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Blockchain adoption and coordination strategies for green supply chains considering consumer privacy concern

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ABSTRACT

Consumers' uncertainty about the value of green products will reduce their willingness to pay, thereby obstructing green product promotion. Blockchain can eliminate this uncertainty but bring privacy concerns. We develop a game theoretical model to study a green supply chain composed of one manufacturer and one retailer, aiming to explore the implications of partial or full blockchain adoption on green product manufacturing. Subsequently, we consider the use of revenue-sharing and cost-sharing contracts as mechanisms to coordinate the supply chain that adopts blockchain technologies. We show that adopting blockchain for some products benefits the manufacturer and the retailer, and consumers' privacy concerns make it impossible for blockchain to be adopted for all products. Interestingly, partial or full blockchain adoption does not affect the green investment level. Furthermore, we find that revenue-sharing and cost-sharing contracts are always beneficial for the manufacturer. However, it can be beneficial for the retailer only when the revenue-sharing or cost-sharing ratio is small. Surprisingly, the effectiveness of the coordinating contract is not affected by consumers' privacy concerns. Finally, when comparing the wholesale price contract with two coordination mechanisms, we find that the manufacturer and the retailer can agree on adopting a cost-sharing contract when both revenue- and cost-sharing ratios are low. When the revenue-sharing ratio is moderate and the cost-sharing ratio is low, a revenue-sharing contract is adopted. In all other cases, trading is conducted according to the wholesale price contract. These insights can contribute to optimize the application of blockchain in green supply chains.

1. Introduction

1.1. Background and motivation

The exacerbation of environmental issues has garnered significant attention from both consumers and businesses amid the ongoing economic development. Consequently, consumer environmental consciousness has sparked an upsurge in demand for green products (Xu & Duan, 2022). To meet this growing preference, numerous manufacturers have embraced green technologies and materials to enhance the sustainability of their offerings. For instance, Apple incorporated renewable energy sources and bio-based renewable plastics in the production of the iPhone 11 Pro (Apple, 2019), while Huawei successfully curtailed carbon emissions by 612 tons in 2018 through the use of recyclable and bio-based materials across their product range (Xu et al., 2021). Similarly, companies like Gree and Haier have made commendable strides in introducing eco-friendly products. These sustainable development endeavors have not only captured consumer interest but also increased consumer demand with such green investments. Furthermore, it is worth noting that the production of green products generally incurs higher costs, thereby reflecting in their comparably higher retail prices when compared to non-green counterparts. Nevertheless, survey results indicate that approximately 20% of consumers exhibit a willingness to purchase green products, even at a premium price point (Hong & Guo, 2019). It is evident that green production not only fuels consumer demand but also enhances the consumers' willingness to pay.

However, when it comes to purchasing green products, consumers face challenges in assessing the extent of sustainable production processes or "green degree" of a product merely based on product appearance. The green degree of a product refers to the extent to which it has been produced and managed in an environmentally responsible manner

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considering material sourcing, production methodologies, logistics, and pollution control throughout the lifecycle of the product (Xu & Duan, 2022). This complexity makes it difficult for consumers to differentiate between certain green products and their conventional counterparts. Consequently, consumer uncertainty arises regarding the inherent value and level of environmental friendliness of these products. Furthermore, limited information exacerbates this uncertainty, potentially reducing consumers' willingness to pay a premium, thus impeding the sales of green products. To address this issue and enable consumers to make informed choices between green and traditional products, many manufacturers employ labeling methods to communicate their products' eco-credentials. However, this approach is susceptible to counterfeit practices. Some producers attach counterfeit "green food" labels to ordinary agricultural products they either produce or acquire at low prices, artificially inflating the quality ratings of these products (Eastday, 2022). In 2018, Hema Fresh manipulated product labels to modify production dates, creating the illusion of freshness (Wu et al., 2023). Relying solely on traditional methods proves inadequate in dispelling consumer uncertainties surrounding green products.

The emergence of blockchain technology presents an opportunity to address this issue effectively. Compared to traditional technologies like RFID, blockchain is a burgeoning technology that possesses key attributes such as immutability, traceability, and credibility (Long et al., 2022). Consequently, it facilitates the provision of transparent and authentic information for both supply chain participants and consumers. Numerous companies have leveraged blockchain to enable consumers access to reliable and traceable information pertaining to product quality (Tao et al., 2023). For example, JD.com utilizes blockchain to track product origins and ensure the integrity of product information. Recently, blockchain has been applied in green practices, with companies like IKEA using it to verify the use of genuinely green materials in their products (Saberi et al., 2019). Specifically, when consumers purchase IKEA's products, they can scan an exclusive QR code on the product or access relevant blockchain platforms through their smartphones to view the manufacturing process, material sources, and environmental impact (Xu & Duan, 2022). This can enhance consumer trust, thereby increasing their tendency to purchase green products.

However, when consumers use smartphones to view IKEA's product information, the blockchain system records their activity, potentially leading to privacy issues (Zhang et al., 2022b). Specifically, blockchain operates on a pseudonymous basis, where users have pseudo-identities within the network. If hackers manage to link these pseudonyms to consumers' real-life identities, this could expose their past purchasing history (Pun et al., 2021). Surveys show that over 90% of consumers express concern about online privacy, with nearly 50% of consumers limiting their activities due to such concerns (Pun et al., 2021). Therefore, the adoption of blockchain might not always be beneficial, as most users are at risk of privacy breaches. In practice, companies must carefully weigh the benefits of using blockchain against the privacy risks associated with its adoption. This underscores that a one-size-fits-all approach may not always be the best, and a strategy that involves selective adoption of blockchain for certain products might be more appropriate. For instance, Yonghui Superstores Co., Ltd. is conducting a pilot project promoting blockchain, where some products have traceability systems while others do not (Yonghui, 2019).

Besides capturing consumer interest to increase demand with green investments, firms within a green supply chain (GSC) need to make decisions related to sustainability initiative investments to improve the product's green degree (Patanjal et al., 2021). For example, in the IKEA case, IKEA collaborates with upstream and downstream firms to jointly invest in renewable energy projects and waste management improvements, committed to achieving 100% renewable energy use and zero waste to landfill (International Business, 2021). Here, they jointly bear the cost of the green supply chain and share the increased revenue from such initiatives. This mechanism of sharing revenues or costs is common in GSCs. For example, Huawei has provided financial support to suppliers who upgrade their production facilities and transform them into green facilities. Walmart and Coca-Cola also employ revenue and cost-sharing to encourage their upstream firms to undertake green activities (Plambeck & Denend, 2011). These mechanisms enable supply chain members to attain profits surpassing those achievable through independent investment, resulting in a Pareto improvement for all involved parties. Therefore, when firms adopt blockchain to improve consumer response to GSC investments, it is imperative to understand the impact of coordinating mechanisms commonly adopted within GSCs on green investment levels and the outcomes of blockchain adoption. This, in turn, is likely to influence the green degree of products, consumer utility, and the profitability of supply chain members. Hence, analyzing the influence of blockchain adoption on contract selection not only enhances the practical implementation of blockchain but also enriches prior research on supply chain coordination.

1.2. Research questions, findings, and contributions

Given the context above, it is pertinent to assess the feasibility of blockchain adoption in GSCs while considering consumer privacy concerns. The adoption of blockchain in this context introduces decision-making complexities related to the operations of GSCs. These complexities include determining whether blockchain should be universally implemented across all products or some products, as well as establishing effective cooperation mechanisms among supply chain members considering the impact of blockchain adoption. However, the existing research in this domain is limited. To fill this research gap, this study adopts game theory with the aim of providing decision-making guidance for the adoption of blockchain in GSCs. Drawing inspiration from observed practices in GSC management, this paper focuses on a specific scenario involving a green product manufacturer and a retailer within the GSC, taking into consideration the privacy concerns of consumers. Specifically, this study aims to address the following research questions.

- *How can blockchain create value for the manufacturer and the retailer in a GSC in the presence of consumer privacy concerns?*
- *In a GSC, is it more beneficial to adopt blockchain for all products or some products?*
- *When adopting blockchain in a GSC, how should the manufacturer and the retailer choose cooperation mechanisms? What impact does blockchain have on this choice?*

Initially, we analyze the equilibrium decisions and profits of the supply chain members in a baseline situation where blockchain technology is not adopted. Subsequently, we examine pricing strategies and green investment decisions when the manufacturer adopts blockchain for all or some products. Additionally, through a comparative analysis of the profits obtained by the GSC members in these two scenarios, we identify the conditions under which the adoption of blockchain proves advantageous for the GSC. Finally, to enhance collaboration among the supply chain members, we perform coordination analysis with revenue-sharing and cost-sharing contracts tailored explicitly for the GSC during the adoption of blockchain. The key findings are as follows.

First, the adoption of blockchain technology for all products is beneficial for the manufacturer, retailer, consumers, and society only when the privacy concerns of consumers are relatively low. When blockchain is partially adopted for some products, the manufacturer, the retailer, consumers and society consistently benefit from blockchain adoption. Meanwhile, their profits in this scenario first decrease and then remain unchanged with the privacy concerns of consumers. This is because as privacy concerns increase and outweigh the benefits of blockchain adoption, blockchain-enabled products will no longer be purchased by anyone, and only the benefits brought by non-blockchain-enabled products will exist, which is unrelated to privacy concerns. Interestingly, we find that adopting blockchain for some products is always better than adopting blockchain for all products. This is mainly caused by competition between the two products.

Second, our research indicates that revenue-sharing and cost-sharing contracts invariably enhance the manufacturer's profit, which further increases with the sharing ratio. In contrast, the retailer experiences a profit increase only at low sharing ratios, with its profit first increasing and then decreasing with the sharing ratio. Thus, we show that we can achieve Pareto improvement by designing coordinating mechanisms with low revenue-sharing or cost-sharing ratios. Interestingly, the conditions for Pareto improvement are unaffected by consumers' privacy concerns when blockchain is adopted for all products. However, when blockchain is adopted for some products, lowering consumers' privacy concerns increases the likelihood of achieving Pareto improvement through a revenue-sharing contract. In contrast, the opposite is true for a cost-sharing contract.

Third, by comparing the wholesale price contract and two coordination mechanisms, we find that when two sharing ratios are low, the manufacturer and the retailer can agree on adopting a cost-sharing contract; When the revenue-sharing ratio is moderate and the cost-sharing ratio is low, a revenue-sharing contract is adopted; In other cases, they can only trade according to the wholesale price contract. This coordinating mechanism adoption is independent of the manufacturer's blockchain adoption strategy. The difference is that when blockchain is adopted for some products, the lower the privacy concerns of consumers, the more likely it is that parties will agree on adopting two sharing contracts. However, when blockchain is adopted for all products, the selection of the mechanism is not affected by consumers' privacy concerns. Therefore, when blockchain is adopted for some products, they need to be careful about consumers' privacy concerns.

This study makes three main contributions. First, existing research mainly explores the conditions for the application of blockchain, while we analyze whether blockchain should be adopted for all products or some products in GSCs. Meanwhile, we consider that blockchain can eliminate consumers' green uncertainty but also cause privacy concerns, which has not been explored in previous research. Second, to optimize blockchain adoption in GSCs, we also explore the coordination mechanisms among supply chain members. Therefore, this paper is the first to combine blockchain, privacy concerns, coordination mechanisms, and the scope of blockchain adoption in the research of GSCs. Third, this study reveals interesting managerial insights, such as the conditions under which manufacturers should use blockchain for some products rather than for all products. Regardless of whether blockchain is adopted for all products or some products, manufacturers and retailers can adopt the same coordination mechanism without being affected by privacy concerns.

The rest of the paper is structured as follows. In Section 2, a literature review is provided. Section 3 presents the model description. Section 4 calculates and compares the equilibrium results under the scenario with and without blockchain. Section 5 explores the coordination strategies with blockchain adoption. Section 6 provides four extensions. Finally, managerial implications and future research suggestions are offered in Section 7. All thresholds and proofs are provided in Appendix.

2. Literature review

In this paper, we contribute to four streams of research. The first stream of research studies the optimal operational decisions of the green supply chains, the second stream analyzes the blockchain adoption in supply chain, the third stream deals with consumer privacy issues in supply chains, and the fourth stream deals with the design of coordination contracts in supply chains. Next, we elaborate on each of the above streams and contrast our work with them.

2.1. Green supply chain management

Currently, the issues of GSC management have garnered significant scholarly attention. Some researchers have examined decision-making problems concerning green investments, which entail the adoption or upgrade of green technologies to mitigate carbon emissions within the supply chain. For example, Chen et al. (2020) explore a GSC context wherein manufacturers and retailers face carbon emission taxes and can reduce emissions through investments in green technologies. Hussain et al. (2020) investigate implementation decisions regarding green technologies under emission reduction subsidy policies. Zhang et al. (2020) focus on the green investment decisions of two companies engaged in quality competition. Modak and Kelle (2021) suggest that manufacturers can opt for corporate social responsibility initiatives to boost demand or invest in recycling activities to reduce carbon emissions. The consideration of green investments has also been analyzed in textile and apparel supply chains (Shen et al., 2021) and within the context of retail competition (Fu et al., 2023; Hosseini-Motlagh et al., 2021). These studies primarily examine whether firms should invest in green products, whereas our paper builds upon the foundation of green investments. Several scholars have researched the impact of green marketing on GSCs. Green marketing plays a crucial role in conveying the environmental characteristics of products and enhancing consumers' environmental responsibility. Wang and Song (2020) examine decision-making regarding marketing efforts in GSCs under conditions of demand uncertainty. Li et al. (2021) and Jafar et al. (2022) analyze the influence of different contract types on marketing efforts within GSCs. Shi et al. (2022), considering various power structures, investigate the value of green marketing and strategies for its implementation. Similarly, we consider the investments by the manufacturer in green products and the adoption of green marketing. However, our research distinguishes itself by exploring the adoption of blockchain to disclose the attributes of green products to stimulate consumer purchases.

2.2. Blockchain adoption in supply chains

Research on the adoption of blockchain technology in supply chain management primarily focuses on its distinct characteristics, with scholars exploring it from three main perspectives. First, blockchain is leveraged for tracking, identification, labeling, and tamper-proofing, thereby enabling consumers to make informed purchases of authentic products while differentiating them from counterfeit ones. Additionally, it aids brand owners in combating the proliferation of counterfeit products (Naoum-Sawaya et al., 2023; Shen et al., 2022). Second, blockchain technology is employed to enhance the credibility, immutability, and transparency of information, facilitating the sharing of enterprise or product data among different entities. This promotes increased levels of trust among businesses and enables more accurate market demand forecasting (Dong et al., 2023; Liu et al., 2023; Niu et al., 2021). Third, blockchain technology is used to mitigate consumer uncertainties regarding product quality and value through its transparency and traceability features, thereby augmenting consumer trust (Wu et al., 2023; Xu et al., 2023b, 2023a; Zhang et al., 2023). While there is extensive research on the adoption of blockchain in supply chain management, studies specifically focusing on its adoption in GSCs remain relatively limited (Lu et al., 2024). In this domain, Xu and Duan (2022) examine the optimal pricing and investment strategies for green products with government subsidies while also exploring the conditions for adopting blockchain. Xu et al. (2023a) focus on the impact of blockchain on green technology investments within a supply chain where manufacturers distribute their products through retailers and online platforms. In contrast to these studies, in addition to addressing uncertainties related to green products through blockchain's transparency, traceability, and immutability features, our study also accounts for potential consumer privacy concerns when blockchain is partially or fully adopted in a GSC. Moreover, we analyze coordination strategies under various levels of blockchain coverage, which have not been explored in prior research.

2.3. Consumer privacy issues in supply chains

Research on consumer privacy concerns mainly focuses on the competition for consumer information and the impact of privacy concerns regarding private information on consumer demand. Tsai et al. (2011) show that when private information is emphasized and easily accessible, some consumers are willing to pay a premium to purchase from websites that prioritize privacy protection. Tucker (2014) demonstrates that enhancing perceived control over privacy led to a nearly twofold increase in user engagement with personalized ads. Casadesus-Masanell and Hervas-Drane (2015) delve into the implications of consumer privacy for market competition as firms compete over consumer information. Gal-Or et al. (2018) investigate how user privacy issues affect competition among online advertising platforms. Johnson et al. (2020) study consumer privacy choices in the context of online display advertising, where advertisers track consumer browsing to improve advertising positioning. Arora and Jain (2024) compare two sales models under data sharing, privacy protection, and government regulation, in which data sharing can reduce quality investment costs. Unlike these studies, we consider consumer privacy concerns when using blockchain technologies adopted by the GSC to increase consumers' trust in the green level of the product. Similarly, Pun et al. (2021) analyze the factors influencing manufacturers' adoption of blockchain to combat counterfeiting when consumers have privacy concerns regarding the use of blockchain. Zhang et al. (2022b) analyze the equilibrium strategies for adopting blockchain among incumbent and new entrant retailers, showing that both retailers are more inclined to adopt blockchain when there are minimal concerns over consumer privacy and a high level of information transparency. Guo et al. (2024) find that the sales prices and quantity of smart products decrease simultaneously with an increase in privacy concerns. We extend these studies by exploring the impact of consumer privacy concerns on cooperation mechanisms when blockchain is partially or fully adopted in a GSC.

2.4. Coordination contracts in supply chains

Several researchers have examined the issue of selecting cooperation mechanisms in GSCs. For example, Qiao et al. (2021) discuss strategies to enhance the performance of the GSC through the use of quantity discounts and cost-sharing contracts and provide criteria for contract selection. Patanjal et al. (2021) investigate various contract types, including wholesale price contracts, cost-sharing contracts, revenue-sharing contracts, and two-part tariff contracts, within a two-stage game theory framework. Shen et al. (2023) explore a government-intervened GSC involving manufacturers and retailers and find that government intervention can facilitate conflict coordination within the GSC. Li et al. (2024) consider consumer aversion to environmental quality degradation and introduce a two-part tariff contract to coordinate the activities of the GSC across multiple periods. Zhang et al. (2022a) examine the decision-making process regarding compliance quality improvement, carbon emission reduction, and green marketing optimization in a GSC comprising one manufacturer and multiple retailers, while considering investment cost-sharing. Note that most existing studies on GSC coordination focus on revenue-sharing and cost-sharing contracts, which aligns with the scope of our study. However, in contrast to the existing literature we study the impact of blockchain adoption on coordination strategies. Yang et al. (2021) show that two-part tariff contracts can achieve supply chain coordination in the presence of blockchain, while cost-sharing, revenue-sharing, and profit-sharing contracts cannot. Liu et al. (2020b) investigate investment decisions and coordination problems within a single-channel green agricultural product supply chain, evaluating the influence of both blockchain and big data on freshness and greenness. These studies explore the conditions for supply chain coordination with blockchain adoption. However, in this study, we not only analyze the selection of Pareto-improving contracts but also explore the mutual influence between blockchain adoption strategies and contract coordination strategies.

3. Model description

We consider a green supply chain system consisting of a manufacturer (referred to as "M") and a retailer (referred to as "R"). The manufacturer produces a green product and sells it to the retailer through a wholesale contract at a unit wholesale price (w). The retailer then sells the product to the market at a unit retail price (p), where $p > w > 0$. In the market, consumer valuations for the product are denoted by the continuous variable v, which follows a density function $f(v)$. We assume v follows a uniform distribution within the range of $[0, 1]$, and the market size is normalized to 1 (Shi et al., 2023).

We assume that consumers possess environmental awareness, which implies that the green degree of products can influence their product valuation and thus demand. Consumers are assumed to derive an environmental value, denoted as $\alpha(e_0 + e)$, from purchasing green products. Here, $(e_0 + e)$ represents the total green degree of the product, e_0 represents the initial green degree, and e represents the manufacturer's green investment level. α reflects the sensitivity of consumer utility to product's green degree (Xu & Duan, 2022). The manufacturer incurs a cost for investing in green initiatives, which is modeled as $\frac{1}{2}ke^2$, where k represents the cost coefficient of green investment. This quadratic cost function is widely adopted in the existing literature, such as Liu et al. (2020a), Xu et al. (2021), and Li et al. (2022). Under the wholesale price contract, the manufacturer bears investment costs and the retailer receives sales revenue.

Consumers often encounter uncertainty regarding the value of green products due to limited and unreliable information. It is assumed that consumers are uncertain regarding the total valuation. Consistent with previous research (Wu et al., 2023; Xu & Duan, 2022), θ is employed to represent the level of consumer certainty. A higher value of θ indicates that consumers have a greater recognition of the value of green products. Therefore, in the absence of blockchain technology in the GSC, the utility function of consumers when purchasing a green product is given as $U_N = \theta(v + \alpha(e_0 + e)) - bp_N$, where b represents the sensitivity of consumer utility to the retail price, and p_N represents the retail price of non-blockchain-enabled products.

When blockchain is adopted, consumers are provided with complete information about the green product, eliminating their uncertainty, i.e., θ is set to 1 (Wu et al., 2023). However, as previously mentioned, blockchain adoption may raise concerns about consumer privacy. Drawing from Pun et al. (2021) and Zhang et al. (2022b), we assume that the degree of consumer privacy concern, corresponding to the privacy cost, is denoted as s. A higher value of s signifies a greater level of privacy concern associated with consumers' use of blockchain. In Section 6.2, we show the robustness of our results in the case of heterogenous privacy concerns where consumers may have different levels of privacy concern. Therefore, when blockchain is adopted, the utility of customers is expressed as $U_B = v + \alpha(e_0 + e) - bp_B - s$, where p_B represents the retail price of blockchain-enabled products. Note that the manufacturer may choose to selectively implement blockchain technology for some products while others remain unaffected (Tao et al., 2023). This creates a competitive environment where blockchain-enabled products coexist with non-blockchain-enabled ones in the market. Note that not all consumers choose to use blockchain once it is provided; thus, in Section 6.3, we study the case where consumers have varying attitudes towards blockchain adoption.

We consider a Stackelberg game in which the manufacturer serves as the leader and the retailer as the follower. The decision sequence can be divided into the following steps. First, the manufacturer decides whether to adopt blockchain and simultaneously determines whether it is adopted for some or all products. Following that, the manufacturer determines the green investment level e. Subsequently, the manufacturer establishes the wholesale prices w_N and w_B, and proposes a wholesale price contract to the retailer. Finally, the retailer determines the retail prices p_N and p_B. Following Niu et al. (2021) and Tao et al. (2023), we assume that the production cost and the unit blockchain

Table 1
Notations and descriptions.

Notations	Descriptions
Decisions	
p_N	Retail price of non-blockchain-enabled products
w_N	Wholesale price of non-blockchain-enabled products
p_B	Retail price of blockchain-enabled products
w_B	Wholesale price of blockchain-enabled products
e	Green investment level
Parameters	
e_0	Initial green degree of the product
v	Base customer valuation of the product, $v \sim U[0,1]$
θ	Degree of consumer uncertainty about the product value, $0 < \theta < 1$
α	Sensitivity of consumer's utility to product's green degree, $\alpha \geq 0$
s	Privacy cost of the consumer, $s \geq 0$
b	Price sensitivity coefficient, $b > 0$
k	Cost coefficient of green production, $k \geq 0$
φ	Revenue-sharing ratio, $0 < \varphi < 1$
λ	Cost-sharing ratio, $0 < \lambda < 1$
Functions	
U	Utility function of consumer
D	Demand function
π_j	Profit function, $j = \{M, R\}$, "M" represents manufacturer, "R" represents retailer
CS	Consumer surplus
SW	Social welfare

adoption cost are zero. In Section 6.1, we show the robustness of our results in the case where there is a unit blockchain adoption cost. Table 1 summarizes the notations of our paper.

Given the option of partial blockchain adoption by the manufacturer, we investigate the following scenarios: (1) Scenario T where blockchain is not adopted; (2) Scenario F where blockchain is adopted for all products; (3) Scenario P where blockchain is adopted for some products. We assume that both supply chain members are risk neutral and profit maximizers. Let π_j^i denote the profit of firm j under scenario i, where $j \in \{M, R\}$ and $i \in \{T, F, P\}$. Subscripts N and B represent non-blockchain-enabled and blockchain-enabled products, respectively. In this study, the term "coverage rate of blockchain" denotes the extent to which products are integrated with blockchain technology, ranging from complete adoption to partial adoption or non-adoption. The coverage rate of blockchain progressively escalates across Model T, Model P, and Model F. The demand, profit functions, and consumer surplus are presented as follows.

(1) Blockchain is not adopted in the traditional supply chain (Model T). According to $D_N^T = \int_{U_N>0}^1 dv$, we obtain that the demand is $D_N^T = 1 + \alpha(e_0 + e^T) - \frac{bp_N^T}{\theta}$. The profit functions of the manufacturer and the retailer and consumer surplus are

$$\pi_M^T = w_N^T D_N^T - \frac{1}{2}k(e^T)^2, \tag{1}$$

$$\pi_R^T = (p_N^T - w_N^T)D_N^T, \tag{2}$$

$$CS^T = \int_{\frac{bp_N^T}{\theta}-\alpha(e_0+e^T)}^1 [\theta(v + \alpha(e_0 + e^T)) - bp_N^T]dv. \tag{3}$$

(2) Blockchain is adopted for all products (Model F). According to $D_B^F = \int_{U_B>0}^1 dv$, we obtain that the demand is $D_B^F = 1+\alpha(e_0+e^F)-bp_B^F-s$. The profit functions of the manufacturer and the retailer are the same as Eqs. (1) and (2), respectively. The consumer surplus is

$$CS^F = \int_{bp_B^F+s-\alpha(e_0+e^F)}^1 [v + \alpha(e_0 + e^F) - bp_B^F - s]dv. \tag{4}$$

(3) Blockchain is adopted for some products (Model P). Following Tao et al. (2023), there is competition between blockchain-enabled and non-blockchain-enabled products. Thus, according to $D_B^P = \int_{U_B>0, U_B>U_N}^1 dv$ and $D_N^P = \int_{U_N>0, U_N>U_B}^1 dv$, we obtain that the demand for products with and without blockchain are $D_B^P = 1 + \alpha(e_0 + e^P) - \frac{b(p_B^P - p_N^P)+s}{1-\theta}$ and $D_N^P = \frac{b(p_B^P - p_N^P)+s}{1-\theta} - \frac{bp_N^P}{\theta}$, respectively. Note that in this case, both demands need to be greater than zero. Otherwise, when the demand for blockchain-enabled products is not greater than zero, Model P is similar to Model T, and consumer surplus is similar to Eq. (3). The profit functions and consumer surplus are

$$\pi_M^P = w_N^P D_N^P + w_B^P D_B^P - \frac{1}{2}k(e^P)^2, \tag{5}$$

$$\pi_R^P = (p_N^P - w_N^P)D_N^P + (p_B^P - w_B^P)D_B^P, \tag{6}$$

$$CS^P = \int_{\frac{b(p_B^P - p_N^P)+s}{1-\theta}-\alpha(e_0+e^P)}^1 [v + \alpha(e_0 + e^P) - bp_B^P - s]dv + \int_{\frac{bp_N^P}{\theta}-\alpha(e_0+e^P)}^{\frac{b(p_B^P - p_N^P)+s}{1-\theta}-\alpha(e_0+e^P)} [\theta(v + \alpha(e_0 + e^P)) - bp_N^P]dv. \tag{7}$$

In these models, social welfare can be formulated as $SW^i = CS^i + \pi_M^i + \pi_R^i$.

4. Blockchain adoption strategies under wholesale price contract

Under the wholesale price contract, we compare the optimal decisions and performances under the three models based on the information shown in Table A1 in Appendix A.

Proposition 1. *Comparing green investment levels and prices for the three scenarios:*

(1) When the privacy cost is low (i.e., $0 < s < \frac{4bk(1-\theta)(1+\alpha e_0)}{4bk-\theta\alpha^2}$): $e^{F*} = e^{P*} > e^{T*}$, $w_B^{F*} = w_B^{P*} > w_N^{P*} > w_N^{T*}$, and $p_B^{F*} = p_B^{P*} > p_N^{P*} > p_N^{T*}$.

(2) When the privacy cost is high (i.e., $\frac{4bk(1-\theta)(1+\alpha e_0)}{4bk-\theta\alpha^2} < s < 1 + \alpha e_0$): $e^{F*} < e^{P*} = e^{T*}$, $w_B^{F*} < w_N^{P*} = w_N^{T*}$, and $p_B^{F*} < p_N^{P*} = p_N^{T*}$.

Proposition 1 shows that when the privacy cost is low, blockchain adoption increases product prices and green investment levels. However, when the privacy cost is high, blockchain adoption decreases them and the adoption of blockchain to some products does not exist. Clearly, lower privacy costs indicate higher efficiency of blockchain, allowing the manufacturer to obtain more profits by increasing wholesale prices and green investment levels, leading to corresponding increases in retail prices. Interestingly, when the privacy cost is low (i.e., the adoption of blockchain to some products exists), the green investment levels and the prices of blockchain-enabled products (w_B, p_B) are the same under Model F and Model P. In contrast, the prices (w_N, p_N) of non-blockchain-enabled products under Model P are not equal to those under Model T. This indicates that for similar products, the competition arising from the application of blockchain does not change the prices of blockchain-enabled products. Still, it does cause the prices of non-blockchain-enabled products to vary depending on the privacy cost. Additionally, the coverage rate of blockchain does not affect the manufacturer's investment levels in green products, and the green investment is only influenced by the privacy cost. This challenges the common perception among consumers that higher blockchain coverage leads to a higher green degree. In practice, when facing green products with different blockchain coverage rates, the manufacturer and the retailer should pay more attention to their prices rather than their green degree.

Proposition 2. *Comparing demands for the three scenarios:*

(1) When the privacy cost is low (i.e., $0 < s < \frac{\alpha^2(1-\theta)(1+\alpha e_0)}{4bk-\theta\alpha^2}$*):* $D_N^{P*} + D_B^{P*} > D_B^{F*} > D_N^{T*}$*;*

(2) When the privacy cost is moderate (i.e., $\frac{\alpha^2(1-\theta)(1+\alpha e_0)}{4bk-\theta\alpha^2} < s < \frac{4bk(1-\theta)(1+\alpha e_0)}{4bk-\theta\alpha^2}$*):* $D_N^{P*} + D_B^{P*} > D_N^{T*} > D_B^{F*}$*;*

(3) When the privacy cost is high (i.e., $\frac{4bk(1-\theta)(1+\alpha e_0)}{4bk-\theta\alpha^2} < s < 1 + \alpha e_0$*):* $D_N^{P*} = D_N^{T*} > D_B^{F*}$.

From Proposition 2, we derive that when the privacy cost is low, the application of blockchain can increase the demand for green products, and competition resulting from partial blockchain coverage leads to the highest demand. When the privacy cost is moderate, the highest demand occurs in the scenario of partial blockchain coverage, while the lowest demand occurs in the scenario of complete coverage. When the privacy cost is high, the demand for non-blockchain-enabled products is highest, and the demand is lowest when the manufacturer adopts blockchain for all products. Interestingly, the demand under the scenario of partial blockchain coverage is always higher than that under complete coverage. This is because in Model P, the demand is composed of two parts: When the privacy cost is low, the demand for blockchain-enabled products dominates, while when the privacy cost is high, the demand for non-blockchain-enabled products dominates, and the competition between the two products also affects demand through price changes. Therefore, adopting blockchain for some products is more advantageous for capturing market share.

Corollary 1. *(1) When* $0 < s < \frac{4bk(1-\theta)(1+\alpha e_0)}{8bk-(1+\theta)\alpha^2}$*,* $D_B^{P*} > D_N^{P*}$*. When* $\frac{4bk(1-\theta)(1+\alpha e_0)}{8bk-(1+\theta)\alpha^2} < s < \frac{4bk(1-\theta)(1+\alpha e_0)}{4bk-\theta\alpha^2}$*,* $D_N^{P*} > D_B^{P*}$*. When* $\frac{4bk(1-\theta)(1+\alpha e_0)}{4bk-\theta\alpha^2} < s < 1 + \alpha e_0$*,* $D_N^{P*} > D_B^{P*} = 0$.

(2) $\frac{D_B^{P*}}{D_B^{P*}+D_N^{P*}} = 1 - \frac{s(4bk-\alpha^2)}{(1-\theta)[4bk(1+\alpha e_0)-\alpha^2 s]}$*, and* $\partial(\frac{D_B^{P*}}{D_B^{P*}+D_N^{P*}})/\partial s < 0$.

Corollary 1 demonstrates that in Model P, when the privacy cost is low, the number of blockchain-enabled products exceeds that of non-blockchain-enabled products. Conversely, when the privacy cost is high, the number of blockchain-enabled products is fewer than that of non-blockchain-enabled products. Additionally, there is a one-to-one correspondence between the proportion of blockchain-enabled products and the level of privacy cost such that as the privacy cost increases, the proportion of blockchain-enabled products decreases. This is because the higher the privacy cost, the lower the net benefits brought by blockchain adoption, and the manufacturer will reduce the quantity of blockchain-enabled products to mitigate the negative impact of high privacy costs.

Theorem 1. *Comparing profits for the three scenarios:*

(1) For the manufacturer:

(i) When $0 < s < (1 + \alpha e_0)\left[1 - \sqrt{\frac{\theta(4bk-\alpha^2)}{4bk-\theta\alpha^2}}\right]$*:* $\pi_M^{P*} > \pi_M^{F*} > \pi_M^{T*}$.

(ii) When $(1 + \alpha e_0)\left[1 - \sqrt{\frac{\theta(4bk-\alpha^2)}{4bk-\theta\alpha^2}}\right] < s < \frac{4bk(1-\theta)(1+\alpha e_0)}{4bk-\theta\alpha^2}$*:* $\pi_M^{P*} > \pi_M^{T*} > \pi_M^{F*}$.

(iii) When $\frac{4bk(1-\theta)(1+\alpha e_0)}{4bk-\theta\alpha^2} < s < 1 + \alpha e_0$*:* $\pi_M^{P*} = \pi_M^{T*} > \pi_M^{F*}$.

(2) For the retailer:

(i) When $0 < s < (1 + \alpha e_0)\left[1 - \frac{(4bk-\alpha^2)\sqrt{\theta}}{4bk-\theta\alpha^2}\right]$*:* $\pi_R^{P*} > \pi_R^{F*} > \pi_R^{T*}$.

(ii) When $(1 + \alpha e_0)\left[1 - \frac{(4bk-\alpha^2)\sqrt{\theta}}{4bk-\theta\alpha^2}\right] < s < \frac{4bk(1-\theta)(1+\alpha e_0)}{4bk-\theta\alpha^2}$*:* $\pi_R^{P*} > \pi_R^{T*} > \pi_R^{F*}$.

(iii) When $\frac{4bk(1-\theta)(1+\alpha e_0)}{4bk-\theta\alpha^2} < s < 1 + \alpha e_0$*:* $\pi_R^{P*} = \pi_R^{T*} > \pi_R^{F*}$.

(3) When $0 < s < \frac{4bk(1-\theta)(1+\alpha e_0)}{4bk-\theta\alpha^2}$*:* $\pi_M^{P*} - \pi_M^{F*} > \pi_R^{P*} - \pi_R^{F*}$.

Theorem 1 shows that the manufacturer's profit is always highest when blockchain is adopted for some products. If the manufacturer adopts blockchain for all products, then only when the privacy cost is low would blockchain adoption increase his profits. Clearly, choosing to adopt blockchain for some products generates competition among the manufacturer's products, which would increase the market coverage of the manufacturer by appealing to different customer preferences, making it the optimal choice for the manufacturer. For the retailer, the variation in her profits is similar to the changes in the manufacturer's profit. Therefore, similar to the manufacturer, it is more advantageous for the retailer if blockchain is adopted for some products rather than all products. Hence, in practical terms, it is advisable for manufacturers not to blindly assume that a higher coverage rate of blockchain translates to better outcomes. Instead, they should be more strategic in adopting blockchain for select products rather than implementing it across all their products. Moreover, by selectively embracing blockchain technology for specific products, manufacturers and retailers can attain a win-win beneficial scenario. Also, we find that manufacturers expect blockchain to be applied to some products more than retailers.

Theorem 2. *Compared with the scenario where blockchain is not adopted, when blockchain is adopted for all products,*

(1) Consumer surplus increases (i.e., $CS^{F*} > CS^{T*}$*) when the privacy cost is low (i.e.,* $0 < s < (1 + \alpha e_0)\left[1 - \frac{(4bk-\alpha^2)\sqrt{\theta}}{4bk-\theta\alpha^2}\right]$*), and decreases (i.e.,* $CS^{F*} < CS^{T*}$*) otherwise.*

(2) Social welfare increases (i.e., $SW^{F*} > SW^{T*}$*) when the privacy cost is low (i.e.,* $0 < s < (1 + \alpha e_0)\left[1 - \frac{(4bk-\alpha^2)\sqrt{\theta(bk(6+b)-\theta\alpha^2)}}{(4bk-\theta\alpha^2)\sqrt{bk(6+b)-\alpha^2}}\right]$*), and decreases (i.e.,* $SW^{F*} < SW^{T*}$*) otherwise.*

Theorem 2 states that when the privacy cost is low, consumer surplus and social welfare are higher when blockchain is adopted for all products compared to the scenario where no products are blockchain-enabled. Conversely, when the privacy cost is high, consumer surplus and social welfare are higher in the scenario where no products are blockchain-enabled. To further compare consumer surplus and social welfare under the three models, we conducted a numerical analysis as shown in Fig. 1. Referring to the parameter settings in Xu and Duan (2022), we have $\theta = 0.8$, $k = 1$, $\alpha = 1$, $b = 1$, and $e_0 = 0.1$. However, the shape and the insights are the same for other parameterizations.

From Fig. 1, we observe that when the privacy cost is low, Model P yields the highest consumer surplus and social welfare. When the privacy cost is high, Model T yields the highest consumer surplus and social welfare. Additionally, in Model F, consumer surplus and social welfare decrease with the privacy cost, while in Model P, they initially decrease and then stay unchanged, ultimately resulting in higher consumer surplus and social welfare compared to Model F. In the hybrid model, Model P, with high privacy cost, the number of blockchain-enabled products decreases while non-blockchain-enabled products increase. Conversely, in scenarios with low privacy costs, there is a greater presence of blockchain-enabled products and a lesser presence of non-blockchain-enabled products. Combining with Theorem 1, the variations in consumer surplus and social welfare are similar to the changes in the profits of the manufacturer and the retailer. Therefore, it is only possible to achieve a win-win situation for the manufacturer, retailer, consumers, and society by adopting blockchain for some products.

5. Coordination mechanisms with blockchain adoption

Through the above analysis, our results show that the privacy concerns arising from blockchain adoption significantly impact the manufacturer's decision regarding green investments and the profits of

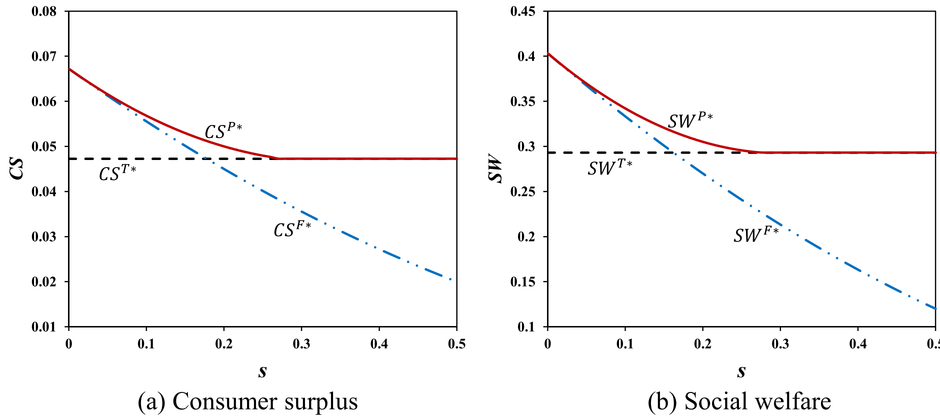


Fig. 1. Comparison of consumer surplus and social welfare under three models.

supply chain members, potentially reducing their willingness to invest in blockchain and green technologies. Moreover, the application of blockchain and investment in green technology can lead to a more severe double marginalization effect, because these technologies increase the decision-making power of the manufacturer to maximize its own profit. Cachon (2003) shows that firms can reduce the double marginalization effect and achieve optimal performance through supply chain contracts. In this context, revenue-sharing or cost-sharing contracts have been proven effective in improving supply chain performance by mitigating the investment risk to one supply chain member (Liu et al., 2020b). Furthermore, revenue-sharing and cost-sharing contracts have become increasingly common across various industries and have lower implementation costs (Cachon & Lariviere, 2005). Therefore, we consider using revenue-sharing and cost-sharing contracts to increase the supply chain performance only when the manufacturer invests in blockchain technology. Under the revenue-sharing contract, we assume that the retailer shares φ portion of the revenue generated from selling the products with the manufacturer, where $0 < \varphi < 1$. However, under the cost-sharing contract, the retailer shares λ portion of the cost of green investment with the manufacturer, where $0 < \lambda < 1$ (Patanjal et al., 2021).

5.1. Revenue-sharing contract

A revenue-sharing contract can be used to increase the supply chain performance when the manufacturer adopts blockchain for all products, which we call the FR model. In the Model FR, the profit functions of the manufacturer and the retailer are:

$$\pi_M^{FR} = (\varphi p_B^{FR} + w_B^{FR})D_B^{FR} - \frac{1}{2}k(e^{FR})^2, \tag{8}$$

$$\pi_R^{FR} = [(1-\varphi)p_B^{FR} - w_B^{FR}]D_B^{FR}. \tag{9}$$

Table A2 in Appendix A presents the optimal decisions and related performances when the manufacturer adopts blockchain for all products under a revenue-sharing contract.

Proposition 3. *Compared with the wholesale price contract, when blockchain is adopted for all products, a revenue-sharing contract*

(1) increases the green investment level (i.e., $e^{FR*} > e^{F*}$).

(2) increases the wholesale price (i.e., $w_B^{FR*} > w_B^{F*}$) when $\frac{2(3bk-\alpha^2)}{4bk-\alpha^2} < \varphi < 1$, and decreases (i.e., $w_B^{FR*} < w_B^{F*}$) otherwise.

(3) increases the retail price (i.e., $p_B^{FR*} > p_B^{F*}$) when $\frac{\alpha^2}{2b(2-\varphi)} < k < \frac{\alpha^2}{b}$, and decreases (i.e., $p_B^{FR*} < p_B^{F*}$) otherwise.

(4) increases demand (i.e., $D_B^{FR*} > D_B^{F*}$).

Proposition 3 states that when the manufacturer adopts blockchain for all products, the revenue-sharing contract enables the manufacturer to share a portion of the retailer's revenues, which incentivizes the manufacturer to increase the green investment level. The change in retail prices is independent of the revenue-sharing ratio, but when the cost coefficient of green investment is low, the revenue-sharing contract can lead to an increase in retail prices. This increase is caused by the higher green investment level. Interestingly, when the revenue-sharing ratio for the manufacturer is high, he tends to set a higher wholesale price. This is because when the revenue-sharing ratio is larger, the role played by the retailer becomes smaller, and in order to increase profits further to compensate for the increased cost of green investment, the manufacturer will set a higher wholesale price. This only affects the internal profit distribution mechanism and does not impact the retail prices. Moreover, the positive effect of increasing the green investment level always outweighs the negative effect of increasing retail prices, and the impact of the privacy cost on different contracts is the same. Thus, the revenue-sharing contract always increases the demand for green products.

Theorem 3. *Compared with the wholesale price contract, when blockchain is adopted for all products, a revenue-sharing contract*

(1) increases the manufacturer's profit (i.e., $\pi_M^{FR*} > \pi_M^{F*}$).

(2) increases the retailer's profit (i.e., $\pi_R^{FR*} > \pi_R^{F*}$) when $0 < \varphi < \frac{\alpha^2(4bk-\alpha^2)}{4b^2k^2}$, and decreases (i.e., $\pi_R^{FR*} < \pi_R^{F*}$) otherwise.

Theorem 3 states that when the manufacturer adopts blockchain for all products, the revenue-sharing contract can always increase the manufacturer's profit. Under the revenue-sharing contract, the manufacturer can profit from not only wholesaling the products but also sharing the sales revenue, and the higher the revenue-sharing ratio, the higher the manufacturer's profit. Surprisingly, the retailer also benefits from this contract when the revenue-sharing ratio is low. Moreover, the retailer's profit experiences an initial rise followed by a decline as the revenue-sharing ratio increases. This is because at lower revenue-sharing ratios, the revenue sharing incentivizes the manufacturer to boost green investment, effectively counterbalancing the loss from sharing the revenue with the manufacturer. However, as the revenue-sharing ratio increases, the ability of green investments to offset revenue loss diminishes. Ultimately, at higher revenue-sharing ratios, the detrimental impact of revenue loss outweighs the positive effects of increased green investments. Furthermore, we find that when the manufacturer adopts blockchain for all products, the impact of the revenue-sharing contract on supply chain decisions and profits is independent of the privacy cost. This is because the influence of the privacy cost on supply chain decisions and profits is the same with or without the revenue-sharing contract. Therefore, when the manufacturer adopts blockchain for all products, the revenue-sharing contract can achieve Pareto improvement when the revenue-sharing ratio is low, and it is not affected by the privacy cost.

A revenue-sharing contract can be used to increase the supply chain performance when the manufacturer adopts blockchain for some products: we call this model PR. In the Model PR, the profit functions of the manufacturer and the retailer are:

$$\pi_M^{PR} = (\varphi p_N^{PR} + w_N^{PR})D_N^{PR} + (\varphi p_B^{PR} + w_B^{PR})D_B^{PR} - \frac{1}{2}k(e^{PR})^2, \quad (10)$$

$$\pi_R^{PR} = [(1-\varphi)p_N^{PR} - w_N^{PR}]D_N^{PR} + [(1-\varphi)p_B^{PR} - w_B^{PR}]D_B^{PR}. \quad (11)$$

Similarly, Table A2 summarizes the optimal decisions and related performances when the manufacturer adopts blockchain for some products under the revenue-sharing contract.

Proposition 4. *Compared with the wholesale price contract, when blockchain is adopted for some products, a revenue-sharing contract*

(1) increases the green investment level (i.e., $e^{PR*} > e^{P*}$).

(2) increases the non-blockchain-enabled products' wholesale price (i.e., $w_N^{PR*} > w_N^{P*}$) when ($0 < \varphi < \frac{8bk-3\alpha^2}{6bk-2\alpha^2}$ and $s > s_1^{PR}$) or ($\frac{8bk-3\alpha^2}{6bk-2\alpha^2} < \varphi < 1$ and $0 < s < s_1^{PR}$), and decreases (i.e., $w_N^{PR*} < w_N^{P*}$) otherwise.

(3) increases the blockchain-enabled products' wholesale price (i.e., $w_B^{PR*} > w_B^{P*}$) when $\frac{6bk-2\alpha^2}{4bk-\alpha^2} < \varphi < 1$, and decreases (i.e., $w_B^{PR*} < w_B^{P*}$) otherwise.

(4) increases the non-blockchain-enabled products' retail price (i.e., $p_N^{PR*} > p_N^{P*}$) when $\frac{\alpha^2}{2b(2-\varphi)} < k < \frac{\alpha^2}{b}$ and $0 < s < s_2^{PR}$, and decreases (i.e., $p_N^{PR*} < p_N^{P*}$) otherwise.

(5) increases the blockchain-enabled products' retail price (i.e., $p_B^{PR*} > p_B^{P*}$) when $\frac{\alpha^2}{2b(2-\varphi)} < k < \frac{\alpha^2}{b}$, and decreases (i.e., $p_B^{PR*} < p_B^{P*}$) otherwise.

Proposition 4 shows that when blockchain is adopted for some products, the revenue-sharing contract can always increase the green investment level. For blockchain-enabled products, the revenue-sharing contract can increase the wholesale price when the revenue-sharing ratio is high and can increase the retail price when the cost coefficient of green investment is low. This is consistent with Proposition 3, which indicates that the coverage rate of blockchain does not change the impact of the revenue-sharing contract on blockchain-enabled products. For non-blockchain-enabled products, when the revenue-sharing ratio is low (high) and the privacy cost is high (low), the revenue-sharing contract leads to an increase in the wholesale price. Non-blockchain-enabled products have corresponding revenue-sharing ratio that make their wholesale prices increase in the face of different privacy costs, which is different from blockchain-enabled products. This is because when the privacy cost is high (i.e., $s > s_1^{PR}$), the competitiveness of non-blockchain-enabled products exceeds that of blockchain-enabled products. This allows the manufacturer to increase the wholesale price of non-blockchain-enabled products to obtain more revenue, even if the revenue-sharing ratio is small. When both the green investment cost coefficient and the privacy cost are low, the revenue-sharing contract leads to an increase in the retail price. The change in retail price also takes into account the influence of the privacy cost for non-blockchain-enabled products.

Proposition 5. *Compared with the wholesale price contract, when blockchain is adopted for some products, a revenue-sharing contract*

(1) increases the non-blockchain-enabled products' demand (i.e., $D_N^{PR*} > D_N^{P*}$).

(2) increases the blockchain-enabled products' demand (i.e., $D_B^{PR*} > D_B^{P*}$) when $0 < s < s_3^{PR}$, and decreases (i.e., $D_B^{PR*} < D_B^{P*}$) otherwise.

(3) increases total demand (i.e., $D_B^{PR*} + D_N^{PR*} > D_B^{P*} + D_N^{P*}$) when $0 < s < s_4^{PR}$, and decreases (i.e., $D_B^{PR*} + D_N^{PR*} < D_B^{P*} + D_N^{P*}$) otherwise.

Proposition 5 states that when blockchain is adopted for some products, the revenue-sharing contract can always increase the demand for non-blockchain-enabled products, and it can increase the demand for blockchain-enabled products when the privacy cost is low. Therefore, when blockchain is adopted for some products, the total demand can increase when the privacy cost is low. This is different from the scenario where blockchain is adopted for all products. Fig. 2 illustrates the impact of the revenue-sharing contract on supply chain profits in this scenario, using the same parameter setting as Fig. 1.

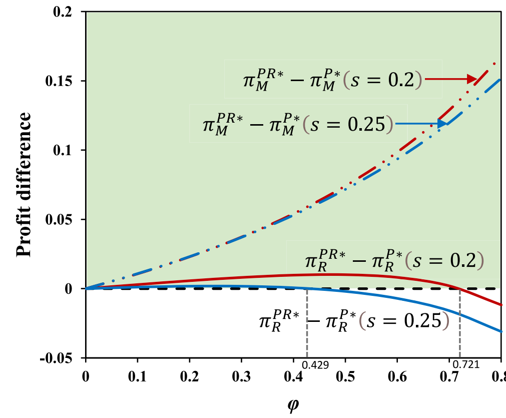


Fig. 2. Profits under the revenue sharing-contract with partial blockchain adoption.

We observe that the revenue-sharing contract always increases the manufacturer's profit and increases the retailer's profit when the revenue-sharing ratio is low. Therefore, similar to the case of all blockchain adoption (Theorem 3), the supply chain can achieve Pareto improvement when the revenue-sharing ratio is low. However, when blockchain is adopted for some products, the lower the privacy cost, the more likely the revenue-sharing contract can lead to Pareto improvement in the supply chain. This is due to the internal competition between blockchain-enabled and non-blockchain-enabled products. Therefore, whether the revenue-sharing contract can result in a win-win situation for both the manufacturer and the retailer depends on the revenue-sharing ratio when blockchain is adopted for all products, while in the context where blockchain is adopted for some products, both the revenue-sharing ratio and the privacy cost need to be taken into account.

5.2. Cost-sharing contract

A cost-sharing contract can be used to increase the supply chain performance when the manufacturer adopts blockchain for all products, which we call the FC model. In the Model FC, the profit functions of the manufacturer and the retailer are as follows.

$$\pi_M^{FC} = w_B^{FC} D_B^{FC} - \frac{1}{2}(1-\lambda)k(e^{FC})^2, \quad (12)$$

$$\pi_R^{FC} = (p_B^{FC} - w_B^{FC})D_B^{FC} - \frac{1}{2}\lambda k(e^{FC})^2. \quad (13)$$

We summarize the optimal decisions and related performances in Table A3 in Appendix A when the manufacturer adopts blockchain for all products under the cost-sharing contract.

Proposition 6. *Compared with the wholesale price contract, when blockchain is adopted for all products, a cost-sharing contract increases the green investment level, wholesale price, retail price, and demand (i.e., $e^{FC*} > e^{F*}$, $w_B^{FC*} > w_B^{F*}$, $p_B^{FC*} > p_B^{F*}$, and $D_B^{FC*} > D_B^{F*}$).*

Proposition 6 states that when the manufacturer adopts blockchain for all products, the cost-sharing contract can always increase the green investment level, wholesale price, retail price, and demand. This is because the retailer sharing the manufacturer's green investment cost will incentivize the manufacturer to increase green investment, allowing the retailer to raise the retail price to increase profits and offset the shared cost. Correspondingly, the manufacturer will increase the wholesale price. Ultimately, since the positive effect of increased green investment on demand outweighs the negative effect of price increases on demand, the cost-sharing contract always leads to an increase in demand.

Theorem 4. *Compared with the wholesale price contract, when blockchain is adopted for all products, a cost-sharing contract*

(1) increases the manufacturer's profit (i.e., $\pi_M^{FC*} > \pi_M^{F*}$).

(2) increases the retailer's profit (i.e., $\pi_R^{FC*} > \pi_R^{F*}$) when $0 < \lambda < \frac{\alpha^2(4bk-\alpha^2)}{2bk(8bk-\alpha^2)}$, and decreases (i.e., $\pi_R^{FC*} < \pi_R^{F*}$) otherwise.

Theorem 4 states that when the manufacturer adopts blockchain for all products, the cost-sharing contract can always increase the manufacturer's profit, and the higher the cost-sharing ratio, the higher the manufacturer's profit. However, the retailer's profit increases when the cost-sharing ratio is low, and it first increases and then decreases with the cost-sharing ratio. Therefore, when the manufacturer adopts blockchain for all products, the cost-sharing contract can achieve Pareto improvement when the cost-sharing ratio is low, regardless of the privacy cost. These conclusions are similar to those under the revenue-sharing contract.

A cost-sharing contract can be used to increase the supply chain performance when the manufacturer adopts blockchain for some products, which we call the PC model. In the Model PC, the profit functions of the manufacturer and the retailer are as follows.

$$\pi_M^{PC} = w_N^{PC} D_N^{PC} + w_B^{PC} D_B^{PC} - \frac{1}{2}(1-\lambda)k(e^{PC})^2, \tag{14}$$

$$\pi_R^{PC} = (p_N^{PC} - w_N^{PC})D_N^{PC} + (p_B^{PC} - w_B^{PC})D_B^{PC} - \frac{1}{2}\lambda k(e^{PC})^2. \tag{15}$$

Table A2 summarizes the optimal decisions and related performances when the manufacturer adopts blockchain for some products under the cost-sharing contract.

Proposition 7. *Compared with the wholesale price contract, when blockchain is adopted for some products, a cost-sharing contract increases the green investment level, wholesale prices, retail prices, and total demand, but does not change the non-blockchain-enabled products' demand (i.e., $e^{PC*} > e^{P*}$, $w_N^{PC*} > w_N^{P*}$, $w_B^{PC*} > w_B^{P*}$, $p_N^{PC*} > p_N^{P*}$, $p_B^{PC*} > p_B^{P*}$, $D_N^{PC*} = D_N^{P*}$, $D_B^{PC*} > D_B^{P*}$, and $D_B^{PC*} + D_N^{PC*} > D_B^{P*} + D_N^{P*}$).*

Proposition 7 states that when the manufacturer adopts blockchain for some products, the cost-sharing contract can always increase the green investment level, wholesale price, retail price, and total demand. These findings are similar to the scenario where blockchain is adopted for all products. The cost-sharing contract can increase the demand for blockchain-enabled products but keeps the demand for non-blockchain-enabled products unchanged. These conclusions are not influenced by the privacy cost, which is different from the findings under the revenue-sharing contract. Additionally, Fig. 3 depicts the impact of the cost-sharing contract on profits in this model.

By comparing the wholesale price contract and the cost-sharing contract in Fig. 3, we observe that the cost-sharing contract can always benefit the manufacturer and the retailer when the cost-sharing ratio is low. Therefore, the supply chain can achieve Pareto improvement when the cost-sharing ratio is low, similar to the findings under the revenue-sharing contract. However, it is not necessarily better for the retailer to have a lower privacy cost. Still, it is advantageous for the retailer when both the cost-sharing ratio and the privacy cost are low. Therefore, the lower the privacy cost, the more likely the manufacturer will choose the cost-sharing contract, while it may not be the case for the retailer.

5.3. Contracts comparison

In this section, we analyze the choices of cooperation mechanisms by the manufacturer and retailer by comparing the decisions and profits under the revenue-sharing contract and the cost-sharing contract. Furthermore, we will explore the impact of blockchain coverage on

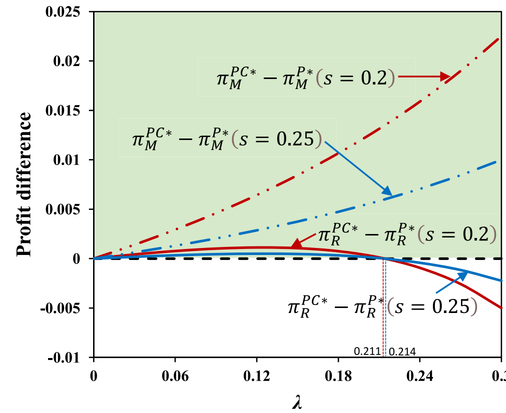


Fig. 3. Profits under the cost-sharing contract with partial blockchain adoption.

contract selection by comparing the conditions for contract selection in the two scenarios. To ensure non-negative demands and prices under the revenue-sharing and cost-sharing contracts, we assume that $k > \max\left\{\frac{\alpha^2}{2b(2-\varphi)}, \frac{\alpha^2}{4b(1-\lambda)}\right\}$ throughout the rest of the paper.

Proposition 8. *Compared with the cost-sharing contract, when blockchain is adopted for all products, a revenue-sharing contract*

(1) increases the green investment level (i.e., $e^{FR*} > e^{FC*}$) when $0 < \lambda < \frac{\varphi}{2}$, and decreases (i.e., $e^{FR*} < e^{FC*}$) otherwise.

(2) increases demand (i.e., $D_B^{FR*} > D_B^{FC*}$) when $0 < \lambda < \frac{2bk\varphi}{2bk\varphi+\alpha^2}$, and decreases (i.e., $D_B^{FR*} < D_B^{FC*}$) otherwise.

(3) increases the wholesale price (i.e., $w_B^{FR*} > w_B^{FC*}$) when $k < \frac{(1-\lambda)\alpha^2-(1-\varphi)^2\alpha^2}{2b\varphi(1-\lambda)(3-2\varphi)}$, and decreases (i.e., $w_B^{FR*} < w_B^{FC*}$) otherwise.

(4) increases the retail price (i.e., $p_B^{FR*} > p_B^{FC*}$) when $k < \frac{(2\varphi-3\lambda)\alpha^2}{2b\varphi(1-\lambda)}$, and decreases (i.e., $p_B^{FR*} < p_B^{FC*}$) otherwise.

Propositions 8(1) and (2) state that if the manufacturer adopts blockchain for all products, then only when the cost-sharing ratio is low will the green investment level and demand under the revenue-sharing contract be higher than under the cost-sharing contract. Propositions 8(3) and (4) state that when the cost coefficient of green investment is low, the wholesale and retail prices under the revenue-sharing contract are higher than those under the cost-sharing contract. This is because a lower cost-sharing ratio leads to lower incentives for the manufacturer under the cost-sharing contract, resulting in a lower green investment level. Similarly, when the cost coefficient of green investment is low, the incentives under the cost-sharing contract are also lower, leading to lower retail prices. However, due to the positive impact of increased green investment outweighing the negative impact of price increases, a lower cost-sharing ratio leads to higher demand under the revenue-sharing contract.

Theorem 5. *Compared with the cost-sharing contract, when blockchain is adopted for all products, a revenue-sharing contract*

(1) increases the manufacturer's profit (i.e., $\pi_M^{FR*} > \pi_M^{FC*}$) when $0 < \lambda < \frac{2bk\varphi}{2bk\varphi+\alpha^2}$, and decreases (i.e., $\pi_M^{FR*} < \pi_M^{FC*}$) otherwise.

(2) increases the retailer's profit (i.e., $\pi_R^{FR*} > \pi_R^{FC*}$) when $\{(k < \frac{\alpha^2}{2b}, 0 < \lambda < \check{\lambda}) \bigcup (\frac{3\alpha^2}{8b} < k < \frac{\alpha^2}{2b}, \hat{\lambda} < \lambda < 1) \bigcup (k > \frac{\alpha^2}{2b})\} \bigcap \{\varphi_1 < \varphi < \varphi_2\}$, and decreases (i.e., $\pi_R^{FR*} < \pi_R^{FC*}$) otherwise.

Similar to the comparison for demand (Proposition 8(2)), Theorem 5 states that when the manufacturer adopts blockchain for all products, only a lower cost-sharing ratio leads to higher profits for the manufacturer under the revenue-sharing contract. This indicates that the reasons for the changes in manufacturer's profit are similar to the reasons for the changes in demand. However, the changes in retailer's

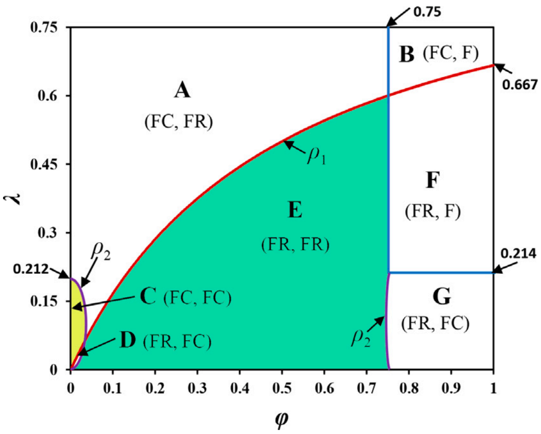


Fig. 4. Contract selection when blockchain is adopted for all products.

profit are more complex. The comparison of retailer's profit under the revenue-sharing contract and the cost-sharing contract is influenced by the revenue-sharing ratio, the cost-sharing ratio, and the cost coefficient of green investment. We present the manufacturer and the retailer's preference for a specific coordinating contract in Fig. 4. For example, $A(FC, FR)$ represents the region where the manufacturer prefers the cost-sharing contract and the retailer prefers the revenue-sharing contract. The meanings of other regions follow a similar logic. The line ρ_1 represents $\pi_M^{FR*} = \pi_M^{FC*}$ and the line ρ_2 represents $\pi_R^{FR*} = \pi_R^{FC*}$.

From Fig. 4, we observe that when the revenue-sharing ratio is high (or low) and the cost-sharing ratio is low, the retailer prefers the cost-sharing contract. When the revenue-sharing ratio is moderate, the retailer prefers the revenue-sharing contract. When both the revenue-sharing ratio and the cost-sharing ratio are high, the retailer prefers the wholesale price contract. Compared to the two sharing contracts, the wholesale price contract is always unfavorable for the manufacturer. However, in cases where it is not possible to reach a specific contract, supply chain members can only transact based on the wholesale price contract. Therefore, when both the revenue-sharing ratio and the cost-sharing ratio are relatively low (Region C), the manufacturer and retailer can agree on adopting the cost-sharing contract. When the revenue-sharing ratio is moderate and the cost-sharing ratio is low (Region E), the manufacturer and retailer can agree on adopting the revenue-sharing contract. In other cases, they can only agree on adopting the wholesale price contract. Additionally, through the comparison of profits, we find that when the manufacturer adopts blockchain for all products, the choice of contracts by supply chain members is not influenced by the privacy cost.

Next, we will analyze the manufacturer and the retailer's contract choice in the scenario where blockchain is adopted for some products. Then, by comparing the choices in the two scenarios, we explore the impact of the coverage rate of blockchain on contract selection.

Proposition 9. *Compared with the cost-sharing contract, when blockchain is adopted for some products, a revenue-sharing contract*

(1) increases the green investment level (i.e., $e^{PR*} > e^{PC*}$) when $0 < \lambda < \frac{\varphi}{2}$, and decreases (i.e., $e^{PR*} < e^{PC*}$) otherwise.

(2) increases the non-blockchain-enabled products' wholesale price (i.e., $w_N^{PR*} > w_N^{PC*}$) when ($0 < \lambda < \lambda_1$ and $0 < s < s_1^{RC}$) or ($\lambda_1 < \lambda < 1$ and $s > s_1^{RC}$), and decreases (i.e., $w_N^{PR*} < w_N^{PC*}$) otherwise.

(3) increases the non-blockchain-enabled products' retail price (i.e., $p_N^{PR*} > p_N^{PC*}$) when ($0 < \lambda < \lambda_2$ and $0 < s < s_2^{RC}$) or ($\lambda_2 < \lambda < 1$ and $s > s_2^{RC}$), and decreases (i.e., $p_N^{PR*} < p_N^{PC*}$) otherwise.

(4) increases the blockchain-enabled products' wholesale price (i.e., $w_B^{PR*} > w_B^{PC*}$) when $k < \frac{(1-\lambda)\alpha^2-(1-\varphi)^2\alpha^2}{2b\varphi(1-\lambda)(3-2\varphi)}$, and decreases (i.e., $w_B^{PR*} < w_B^{PC*}$) otherwise.

(5) increases the blockchain-enabled products' retail price (i.e., $p_B^{PR*} > p_B^{PC*}$) when $k < \frac{(2\varphi-3\lambda)\alpha^2}{2b\varphi(1-\lambda)}$, and decreases (i.e., $p_B^{PR*} < p_B^{PC*}$) otherwise.

Proposition 9 states that when the manufacturer adopts blockchain for some products if the cost-sharing ratio is low, then the green investment level is higher under the revenue-sharing contract. For blockchain-enabled products, when the cost coefficient of green investment is low, the wholesale and retail prices are higher under the revenue-sharing contract. These findings are consistent with Proposition 8. It indicates that the coverage rate of blockchain does not change the influence of the cooperative mechanism on the green degree and prices of products. For non-blockchain-enabled products, when both the cost-sharing ratio and the privacy cost are low or high, the wholesale and retail prices are lower under the revenue-sharing contract. Unlike blockchain-enabled products, pricing for non-blockchain-enabled products needs to consider the impact of the privacy cost.

Proposition 10. *Compared with the cost-sharing contract, when blockchain is adopted for some products, a revenue-sharing contract*

(1) increases the non-blockchain-enabled products' demand (i.e., $D_N^{PR*} > D_N^{PC*}$).

(2) increases the blockchain-enabled products' demand (i.e., $D_B^{PR*} > D_B^{PC*}$) when ($0 < \lambda < \lambda_3$ and $0 < s < s_3^{RC}$) or ($\lambda_3 < \lambda < 1$ and $s > s_3^{RC}$), and decreases (i.e., $D_B^{PR*} < D_B^{PC*}$) otherwise.

(3) increases total demand (i.e., $D_B^{PR*} + D_N^{PR*} > D_B^{PC*} + D_N^{PC*}$) when ($0 < \lambda < \lambda_4$ and $0 < s < s_4^{RC}$) or ($\lambda_4 < \lambda < 1$ and $s > s_4^{RC}$), and decreases (i.e., $D_B^{PR*} + D_N^{PR*} < D_B^{PC*} + D_N^{PC*}$) otherwise.

Proposition 10 states that when the manufacturer adopts blockchain for some products, the demand for non-blockchain-enabled products is always higher under the revenue-sharing contract, while the demand for blockchain-enabled products is higher under the revenue-sharing contract when both the cost-sharing ratio and the privacy cost are low or high. Therefore, the total demand is higher under the revenue-sharing contract when both the cost-sharing ratio and the privacy cost are low or high. Fig. 5 illustrates the choices of cooperation mechanisms by supply chain members in the scenario where blockchain is adopted for some products. The explanations of regions are similar to Fig. 4. Considering Figs. 4 and 5, we find that the coverage rate of blockchain does not influence the choices of cooperation mechanisms by supply chain members. There is only one difference between the two scenarios: In the scenario where blockchain is adopted for some products, the higher the privacy cost, the lower the likelihood for the manufacturer and retailer to agree on a revenue-sharing contract and cost-sharing contract. Therefore, regardless of the number of products adopting blockchain, when both the revenue-sharing ratio and the cost-sharing ratio are low, the cost-sharing contract is chosen. When the revenue-sharing ratio is moderate and the cost-sharing ratio is low, the revenue-sharing contract is chosen. In other cases, the wholesale price contract is adopted. Meanwhile, when the manufacturer adopts blockchain for some products, they need to consider the privacy cost.

5.4. Blockchain adoption strategies under coordination mechanisms

In this section, we explore the impact of coordination mechanisms on blockchain adoption strategies. To do this, we define Models TR and TC to represent the cases where revenue-sharing and cost-sharing contracts are adopted without blockchain adoption. In Model TR, the profit functions of the manufacturer and retailer are identical to Eqs. (8) and (9), respectively. In Model TC, their profit functions align with Eqs. (12) and (13). The optimal decisions and associated performances are summarized in Table A4 in Appendix A. The analysis is not mathematically tractable; therefore, we use numerical analysis to explore the impact of coordination mechanisms on blockchain adoption strategies. Fig. 6, using the same parameter settings as Fig. 1, illustrates the comparison of the manufacturer and retailer's profits under revenue-sharing (left panel) and cost-sharing (right panel) contracts with and without blockchain adoption.

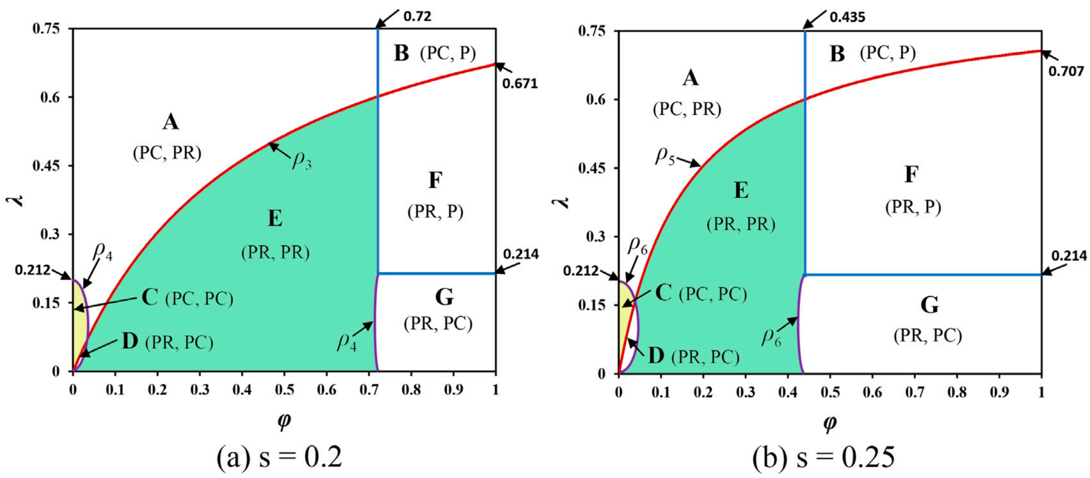


Fig. 5. Contract selection when blockchain is adopted for some products.

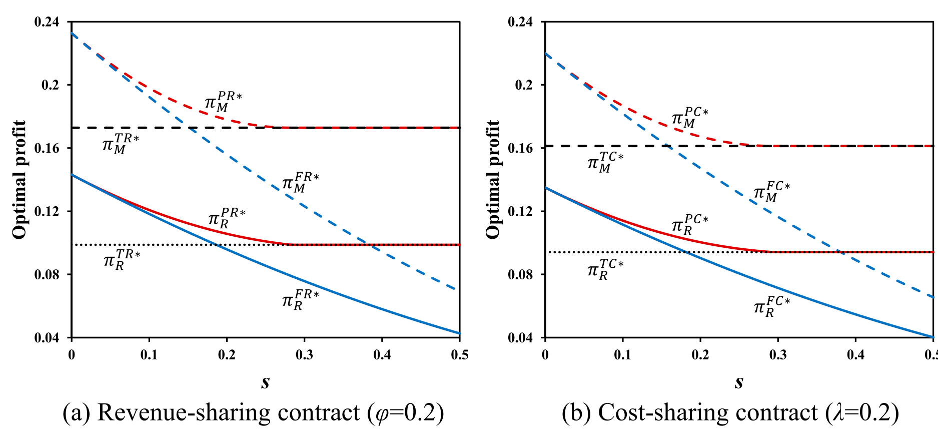


Fig. 6. The impact of coordination mechanisms on blockchain adoption strategies.

Based on Fig. 6, we observe that, regardless of whether a revenue-sharing or cost-sharing contract is in place, when the privacy cost is low, the profits of the manufacturer and the retailer are highest if adopting blockchain for some products. In contrast, when the privacy cost is high, the profits of the manufacturer and the retailer are highest when blockchain is not adopted. It is noteworthy that adopting blockchain for all products is not optimal for the manufacturer. In fact, the profits for both the manufacturer and retailer initially decrease and then remain unchanged as the privacy cost increases when adopting blockchain for some products. These observations align with the insights provided by Theorem 1. Consequently, the coordination mechanisms do not alter the strategies regarding blockchain adoption, underscoring the robustness of our conclusions.

Furthermore, by substituting the parameter values into Theorem 1 and Fig. 6, we can obtain that under the wholesale price contract, when $s < 0.275$, it is preferred way for the manufacturer and the retailer to adopt blockchain for some products (i.e., $\pi_M^{P*} > \pi_M^{T*}$ and $\pi_R^{P*} > \pi_R^{T*}$). Otherwise, blockchain is not adopted (i.e., $\pi_M^{P*} = \pi_M^{T*}$ and $\pi_R^{P*} = \pi_R^{T*}$). Under the revenue-sharing contract and the cost-sharing contract, the threshold points are $s = 0.283$ and $s = 0.293$, respectively. By comparing these threshold points, we find that the revenue-sharing contract and the cost-sharing contract can promote the adoption of blockchain by the manufacturer and the retailer. However, no matter how the sharing ratio changes, adopting blockchain for all products is not a preferred way. Therefore, these supply chain contracts can only promote the adoption of blockchain but will not change the preferred way of blockchain adoption.

6. Extensions

6.1. Unit blockchain adoption cost

In practice, the implementation of blockchain technology can incur costs. Following the studies by Niu et al. (2021) and Xu and Duan (2022), the manufacturer is required to pay a unit cost, denoted as c, for each product that is registered and sold through blockchain technology. In this case, we refer to the scenarios where the manufacturer adopts blockchain for all or some products under the wholesale price contract as Model CF and Model CP, respectively. In Models CF and CP, the profit functions of the manufacturer are defined as follows.

$$\pi_M^{CF} = (w_B^{CF} - c)D_B^{CF} - \frac{1}{2}k(e^{CF})^2, \tag{16}$$

$$\pi_M^{CP} = w_N^{CP} D_N^{CP} + (w_B^{CP} - c)D_B^{CP} - \frac{1}{2}k(e^{CP})^2. \tag{17}$$

Table A5 in Appendix A presents a summary of the optimal decisions and corresponding performances when considering the unit cost of blockchain adoption under the wholesale price contract. By examining Tables A1 and A5, we observe that when the manufacturer faces a unit cost of blockchain adoption, the total cost incurred by adopting blockchain technology can be represented as $s + bc$. This implies that the manufacturer's profit is maximized when blockchain is adopted for some products. Only when the total cost of adopting blockchain remains below a specific threshold can the retailer benefit from blockchain adoption. Notably, this threshold aligns with Theorem 1. Hence, the impact of the unit cost of blockchain adoption and privacy cost on the adoption itself exhibits consistency, thus validating the robustness of our findings.

6.2. Heterogeneous privacy concerns

In Section 4, consumer privacy concerns are modeled by exogenously given privacy costs, applicable to all customers. However, consumers are heterogeneous in terms of their valuation of green products. Therefore, it is reasonable to believe that they also have diversified concerns about privacy. Following Pun et al. (2021), we assume that consumers exhibit heterogeneous privacy concerns and the privacy cost is a random variable with probability distribution function (PDF) $g(s)$ that is uniformly distributed between $\underline{s}$ and $\bar{s}$. Further, to eliminate unrealistic cases of negative utility because of random privacy cost, we assume that the privacy cost should not exceed the product value, so we normalize the domain of $g(s)$ to $\underline{s} = 0$ and $\bar{s} = 1+\alpha e_0$. Consequently, when blockchain technology is adopted for all products (Model FH) or some products (Model PH), the demand functions can be expressed as follows:

$$D_B^{FH} = \int_0^{1+\alpha e_0} g(s) \int_{bp_B^{FH}+s-\alpha(e_0+e^{FH})}^{1} dv ds, \tag{18}$$

$$D_B^{PH} = \int_0^{1+\alpha e_0} g(s) \int_{\frac{b(p_B^{PH}-p_N^{PH})+s}{1-\theta}-\alpha(e_0+e^{PH})}^{1} dv ds, \tag{19}$$

$$D_N^{PH} = \int_0^{1+\alpha e_0} g(s) \int_{\frac{bp_N^{PH}}{\theta}-\alpha(e_0+e^{PH})}^{\frac{b(p_B^{PH}-p_N^{PH})+s}{1-\theta}-\alpha(e_0+e^{PH})} dv ds. \tag{20}$$

The profit functions for Models FH and PH are similar to those in Models F and P, respectively. In Appendix A, Table A6 displays the optimal decisions and profits.

Proposition 11. *Comparing profits for the three scenarios when considering heterogeneous privacy concerns:*

(1) For the manufacturer:
- *(i) When* $0 < \theta < \frac{4bk(1+\alpha e_0)}{16bk-3\alpha^2(1+\alpha e_0)}$: $\pi_M^{PH*} > \pi_M^{FH*} > \pi_M^{T*}$.
- *(ii) When* $\frac{4bk(1+\alpha e_0)}{16bk-3\alpha^2(1+\alpha e_0)} < \theta < \frac{4bk}{8bk-\alpha^2(1+\alpha e_0)}$: $\pi_M^{PH*} > \pi_M^{T*} > \pi_M^{FH*}$.
- *(iii) When* $\frac{4bk}{8bk-\alpha^2(1+\alpha e_0)} < \theta < 1$: $\pi_M^{PH*} = \pi_M^{T*} > \pi_M^{FH*}$.

(2) For the retailer:
- *(i) When* $0 < \theta < \theta^H$: $\pi_R^{PH*} > \pi_R^{FH*} > \pi_R^{T*}$.
- *(ii) When* $\theta^H < \theta < \frac{4bk}{8bk-\alpha^2(1+\alpha e_0)}$: $\pi_R^{PH*} > \pi_R^{T*} > \pi_R^{FH*}$.
- *(iii) When* $\frac{4bk}{8bk-\alpha^2(1+\alpha e_0)} < \theta < 1$: $\pi_R^{PH*} = \pi_R^{T*} > \pi_R^{FH*}$.

(3) When $0 < \theta < \frac{4bk}{8bk-\alpha^2(1+\alpha e_0)}$: $\pi_M^{PH*} - \pi_M^{FH*} > \pi_R^{PH*} - \pi_R^{FH*}$.

Proposition 11 states that if consumers have heterogeneous privacy concerns, then when consumers have high uncertainty about the product value θ, applying blockchain to some products is most beneficial for both the manufacturer and the retailer, and not adopting blockchain is the least favorable option. When consumers have moderate uncertainty about the product value, applying blockchain to some products remains the most beneficial, while applying blockchain to all products remains the least favorable option. When consumers have a low degree of uncertainty about the product value, applying blockchain to some products will not be viable. Under such conditions, this model will be similar to the model without blockchain. In this case, not adopting blockchain is the most beneficial option, while applying blockchain to all products remains the least favorable option. Additionally, the manufacturer is more inclined than the retailer to apply blockchain to some products. These conclusions are similar to those in Theorem 1. Therefore, consumer heterogeneity in privacy concerns does not alter our core conclusion.

6.3. Different blockchain sensitivities

Consumers have varying attitudes towards blockchain technology: some consumers trust the products' information provided by the blockchain, while some consumers will not care about this information. Therefore, in this section, we study the differing sensitivities of consumers towards blockchain. We assume that the proportion of blockchain-sensitive consumers is β, where $0 < \beta < 1$, and the proportion of blockchain-insensitive consumers is $1-\beta$. When blockchain is adopted for certain products, we assume that γ proportion of blockchain-insensitive consumers choose blockchain-enabled products and $1-\gamma$ choose non-blockchain-enabled products, with $0 < \gamma < 1$. Thus, when blockchain technology is implemented across all products (Model FI) or selectively on some products (Model PI), the demand functions can be expressed as follows:

$$D_B^{FI} = \beta \int_{bp_B^{FI}+s-\alpha(e_0+e^{FI})}^{1} dv + (1-\beta) \int_{\frac{bp_B^{FI}}{\theta}-\alpha(e_0+e^{FI})}^{1} dv, \tag{21}$$

$$D_B^{PI} = \beta \int_{\frac{b(p_B^{PI}-p_N^{PI})+s}{1-\theta}-\alpha(e_0+e^{PI})}^{1} dv + (1-\beta)\gamma \int_{\frac{bp_B^{PI}}{\theta}-\alpha(e_0+e^{PI})}^{1} dv, \tag{22}$$

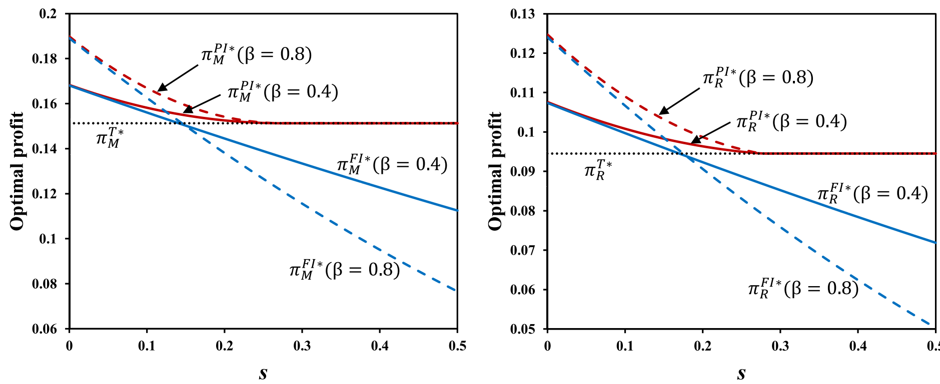
$$D_N^{PI} = \beta \int_{\frac{bp_N^{PI}}{\theta}-\alpha(e_0+e^{PI})}^{\frac{b(p_B^{PI}-p_N^{PI})+s}{1-\theta}-\alpha(e_0+e^{PI})} dv + (1-\beta)(1-\gamma) \int_{\frac{bp_N^{PI}}{\theta}-\alpha(e_0+e^{PI})}^{1} dv. \tag{23}$$

Under the wholesale price contract, the profit functions for Models FI and PI are similar to those of Models F and P, respectively. The optimal decisions and associated performances are summarized in Table A7, in Appendix A. Fig. 7 illustrates the impacts of consumers' different blockchain sensitivity on the manufacturer and retailer's profits. It shows that, irrespective of consumers' sensitivity to blockchain, when the privacy costs are low, applying blockchain to some products is most beneficial for both the manufacturer and retailer. Conversely, when privacy costs are high, not utilizing blockchain proves to be the most advantageous. Applying blockchain to all products never emerges as the most beneficial strategy. This aligns with Theorem 1, indicating that consumers' sensitivity towards blockchain does not alter blockchain adoption strategies. Moreover, when blockchain is adopted for some products, the greater the consumers' sensitivity to blockchain, the more advantageous it is for both the manufacturer and retailer. However, applying blockchain to all products becomes less advantageous as consumer sensitivity towards blockchain increases, particularly when privacy costs are high.

7. Conclusion

7.1. Concluding remarks

As consumer awareness of environmental issues continues to grow, an increasing number of individuals are favoring green products. However, the lack of product information introduces uncertainty among consumers, which subsequently diminishes their willingness to purchase green products. Blockchain has emerged as a promising solution to alleviate this uncertainty, albeit with potential privacy concerns. We study a green supply chain comprising a manufacturer and a retailer with consumer's privacy costs. Our analysis encompasses the examination of conditions and model selection for adopting blockchain, covering scenarios where blockchain is adopted for all or some products. Furthermore, with the aim of enhancing profits for all supply chain members engaged in blockchain adoption, we investigate the



(a) Manufacturer (b) Retailer

Fig. 7. The impact of blockchain sensitivity on blockchain adoption strategies ($\gamma = 0.5$).

conditions for achieving Pareto improvement through revenue-sharing and cost-sharing contracts in both scenarios, as well as exploring the influence of the coverage rate of blockchain. We provide recommendations pertaining to the selection of cooperation mechanisms, which can effectively strengthen collaboration among the entities involved. As a concluding remark, we highlight the key findings we have obtained.

First, the adoption of blockchain for all products is advantageous for the manufacturer, retailer, consumers, and society when the privacy cost is relatively low. In the scenario where blockchain is adopted for some products, the competition between products with and without blockchain capabilities primarily benefits the manufacturer and the retailer. Consumer surplus and social welfare in this scenario first decrease and then remain unchanged with the privacy cost, and blockchain becomes unfavorable when the privacy cost is high. Blockchain can lead to increased levels of green investment, wholesale and retail prices, and demand when the privacy cost is low. These conclusions hold in all and partial blockchain adoption models. Consequently, the privacy cost plays a crucial role. It is essential for firms to refrain from blindly adopting blockchain in practice. Although it may always be advantageous for manufacturing firms, in most cases, blockchain should be adopted when the privacy cost is low, thereby also enhancing the green degree of products.

Second, by comparing scenarios where blockchain is adopted for all or some products, we find that blockchain adoption for some products is always better than for all products. This conclusion holds for the manufacturer, retailer, consumers, society, and total demand. Notably, compared to the retailer, the manufacturer exhibits a stronger preference for employing blockchain selectively. However, regardless of the scenario, the green investment levels, wholesale prices, and retail prices for blockchain-enabled products remain consistent. Common perception implies that a higher coverage rate of blockchain among products translates to greater benefits for firms, or that, under specific conditions, embracing blockchain for all products proves more favorable. Interestingly, our findings indicate that fostering competition between products with and without blockchain, achieved by adopting blockchain for some products, offers the most advantageous outcome for firms. Moreover, this approach does not compromise the green degree of products. Importantly, this finding holds irrespective of the privacy cost and provides valuable insights for resource-constrained firms seeking to adopt blockchain. These results are shown to be robust with regard to factors such as unit blockchain adoption cost, heterogeneous privacy concerns, coordination mechanisms, and varying blockchain sensitivities.

Third, through our analysis of coordination in both scenarios of blockchain adoption, we find that both revenue-sharing contracts and cost-sharing contracts consistently benefit the manufacturer, with his profit increasing with the sharing ratio. Conversely, the retailer benefits from a lower sharing ratio, with her profit first increasing and then decreasing with the sharing ratio. Consequently, Pareto improvement within the supply chain can be realized by designing lower sharing ratios. These findings hold irrespective of the coverage rate of blockchain, meaning they apply to both scenarios of blockchain adoption. Interestingly, in the scenario where blockchain is adopted for all products, the conditions for Pareto improvement are unaffected by the privacy cost. However, in the scenario where blockchain is adopted for some products, lower privacy costs increase the likelihood of achieving Pareto improvement through a revenue-sharing contract. In contrast, the opposite holds for the cost-sharing contract. Hence, when designing supply chain contracts, firms should prioritize considering the coverage rate of blockchain and subsequently design lower sharing ratios while also taking into account whether they are influenced by the privacy cost, thereby ensuring improved profitability for all members.

Fourth, by comparing the wholesale price contract, revenue-sharing contract, and cost-sharing contract, we find that for the manufacturer, the revenue-sharing and cost-sharing contracts are always better than the wholesale price contract, and the revenue-sharing contract is preferred when the cost-sharing ratio is low. For the retailer, the revenue-sharing contract is preferred when the revenue-sharing ratio is moderate. Therefore, when two sharing ratios are low, both parties agree on adopting a cost-sharing contract. When the revenue-sharing ratio is moderate and the cost-sharing ratio is low, both parties agree on adopting a revenue-sharing contract. In other cases, due to the inability to reach a consensus, transactions can only be carried out according to the wholesale price contract. These contract selection strategies are the same in both blockchain adoption scenarios. The difference is that when blockchain is adopted for all products, the choice of cooperation mechanism is not affected by the privacy cost. However, when blockchain is adopted for some products, the choice of cooperation mechanism needs to consider the impact of the privacy cost, and the lower the privacy cost, the more likely they are to adopt two sharing contracts.

7.2. Managerial insights

In practice, the selection of blockchain's coverage rate by manufacturers and retailers inevitably involves considerations of consumers' privacy concerns and collaboration mechanisms. From the above findings, we provide important managerial insights for manufacturers and retailers.

First, it is generally believed that blockchain should be fully adopted when it is proven to be effective. However, our analysis shows that, regardless of whether the benefits of blockchain in eliminating green uncertainty can offset the privacy costs, the manufacturer and the retailer should always adopt blockchain for some products rather than all products. They should determine the quantity of blockchain-enabled products according to the level of privacy cost. Specifically, as the privacy cost increases, they should reduce the quantity of blockchain-enabled products until blockchain is not adopted for any products. Since the manufacturer can obtain more profits from blockchain, it should encourage the retailer to sell blockchain-enabled products. After they decide to adopt blockchain, the manufacturer can increase green investment without considering the blockchain's coverage rate. Meanwhile, they can raise the wholesale price and the retail price. These actions can enable blockchain adoption to achieve a win-win situation for the manufacturer, the retailer, consumers and society in the application of blockchain.

Second, no matter which collaboration mechanism the retailer offers to the manufacturer, they are all likely to achieve Pareto improvement. For the manufacturer, any collaboration mechanism is better than the wholesale price contract. However, for the retailer, it is best to choose the cost-sharing or revenue-sharing contract when the sharing ratio is relatively low, and this action should do so more as the privacy cost increases. Additionally, this action of the retailer can motivate the manufacturer to increase green investment, which is not affected by the blockchain's coverage rate and privacy cost. Meanwhile, the probability of blockchain adoption will also increase. Therefore, for green product retailers, such as IKEA, whether for the purpose of improving the green level or applying blockchain, they should offer cost-sharing or revenue-sharing contracts to manufacturers.

Third, when all three types of contracts are available, the manufacturer should always abandon the wholesale price contract. However, before deciding which contract to offer to the manufacturer, the retailer needs to distinguish different contracts according to the sharing ratio. Specifically, when the revenue-sharing ratio is moderate, the retailer should choose the revenue-sharing contract. When the revenue-sharing ratio is low or high, the retailer should choose the cost-sharing contract when the cost-sharing ratio is low, otherwise, the wholesale price contract should be chosen. Moreover, when blockchain is adopted for all products, their choice does not need to consider the privacy cost. However, when blockchain is adopted for some products, they need to be careful about consumers' privacy concerns. The higher this cost is, the more ineffective the revenue-sharing contract will be. Therefore, the retailer should take notice of the blockchain's coverage rate and the privacy cost when offering contracts to the manufacturer.

7.3. Limitations and future studies

We extend the main model to evaluate the impacts of unit blockchain adoption cost, heterogeneous privacy concerns, and different blockchain sensitivities on the main insights we derive from the model. We conclude that these modeling assumptions do not change the blockchain adoption strategies. However, there are still some limitations that open opportunities for future research. First, it is crucial and intriguing to consider the secondary costs associated with blockchain technology research and development investments, as well as further explore the optimal investment level in blockchain technology. Second, investigating competition among multiple manufacturers is an area worth exploring in future research. Third, manufacturers and retailers may exhibit varying risk preferences when adopting blockchain technology. Examining the impact of these risk preferences on operational decisions for manufacturers and retailers and analyzing the associated coordination issues, can yield novel and substantial findings.

CRediT authorship contribution statement

Changhua Liao: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Qihui Lu:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Salar Ghamat:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Helen Huifen Cai:** Writing – review & editing.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ejor.2024.12.022.

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