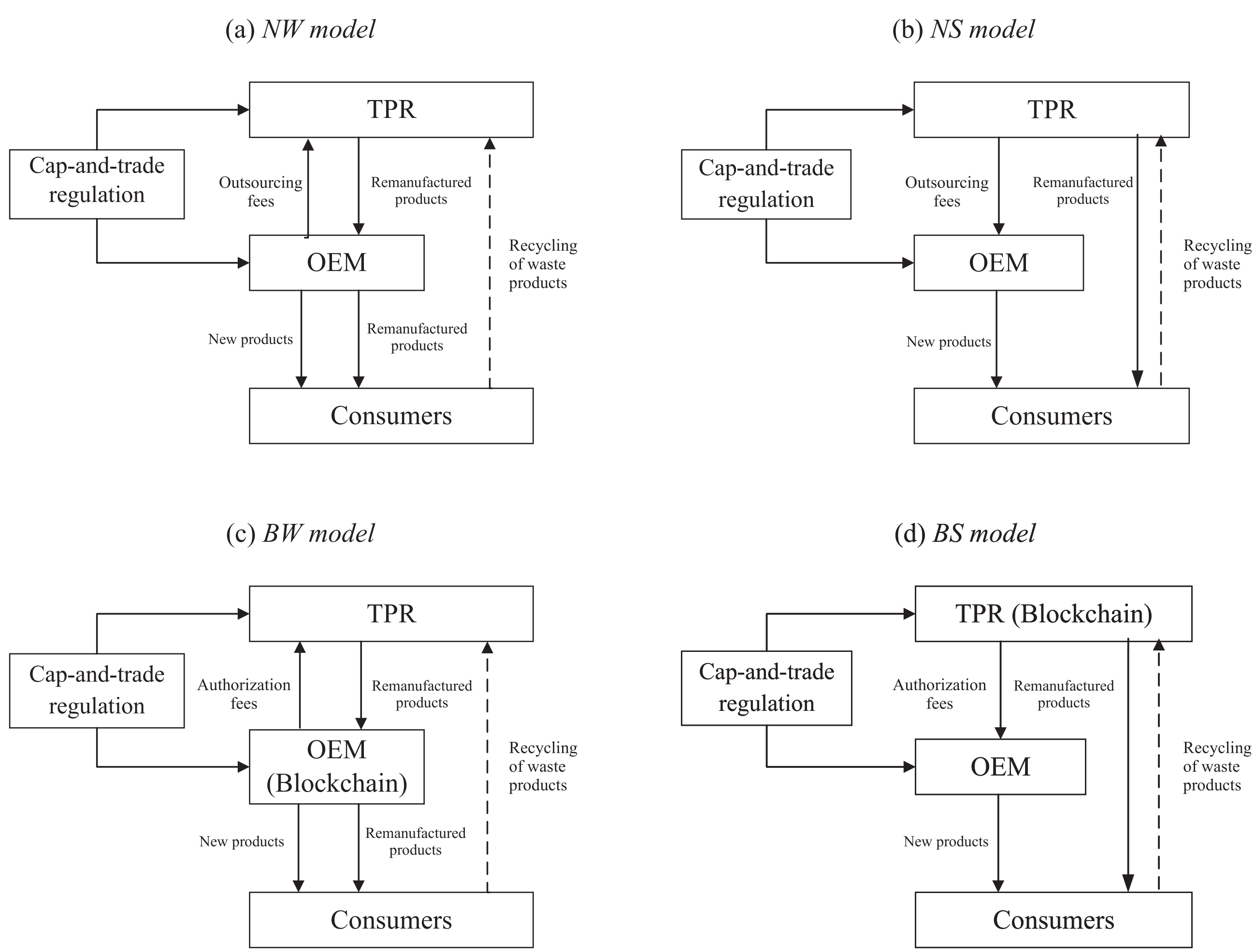


Fig. 1. Supply chain structures.

Table 2
Parameter and definitions.

Notations	Definitions
α	Disclosure degree of remanufactured product information, $0 < \alpha \le 1$
b	Unit blockchain adoption cost
p_e	Carbon trading price
E	Carbon emission quotas set by the government under a CTP
e_n/e_r	Unit environmental effects of a new/remanufactured product, $e_n > e_r$
c_n/c_r	Unit production cost of a new/remanufactured product, $c_n > c_r$
p_n/p_r	Selling price of new/remanufactured products
π_n/π_r	Profit of the OEM/TPR
Index	
n/r	OEM/TPR
NW/BW	Outsourcing remanufacturing mode without/with blockchain
NS/BS	Authorization remanufacturing mode without/with blockchain
Decision variables	
q_n/q_r	Quantity of new/remanufactured products
τ	The recycling rate of waste products, $0 < \tau < 1$
ω	Unit outsourcing fee
z	Unit authorization fee

(Yang et al., 2022), this paper assumes that the disclosure degree of remanufactured product information is denoted by α. when the OEM/TPR makes information disclosure via blockchain, $\alpha = 1$, otherwise $0 < \alpha < 1$. Additionally, the unit cost incurred when adopting blockchain technology is represented by b.

From Assumptions 1 and 2, consumers have a WPT of θ for the new product and $\alpha\delta\theta$ for the remanufactured product. According to Yang et al. (2022) and Niu et al. (2022), the utility of consumers buying new products and remanufactured products is $u_n = \theta - p_n$ and $u_r = \alpha\delta\theta - p_r$ respectively. Based on net utility maximization, the relationship between the market demand for the two products and the retail price per unit is respectively $q_n = 1 - \frac{p_n - p_r}{1-\alpha\delta}$, $q_r = \frac{p_n - p_r}{1-\alpha\delta} - \frac{p_r}{\alpha\delta}$. Thus, the inverse demand function for the two products is expressed as:

$$p_n(q_n, q_r) = 1 - q_n - \alpha\delta q_r \tag{1}$$

$$p_r(q_n, q_r) = \alpha\delta(1 - q_n - q_r) \tag{2}$$

Assumption 3. For used products, the TPR cannot take back all of them, so we assume that the collection rate of used products is $\tau \in (0, 1)$. Drawing on Xia et al. (2023), the recovery cost function is $\frac{k}{2}(\tau q_n)^2$, where k is the recycling scale coefficient for used products.

Assumption 4. The unit production cost of the new product and the remanufactured product are denoted as c_n and c_r, assuming $0 < c_r < c_n$. Following a similar assumption as Tang et al. (2020), it is assumed that $\delta c_n > c_r$ and $\delta > c_n$.

Assumption 5. Suppose the government gives OEM and TPR the same carbon allowances, less than what is needed to produce a new product and more than what is needed to produce a remanufactured product. If there is a shortage or surplus of carbon credits, OEM and TPR can choose to buy or sell them, and the carbon price is traded at p_e.

4. Model formulations and solution

4.1. Model NW

In model NW, the TPR recycles and manufactures used products and next delivers the finished products to the OEM, which sells new products as well as remanufactured products to consumers and does not adopt blockchain. The OEM first determines q_n and ω. Then, the TPR determines τ to optimize profits. The profits of the OEM and TPR are as follows:

$$\pi_n^{NW}(q_n^{NW}, \omega^{NW}) = (p_n^{NW} - c_n)q_n^{NW} + (p_r^{NW} - \omega^{NW})q_r^{NW} - (e_n q_n^{NW} - E)p_e \tag{3}$$

$$\pi_r^{NW}(\tau^{NW}) = (\omega^{NW} - c_r)q_r^{NW} - \frac{k}{2}(\tau^{NW}q_n^{NW})^2 - (e_r q_r^{NW} - E)p_e \tag{4}$$

According to backward induction, the optimal solution of model NW is shown in Table 3. Refer to Appendix A for the derivation process.

4.2. Model BW

In model BW, the TPR produces remanufactured products and delivers them to the OEM, which sells new products as well as remanufactured products to consumers and discloses the information for remanufactured products through blockchain technology. Similarly, the OEM first determines q_n and ω. Subsequently, the TPR determines τ. The profits of the OEM and TPR are as follows:

$$\pi_n^{BW}(q_n^{BW}, \omega^{BW}) = (p_n^{BW} - c_n)q_n^{BW} + (p_r^{BW} - \omega^{BW} - b)q_r^{BW} - (e_n q_n^{BW} - E)p_e \tag{5}$$

$$\pi_r^{BW}(\tau^{BW}) = (\omega^{BW} - c_r)q_r^{BW} - \frac{k}{2}(\tau^{BW}q_n^{BW})^2 - (e_r q_r^{BW} - E)p_e \tag{6}$$

Applying backward induction, the optimal solution of model BW is presented in Table 3. Refer to Appendix B for details on the derivation process.

4.3. Model NS

In model *NS*, the TPR independently markets remanufactured products, compensates the OEM through authorization fees, and does not adopt blockchain. In this case, the OEM first determines q_n and z. Then, the TPR determines the recycling rate of waste products τ. The profits of the OEM and TPR are as follows:

$$\pi_n^{NS}(q_n^{NS}, z^{NS}) = (p_n^{NS} - c_n)q_n^{NS} + z^{NS}q_r^{NS} - (e_n q_n^{NS} - E)p_e \tag{7}$$

$$\pi_r^{NS}(\tau^{NS}) = (p_r^{NS} - c_r - z^{NS})q_r^{NS} - \frac{k}{2}(\tau^{NS}q_n^{NS})^2 - (e_r q_r^{NS} - E)p_e \tag{8}$$

According to backward induction, the optimal solution of model NS is presented in Table 4. For a detailed step-by-step derivation process, please refer to Appendix C.

4.4. Model BS

In model *BS*, the TPR sells the remanufactured products on its own, pays a unit fee to the OEM, and discloses information about the remanufactured products through blockchain technology. The profits of the OEM and TPR are as follows:

$$\pi_n^{BS}(q_n^{BS}, z^{BS}) = (p_n^{BS} - c_n)q_n^{BS} + z^{BS}q_r^{BS} - (e_n q_n^{BS} - E)p_e \tag{9}$$

$$\pi_r^{BS}(\tau^{BS}) = (p_r^{BS} - c_r - z^{BS} - b)q_r^{BS} - \frac{k}{2}(\tau^{BS}q_n^{BS})^2 - (e_r q_r^{BS} - E)p_e \tag{10}$$

By backward induction, the optimal solution of model BS is presented in Table 4. For a detailed step-by-step derivation process, please refer to Appendix D.

5. Model analysis

In this section, we first compare the prices and sales of new and remanufactured products under different models. Subsequently, we analyze the profits of the OEM and TPR across four different models to explore their options for adopting blockchain technology and remanufacturing modes. Finally, CTP and environmental impact are considered.

Table 3
The optimal solution in outsourcing remanufacturing mode.

	Model *NW*	Model *BW*
p_n^*	$\frac{1+c_n+e_np_e}{2}$	$\frac{1+c_n+e_np_e}{2}$
p_r^*	$\alpha\delta\left[\frac{1}{2}+\frac{k(c_n+e_np_e)+(1-\alpha\delta)(c_r+e_rp_e)}{2(k+\alpha\delta(1-\alpha\delta))}\right]$	$\delta\left[\frac{1}{2}+\frac{k(c_n+e_np_e)+(1-\delta)(c_r+e_rp_e+b)}{2(k+\delta-\delta^2)}\right]$
q_n^*	$\frac{1}{2}-\frac{(k+\alpha\delta)(c_n+e_np_e)-\alpha\delta(c_r+e_rp_e)}{2(k+\alpha\delta(1-\alpha\delta))}$	$\frac{1}{2}-\frac{(k+\delta)(c_n+e_np_e)-\delta(c_r+e_rp_e+b)}{2(k+\delta-\delta^2)}$
q_r^*	$\frac{\alpha\delta(c_n+e_np_e)-(c_r+e_rp_e)}{2(k+\alpha\delta(1-\alpha\delta))}$	$\frac{\delta(c_n+e_np_e)-(c_r+e_rp_e+b)}{2(k+\delta-\delta^2)}$
π_n^*	$\frac{(1-c_n-e_np_e)^2}{4}+\frac{[\alpha\delta(c_n+e_np_e)-(c_r+e_rp_e)]^2}{4(k+\alpha\delta(1-\alpha\delta))}+Ep_e$	$\frac{(1-c_n-e_np_e)^2}{4}+\frac{[\delta(c_n+e_np_e)-(c_r+e_rp_e+b)]^2}{4(k+\delta-\delta^2)}+Ep_e$
π_r^*	$\frac{k(\alpha\delta(c_n+e_np_e)-(c_r+e_rp_e))^2}{8(k+\alpha\delta(1-\alpha\delta))^2}+Ep_e$	$\frac{k(\delta(c_n+e_np_e)-(c_r+e_rp_e+b))^2}{8(k+\delta-\delta^2)^2}+Ep_e$
ω^*	$c_r+e_rp_e+\frac{k(\alpha\delta(c_n+e_np_e)-(c_r+e_rp_e))}{2(k+\alpha\delta(1-\alpha\delta))}$	$c_r+e_rp_e+\frac{k\delta(c_n+e_np_e)-k(c_r+e_rp_e+b)}{2(k+\delta-\delta^2)}$
τ^*	$\frac{\alpha\delta(c_n+e_np_e)-(c_r+e_rp_e)}{(k+\alpha\delta)(1-c_n+e_np_e)+\alpha\delta(c_r+e_rp_e-\alpha\delta)}$	$\frac{\delta(c_n+e_np_e)-(c_r+e_rp_e+b)}{(k+\delta)(1-c_n+e_np_e)+\delta(c_r+e_rp_e-\delta+b)}$

Table 4
The optimal solution in authorization remanufacturing mode.

	Model *NS*	Model *BS*
p_n^*	$\frac{1+c_n+e_np_n}{2}$	$\frac{1+c_n+e_np_n}{2}$
p_r^*	$\alpha\delta\left[\frac{1}{2}+\frac{(k+\alpha\delta)(c_n+e_np_e)+(1-\alpha\delta)(c_r+e_rp_e)}{2(k+\alpha\delta(2-\alpha\delta))}\right]$	$\delta\left[\frac{1}{2}+\frac{(k+\delta)(c_n+e_np_e)+(1-\delta)(c_r+e_rp_e+b)}{2(k+2\delta-\delta^2)}\right]$
q_n^*	$\frac{1}{2}-\frac{(2\alpha\delta+k)(c_n+e_np_e)-\alpha\delta(c_r+e_rp_e)}{2(k+\alpha\delta(2-\alpha\delta))}$	$\frac{1}{2}-\frac{(2\delta+k)(c_n+e_np_e)-\delta(c_r+e_rp_e+b)}{2(k+2\delta-\delta^2)}$
q_r^*	$\frac{\alpha\delta(c_n+e_np_e)-c_r+e_rp_e)}{2(k+\alpha\delta(2-\alpha\delta))}$	$\frac{\delta(c_n+e_np_e)-(c_r+e_rp_e+b)}{2(k+2\delta-\delta^2)}$
π_n^*	$\frac{(1-c_n-e_np_e)^2}{4}+\frac{[\alpha\delta(c_n+e_np_e)-(c_r+e_rp_e)]^2}{4(k+\alpha\delta(2-\alpha\delta))}+Ep_e$	$\frac{(1-c_n-e_np_e)^2}{4}+\frac{[\delta(c_n+e_np_e)-(c_r+e_rp_e+b)]^2}{4(k+2\delta-\delta^2)}+Ep_e$
π_r^*	$\frac{(k+2\alpha\delta)(\alpha\delta(c_n+e_np_e)-(c_r+e_rp_e))^2}{8(k+\alpha\delta(2-\alpha\delta))^2}+Ep_e$	$\frac{(k+2\delta)(\delta(c_n+e_np_e)-(c_r+e_rp_e+b))^2}{8(k+2\delta-\delta^2)^2}+Ep_e$
z^*	$\frac{\alpha\delta-c_r-e_rp_e}{2}$	$\frac{\delta-c_r-e_rp_e-b}{2}$
τ^*	$\frac{\alpha\delta(c_n+e_np_e)-(c_r+e_rp_e)}{(k+2\alpha\delta)(1-c_n-e_np_e)+\alpha\delta(c_r+e_rp_e-\alpha\delta)}$	$\frac{\delta(c_n+e_np_e)-(c_r+e_rp_e+b)}{(k+2\delta)(1-c_n-e_np_e)+\delta(c_r+e_rp_e+b-\delta)}$

5.1. Comparison of equilibrium results

Proposition 1. Comparing the retail prices of new products and remanufactured products under the four models, the relationship is as follows:

(a) $p_n^{NW*}=p_n^{BW*}=p_n^{NS*}=p_n^{BS*}$, $p_r^{NW*}<p_r^{BW*}$,$p_r^{NS*}<p_r^{BS*}$;
(b) $p_r^{NW*}<p_r^{NS*}$, $p_r^{BW*}<p_r^{BS*}$.

Proof. See Appendix E.

Proposition 1(a) shows that the adoption of blockchain does not affect the price of new products regardless of the remanufacturing mode. This is because OEMs dominate the supply chain being able to make complete decisions on the selling price of new products and the adoption of blockchain technology does not change this. For remanufactured products, blockchain invariably results in price increases. Adopting blockchain increases the costs of remanufactured products while also enhancing their competitiveness, both of which contribute to higher prices overall.

Proposition 1(b) implies that whether blockchain technology is adopted or not, remanufactured product prices are elevated in the authorization remanufacturing mode. This is because new products lack the environmental and cost advantages associated with remanufactured products. In the authorization remanufacturing mode, remanufactured products are marketed by the TPR, leading to heightened competition between the two products. Consequently, in response to the competition from the TPR, the OEM increased authorization fees, ultimately resulting in higher prices for remanufactured products.

Management Insight: Blockchain technology can improve product security, quality, and transparency on the one hand, thereby reducing consumer distrust of products. On the other hand, the cost of implementation may lead to an increase in the price of products, which may reduce consumers' willingness to buy. Therefore, manufacturers need to conduct a comprehensive cost-benefit analysis to decide whether to introduce blockchain technology. Government support and guidance play a significant role in accelerating technological development and promoting innovative applications. Governments can use various means, such as providing tax incentives, subsidies, or rewards, to encourage enterprises to invest in and adopt blockchain technology.

Proposition 2. Comparing the unit outsourcing fee under the outsourcing remanufacturing mode and the unit authorization fee under the authorization remanufacturing mode, the relationship is as follows:

(a) If $b\leqslant b_1$, $\omega^{NW*}\leqslant\omega^{BW*}$, otherwise, $\omega^{NW*}>\omega^{BW*}$;
(b) If $b\leqslant b_2$, $z^{NS*}\leqslant z^{BS*}$, otherwise, $z^{NS*}>z^{BS*}$.

Proof. See Appendix F.

Proposition 2 suggests that adopting blockchain technology increases the outsourcing and authorization fees when the unit blockchain cost is low. The reason is that adopting blockchain at this time will expand the profits generated by remanufactured products. Under the outsourcing mode, the OEM directly gains from remanufactured product sales, opting to raise outsourcing fees incrementally to ensure mutual benefits for the TPR. Under the authorization mode, the OEM generates profits from remanufactured products by increasing authorization fees.

Management Insights: In practice, to prevent competition and free-riding behavior by TPRs, OEMs authorize or outsource remanufacturing operations to TPRs based on intellectual property protection. OEMs should adopt a series of strategies to maintain a dominant position, including building a solid supply chain network, adopting advanced technology, continuous innovation, and focusing on sustainability. At the same time, there is a need to balance the relationship with the TPRs and ensure the interests of the partners to maintain a long-term collaborative and win–win relationship.

Proposition 3. Comparing the sales of new products and remanufactured products under the four models, the relationship is as follows:

(a) If $b \leqslant b_3$, $q_n^{NW*} \geqslant q_n^{BW*}$, otherwise, $q_n^{NW*} < q_n^{BW*}$; If $b \leqslant b_4$, $q_n^{NS*} \geqslant q_n^{BS*}$, otherwise, $q_n^{NS*} < q_n^{BS*}$; If $b \leqslant b_5$, $q_r^{NW*} \leqslant q_r^{BW*}$, otherwise, $q_r^{NW*} > q_r^{BW*}$; If $b \leqslant b_6$, $q_r^{NS*} \leqslant q_r^{BS*}$, otherwise, $q_r^{NS*} > q_r^{BS*}$;
(b) $q_n^{NW*} < q_n^{NS*}$,$q_n^{BW*} < q_n^{BS*}$; $q_r^{NW*} > q_r^{NS*}$, $q_r^{BW*} > q_r^{BS*}$.

Proof. See Appendix G.

Proposition 3(a) suggests that when the unit blockchain adoption cost is low, adopting blockchain can boost new product sales while reducing remanufactured product sales. This is because, on the one hand, adopting blockchain technology increases consumers' WTP for remanufactured products, consequently boosting the demand for remanufactured products. On the other hand, the increased expenses associated with blockchain compels the OEM and TPR to elevate the remanufactured product prices, leading to a reduction of their utility and demand. When the costs of adopting blockchain are low, the benefits derived from blockchain technology surpass its costs. At this time, adopting blockchain increases the competitive advantage of remanufactured products, which in turn boosts their market share while decreasing the market share of new products.

According to Proposition 3(b), new product sales are always lower, and remanufactured product sales are always higher under the outsourcing remanufacturing mode. The cost advantage of new products is weaker under the CTP. Thus, in the outsourcing mode, the OEM will expand the production of remanufactured products to make more profit. In the authorization mode, the OEM produces more new products to maintain the competitive advantage. Hence, outsourcing remanufacturing proves more effective in scaling up remanufacturing production compared to authorization remanufacturing.

Management Insights: To expand the scale of remanufacturing production, on the one hand, OEMs and TPRs can invest in the research and development of new technologies, like blockchain technology. By introducing new technologies, OEMs and TPRs can achieve a higher level of quality control and improve the competitiveness of products. On the other hand, compared with authorization remanufacturing, OEMs can improve the unfavorable position of new products being eroded by remanufactured products in terms of market share through selling price adjustments under outsourcing remanufacturing.

5.2. Optimal model selection strategies

Proposition 4. The profits of the OEM under the four models satisfy the following relationship:

(a) If $b \leqslant B_1$, $\pi_n^{NW*} \leqslant \pi_n^{BW*}$, otherwise, $\pi_n^{NW*} > \pi_n^{BW*}$; If $b \leqslant B_2$, $\pi_n^{NS*} \leqslant \pi_n^{BS*}$, otherwise, $\pi_n^{NS*} > \pi_n^{BS*}$;
(b) $\pi_n^{NW*} > \pi_n^{NS*}$,$\pi_n^{BW*} > \pi_n^{BS*}$.

Proof. See Appendix H.

Proposition 4(a) suggests that the OEM's profits will increase with adopting blockchain when the unit blockchain adoption cost is low. According to Propositions 4–6, at this point, adopting blockchain increases the demand for remanufactured products. In the outsourcing mode, the OEM possesses the authority to market remanufactured products and it can adopt blockchain technology for information disclosure. Thus, when blockchain costs are low, the OEM tends to adopt blockchain. Similarly, in the authorization mode, the OEM responds to competition from the TPR by adjusting authorization fees. When blockchain adoption costs are low, the total authorization fees are sufficient to compensate OEM's lost profits on new products, at which point the OEM will support TPR in adopting blockchain technology.

Proposition 4(b) demonstrates that regardless of adopting blockchain, OEM is favoring outsourcing remanufacturing. This is because, under outsourcing remanufacturing, the OEM has the right to sell both new and remanufactured products, with the flexibility to optimize profits by adjusting the retail prices for both products and outsourcing fees. While blockchain technology improves supply chain transparency and traceability, it does not change the dominant position of the OEM, and the OEM can still be more profitable through flexible pricing. Adopting blockchain thus does not change the OEM's selection of optimal remanufacturing mode.

Management Insights: Blockchain technology has potential benefits in remanufacturing, including improved transparency and traceability of product information. When considering blockchain technology, OEMs and TPRs should conduct a cost-benefit analysis, especially regarding the cost of blockchain usage. By optimizing technology architecture, adopting open-source software, improving operational efficiency, and collaborating with TPRs, OEMs can effectively reduce blockchain development, deployment, and maintenance costs. In addition, OEMs need to pay close attention to technology trends, as well as adjust their corporate technology strategies promptly to ensure their competitiveness.

Proposition 5. The profits of the TPR under the four models satisfy the following relationship:

(a) If $b \leqslant B_3$, $\pi_r^{NW*} \leqslant \pi_r^{BW*}$, otherwise, $\pi_n^{NW*} > \pi_n^{BW*}$; If $b \leqslant B_4$, $\pi_r^{NS*} \leqslant \pi_r^{BS*}$, otherwise, $\pi_r^{NS*} > \pi_r^{BS*}$;
(b) If $\alpha\delta > \frac{1}{2}$ and $k > \frac{2\alpha\delta(1-\alpha\delta)^2}{2\alpha\delta-1}$, $\pi_r^{NW*} > \pi_r^{NS*}$, otherwise, $\pi_r^{NW*} < \pi_r^{NS*}$; If $\delta > \frac{1}{2}$ and $k > \frac{2\delta(1-\delta)^2}{2\delta-1}$, $\pi_r^{BW*} > \pi_r^{BS*}$, otherwise, $\pi_r^{BW*} < \pi_r^{BS*}$.

Proof. See Appendix I.

Proposition 5(a) shows that when the unit blockchain adoption cost is low, the TPR gains greater profits from adopting blockchain. This is because adopting blockchain at this time increases remanufactured products' demand without causing a significant surge in prices. Thus, the TPR can get more profit from selling the remanufactured products. Conversely, when the blockchain adoption cost is high, remanufactured product sales decrease due to a substantial increase in prices, leading to an overall decrease in the profit of the TPR.

According to Proposition 5(b), TPR tends to favor the outsourcing remanufacturing mode when consumer preference is greater than 0.5, and the used product recycling scale parameter is greater than a specific threshold. Under the outsourcing remanufacturing mode, TPR's primary source of profit is the total outsourcing fees, while under the authorization remanufacturing mode the primary source of profit is sales of remanufactured products. When consumer preference is greater than 0.5 but less than a certain value, the TPR can make more profit under the authorization of remanufacturing. However, as consumer preference increases, making the remanufactured product more competitive, the OEM raises authorization fees to cope with the competition. At this point, the profit of the TPR under the authorization remanufacturing then decreases, and the TPR is more inclined to the outsourcing remanufacturing mode. In conjunction with Proposition 9, when consumer preferences and the parameters of the scale of recycling of used products satisfy certain conditions, both OEM and TPR will realize a win–win situation under outsourcing remanufacturing.

Management Insights: Adopting blockchain has a notable effect on the strategy and profitability of TPRs. In cases where blockchain costs are low, TPRs can more actively support adopting blockchain technology because the potential return on investment is more attractive. However, in the case of higher costs, they need to develop a more prudent technology investment strategy, possibly opting for an incremental implementation approach to minimize initial investment risk.

Corollary 1. If $\alpha\delta > \frac{1}{2}$ and $\frac{2\delta(1-\delta)^2}{2\delta-1} < k < \frac{2\alpha\delta(1-\alpha\delta)^2}{2\alpha\delta-1}$, adoption of blockchain technology shifts the mode preference of the TPR from authorization to outsourcing.

Corollary 1 suggests that adopting blockchain changes the pattern preferences of the TPR when certain conditions are met in terms of consumer preferences and used product recycling scale parameters. Specifically, TPR tends to shift from the authorization remanufacturing to the outsourcing remanufacturing. This is because adopting blockchain can improve the disclosure degree of remanufactured product information, with a consequent increase in consumer preference for remanufactured products. Increased consumer preference makes it more advantageous for a TPR to choose an outsourcing remanufacturing mode after the application of blockchain in situations where the TPR would otherwise choose an authorization remanufacturing mode.

The conclusion of Corollary 1 clearly is shown in Fig. 2 by considering the mode choices for remanufacturing without and with blockchain. When the information disclosure degree is low, i.e., when consumer preference for remanufactured products is low, TPR will choose the authorization remanufacturing. But when blockchain is adopted, TPR will choose outsourcing remanufacturing. (The relevant parameters are $c_n = 0.2$, $c_r = 0.1$, $\delta = 0.8$, $e_n = 1$, $e_r = 0.6$, $p_e = 0.1$, $E = 2$, and $k = 1.1$.)

5.3. Cap-and-trade policy and environmental impacts

Proposition 6. The effect of the carbon trading price p_e on optimal solutions under the four models is as follows:

(a) $\frac{\partial p_n^{i*}}{\partial p_e} > 0$, $\frac{\partial p_r^{i*}}{\partial p_e} > 0$;

(b) $\frac{\partial q_n^{i*}}{\partial p_e} < 0$; If $\frac{e_r}{e_n} < \alpha\delta, \frac{\partial q_r^{NW*}}{\partial p_e} > 0, \frac{\partial q_r^{NS*}}{\partial p_e} > 0$, otherwise, $\frac{\partial q_r^{NW*}}{\partial p_e} < 0, \frac{\partial q_r^{NS*}}{\partial p_e} < 0$; If $\frac{e_r}{e_n} < \delta, \frac{\partial q_r^{BW*}}{\partial p_e} > 0, \frac{\partial q_r^{BS*}}{\partial p_e} > 0$, otherwise, $\frac{\partial q_r^{BW*}}{\partial p_e} < 0, \frac{\partial q_r^{BS*}}{\partial p_e} < 0$;

(c) $\frac{\partial \omega^{NW*}}{\partial p_e} > 0$, $\frac{\partial \omega^{BW*}}{\partial p_e} > 0$, $\frac{\partial z^{NS*}}{\partial p_e} < 0$, $\frac{\partial z^{BS*}}{\partial p_e} < 0$;

(d) If $p_e < p_1^i$, $\frac{\partial \pi_n^{i*}}{\partial p_e} > 0$, otherwise, $\frac{\partial \pi_n^{i*}}{\partial p_e} < 0$; If $p_e < p_2^i$, $\frac{\partial \pi_r^{i*}}{\partial p_e} > 0$, otherwise, $\frac{\partial \pi_r^{i*}}{\partial p_e} < 0$, where $i \in \{NW, BW, NS, BS\}$.

Proof. See Appendix J.

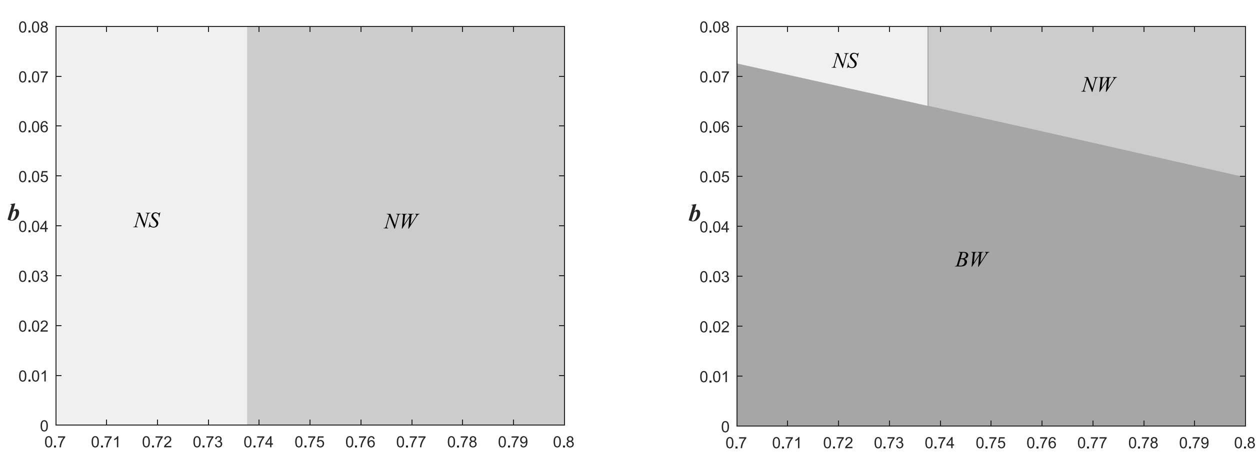
Proposition 6(a) demonstrates that the retail prices of new and remanufactured products are positively correlated with the carbon trading price under all four models. Higher carbon prices mean higher manufacturing costs to buy carbon credits to ensure smooth production. At the same time, it also implies an increase in the revenue from selling surplus carbon emission quotas. Under cost pressures, manufacturers of both products will raise the unit retail prices and increase investments in emission reduction technologies.

As shown in Proposition 6(b), new product sales are negatively correlated with the carbon trading price, while remanufactured product sales change depending on the ratio of carbon emissions of the two products and consumer preferences. This is because new products lack cost and emission reduction advantages compared to remanufactured products. Therefore, when the carbon trading price is high, the OEM will produce fewer new products to lower production costs and carbon emissions. In addition, when remanufactured products have low carbon emissions or high consumer preferences, the escalation in carbon trading price will strengthen the competitive advantage of remanufactured products. Therefore, the TPR will scale up remanufactured product output.

Proposition 6(c) indicates that with the rise of carbon trading prices, outsourcing fees increase, and authorization fees decrease. Higher carbon prices raise the cost of remanufacturing. In the outsourcing mode, the OEM will appropriately increase outsourcing fees to compensate for TPR losses. In the authorization mode, the OEM will appropriately decrease authorization fees to prevent the cost of remanufactured products from becoming excessively high, thereby increasing the total authorization fees. In combination with the above, it can be seen from Proposition 6(d) that implementing the CTP enhances the profits of two product manufacturers only when the carbon trading price exceeds a certain threshold.

Management Insight: The CTP can stimulate and guide manufacturing enterprises to lower carbon emissions, thereby fostering the advancement of remanufacturing practices. The government can discourage manufacturers from remanufacturing by modifying the carbon trading price, but it should be careful not to set it too high, lest manufacturers only gain profits by selling carbon emission allowances, hindering the advancement of remanufacturing. TPRs should give full play to the low emissions and low cost of remanufactured products and increase technological investment and R&D to improve output rates, thereby lowering carbon emissions and enhancing earnings. OEMs can maximize their benefits by choosing appropriate remanufacturing modes.

Drawing on Zhou et al. (2023), to analyze the environmental impact



(a) Without blockchain (b) With blockchain

Fig. 2. Optimal models for the TPR without and with blockchain.

of blockchain technology, the expression for the environmental impact is as follows: $EI = e_n q_n + e_r q_r$.

Proposition 7. The environmental impacts under the four models have the following relationship:

(a) If $b \leqslant B_5$, $EI^{NW*} \geqslant EI^{BW*}$, otherwise, $EI^{NW*} < EI^{BW*}$; If $b \leqslant B_6$, $EI^{NS*} \geqslant EI^{BS*}$, otherwise, $EI^{NS*} < EI^{BS*}$;
(b) If $\frac{e_r}{e_n} \leqslant \alpha\delta$, $EI^{NW*} \leqslant EI^{NS*}$, otherwise, $EI^{NW*} > EI^{NS*}$; If $\frac{e_r}{e_n} \leqslant \delta$, $EI^{BW*} \leqslant EI^{BS*}$, otherwise, $EI^{BW*} > EI^{BS*}$.

Proof. See Appendix K.

The result in Proposition 7(a) indicates that when blockchain costs are low, adopting blockchain is environmentally advantageous in both remanufacturing modes. Remanufactured products boast greater environmental friendliness in comparison to new products. According to Proposition 2, adopting blockchain at this time has led to increased remanufactured product sales and decreased new product sales, which mitigates the environmental impact.

Proposition 7(b) shows that when the ratio of carbon emissions per unit between remanufactured and new products is low, the environmental impact under the outsourcing remanufacturing mode is smaller. This is because the increased competition between the two products under the authorization mode results in lower sales of remanufactured products than under the outsourcing mode. Therefore, outsourcing remanufacturing becomes environmentally advantageous when the carbon emissions of two products meet the conditions.

Management Insight: To reduce environmental impact, OEMs and TPRs should choose to collaborate and take full advantage of blockchain technology. They can promote remanufacturing and circular economy concepts by adopting sustainable materials and production processes and optimizing product design to improve longevity and repairability. Governments can strengthen environmental policies at the regulatory level, create incentives for companies to adopt environmentally friendly technologies and practices, and encourage green innovation. Conversely, consumers can take personal action to support sustainable consumption by purchasing eco-friendly products, reducing waste, and improving energy efficiency. Manufacturers reduce emissions more effectively with the concerted efforts of governments, manufacturers, and consumers.

6. Numerical analysis

To further display the above conclusions and analyze the impact of the unit blockchain adoption cost b and the disclosure degree of remanufactured product information α on the optimal decision-making of the supply chain members. The relevant parameters are numerically analyzed in this part using Matlab software. In references (Xia et al., 2023; Gong et al., 2023), the parameters are selected according to the qualifications while satisfying the assumptions of the model. The relevant parameters are: $c_n = 0.2$, $c_r = 0.1$, $\delta = 0.8$, $e_n = 1$, $e_r = 0.6$, $p_e = 0.1$, $E = 2$, $k = 1.1$.

6.1. Changes in pricing decisions

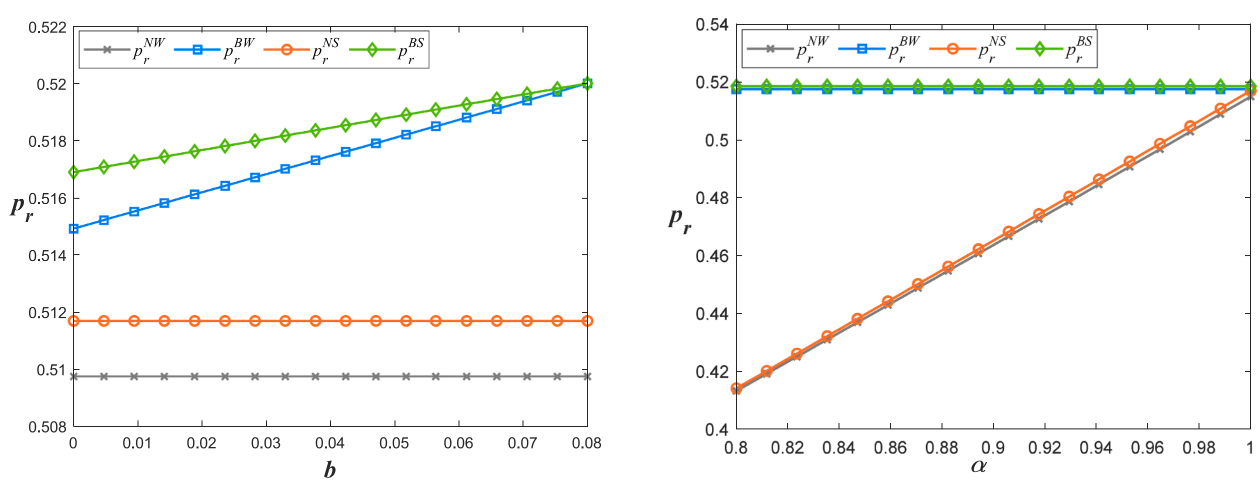
To visualize the impact of parameters b and α on the optimal pricing of the remanufactured products, based on the above settings, we set the following parameters $b = 0.05$, $\alpha = 0.9$. The optimal pricing for different values of b and α is shown in Fig. 3. In addition, since new product prices are not affected by b and α, the numerical analysis of new product prices is omitted.

As shown in Fig. 3, in models with blockchain technology (Model *BW* and *BS*), the optimal pricing of remanufactured products rises as b increases. The rising blockchain costs increase production costs for TPR, prompting the TPR to increase its price to maintain profitability. In models without blockchain technology (Model *NW* and *NS*), the optimal pricing of remanufactured products rises as α increases. The higher α, the greater the consumers' WTP, consequently driving up remanufactured product prices. To sum up, adopting blockchain technology will always improve the pricing of remanufactured products.

6.2. Changes in sales

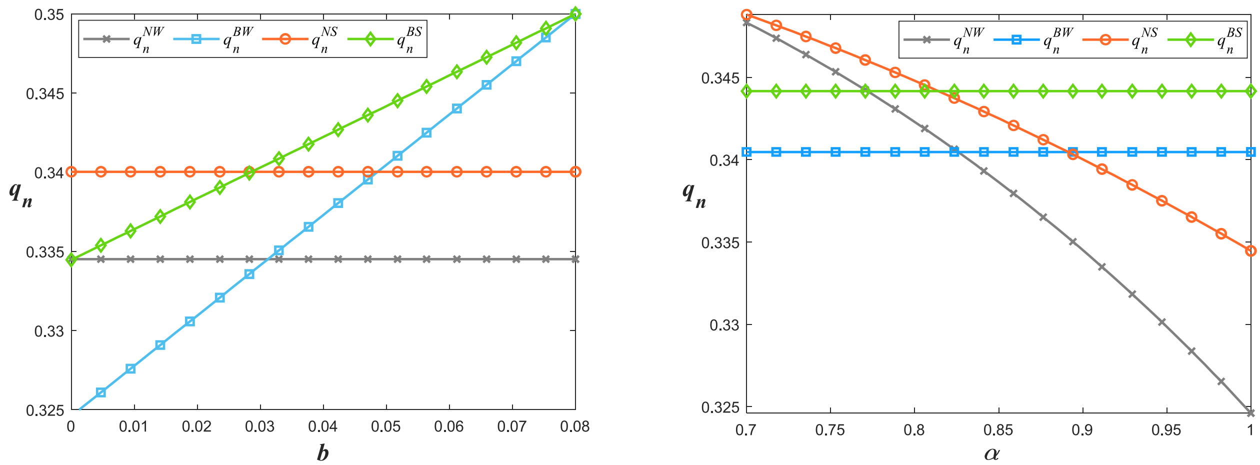
To visualize the effects of the parameters b and α on the optimal sales of new and remanufactured products, based on the above settings, we set $b = 0.05$, $\alpha = 0.9$. The sales volumes for different values of b and α are shown in Fig. 4 and Fig. 5.

As can be seen in Fig. 4 and Fig. 5, in models with blockchain technology (Model *BW* and *BS*), as b increases, new product sales increase, and remanufactured product sales decrease. Therefore, the adoption of blockchain technology can stimulate remanufactured product sales, thereby contributing to the development of remanufacturing to some extent. In models without blockchain technology (Model *NW* and *NS*), new product sales decrease as α increases, while remanufactured product sales increase as α increases. Furthermore, regardless of the adoption of blockchain technology, remanufactured product sales under the outsourcing remanufacturing are greater than those under the authorization remanufacturing, indicating that the outsourced remanufacturing can effectively expand the



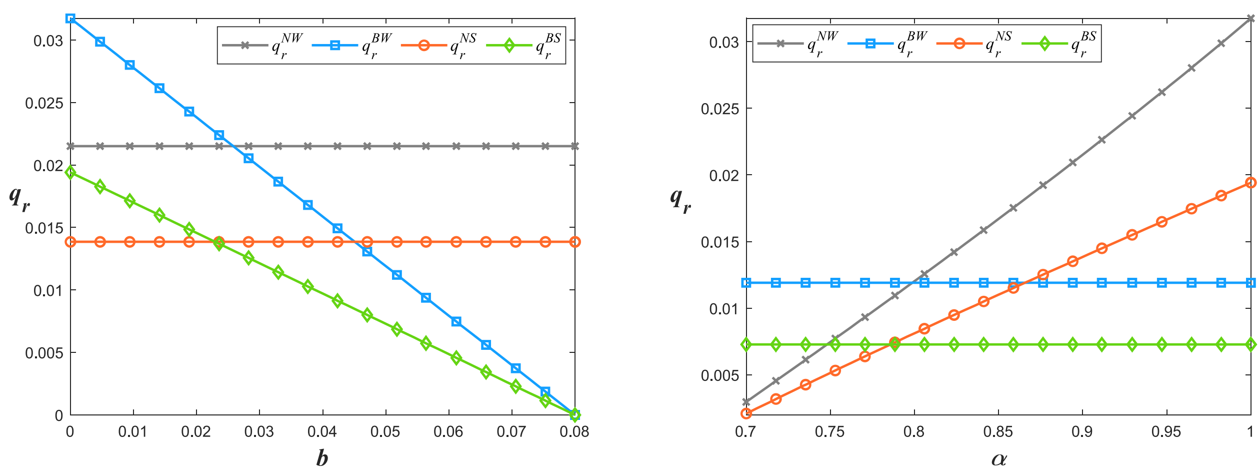
(a) Parameter b (b) Parameter α

Fig. 3. Changes in remanufactured products' pricing decisions.



(a) Parameter b (b) Parameter α

Fig. 4. Changes in new products' sales.

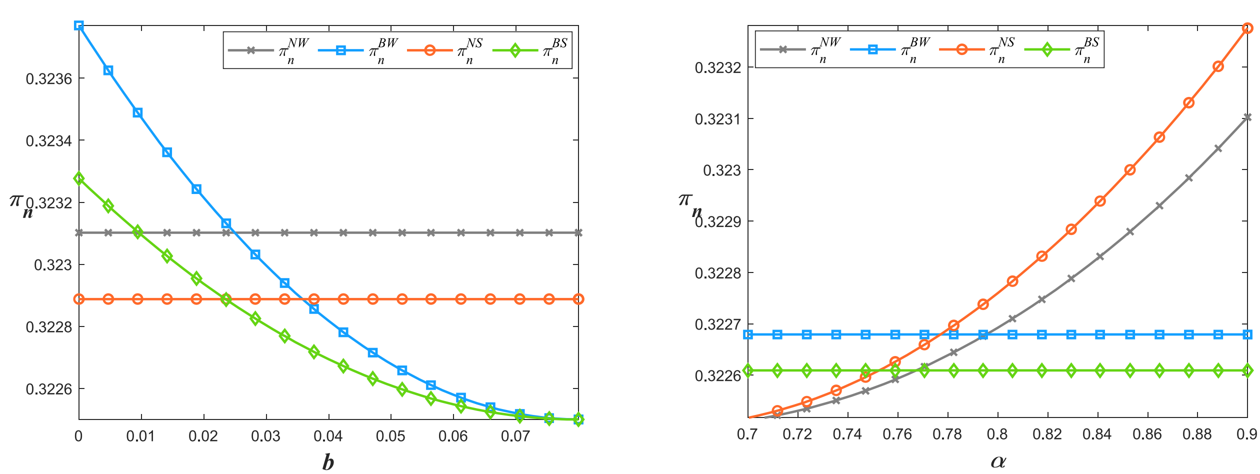


(a) Parameter b (b) Parameter α

Fig. 5. Changes in remanufacturing products' sales.

remanufacturing production scale.

From the above, it can be inferred that adopting blockchain can increase remanufactured product sales when b is low or α is low. Under these conditions, adopting blockchain can facilitate the expansion of the remanufacturing production scale.



(a) Parameter b (b) Parameter α

Fig. 6. Changes in the OEM's profit.

6.3. Changes of profits

To visualize the impact of the parameters b and α on the optimal profits of the OEM and TPR, based on the above settings, we set the following parameters $b = 0.05$, $\alpha = 0.9$. The profits for different values of b and α are shown in Fig. 6 and Fig. 7.

As shown in Fig. 6 and Fig. 7, the profit of both the OEM and the TPR decreases as b increases in models with blockchain technology (Model *BW* and *BS*). The reason for this is that heightened blockchain costs result in elevated remanufactured product prices, subsequently diminishing their demand and thereby reducing profits for both the TPR and OEM. In the models without blockchain technology (Model *NW* and *NS*), the profits of both the OEM and TPR rise with an increase in α. This is attributed to the enhanced competitiveness of remanufactured products as α increases, benefiting both the OEM and TPR.

In addition, OEM/TPR should choose to adopt blockchain when b is low or when α is low. This is because b directly affects remanufactured product costs. And when α is low, adopting blockchain more significantly improves the disclosure of remanufactured product information. Therefore, the benefits of adopting blockchain become more pronounced when b is low and α is low, at which time OEM/TPR should adopt blockchain technology. Instead, it is a more advantageous strategy for the OEM/TPR to choose not to adopt blockchain technology.

7. Conclusions

7.1. Summary of findings

This paper considers a supply chain consisting of an OEM and a TPR under the cap-and-trade policy. Firstly, four-game models are established to study the selection of outsourcing and authorization third-party remanufacturing modes and blockchain adoption from OEM and TPR. Secondly, we find out the equilibrium solution of the four modes and carry on the sensitivity analysis and comparison analysis to optimal prices, optimal quantities, and the optimal profit. Finally, through numerical analysis, we further study the OEM and TPR adoption of blockchain technology and remanufacturing mode selection strategy. The main findings are as follows.

(1) Both cap-and-trade policy and blockchain technology have the potential to amplify remanufacturing production. Specifically, when the unit carbon emission of the remanufactured product is low, the cap-and-trade policy increases remanufactured product sales. Additionally, When the unit blockchain adoption cost is low, blockchain technology increases remanufactured product sales while diminishing new product sales.

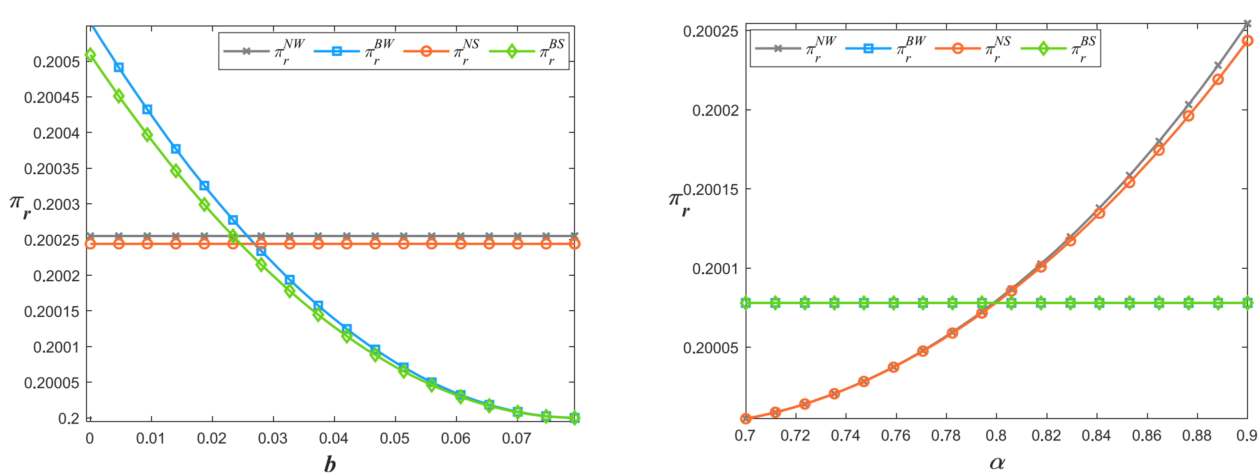
(2) When the unit blockchain adoption cost is low, OEM and TPR should adopt blockchain technology to disclose product information. In addition, the disclosure degree of remanufactured product information significantly influences the blockchain adoption strategy for OEM and TPR. Specifically, OEM and TPR should consider adopting blockchain technology when the disclosure degree of remanufactured product information is low. Furthermore, the threshold for blockchain adoption in outsourced remanufacturing is higher than in authorization remanufacturing.

(3) Regardless of adopting blockchain technology, OEM always prefers the outsourcing remanufacturing mode, and TPR prefers the outsourcing remanufacturing mode when consumer preference for remanufactured products is high. The adoption of blockchain technology increases consumer preference for remanufactured products, and therefore, in some cases, the adoption of blockchain has changed the optimal mode choice for TPR from authorization to outsourcing.

(1) Comparisons of environmental impacts show that adopting blockchain is beneficial to the environment when the unit blockchain adoption cost is low. Besides, authorization remanufacturing is more beneficial to the environment than outsourced remanufacturing when consumer preference for remanufactured products is low. If consumer preference for remanufactured products is high, outsourced remanufacturing is beneficial to the entire supply chain and the environment.

7.2. Managerial insights

Remanufacturing: To control carbon emissions and foster the development of the remanufacturing industry, the joint efforts of the government, manufacturers, and consumers are needed. The government should, on the one hand, improve the efficiency of the carbon trading market and set a reasonable carbon trading price. On the other hand, it should increase investment in new technologies to encourage and guide enterprises to adopt blockchain technology. Remanufacturing enterprises should maximize the low-carbon advantages of remanufactured products, continuously innovate remanufacturing technologies, and improve quality and production efficiency. Furthermore, enterprises should actively develop the market for remanufactured products, strengthen product publicity, and increase awareness to attract more consumers. Consumers should cultivate low-carbon environmental awareness, respond to the national call, and actively buy



(a) Parameter b (b) Parameter α

Fig. 7. Changes in the TPR's profit.

remanufactured products.

Blockchain technology: Blockchain has the potential to improve consumer perception regarding the quality of remanufactured products by disclosing quality information. However, its adoption faces several challenges. These include the need for standardized data formats, interoperability among different blockchain platforms, scalability issues, and ensuring data privacy and security. For example, IBM is a company actively exploring blockchain applications. Although blockchain technology can improve data security and transparency, it is performance limitations and data privacy issues remain one of the challenges IBM faces in promoting blockchain. Collaborative efforts and technological innovations are crucial for surmounting these challenges and fully realizing the potential of blockchain in various industries.

7.3. Future studies

This paper has some limitations and can be expanded as follows. On the one hand, the consideration in this paper is restricted to the information disclosure of remanufactured products facilitated by blockchain technology. In real life, however, blockchain technology can execute functions such as information sharing and carbon footprint tracking. On the other hand, in practice, OEMs can manufacture both remanufactured and new products simultaneously. Investigating OEMs' decision-making between self-remanufacturing and third-party remanufacturing, under the impact of blockchain technology, is also a valuable area of study.

CRediT authorship contribution statement

Yanliang Zhang: Writing – review & editing, Supervision, Conceptualization. **Jingrui Zhang:** Writing – original draft, Formal analysis, Data curation. **Yanjie Zhou:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Huadong Zhao:** Supervision, Methodology, Conceptualization. **Yanpei Cheng:** Software, Data curation.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Proof of the equilibrium results in model *NW*

By substituting $q_{\mathrm{r}}^{NW} = \tau^{NW} q_{\mathrm{n}}^{NW}$ into Eq. (4), π_r^{NW} can be expressed as

$$\pi_r^{NW} = \left(\omega^{NW} - c_r\right)\tau^{NW} q_{\mathrm{n}}^{NW} - \frac{k}{2}\left(\tau^{NW} q_n^{NW}\right)^2 - \left(e_r \tau^{NW} q_n^{NW} - E\right)p_e \tag{A.1}$$

The first- and second-order derivatives of τ^{NW} Eq. (A.1) are as follows: $\frac{\partial \pi_r^{NW}}{\partial \tau^{NW}} = (\omega^{NW} - c_r - e_r p_e) q_{\mathrm{n}}^{NW} - k q_n^{NW^2} \tau^{NW}$; $\frac{\partial^2 \pi_r^{NW}}{\partial \tau^{NW2}} = -k q_n^{NW^2} < 0$, thus Eq. (4) is a concave function of τ^{NW}. Let $\frac{\partial \pi_r^{NW}}{\partial \tau^{NW}} = 0$, and solve it. We obtain $\tau^{NW*} = \frac{\omega^{NW} - c_r - e_r p_e}{k q_n^{NW}}$.

Substituting $q_{\mathrm{r}}^{NW} = \tau^{NW} q_{\mathrm{n}}^{NW}$, Eq. (1), and Eq. (2) into Eq. (3), π_n^{NW} is as follows:

$$\pi_n^{NW} = \left(1 - q_n^{NW} - c_n\right) q_{\mathrm{n}}^{NW} + \frac{\left(\alpha\delta - 2\alpha\delta q_n^{NW} - \omega^{NW}\right)\left(\omega^{NW} - c_r - e_r p_e\right)}{k} - \frac{\alpha\delta\left(\omega^{NW} - c_r - e_r p_e\right)^2}{k^2} - \left(e_n q_n^{NW} - E\right)p_e \tag{A.2}$$

The first- and second-order derivatives of q_n^{NW}, ω^{NW} in Eq. (A.2) are shown as follows: $\frac{\partial \pi_r^{NW}}{\partial q_n^{NW}} = 1 - c_n - e_n p_e - 2q_n^{NW} - \frac{2\alpha\delta\left(\omega^{NW} - c_r - e_r p_e\right)}{k}$, $\frac{\partial \pi_r^{NW}}{\partial \omega^{NW}} = \frac{(2\alpha\delta + k)(c_r + e_r p_e) + \alpha\delta k\left(1 - 2q_n^{NW}\right) - 2(\alpha\delta + k)\omega^{NW}}{k^2}$, $\frac{\partial^2 \pi_n^{NW}}{\partial q_n^{NW2}} = -2$, $\frac{\partial^2 \pi_n^{NW}}{\partial q_n^{NW} \partial \omega^{NW}} = -\frac{2\alpha\delta}{k}$, $\frac{\partial^2 \pi_n^{NW}}{\partial \omega^{NW2}} = -\frac{2(\alpha\delta + k)}{k^2}$, $\frac{\partial^2 \pi_n^{NW}}{\partial q_n^{NW} \partial \omega^{NW}} = -\frac{2\alpha\delta}{k}$.

The following is the Hessian matrix of q_n^{NW}, ω^{NW} in Eq. (A.2): $H = \begin{bmatrix} -2 & -\dfrac{2\delta}{k} \\ -\dfrac{2\delta}{k} & -\dfrac{2(\alpha\delta + k)}{k^2} \end{bmatrix}$. The Hessian determinant is $|H| = \frac{4(k + \alpha\delta - \alpha^2\delta^2)}{k^2} > 0$, and $-2 < 0$. So q_n^{NW} and ω^{NW} in Eq. (A.2) are concave functions.

Solving the first-order conditions $\frac{\partial \pi_r^{NW}}{\partial q_n^{NW}} = 0$ and $\frac{\partial \pi_r^{NW}}{\partial \omega^{NW}} = 0$, we obtain $q_n^{NW*} = \frac{1}{2} - \frac{(k + \alpha\delta)(c_n + e_n p_e) - \alpha\delta(c_r + e_r p_e)}{2[k + \alpha\delta(1 - \alpha\delta)]}$, $\omega^{NW*} = c_r + e_r p_e + \frac{k[\alpha\delta(c_n + e_n p_e) - (c_r + e_r p_e)]}{2[k + \alpha\delta(1 - \alpha\delta)]}$.

We substitute q_n^{NW*} and ω^{NW*} into τ^{NW*} to obtain $\tau^{NW*} = \frac{\alpha\delta(c_n + e_n p_e) - (c_r + e_r p_e)}{(k + \alpha\delta)(1 - c_n + e_n p_e) + \alpha\delta(c_r + e_r p_e - \alpha\delta)}$.

Further, according to $q_{\mathrm{r}}^{NW*} = \tau^{NW*} q_{\mathrm{n}}^{NW*}$, $q_{\mathrm{r}}^{NW*} = \frac{\alpha\delta(c_n + e_n p_e) - (c_r + e_r p_e)}{2[k + \alpha\delta(1 - \alpha\delta)]}$.

Likewise, based on Eq. (1) and (2), we obtain $p_n^{NW*} = \frac{1 + c_n + e_n p_e}{2}$, $p_r^{NW*} = \alpha\delta\left[\frac{1}{2} + \frac{k(c_n + e_n p_e) + (1 - \alpha\delta)(c_r + e_r p_e)}{2[k + \alpha\delta(1 - \alpha\delta)]}\right]$.

Finally, by substituting the above optimal values π_n^{NW*}, π_r^{NW*}, we obtain $\pi_n^{NW*} = \frac{(1 - c_n - e_n p_e)^2}{4} + \frac{[\alpha\delta(c_n + e_n p_e) - (c_r + e_r p_e)]^2}{4[k + \alpha\delta(1 - \alpha\delta)]} + E p_e$, $\pi_r^{NW*} = \frac{k[\alpha\delta(c_n + e_n p_e) - (c_r + e_r p_e)]^2}{8[k + \alpha\delta(1 - \alpha\delta)]^2} + E p_e$.

Appendix B. Proof of the equilibrium results in model *BW*

The proof is similar to Appendix A.

Appendix C. Proof of the equilibrium results in model *NS*

The proof is similar to Appendix A.

Appendix D. Proof of the equilibrium results in model *BS*

The proof is similar to Appendix A.

Appendix E. Proof of Proposition 1

For (a), $p_n^{NW*} = p_n^{BW*} = p_n^{NS*} = p_n^{BS*} = \frac{1+c_n+e_np_e}{2}$, $p_r^{NW*} - p_r^{BW*} = \frac{1}{2}\delta\left(-1+\alpha+\frac{\alpha[k(c_n+e_np_e)+(1-\alpha\delta)(c_r+e_rp_e)]}{k+\alpha\delta(1-\alpha\delta)} - \frac{k(c_n+e_np_e)+(1-\delta)(b+c_r+e_rp_e)}{k+\delta-\delta^2}\right) < 0 \Leftrightarrow p_r^{NW*} < p_r^{BW*}$, $p_r^{NS*} - p_r^{BS*} = \frac{1}{2}\delta\left(-1+\alpha+\frac{\alpha[(k+\alpha\delta)(c_n+e_np_e)+(1-\alpha\delta)(c_r+e_rp_e)]}{k+\alpha\delta(2-\alpha\delta)} - \frac{(k+\delta)(c_n+e_np_e)-(-1+\delta)(b+c_r+e_rp_e)}{k-(-2+\delta)\delta}\right) < 0 \Leftrightarrow {}_r^{NS*} < p_r^{BS*}$.

For (b), $p_r^{NW*} - p_r^{NS*} = -\frac{\alpha^2\delta^2(1-\alpha\delta)[\alpha\delta c_n-c_r+(\alpha\delta e_n-e_r)p_e]}{2[k+\alpha\delta(1-\alpha\delta)][k+\alpha\delta(2-\alpha\delta)]} < 0 \Leftrightarrow p_r^{NW*} < p_r^{NS*}$, $p_r^{BW*} - p_r^{BS*} = -\frac{(1-\delta)\delta^2[\delta c_n-c_r-b+(\delta e_n-e_r)p_e]}{2(k+2\delta-\delta^2)(k+\delta-\delta^2)} \Leftrightarrow p_r^{BW*} < p_r^{BS*}$.

Appendix F. Proof of Proposition 2

For (a), $\omega^{NW*} - \omega^{BW*} = \frac{1}{2}\left(\frac{k[\alpha\delta c_n-c_r+(\alpha\delta e_n-e_r)p_e]}{k+\alpha\delta(1-\alpha\delta)} + \frac{k[b-\delta c_n+c_r+(-\delta e_n+e_r)p_e]}{k+\delta-\delta^2}\right)$, by solving $\omega^{NW*} - \omega^{BW*} = 0$, we obtain $b_1 = \frac{(1-\alpha)\delta\left[\left(k+\alpha\delta^2\right)c_n-(-1+\delta+\alpha\delta)c_r+\left[\left(k+\alpha\delta^2\right)e_n-(-1+\delta+\alpha\delta)e_r\right]p_e\right]}{k+\alpha\delta(1-\alpha\delta)}$. If $b \leqslant b_1$, $\omega^{NW*} \geqslant \omega^{BW*}$, otherwise, $\omega^{NW*} < \omega^{BW*}$.

For (b), $z^{NS*} - z^{BS*} = \frac{1}{2}(b-\delta+\alpha\delta)$, by solving $z^{NS*} - z^{BS*} = 0$, we obtain $b_2 = \delta - \alpha\delta$. If $b \leqslant b_2$, $z^{NS*} \leqslant z^{BS*}$, otherwise, $z^{NS*} > z^{BS*}$.

Appendix G. Proof of Proposition 3

For (a), $q_n^{NW*} - q_n^{BW*} = \frac{1}{2}\left(-\frac{(k+\alpha\delta)(c_n+e_np_e)-\alpha\delta(c_r+e_rp_e)}{k+\alpha\delta(1-\alpha\delta)} + \frac{(k+\delta)(c_n+e_np_e)-\delta(b+c_r+e_rp_e)}{k+\delta-\delta^2}\right)$, by solving $q_n^{NW*} - q_n^{BW*} = 0$, we obtain $b_3 = \frac{(1-\alpha)\left[\delta(k+k\alpha+\alpha\delta)c_n-\left(k+\alpha\delta^2\right)c_r+\left[\delta(k+k\alpha+\alpha\delta)e_n-\left(k+\alpha\delta^2\right)e_r\right]p_e\right]}{k+\alpha\delta(1-\alpha\delta)}$. If $b \leqslant b_3$, $q_n^{NW*} \geqslant q_n^{BW*}$, otherwise, $q_n^{NW*} < q_n^{BW*}$. $q_n^{NS*} - q_n^{BS*} = \frac{1}{2}\left(-\frac{(k+2\alpha\delta)(c_n+e_np_e)-\alpha\delta(c_r+e_rp_e)}{k+\alpha\delta(2-\alpha\delta)} + \frac{(k+2\delta)(c_n+e_np_e)-\delta(b+c_r+e_rp_e)}{k+(2-\delta)\delta}\right)$, by solving $q_n^{NS*} - q_n^{BS*} = 0$, we obtain $b_4 = \frac{(1-\alpha)\left[\delta(k+k\alpha+2\alpha\delta)c_n-\left(k+\alpha\delta^2\right)c_r+\left[\delta(k+k\alpha+2\alpha\delta)e_n-\left(k+\alpha\delta^2\right)e_r\right]p_e\right]}{k+\alpha\delta(2-\alpha\delta)}$. If $b \leqslant b_4$, $q_n^{NS*} \geqslant q_n^{BS*}$, otherwise, $q_n^{NS*} < q_n^{BS*}$. $q_r^{NW*} - q_r^{BW*} = \frac{1}{2}\left(\frac{\alpha\delta c_n-c_r+(\alpha\delta e_n-e_r)p_e}{k+\alpha\delta(1-\alpha\delta)} + \frac{b-\delta c_n+c_r+(-\delta e_n+e_r)p_e}{k+\delta-\delta^2}\right)$, by solving $q_r^{NW*} - q_r^{BW*} = 0$, we obtain $b_5 = \frac{(1-\alpha)\delta\left[\left(k+\alpha\delta^2\right)c_n-(-1+\delta+\alpha\delta)c_r+\left[\left(k+\alpha\delta^2\right)e_n-(-1+\delta+\alpha\delta)e_r\right]p_e\right]}{k+\alpha\delta(1-\alpha\delta)}$. If $b \leqslant b_5$, $q_r^{NW*} \leqslant q_r^{BW*}$, otherwise, $q_r^{NW*} > q_r^{BW*}$.$q_r^{NS*} - q_r^{BS*} = \frac{1}{2}\left(\frac{\alpha\delta c_n-c_r+(\alpha\delta e_n-e_r)p_e}{k+\alpha\delta(2-\alpha\delta)} + \frac{b-\delta c_n+c_r+(-\delta e_n+e_r)p_e}{k-(-2+\delta)\delta}\right)$, by solving $q_r^{NS*} - q_r^{BS*} = 0$, we obtain $b_6 = \frac{(1-\alpha)\delta\left[\left(k+\alpha\delta^2\right)c_n-(-2+\delta+\alpha\delta)c_r+\left[\left(k+\alpha\delta^2\right)e_n-(-2+\delta+\alpha\delta)e_r\right]p_e\right]}{k+\alpha\delta(2-\alpha\delta)}$. If $b \leqslant b_6$, $q_r^{NS*} \leqslant q_r^{BS*}$, otherwise, $q_r^{NS*} > q_r^{BS*}$.

For (b), $q_n^{NW*} - q_n^{NS*} = -\frac{\alpha^2\delta^2[\alpha\delta c_n-c_r+(\alpha\delta e_n-e_r)p_e]}{2[k+\alpha\delta(1-\alpha\delta)][k+\alpha\delta(2-\alpha\delta)]} < 0 \Leftrightarrow q_n^{NW*} < q_n^{NS*}$, $q_n^{BW*} - q_n^{BS*} = -\frac{\delta^2[\delta c_n-c_r-b+(\delta e_n-e_r)p_e]}{2(k+2\delta-\delta^2)(k+\delta-\delta^2)} < 0 \Leftrightarrow q_n^{BW*} < q_n^{BS*}$, $q_r^{NW*} = q_r^{NS*} = \frac{\alpha\delta(\alpha\delta c_n-c_r+(\alpha\delta e_n-e_r)p_e)}{2[k+\alpha\delta(1-\alpha\delta)][k+\alpha\delta(2-\alpha\delta)]} > 0 \Leftrightarrow q_r^{NW*} > q_r^{NS*}$, $q_r^{BW*} - q_r^{BS*} = \frac{\delta(\delta c_n-c_r-b+(\delta e_n-e_r)p_e)}{2(k+2\delta-\delta^2)(k+\delta-\delta^2)} > 0 \Leftrightarrow q_r^{BW*} > q_r^{BS*}$.

Appendix H. Proof of Proposition 4

For (a), $\pi_n^{NW*} - \pi_n^{BW*} = \frac{1}{4}\left(\frac{[\alpha\delta c_n-c_r+(\alpha\delta e_n-e_r)p_e]^2}{k+\alpha\delta(1-\alpha\delta)} + \frac{[\delta c_n-c_r-b+(\delta e_n-e_r)p_e]^2}{k+\delta-\delta^2}\right)$, by solving $\pi_n^{NW*} - \pi_n^{BW*} = 0$, we obtain $B_1 = \delta(c_n+e_np_e) - (c_r+e_rp_e) + [\alpha\delta(c_n+e_np_e) - (c_r+e_rp_e)]\sqrt{\frac{k+\delta-\delta^2}{k+\alpha\delta(1-\alpha\delta)}}$. If $b \leqslant B_1$, $\pi_n^{NW*} \leqslant \pi_n^{BW*}$, otherwise, $\pi_n^{NW*} > \pi_n^{BW*}$.$\pi_n^{NS*} - \pi_n^{BS*} = \frac{1}{4}\left(\frac{[\alpha\delta c_n-c_r+(\alpha\delta e_n-e_r)p_e]^2}{k+\alpha\delta(2-\alpha\delta)} + \frac{[\delta c_n-c_r-b+(\delta e_n-e_r)p_e]^2}{k+(2-\delta)\delta}\right)$, by solving $\pi_n^{NS*} - \pi_n^{BS*} = 0$, we obtain $B_2 = \delta(c_n+e_np_e) - (c_r+e_rp_e) + [\alpha\delta(c_n+e_np_e) - (c_r+e_rp_e)]\sqrt{\frac{k+2\delta-\delta^2}{k+\alpha\delta(2-\alpha\delta)}}$. If $b \leqslant B_2$, $\pi_n^{NS*} \leqslant \pi_n^{BS*}$, otherwise, $\pi_n^{NS*} > \pi_n^{BS*}$.

For (6), $\pi_n^{NW*} - \pi_n^{NS*} = \frac{\alpha\delta(\alpha\delta c_n-c_r+(\alpha\delta e_n-e_r)p_e)^2}{4(k+\alpha\delta(1-\alpha\delta))(k+\alpha\delta(2-\alpha\delta))} > 0 \Leftrightarrow \pi_n^{NW*} > \pi_n^{NS*}$,$\pi_n^{BW*} - \pi_n^{BS*} = \frac{\delta(b-\delta c_n+c_r+(-\delta e_n+e_r)p_e)^2}{4(k+\delta-\delta^2)(k+2\delta-\delta^2)} > 0 \Leftrightarrow \pi_n^{BW*} > \pi_n BS^*$.

Appendix I. Proof of Proposition 5

For (a), $\pi_r^{NW*} - \pi_r^{BW*} = \frac{1}{8}k\left(\frac{[\alpha\delta c_n-c_r+(\alpha\delta e_n-e_r)p_e]^2}{(k+\alpha\delta-\alpha^2\delta^2)^2} + \frac{[\delta c_n-c_r-b+(\delta e_n-e_r)p_e]^2}{(k+\delta-\delta^2)^2}\right)$, by solving $\pi_r^{NW*} - \pi_r^{BW*} = 0$, we obtain $B_3 = \frac{(1-\alpha)\delta\left[\left(k+\alpha\delta^2\right)c_n-(-1+\delta+\alpha\delta)c_r+\left[\left(k+\alpha\delta^2\right)e_n-(-1+\delta+\alpha\delta)e_r\right]p_e\right]}{k+\alpha\delta(1-\alpha\delta)}$. If $b \leqslant B_3$, $\pi_r^{NW*} \leqslant \pi_r^{BW*}$, otherwise, $\pi_n^{NW*} > \pi_n^{BW*}$.$\pi_r^{NS*} - \pi_r^{BS*} = \frac{1}{8}\left(\frac{(k+2\alpha\delta)(-\alpha\delta c_n+c_r+(-\alpha\delta e_n+e_r)p_e)^2}{(k+2\alpha\delta-\alpha^2\delta^2)^2} - \frac{(k+2\delta)(b-\delta c_n+c_r+(-\delta e_n+e_r)p_e)^2}{(k+2\delta-\delta^2)^2}\right)$, by solving $\pi_r^{NS*} - \pi_r^{BS*} = 0$, we obtain $B_4 = \delta c_n - c_r + \delta e_n p_e - e_r p_e + \frac{\left(k+2\delta-\delta^2\right)(\alpha\delta c_n-c_r+(\alpha\delta e_n-e_r)p_e)}{(k+2\alpha\delta-\alpha^2\delta^2)}\sqrt{\frac{(k+2\alpha\delta)}{(k+2\delta)}}$. If $b \leqslant B_4$, $\pi_r^{NS*} \leqslant \pi_r^{BS*}$, otherwise, $\pi_r^{NS*} > \pi_r^{BS*}$.

For (b), $\pi_r^{NW*} - \pi_r^{NS*} = \frac{\alpha^2\delta^2\left(-k+2k\alpha\delta-2\alpha\delta(-1+\alpha\delta)^2\right)[\alpha\delta c_n-c_r+(\alpha\delta e_n-e_r)p_e]^2}{8[k+\alpha\delta(1-\alpha\delta)]^2[k+\alpha\delta(2-\alpha\delta)]^2}$, by solving $\pi_r^{NW*} - \pi_r^{NS*} = 0 \Leftrightarrow 2k\alpha\delta - k - 2\alpha\delta(1-\alpha\delta)^2 = 0$, we obtain $\alpha\delta > \frac{1}{2}$ and

$k > \frac{2\alpha\delta(1-\alpha\delta)^2}{2\alpha\delta-1}$. If $\alpha\delta > \frac{1}{2}$ and $k > \frac{2\alpha\delta(1-\alpha\delta)^2}{2\alpha\delta-1}$, $\pi_r^{NW*} > \pi_r^{NS*}$.$\pi_r^{BW*} - \pi_r^{BS*} = \frac{\delta^2\left(2k\delta-k+2(1-\delta)^2\delta\right)[b-\delta c_n+c_r+(-\delta e_n+e_r)p_e]^2}{8(k+2\delta-\delta^2)^2(k+\delta-\delta^2)^2}$, by solving $\pi_r^{BW*} - \pi_r^{BS*} = 0 \Leftrightarrow 2k\delta - k + 2(1-\delta)^2\delta = 0$, we $\delta > \frac{1}{2}$ and $k > \frac{2\delta(1-\delta)^2}{2\delta-1}$. If $\delta > \frac{1}{2}$ and $k > \frac{2\delta(1-\delta)^2}{2\delta-1}$, $\pi_r^{BW*} > \pi_r^{BS*}$, otherwise, $\pi_r^{BW*} < \pi_r^{BS*}$.

Appendix J. Proof of Proposition 6

In model *NW*, $\frac{\partial p_n^{NW*}}{\partial p_e} = \frac{e_n}{2} > 0$,$\frac{\partial p_r^{NW*}}{\partial p_e} = \frac{\alpha\delta[ke_n+(1-\alpha\delta)e_r]}{2[k+\alpha\delta(1-\alpha\delta)]} > 0$,$\frac{\partial q_n^{NW*}}{\partial p_e} = -\frac{(k+\alpha\delta)e_n-\alpha\delta e_r}{2[k+\alpha\delta(1-\alpha\delta)]} < 0$.$\frac{\partial q_r^{NW*}}{\partial p_e} = \frac{\alpha\delta e_n - e_r}{2[k+\alpha\delta(1-\alpha\delta)]}$, If $\frac{e_r}{e_n} < \alpha\delta$,$\frac{\partial q_r^{NW*}}{\partial p_e} > 0$, otherwise, $\frac{\partial q_r^{NW*}}{\partial p_e} < 0$.$\frac{\partial \omega^{NW*}}{\partial p_e} = e_r + \frac{k(\alpha\delta e_n-e_r)[\alpha\delta(c_n+e_np_e)-c_r-e_rp_e]}{2[k+\alpha\delta(1-\alpha\delta)]} > 0$.$\frac{\partial \pi_n^{NW*}}{\partial p_e} = E + \frac{1}{2}e_n(-1+c_n+e_np_e) + \frac{(\alpha\delta e_n-e_r)[\alpha\delta c_n - c_r + (\alpha\delta e_n - e_r)p_e]}{2[k+\alpha\delta(1-\alpha\delta)]}$, letting $\frac{\partial \pi_n^{NW*}}{\partial p_e} = 0$, we obtain $p_1^{NW} = \frac{-2a[k+\alpha\delta(1-\alpha\delta)]+[k+\alpha\delta(1-\alpha\delta)-(k+\alpha\delta)c_n+\alpha\delta c_r]e_n+(\alpha\delta c_n-c_r)e_r}{(k+\alpha\delta)e_n^2-2\alpha\delta e_ne_r+e_r^2}$. If $p_e < p_1^{NW}$,$\frac{\partial \pi_n^{NW*}}{\partial p_e} > 0$, otherwise,$\frac{\partial \pi_n^{NW*}}{\partial p_e} < 0$.$\frac{\partial \pi_r^{NW*}}{\partial p_e} = E + \frac{k(\alpha\delta e_n-e_r)[-c_r-e_rp_e+\alpha\delta(c_n+e_np_e)]}{4[k+\alpha\delta(1-\alpha\delta)]^2}$, letting $\frac{\partial \pi_r^{NW*}}{\partial p_e} = 0$, we obtain $p_2^{NW} = \frac{-4a[k+\alpha\delta(1-\alpha\delta)]^2+k(\alpha\delta c_n-c_r)(-\alpha\delta e_n+e_r)}{k(-\alpha\delta e_n+e_r)^2}$. If $p_e < p_2^{NW}$, $\frac{\partial \pi_r^{NW*}}{\partial p_e} > 0$, otherwise, $\frac{\partial \pi_r^{NW*}}{\partial p_e} < 0$.

Proofs in model *BW*, model *NW*, and model *BS* are similar to those in model *NW*.

Appendix K. Proof of Proposition 7

$$EI^{NW*} = -\frac{(k+\alpha\delta)e_n^2p_e + e_r(-\alpha\delta c_n + c_r + e_rp_e) + e_n[-k+\alpha\delta(-1+\alpha\delta)+(k+\alpha\delta)c_n - \alpha\delta(c_r+2e_rp_e)]}{2[k+\alpha\delta(1-\alpha\delta)]}$$

$$EI^{BW*} = -\frac{(k+\delta)e_n^2p_e + e_r(b-\delta c_n + c_r + e_rp_e) - e_n[k+(1+b-\delta)\delta - (k+\delta)c_n + \delta c_r + 2\delta e_rp_e]}{2(k+\delta-\delta^2)}$$

$$EI^{NS*} = -\frac{(k+2\alpha\delta)e_n^2p_e + e_r(-\alpha\delta c_n + c_r + e_rp_e) + e_n[-k+\alpha\delta(-2+\alpha\delta)+(k+2\alpha\delta)c_n - \alpha\delta(c_r+2e_rp_e)]}{2[k+\alpha\delta(2-\alpha\delta)]}$$

$$EI^{BS*} = -\frac{(k+2\delta)e_n^2p_e + e_r(b-\delta c_n + c_r + e_rp_e) - e_n[k+(2+b-\delta)\delta - (k+2\delta)c_n + \delta c_r + 2\delta e_rp_e]}{2(k+2\delta-\delta^2)}$$

For (a), by solving $EI^{NW*} - EI^{BW*} = 0$, we obtain $B_5 = \frac{(-1+\alpha)\delta\begin{pmatrix} c_r\left[(k+\alpha\delta^2)e_n - (-1+\delta+\alpha\delta)e_r\right] + c_n\left[-\delta(k+k\alpha+\alpha\delta)e_n + (k+\alpha\delta^2)e_r\right] \\ -\left[\delta(k+k\alpha+\alpha\delta)e_n^2 - 2(k+\alpha\delta^2)e_ne_r + (-1+\delta+\alpha\delta)e_r^2\right]p_e \end{pmatrix}}{[k+\alpha\delta(1-\alpha\delta)](\delta e_n - e_r)}$. If $b \leqslant B_5$, $EI^{NW*} \geqslant EI^{BW*}$, otherwise, $EI^{NW*} < EI^{BW*}$. By solving $EI^{NS*} - EI^{BS*} = 0$, we obtain $B_6 = \frac{(-1+\alpha)\delta\begin{pmatrix} c_r\left[-(k+\alpha\delta^2)e_n + (-2+\delta+\alpha\delta)e_r\right] + c_n\left[\delta(k+k\alpha+2\alpha\delta)e_n - (k+\alpha\delta^2)e_r\right] \\ +\left(\delta(k+k\alpha+2\alpha\delta)e_n^2 - 2(k+\alpha\delta^2)e_ne_r + (-2+\delta+\alpha\delta)e_r^2\right)p_e \end{pmatrix}}{[k+\alpha\delta(2-\alpha\delta)](\delta e_n - e_r)}$. If $b \leqslant B_6$, $EI^{NS*} \geqslant EI^{BS*}$, otherwise, $EI^{NS*} < EI^{BS*}$.

For (b), $EI^{NW*} - EI^{NS*} = -\frac{\alpha\delta(\alpha\delta e_n - e_r)[\alpha\delta c_n - c_r + (\alpha\delta e_n - e_r)p_e]}{2[k+\alpha\delta(1-\alpha\delta)][k+\alpha\delta(2-\alpha\delta)]}$, by solving $EI^{NW*} - EI^{NS*} = 0 \Leftrightarrow \alpha\delta e_n - e_r = 0$, we obtain $\frac{e_r}{e_n} \leqslant \alpha\delta$. If $\frac{e_r}{e_n} \leqslant \alpha\delta$, $EI^{NW*} \leqslant EI^{NS*}$, otherwise, $EI^{NW*} > EI^{NS*}$. $EI^{BW*} - EI^{BS*} = \frac{\delta(\delta e_n - e_r)[b-\delta c_n + c_r + (-\delta e_n + e_r)p_e]}{2(k+2\delta-\delta^2)(k+\delta-\delta^2)}$, by solving $EI^{BW*} - EI^{BS*} = 0 \Leftrightarrow \delta e_n - e_r = 0$, we obtain $\frac{e_r}{e_n} \leqslant \delta$. If $\frac{e_r}{e_n} \leqslant \delta$, $EI^{BW*} \leqslant EI^{BS*}$, otherwise, $EI^{BW*} > EI^{BS*}$.

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