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RESEARCH ON LOW-CARBON SUPPLY CHAIN EMISSION REDUCTION STRATEGIES BASED ON BLOCKCHAIN TECHNOLOGY

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Abstract. The difficulty of regulating carbon trading due to information asymmetry and low consumer trust in low-carbon products are key factors hindering companies from reducing emissions. This paper examines a manufacturer-led secondary low-carbon supply chain consisting of a single supplier and a retailer, focusing on the impact of blockchain technology on carbon transaction costs and consumers' low-carbon preferences. Utilizing Stackelberg game theory, the paper constructs a supply chain decision model for emission reduction, determining the payment matrix and analyzing the stable strategy for blockchain adoption through evolutionary game theory. The findings indicate that retailers' adoption of blockchain technology significantly promotes emission reduction within the supply chain, whereas manufacturers' adoption has minimal impact. Additionally, the study reveals that variations in blockchain adoption costs and carbon quotas result in multiple evolutionary stable strategies. Specifically, when blockchain adoption costs and carbon quotas are below certain thresholds, the system reaches a unique equilibrium where both parties adopt blockchain technology.

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1. Introduction

On 22 September 2020, China proposed the carbon peaking and carbon neutrality goals goal at the seventy-fifth session of the United Nations General Assembly. China faces the challenge of achieving carbon neutrality in a short time, with a total amount of carbon emission reduction equivalent to twice that of the USA and three times that of the 28 countries of the EU. To achieve this goal, reducing supply chain emissions is an essential step towards low-carbon development and achieving carbon peak and carbon neutrality. It is important to note that achieving carbon neutrality in China is much more challenging than in the European Union, which took 71 years, and in the United States, which took 43 years [1]. In this context, the supply chain emerges as a crucial avenue for realizing low-carbon development and achieving peak and carbon neutrality targets. However, the effective regulation of carbon trading faces obstacles due to information asymmetry and low consumer trust in green products, which are critical barriers for companies seeking to reduce emissions [2]. Unfortunately, certain companies prioritize their interests, leading to cases of misrepresentation of carbon information driven by profit motives. For example, the case of Volkswagen's manipulation of carbon emissions data for approximately 98 000 petrol vehicles in 2015 highlights the need for government authorities to verify the authenticity of carbon

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Keywords. Blockchain technology, carbon emission reduction, strategy choice, evolutionary game.

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emissions reported by companies. However, the complicated nature of carbon trading and the limitations of a central server in ensuring traceability and data integrity hinder the effectiveness of China's carbon trading market. On the other hand, as environmental awareness grows, consumers prefer environmentally friendly options and tend to purchase low-carbon products [3]. Nevertheless, some companies resort to exaggerating the environmental value of their products and making false claims to boost sales and profits. As a result, consumers' trust in low-carbon products is reduced, which affects their willingness to support green purchases [4]. Therefore, the accuracy and traceability of low-carbon information significantly influence the decision-making processes of supply chain actors aiming to reduce emissions.

As a new paradigm in information computing, blockchain technology has expanded its influence in various fields, including digital finance, supply chain management, e-government and the Internet of Things. With its openness, transparency and decentralisation attributes, blockchain technology builds mutual trust among stakeholders and reduces the costs associated with rebuilding or maintaining trust [5, 6]. The core strengths of the green supply chain lie in its ability to promote sustainable development in manufacturing and establish environmentally friendly supply chains [7, 8]. There are already practices that apply blockchain technology to reduce supply chain emissions. Numerous retailers have invested in blockchain for commodity traceability, such as Walmart's collaboration with IBM and Dole to improve safety controls in the food supply chain and ensure credible food quality and safety. Cross-border e-commerce platforms such as eBay, Tmall and JD have also adopted blockchain for product traceability to foster customer trust and improve perceptions of product quality on their respective platforms. In addition, manufacturers can leverage blockchain technology for carbon trading. In this way, blockchain technology can contribute to the greening of supply chains.

The technical challenges and costs associated with independently implementing blockchain technology are substantial for non-Internet enterprises such as manufacturers and retailers. As a result, these companies often opt to adopt blockchain through existing platforms, which requires them to incur additional blockchain-related expenses. These costs significantly influence their decisions regarding the adoption of blockchain technology. This paper addresses three key issues: (1) How blockchain technology impacts supply chain emission reduction decisions; (2) The conditions under which manufacturers and retailers choose to implement blockchain technology; (3) Strategies to encourage supply chain enterprises to invest in blockchain technology jointly. Contributions to the relevant research areas are: (1) The research on reducing carbon emissions in the supply chain using blockchain technology currently lacks a carbon quota trading link. Additionally, most studies do not consider the impact of carbon trading costs on a company's decision-making regarding emission reduction. This paper considers the impact of blockchain technology on carbon transaction costs and consumer low-carbon preferences; (2) The paper introduces the blockchain introduction cost into the blockchain strategy choice, supplements related studies, and derives the sufficient conditions for manufacturers and retailers to introduce blockchain technology; (3) This paper utilises the Stackelberg game and evolutionary game fitting methods to conduct research, which enhances the methodology of decision-making research.

The rest of this paper is organised as follows. Section 2 provides a review of pertinent literature. Section 3 defines the problem, introduces the parameters, and constructs a supply chain emission reduction model under different strategies. Section 4 develops an evolutionary game model and analyses the impact of critical parameters on strategy selection within a dual equilibrium framework. Lastly, Section 5 gives conclusions before delineating avenues for future research.

2. Literature review

2.1. Supply chain reduction

The current state of academic research on supply chain emissions reduction decisions is well established, with extensive research on inter-firm competition in this area by domestic and international scholars. The research focuses on three main categories:

(1) Manufacturers and retailers: Zhou and Ye [9] analysed joint abatement strategies within a secondary supply chain system of manufacturers and retailers, considering single and dual channels and advertising cooperation. Xia *et al.* [10] examined the dynamic low-carbon strategies of supply chain firms and proposed a cooperation agreement between manufacturers and retailers.

(2) Suppliers and manufacturers: Wang *et al.* [11] investigated the impact of cost-sharing and wholesale price premium contracts on supply chain emission reduction decisions, considering consumers' low-carbon environmental awareness. Zu *et al.* [12] constructed a differential game model for manufacturers and suppliers to study optimal emission reduction strategies and profit levels under market regulation, government intervention and channel coordination. Ma *et al.* [13] explored the issue of a coordinated pricing game in a secondary supply chain consisting of a manufacturer and multiple suppliers under inventory constraints and a carbon tax.

(3) Governments or third parties: Xue *et al.* [14] investigated the impact of government subsidies on firms' carbon abatement rates in a supply chain context. Lim and Kim [15] found that combining technology subsidies with a carbon tax can lead to economic growth without increasing carbon emissions. Che *et al.* [16] explored optimising a two-channel supply chain considering emission reduction and unit product reduction under government technology subsidies. Galinato and Yoder [17] showed that providing subsidies for low-carbon products leads to more significant emission reduction benefits for firms than taxing high-carbon products. Brown *et al.* [18] conducted studies on output subsidies and highlighted their effectiveness in reducing the cost burden of emissions pricing and mitigating electricity price increases.

Most studies on reducing supply chain emissions do not consider the transfer of information between cooperating entities or the disclosure of carbon emissions. Suppliers and manufacturers find it challenging to trust each other, cooperation is costly, and consumers need help identifying low-carbon products due to false marketing and a mixed market. Consumers may question the validity of low-carbon products due to limited access to, or difficulty in verifying, information about a product's carbon emissions. This lack of transparency can undermine demand for low-carbon products, ultimately impacting corporate decision-making.

2.2. Blockchain and supply chain management

Since the introduction of blockchain in 2008, scholars have explored its innovative development in three key areas. Firstly, in terms of infrastructure, researchers have focused on improving consensus algorithms [19], data management [20], and smart contracts [21]. Secondly, in terms of top-level design, attention has been paid to establishing a global blockchain technology governance system [22], developing governance solutions [23], and addressing application challenges [24]. Thirdly, market applications are being explored, such as blockchain technology in energy [25], healthcare [26], and supply chain management [27]. Research on the application of blockchain technology in supply chains is still in its early stages and can be categorised into three main directions:

(1) Qualitative research on blockchain and supply chain management: Kshetri [28] investigated the real-world application of blockchain and its impact on key supply chain objectives such as cost, quality and flexibility. Yadav and Singh [29] identified significant variables related to blockchain technology from the literature. They analysed them using PCA and fuzzy-DEMATEL methods to identify six key challenges in integrating blockchain with sustainable supply chains. Tönnissen and Teuteberg [30] conducted a case study on using blockchain technology in supply chain operations and management.

(2) Research on blockchain and supply chain technology applications: Kim and Laskowski [19] argued that the combination of the Internet of things and blockchain-enabled product traceability and proposed intelligent contracts that can be executed on the Ethereum platform. Azzi *et al.* [31] built an authentic, secure, reliable and transparent information system by integrating blockchain technology into the supply chain framework. Sheng [32] developed an information resource-sharing model based on blockchain technology to address information asymmetry in supply chain transactions and enable disintermediated mutual trust exchange. However, system inefficiencies may arise from information congestion.

(3) Blockchain and supply chain management decision research: Fan *et al.* [33] examined supply chain production and pricing decisions with and without blockchain technology, considered consumer traceability awareness, and discussed the conditions for supply chain adoption of blockchain technology. Liu and Li [34] examined supply chain decisions before and after investing in blockchain technology, analysing the cost investment threshold of blockchain technology in different cases, particularly addressing the misreporting of freshness information in the supply chain. Previous research has established the role of blockchain technology in reducing costs, increasing efficiency and fostering trust within the supply chain, thereby promoting sustainable supply chain development. In addition, the adoption of blockchain technology can affect the competitive strategies of supply chain firms, making it a burgeoning research topic in supply chain management.

Early studies on blockchain technology research have primarily focused on developing computer databases. However, there is limited literature on the application of blockchain technology in low-carbon supply chains. Studies on low-carbon supply chains have primarily analysed the impact of blockchain technology on supply chain operations and emission reduction based on empirical evidence. The evidence proves that blockchain technology can improve supply chain efficiency, reduce costs, ensure transparent and reliable information in the carbon tracking process, reduce the cost of carbon trading, provide reliable recycling information for enterprises and consumers, and improve the quality screening mechanism of recycled parts and components. However, more research is required to understand the mechanism by which blockchain technology affects the reduction of emissions in the supply chain, as well as the decision-making process for enterprise recycling and government policy formulation based on this.

2.3. Blockchain and supply chain emission reduction

Regarding supply chain carbon reduction, blockchain technology enables product traceability and carbon footprint tracking [35, 36]. In addition, using smart contracts can reduce inefficiencies in transaction processes. Combining existing literature with practical applications, implementing blockchain technology in supply chains can impact emission reduction: (1) Foster consumer trust and promote low-carbon preferences [8]. (2) Improve the efficiency of carbon certification and tracking in the carbon trading process, thereby reducing transaction costs.

Research in supply chain emission reduction decisions under blockchain technology is still developing. Manupati *et al.* [36] proposed a blockchain-based approach to address different production allocations in a multi-level supply chain under a carbon tax policy, demonstrating the effectiveness of a distributed ledger-based blockchain approach in minimising total costs and carbon reduction expenditures. Cole *et al.* [37] highlighted that combining blockchain and supply chain management can significantly facilitate supply chain credit management, effectively bridging the trust gap between nodal companies. The decentralised nature of blockchain, combined with symmetric encryption, authorisation technology, consensus mechanisms and innovative smart contracts, can effectively address trust and security challenges in supply chain management. Liang and Xiao [38] examined the impact of blockchain technology on pricing decisions and direct sales and distribution channel selection in a dual-channel supply chain context. Numerous studies support the notion that blockchain technology can help reduce emissions within supply chains. For example, Yan and Zhang [39] used a Stackelberg game to study a three-tier supply chain model consisting of retailers, suppliers, and logistics service integrators. They showed that blockchain technology could reduce transaction costs and enable information sharing, thereby increasing profits across the supply chain. Li *et al.* [40] found that the “blockchain + collaborative emission reduction” information-sharing mechanism can effectively increase supply chain profits while eliminating information rent.

The existing literature confirms that blockchain technology can mitigate information asymmetry, reduce transaction costs, and optimise enterprise resource allocation. Given the multiple impacts of blockchain on the supply chain, competitive strategies among supply chain firms are undergoing significant changes, making competitive decision-making a prominent area of research. However, current research on supply chain emission reduction decisions under blockchain technology has certain limitations. The influence of blockchain imple-

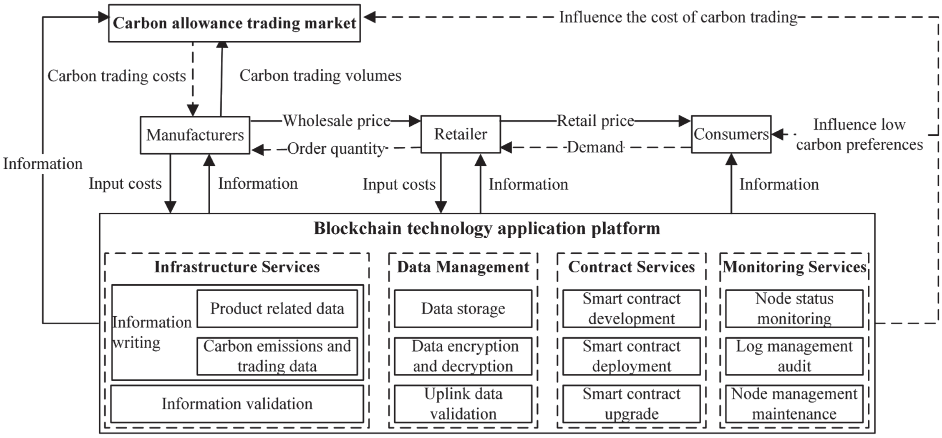


FIGURE 1. Framework for a supply chain abatement model based on a blockchain platform.

mentation costs on adoption strategies remains unexplored. Most studies focus on subsidy strategies, pricing decisions, and emission reduction decisions by governments and firms, neglecting the significant impact of the introduction cost of blockchain on firms' decisions. Moreover, the impact of blockchain technology on carbon trading is often overlooked. The application of blockchain technology directly affects the cost of carbon trading, which plays a crucial role in emission reduction decisions. As a result, scholars have yet to adequately consider carbon trading and the impact of blockchain technology on this aspect in the context of supply chain emissions reduction.

3. DECISION MODEL FOR EMISSION REDUCTION WITH DIFFERENT BLOCKCHAIN INTRODUCTION STRATEGIES

3.1. Problem description

Figure 1 shows that the decision to reduce emissions in the supply chain is influenced by various factors, including consumers' preference for low carbon, the cost of carbon trading, carbon quotas, and the coefficient of difficulty in reducing emissions. Manufacturers make decisions on emission reduction based on the cost of emission reduction inputs, carbon trading cost, and retailers' order quantity, among other factors. They buy and sell carbon quotas in the carbon market and sell excess quotas if their carbon emissions exceed the quota. Conversely, they purchase quotas if their emissions exceed the quota. The retailer determines the retail price based on the wholesale price set by the manufacturer and the demand for the product. The price and the consumer's low-carbon preference influence the quantity of the product demanded. The higher the consumer's low-carbon preference, the higher the quantity demanded. The blockchain platform can offer precise and transparent information through distributed storage, smart contracts, and other technologies. This can increase consumers' preference for low-carbon options and reduce the carbon transaction costs of enterprises. As a result, it can influence the supply chain's decision to reduce emissions. The promotion of low-carbon consumer preferences is primarily achieved through the use of blockchain-based traceability platforms [8]. Currently, most traceability platform applications in China are used by retailers such as Tmall and JD. Meanwhile, reducing carbon trading costs is dependent on using blockchain-based carbon trading platforms [36], which manufacturers mainly introduce. However, the cost of implementing blockchain technology may impact the decision of enterprises to adopt it.

This paper examines a secondary supply chain comprising a single manufacturer and a retailer in the context of carbon trading. The study proposes that the manufacturer can reduce the cost of carbon trading by introducing

TABLE 1. Blockchain introduction strategy portfolio.

	Retailers	
Manufacturers	Blockchain	No blockchain
Blockchain	(Y, Y)	(Y, N)
No Blockchain	(N, Y)	(N, N)

blockchain technology to build a carbon trading platform. The retailer's introduction of blockchain technology to build a traceability platform can potentially increase consumer preference for low-carbon products. Third-party institutions, such as the government and research institutes, are investing in the construction of blockchain technology. The manufacturer and retailer are responsible for the cost of introducing the technology. The study uses the Stackelberg game method by introducing blockchain technology to determine emission reduction decisions in a manufacturer-led supply chain. The supply chain comprises a few large manufacturers and many small retailers. The decision set includes using blockchain technology (Y) or not (N), in addition to the original emission reduction decisions. Table 1 illustrates the combinations of blockchain implementation strategies for the manufacturer and the retailer.

3.2. Model parameters and assumptions

The relevant parameters of the model are as shown in Table 2. To facilitate the study, the following assumptions are made before modelling:

(1) The manufacturer is the supply chain's primary source of carbon emissions. As the reduction of carbon emissions increases, the marginal abatement cost and the abatement implementation cost for the manufacturer also increase. Therefore, the abatement implementation cost for manufacturers is assumed to be $\frac{1}{2}U\gamma^2$ [41].

(2) Product demand is affected by both the product price and the level of emission reduction. The information exchange between the manufacturer and the retailer is assumed to be symmetric, and the market can be completely cleared. Thus, the product demand function is expressed as $q = a - bp + \lambda y$ [42]. The sensitivity coefficient of the consumer to the retail price, b, does not affect the optimal outcome and can be set to 1 to simplify calculations [43].

(3) The adoption of blockchain technology by retailers has an impact of $\alpha(\alpha \geq 1)$, which increases consumers' low-carbon preferences [8]. Similarly, manufacturers' adoption of blockchain technology reduces carbon transaction costs with an impact degree of $\beta(0 < \beta \leq 1)$. The cost of adopting blockchain technology for manufacturers and retailers is C_b [36].

The unit carbon trading costs and product demand under different strategies are shown in Table 3 below.

3.3. Solving and analysing decision-making models under different strategies

3.3.1. Neither manufacturers nor retailers are introducing blockchain technology

We construct an emission reduction decision model where neither the manufacturer nor the retailer adopts blockchain technology. In this model, the manufacturer invests in emission reduction, produces low-carbon products, and operates under a carbon quota system. If the manufacturer's carbon emissions exceed the allocated quotas, it must purchase additional quotas in the carbon trading market. Conversely, the manufacturer can sell the surplus quotas if emissions are below the quota. The retailer then sells the low-carbon products. The profit function governing the interactions between the manufacturer and the retailer is as follows:

$$\pi_m^{NN} = (w - c)q - [(e - \gamma)q - E_s]m - \frac{1}{2}U\gamma^2 \tag{1}$$

TABLE 2. Parameter settings of the model.

Participating	Description
e	Manufacturer's initial carbon emissions per unit of product. $e > 0$
e_s	Manufacturer's initial carbon allowance. $e_s > 0$
a	Market volume parameter.
b	Parameter of consumer sensitivity to retail price. $b = 1$
c	Manufacturer's marginal cost of production.
λ	Consumers' low carbon preferences. $\lambda > 1$
m	The cost per unit of carbon credits. $m > 0$
U	The abatement cost factor.
α	The degree of impact of blockchain on consumer low carbon preferences. $\alpha > 1$
β	Impact degree for blockchain on carbon trading costs. $0 < \beta < 1$
w	The wholesale price per unit of product.
γ	Manufacturer carbon emissions.
p	The retail price per unit of product.
C_b	Introducing cost to blockchain technology. $C_b > 0$
π_m	Manufacturers' profits.
π_r	Retailer profits.

TABLE 3. Carbon trading and product demand.

Strategy portfolio	m	q
(Y, Y)	βm	$a - bp + \alpha\lambda\gamma$
(Y, N)	βm	$a - bp + \lambda\gamma$
(N, Y)	m	$a - bp + \alpha\lambda\gamma$
(N, N)	m	$a - bp + \lambda\gamma$

$$\pi_r^{NN} = (p - w)q. \tag{2}$$

Theorem 1. *When $U > \frac{(m+\lambda)^2}{4}$ there exists an optimal retail price p^{NN} and wholesale price w^{NN} and carbon emission reduction γ^{NN} that maximises retailer and manufacturer profits.*

Proof. Using the backward solution method based on the Stackelberg game, the retailer aims to maximize revenue p^{NN}. Substituting $q = a - p + \lambda\gamma$ into equation (2) and setting $\frac{\partial \pi_r^{NN}}{\partial p} = 0$:

$$p^{NN} = \frac{a + w + \gamma\lambda}{2}. \tag{3}$$

Substituting p^{NN} into equation (1) to obtain the Hessian matrix of π_m^{NN}:

$$H_1 = \begin{bmatrix} \dfrac{\partial^2 \pi_m^{NN}}{\partial w^2} & \dfrac{\partial^2 \pi_m^{NN}}{\partial w \partial \gamma} \\ \dfrac{\partial^2 \pi_m^{NN}}{\partial \gamma \partial w} & \dfrac{\partial^2 \pi_m^{NN}}{\partial \gamma^2} \end{bmatrix} = \begin{bmatrix} -1 & \dfrac{e(\lambda - m)}{2} \\ \dfrac{e(\lambda - m)}{2} & -U + m\lambda \end{bmatrix}.$$

When the abatement cost coefficient $U > \frac{(m+\lambda)^2}{4}$, it can be observed that $\frac{4U-(m+\lambda)^2}{4} > 0$. As a result, the Hessian matrix is negative definite, indicating the existence of optimal w^{NN} and γ^{NN} values that maximize π_m^{NN}.

Setting $\frac{\partial\pi_m^{NN}}{\partial w}=0$, $\frac{\partial\pi_m^{NN}}{\partial\gamma}=0$, and the association can be obtained:

$$w^{NN}=\frac{a+c+\lambda\gamma^{NN}+m(e-\gamma^{NN})}{2} \tag{4}$$

$$\gamma^{NN}=\frac{(a-c-em)(m+\lambda)}{4U-(m+\lambda)^2}. \tag{5}$$

Substituting equations (4) and (5) into equations (1)–(3):

$$p^{NN}=\frac{3a+3\lambda\gamma^{NN}+c+m(e-\gamma^{NN})}{4} \tag{6}$$

$$\pi_m^{NN}=\frac{U(a-c-em)^2}{2[4U-(m+\lambda)^2]}+me_s \tag{7}$$

$$\pi_r^{NN}=\frac{U^2(a-c-em)^2}{[4U-(m+\lambda)^2]^2}. \tag{8}$$

□

3.3.2. *Only manufacturers introduce blockchain technology*

Construct a decision model for reducing emissions in which the manufacturer introduces blockchain technology, and the retailer does not. The manufacturer introduces blockchain technology to reduce its carbon transaction costs and pays the cost of introducing it simultaneously. The retailer then sells the low-carbon products. The profit function governing the interactions between the manufacturer and the retailer is as follows:

$$\pi_m^{YN}=(w-c)q-[(e-\gamma)q-e_s]\beta m-\frac{1}{2}U\gamma^2-C_b \tag{9}$$

$$\pi_r^{YN}=(p-w)q. \tag{10}$$

Theorem 2. *When $U>\frac{(\beta m+\lambda)^2}{4}$ there exists an optimal retail price p^{YN} and wholesale price w^{YN} and carbon emission reduction γ^{YN} that maximises the retailer's and manufacturer's profits.*

Proof. Using the backward solution method based on the Stackelberg game, the retailer aims to maximize revenue p^{NN}. Substituting $q=a-p+\lambda\gamma$ into equation (2) and setting $\frac{\partial\pi_r^{YN}}{\partial p}=0$:

$$p^{YN}=\frac{a+w+\alpha\gamma\lambda}{2}. \tag{11}$$

Substituting p^{YN} into equation (9) to obtain the Hessian matrix of π_m^{YN}:

$$H_2=\begin{bmatrix}\frac{\partial^2\pi_m^{YN}}{\partial w^2} & \frac{\partial^2\pi_m^{YN}}{\partial w\partial\gamma}\\ \frac{\partial^2\pi_m^{YN}}{\partial\gamma\partial w} & \frac{\partial^2\pi_m^{YN}}{\partial\gamma^2}\end{bmatrix}=\begin{bmatrix}-1 & \frac{e(\lambda-\beta m)}{2}\\ \frac{e(\lambda-\beta m)}{2} & -U+\beta m\lambda\end{bmatrix}.$$

When the abatement cost coefficient satisfies $U>\frac{(\beta m+\lambda)^2}{4}$, it can be seen that $-1<0$ and $\frac{4U-(\beta m+\lambda)^2}{4}>0$. The Hessian matrix is negative definite, which means there exists an optimal w^{YN} and γ^{YN} such that π_m^{YN} obtains the maximum value.

Setting $\frac{\partial\pi_m^{YN}}{\partial w}=0$, $\frac{\partial\pi_m^{YN}}{\partial\gamma}=0$, and the association can be obtained:

$$w^{YN}=\frac{a+c+\lambda\gamma^{YN}+\beta m(e-\gamma^{YN})}{2} \tag{12}$$

$$\gamma^{YN} = \frac{(a-c-e\beta m)(\beta m+\lambda)}{4U-(\beta m+\lambda)^2}. \tag{13}$$

Substituting equations (12) and (13) into equations (9)–(11):

$$p^{YN} = \frac{3a+3\lambda\gamma^{YN}+c+\beta m(e-\gamma^{YN})}{4} \tag{14}$$

$$\pi_m^{YN} = \frac{U(a-c-em\beta)^2}{2(4U-(\beta m+\lambda)^2)} + \beta m e_s - C_b \tag{15}$$

$$\pi_r^{YN} = \frac{U^2(a-c-e\beta m)^2}{[4U-(\beta m+\lambda)^2]^2}. \tag{16}$$

□

Corollary 1. *When initial carbon emissions per unit* $e < \frac{(a-c)\lambda}{4U-\lambda^2}$, $\beta \in (0,1)$ *or* $e > \frac{(a-c)\lambda}{4U-\lambda^2}$, $\beta \in (0, \min(\overline{\beta}, 1))$, *manufacturers' optimal emission reductions increase as* β *increases.*

Proof. $\frac{\partial\gamma^{YN}}{\partial\beta} = \frac{4U(a-c-e\lambda)+\lambda^2(a-c+e\lambda)+\beta^2m^2(a-c+e\lambda)+\beta(2am\lambda-2cm\lambda+2em(-4U+\lambda^2))}{(4U-(m\beta+\lambda)^2)^2}$, setting $f_1(\beta) = 4U(a-c-e\lambda)+\lambda^2(a-c+e\lambda)+\beta^2m^2(a-c+e\lambda)+\beta(2am\lambda-2cm\lambda+2em(-4U+\lambda^2))$, then $\frac{\partial\gamma^{YN}}{\partial\beta} = \frac{f_1(\beta)}{(4U-(m\beta+\lambda)^2)^2}$. Currently known $4U(a-c-e\lambda)+\lambda^2(a-c+e\lambda) > 0$, $m^2(a-c+e\lambda) > 0$. Then $f_1(\beta)$ is a binary primary function that opens upward about β and intersects the y-axis at a value greater than 0. Therefore, it is sufficient to consider the value of $2am\lambda-2cm\lambda+2em(-4U+\lambda^2)$. When $2a\lambda+2e\lambda^2-2c\lambda-8eU > 0$, $e < \frac{(a-c)\lambda}{4U-\lambda^2}$, $\beta \in (0,1)$, $f_1(\beta) > 0$, $\frac{\partial\gamma^{YN}}{\partial\beta} > 0$. When $2a\lambda+2e\lambda^2-2c\lambda-8eU < 0$, $e > \frac{(a-c)\lambda}{4U-\lambda^2}$, setting $f_1(\beta) = 0$, $\bar{\beta} = \frac{m(4eU-\lambda(a-c+e\lambda))-2\sqrt{m^2U(8Ue^2+2ac+2ce\lambda-2ae\lambda-a^2-c^2-e^2\lambda^2)}}{m^2(a-c+e\lambda)}$. When $\beta \in (0, \min(\overline{\beta}, 1))$, $f_1(\beta) > 0$, $\frac{\partial\gamma^{YN}}{\partial\beta} > 0$. Corollary 1 is proved. □

Corollary 2. *The use of blockchain technology by manufacturers does not significantly contribute to reducing supply chain emissions. Carbon reductions increase when* $e > \frac{(a-c)\lambda}{4U-\lambda^2}$, $\beta > \frac{\overline{m}}{m}$ *and* $m > m_1$.

Proof. Since $\beta < 1, \beta m < m$. Setting $f_2(x) = \frac{(a-c-ex)(x+\lambda)}{4U-(x+\lambda)^2}$, then it is sufficient to determine $f_2(\beta m) = \gamma^{YN}$ and $f_2(m) = \gamma^{NN}$, the derivation for γ^{NN} : $\frac{\partial\gamma^{NN}}{\partial m} = \frac{4U(a-c-e\lambda)+\lambda^2(a-c+e\lambda)+m^2(a-c+e\lambda)+m(2a\lambda+2e\lambda^2-2c\lambda-8eU)}{(m^2-4U+2m\lambda+\lambda^2)^2}$, setting $\frac{\partial\gamma^{NN}}{\partial m} = 0$, $m_1 = \frac{4eU-a\lambda+c\lambda-e\lambda^2-2\sqrt{-U(a^2+c^2-2ce\lambda-2a(c-e\lambda)+e^2(-4U+\lambda^2))}}{a-c+e\lambda}$. Currently known $a-c+e\lambda > 0$, $4U(a-c-e\lambda)+\lambda^2(a-c+e\lambda) > 0$, so when $2a\lambda+2e\lambda^2-2c\lambda-8eU > 0$, $e < \frac{(a-c)\lambda}{4U-\lambda^2}$, $f_2(\beta m) < f_2(m)$, which means $\gamma^{YN} < \gamma^{NN}$. And when $2a\lambda+2e\lambda^2-2c\lambda-8eU < 0$, $e > \frac{(a-c)\lambda}{4U-\lambda^2}$, which means when the manufacturer's initial carbon emissions are high, there exists $\overline{m} \neq m$ such that $f_2(\overline{m}) = \gamma^{NN} = f_2(m)$, which can be obtained:

$$\begin{cases} \gamma^{YN} > \gamma^{NN} & \text{when } \beta > \frac{\overline{m}}{m} \text{ and } m > m_1 \\ \gamma^{YN} < \gamma^{NN} & \text{else.} \end{cases} \tag{17}$$

Corollary 2 is proved. □

3.3.3. *Only retailers introduce blockchain technology*

Construct a decision model for abatement where retailers introduce blockchain technology, and manufacturers do not. The introduction of blockchain technology by retailers enhances consumers' preference for low-carbon products, which increases demand while the manufacturers make abatement inputs. The profit function of both manufacturers and retailers is:

$$\pi_m^{NY} = (w-c)q - [(e-\gamma)q - e_s]m - \frac{1}{2}U\gamma^2 \tag{18}$$

$$\pi_r^{YN} = (p-w)q - C_b. \tag{19}$$

Theorem 3. *When* $U > \frac{(m+\alpha\lambda)^2}{4}$*, there exists an optimal retail price* p^{NY}*, wholesale price* w^{NY} *and carbon emission reduction* γ^{NY}*, which maximise the profit of retailers and manufacturers.*

Proof. Using the backward solution method based on the Stackelberg game, the retailer aims to maximize revenue p^{NY}. Substituting $q = a - p + \lambda\gamma$ into equation (19) and setting $\frac{\partial \pi_r^{YN}}{\partial p} = 0$:

$$p^{NY} = \frac{a + w + \gamma\lambda}{2}. \tag{20}$$

Substituting p^{NY} into equation (18) to obtain the Hessian matrix of π_m^{NY}:

$$H_3 = \begin{bmatrix} \dfrac{\partial^2 \pi_m^{NY}}{\partial w^2} & \dfrac{\partial^2 \pi_m^{NY}}{\partial w \partial \gamma} \\ \dfrac{\partial^2 \pi_m^{NY}}{\partial \gamma \partial w} & \dfrac{\partial^2 \pi_m^{NY}}{\partial \gamma^2} \end{bmatrix} = \begin{bmatrix} -1 & \dfrac{e(\alpha\lambda - m)}{2} \\ \dfrac{e(\alpha\lambda - m)}{2} & -U + \alpha m \lambda \end{bmatrix}.$$

When the abatement cost coefficient $U > \frac{(m+\alpha\lambda)^2}{4}$, it can be seen that $-1 < 0$ and $\frac{4U-(m+\alpha\lambda)^2}{4} > 0$. The Hessian matrix is negative definite, which means there exists an optimal w^{NY} and γ^{NY} such that π_m^{NY} obtains the maximum value.

Setting $\frac{\partial \pi_m^{NY}}{\partial w} = 0$, $\frac{\partial \pi_m^{NY}}{\partial \gamma} = 0$, the association can be obtained:

$$w^{NY} = \frac{a + c + \alpha\lambda\gamma^{NY} + m(e - \gamma^{NY})}{2} \tag{21}$$

$$\gamma^{NY} = \frac{(a - c - em)(m + \alpha\lambda)}{4U - (m + \alpha\lambda)^2}. \tag{22}$$

Substituting equations (20) and (21) into equations (17)–(19):

$$p^{NY} = \frac{3a + 3\alpha\lambda\gamma^{NY} + c + m(e - \gamma^{NY})}{4} \tag{23}$$

$$\pi_m^{NY} = \frac{U(a - c - em)^2}{2[4U - (m + \alpha\lambda)^2]} + me_s \tag{24}$$

$$\pi_r^{NY} = \frac{U^2(a - c - em)^2}{[4U - (m + \alpha\lambda)^2]^2} - C_b. \tag{25}$$

□

Corollary 3. *Manufacturers' optimal carbon emission reductions increase as blockchain's influence on consumers' low-carbon preferences* α *increases.*

Proof. $\frac{\partial \gamma^{NY}}{\partial \alpha} = \frac{(a-c-em)\lambda(4U+(m+\alpha\lambda)^2)}{[4U-(m+\alpha\lambda)^2]^2} > 0$. Corollary 3 is proved. □

Corollary 4. *Retailers introduce blockchain technology to help reduce emissions in the supply chain.*

Proof. $\gamma^{NY} - \gamma^{NN} = \frac{(a-c-em)(m+\alpha\lambda)}{4U-(m+\alpha\lambda)^2} - \frac{(a-c-em)(m+\lambda)}{4U-(m+\lambda)^2}$. Since $\alpha > 1$, it can be obtained that $4U - (m+\alpha\lambda)^2 < 4U - (m+\lambda)^2$ and $m + \alpha\lambda > m + \lambda$. So $\frac{(a-c-em)(m+\alpha\lambda)}{4U-(m+\alpha\lambda)^2} > \frac{(a-c-em)(m+\lambda)}{4U-(m+\lambda)^2}$, $\gamma^{NY} > \gamma^{NN}$. Corollary 4 is proved. □

3.3.4. Manufacturers and retailers introduce blockchain technology

Construct a decision model for reducing emissions where the manufacturer and retailer implement blockchain technology. The retailer's adoption of blockchain technology enhances consumers' low-carbon preferences, increasing the demand for low-carbon products. Simultaneously, Manufacturers make emissions reduction investments and blockchain technology investments. Therefore, the profit function of manufacturers and retailers is:

$$\pi_m^{YY} = (w-c)q - [(e-\gamma)q - e_s]\beta m - \frac{1}{2}U\gamma^2 - C_b \tag{26}$$

$$\pi_r^{YY} = (p-w)q - C_b. \tag{27}$$

Theorem 4. *When $U > \frac{(\beta m+\alpha\lambda)^2}{4}$, there exists an optimal retail price p^{YY}, wholesale price w^{YY} and carbon emission reduction γ^{YY} that maximises the retailer's and manufacturer's profits.*

Proof. Using the backward solution method based on the Stackelberg game, the retailer aims to maximize revenue p^{YY}. Substituting $q = a - p + \lambda\gamma$ into equation (18) and setting $\frac{\partial \pi_r^{YN}}{\partial p} = 0$:

$$p^{YY} = \frac{a + w + \alpha\gamma\lambda}{2}. \tag{28}$$

Substituting p^{YY} into equation (25) to obtain the Hessian matrix of π_m^{NY} is:

$$H_4 = \begin{bmatrix} \dfrac{\partial^2 \pi_m^{YY}}{\partial w^2} & \dfrac{\partial^2 \pi_m^{YY}}{\partial w \partial \gamma} \\ \dfrac{\partial^2 \pi_m^{YY}}{\partial \gamma \partial w} & \dfrac{\partial^2 \pi_m^{YY}}{\partial \gamma^2} \end{bmatrix} = \begin{bmatrix} -1 & \dfrac{e(\alpha\lambda - \beta m)}{2} \\ \dfrac{e(\alpha\lambda - \beta m)}{2} & -U + \alpha\beta m\lambda \end{bmatrix}.$$

When the abatement cost coefficient $U > \frac{(\beta m+\alpha\lambda)^2}{4}$, it can be seen that $-1 < 0$ and $\frac{4U-(\beta m+\alpha\lambda)^2}{4} > 0$. The Hessian matrix is negative definite, which means there exists an optimal w^{YY} and γ^{YY} such that π_m^{YY} obtains the maximum value. Setting $\frac{\partial \pi_m^{YY}}{\partial w} = 0$ and $\frac{\partial \pi_m^{YY}}{\partial \gamma} = 0$, the association can be obtained:

$$w^{YY} = \frac{a + c + \alpha\lambda\gamma^{YY} + \beta m(e - \gamma^{YY})}{2} \tag{29}$$

$$\gamma^{YY} = \frac{(a - c - e\beta m)(m\beta + \alpha\lambda)}{4U - (\beta m + \alpha\lambda)^2}. \tag{30}$$

Substituting equations (29) and (30) into equations (26)–(28).

$$p^{YY} = \frac{3a + 3\alpha\lambda\gamma^{YY} + c + \beta m(e - \gamma^{YY})}{4} \tag{31}$$

$$\pi_m^{YY} = \frac{U(a - c - e\beta m)^2}{2(4U - (\beta m + \alpha\lambda)^2)} + \beta m e_s - C_b \tag{32}$$

$$\pi_r^{YY} = \frac{U^2(a - c - e\beta m)^2}{(4U - (\beta m + \alpha\lambda)^2)^2} - C_b. \tag{33}$$

□

3.4. Decision model solution results for abatement of different blockchain introduction strategies

This paper examines firm decision-making in the context of carbon quota trading policies. Manufacturers face constraints imposed by carbon quotas on emission reduction inputs and carbon trading, while the cost

Table 4. Profit function.

Strategy portfolio	π_m	π_r
(N,N)	$(w-c)q-[(e-\lambda)q-e_s]m-\frac{1}{2}U\gamma^2$	$(p-w)q$
(Y,N)	$(w-c)q-[(e-\lambda)q-e_s]\beta m-\frac{1}{2}U\gamma^2-C_b$	$(p-w)q$
(N,Y)	$(w-c)q-[(e-\lambda)q-e_s]m-\frac{1}{2}U\gamma^2$	$(p-w)q-C_b$
(Y,Y)	$(w-c)q-[(e-\lambda)q-e_s]\beta m-\frac{1}{2}U\gamma^2-C_b$	$(p-w)q-C_b$

Table 5. Under each combination of strategies w^*, p^* and γ^*.

Strategy portfolio	w^*	p^*	γ^*
(N,N)	$\frac{a+c+\lambda\gamma^{NN}+m(e-\gamma^{NN})}{2}$	$\frac{3a+c+3\lambda\gamma^{NN}+m(e-\gamma^{NN})}{4}$	γ^{NN}
(Y,N)	$\frac{a+c+\lambda\gamma^{YN}+\beta m(e-\gamma^{YN})}{2}$	$\frac{3a+c+3\lambda\gamma^{YN}+\beta m(e-\gamma^{YN})}{4}$	γ^{YN}
(N,Y)	$\frac{a+c+\alpha\lambda\gamma^{NY}+m(e-\gamma^{NY})}{2}$	$\frac{3a+c+3\alpha\lambda\gamma^{NY}+m(e-\gamma^{NY})}{4}$	γ^{NY}
(Y,Y)	$\frac{a+c+\alpha\lambda\gamma^{YY}+\beta m(e-\gamma^{YY})}{2}$	$\frac{3a+c+3\alpha\lambda\gamma^{YY}+\beta m(e-\gamma^{YY})}{4}$	γ^{YY}

Table 6. Optimal profit under each strategy combination.

Strategy portfolio	π_m^*	π_r^*
(N,N)	$\frac{UK_1}{2T_1}+me_s$	$\frac{U^2K_1}{{T_1}^2}$
(Y,N)	$\frac{UK_2}{2T_2}+\beta me_s-C_b$	$\frac{U^2K_2}{{T_2}^2}$
(N,Y)	$\frac{UK_1}{2T_3}+me_s$	$\frac{U^2K_1}{{T_3}^2}-C_b$
(Y,Y)	$\frac{UK_2}{2T_4}+\beta me_s-C_b$	$\frac{U^2K_2}{{T_4}^2}-C_b$

of introducing blockchain technology is borne by the party introducing it. Therefore, the profit functions of manufacturers and retailers under each blockchain adoption strategy are presented in Table 4. The model is solved using the inverse solution method. Table 5 shows the strategy combinations corresponding to the optimal values of w^*, p^* and γ^*, while Table 6 shows the optimal profit for each strategy combination.

Setting $\gamma^{NN}=\frac{(a-c-em)(m+\lambda)}{4U-(m+\lambda)^2}$, $\gamma^{YN}=\frac{(a-c-e\beta m)(\beta m+\lambda)}{4U-(\beta m+\lambda)^2}$, $\gamma^{NY}=\frac{(a-c-em)(m+\alpha\lambda)}{4U-(\beta m+\lambda)^2}$, $\gamma^{YY}=\frac{(a-c-e\beta m)(m\beta+\alpha\lambda)}{4U-(\beta m+\alpha\lambda)^2}$, $K_1=(a-c-em)^2$, $K_2=(a-c-em\beta)^2$, $T_1=4U-(m+\lambda)^2$, $T_2=4U-(\beta m+\lambda)^2$, $T_3=4U-(m+\alpha\lambda)^2$ and $T_4=4U-(\beta m+\alpha\lambda)^2$.

Corollary 5. *Retailers are pinning blockchain technology by statutes to emission reductions within the supply chain. In contrast, when manufacturers implement blockchain technology, it primarily alleviates the constraints imposed by carbon trading on their emission reduction efforts, with minimal impact on overall supply chain emissions. An increase in carbon emission reductions per unit of product occurs only when* $\beta>\frac{\overline{m}}{m}$ *and* $m>m_1$.

Proof. Since $\alpha>1$, it follows that $\gamma^{NY}-\gamma^{NN}=\frac{(a-c-em)(m+\alpha\lambda)}{4U-(m+\alpha\lambda)^2}-\frac{(a-c-em)(m+\lambda)}{4U-(m+\lambda)^2}>0$. Since $\beta<1$, it follows that $\beta m<m$, $f_2(x)=\frac{(a-c-ex)(x+\lambda)}{4U-(x+\lambda)^2}$. Then judge $f_2(\beta m)=\gamma^{YN}$ and $f_2(m)=\gamma^{NN}$, and derivation of γ^{NN} yields $\frac{\partial\gamma^{NN}}{\partial m}=\frac{4U(a-c-e\lambda)+\lambda^2(a-c+e\lambda)+m^2(a-c+e\lambda)+m(2a\lambda+2e\lambda^2-2c\lambda-8eU)}{(m^2-4U+2m\lambda+\lambda^2)^2}$. Set $\frac{\partial\gamma^{NN}}{\partial m}=0$, solve the equation to

find $m_1 = \frac{4eU-a\lambda+c\lambda-e\lambda^2-2\sqrt{-U(a^2+c^2-2ce\lambda-2a(c-e\lambda)+e^2(-4U+\lambda^2)}}{a-c+e\lambda}$. Currently known that $a-c+e\lambda > 0$ and $4U(a-c-e\lambda)+\lambda^2(a-c+e\lambda) > 0$, it follows that when $2a\lambda+2e\lambda^2-2c\lambda-8eU > 0$, $e < \frac{(a-c)\lambda}{4U-\lambda^2}$. Due to $\frac{(a-c)\lambda}{4U-\lambda^2} < \gamma^{YN}$, but $e > \gamma^{YN}$, so this case doe not exist. When $2a\lambda+2e\lambda^2-2c\lambda-8eU < 0$, $e > \frac{(a-c)\lambda}{4U-\lambda^2}$, which means when the manufacturer's initia carbon emissions are high, the presence of $\overline{m} \neq m$ such that holds $f_2(\overline{m}) = \gamma^{NN} = f_2(m)$, the association can be obtained.

$$\begin{cases} \gamma^{YN} > \gamma^{NN} & \text{when } \beta > \frac{\overline{m}}{m} \text{ and } m > m_1 \\ \gamma^{YN} < \gamma^{NN} & \text{else.} \end{cases} \tag{34}$$

Corollary 5 is therefore proven. □

4. Game analysis of the evolution of blockchain introduction strategies

4.1. Construction and solution of the evolutionary game model

Assuming the adoption proportions of manufacturers introducing blockchain technology (Y) as $x(0 \leq x \leq 1)$ and not introducing blockchain technology (N) as $1-x$ and similarly, assuming the adoption proportions of retailers introducing blockchain technology (Y) as $y(0 \leq y \leq 1)$and not introducing blockchain technology (N) as $1-y$.

The adaptation level of the manufacturer's strategy for introducing blockchain technology U_1Y:

$$U_{1Y} = y\pi_m^{YY} + (1-y)\pi_m^{YN}. \tag{35}$$

The adaptation level without the introduction of blockchain technology U_1N:

$$U_{1N} = y\pi_m^{NY} + (1-y)\pi_m^{NN}. \tag{36}$$

The average adaptation level $\overline{U_1}$:

$$\overline{U_1} = xU_{1Y} + (1-x)U_{1N}. \tag{37}$$

Similarly, the adaptation level of retailers introducing blockchain technology U_2Y:

$$U_{2Y} = x\pi_r^{YY} + (1-x)\pi_r^{NY}. \tag{38}$$

The adaptation level without the introduction of blockchain technology U_2N:

$$U_{2N} = x\pi_r^{YN} + (1-x)\pi_r^{NN}. \tag{39}$$

The average adaptation level $\overline{U_2}$:

$$\overline{U_2} = yU_{2Y} + (1-y)U_{2N}. \tag{40}$$

The manufacturer's replication dynamics equation X_t:

$$X_t = \frac{\mathrm{d}x}{\mathrm{d}t} = x(1-x)\big[y\big(\pi_m^{YY}-\pi_m^{NY}\big) + (1-y)\big(\pi_m^{YN}-\pi_m^{NN}\big)\big]. \tag{41}$$

The equation for the replication dynamics of the retailer Y_t:

$$Y_t = \frac{\mathrm{d}y}{\mathrm{d}t} = y(1-y)\big[x\big(\pi_r^{YY}-\pi_r^{YN}\big) + (1-x)\big(\pi_r^{NY}-\pi_r^{NN}\big)\big]. \tag{42}$$

The equilibrium points of the evolving game system can be obtained by setting $X_t = \frac{\mathrm{d}x}{\mathrm{d}t} = 0$, $Y_t = \frac{\mathrm{d}y}{\mathrm{d}t} = 0$, the five equilibria of the evolving game system are obtained as $(0,0)$, $(0,1)$, $(1,0)$, $(1,1)$, and $(\frac{\pi_r^{NY}-\pi_r^{NN}}{\pi_r^{NY}+\pi_r^{YN}-\pi_r^{NN}-\pi_r^{YY}}, \frac{\pi_m^{YN}-\pi_m^{NN}}{\pi_m^{NY}+\pi_m^{YN}-\pi_m^{NN}-\pi_m^{YY}})$.

Table 7. Equilibrium point stability parameters.

Balance point	c_{11}	c_{12}	c_{21}	c_{22}
$(0,0)$	$\pi_m^{YN}-\pi_m^{NN}$	0	0	$\pi_r^{NY}-\pi_r^{NN}$
$(0,1)$	$\pi_m^{YY}-\pi_m^{NY}$	0	0	$\pi_r^{NN}-\pi_r^{NY}$
$(1,0)$	$\pi_m^{NN}-\pi_m^{YN}$	0	0	$\pi_r^{YY}-\pi_r^{YN}$
$(1,1)$	$\pi_m^{NY}-\pi_m^{YY}$	0	0	$\pi_r^{YN}-\pi_r^{YY}$
(x^*,y^*)	0	$*$	$*$	0

4.2. Evolutionary game strategy analysis

The stability of the equilibrium points in the evolutionary game system is analyzed using the Jacobi matrix, which is represented as:

$$J=\begin{bmatrix}\frac{\partial X_t}{\partial x} & \frac{\partial X_t}{\partial y}\\ \frac{\partial Y_t}{\partial x} & \frac{\partial Y_t}{\partial y}\end{bmatrix}=\begin{bmatrix}c_{11} & c_{12}\\ c_{21} & c_{22}\end{bmatrix}. \tag{43}$$

The elements of the Jacobi matrix are given by:

$$c_{11}=(1-2x)\left[y\left(\pi_m^{YY}-\pi_m^{NY}\right)+(1-y)\left(\pi_m^{YN}-\pi_m^{NN}\right)\right] \tag{44}$$

$$c_{12}=x(1-x)\left(\pi_m^{YY}-\pi_m^{NY}-\pi_m^{YN}+\pi_m^{NN}\right) \tag{45}$$

$$c_{21}=y(1-y)\left(\pi_r^{YY}-\pi_r^{YN}-\pi_r^{NY}+\pi_r^{NN}\right) \tag{46}$$

$$c_{22}=(1-2y)\left[x\left(\pi_r^{YY}-\pi_r^{YN}\right)+(1-x)\left(\pi_r^{NY}-\pi_r^{NN}\right)\right]. \tag{47}$$

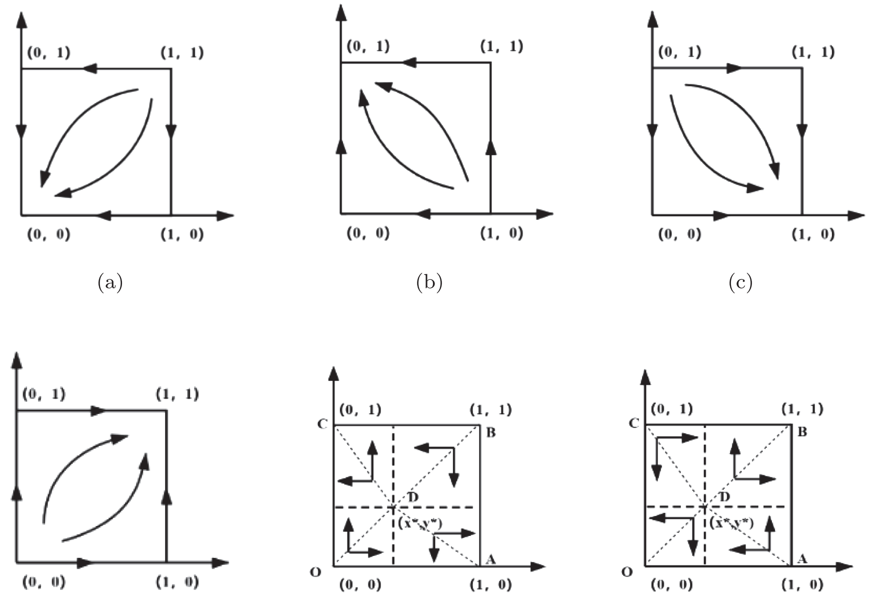
By evaluating the stability parameters at the equilibrium points, Table 7 can be derived. A simplification of the stability analysis leads to the following corollaries. Assuming that m and λ are constants, the evolutionary stabilization strategy of the system evolves with C_b and e_s. Set $A_1=\frac{U^2K_1({T_1}^2-{T_3}^2)}{{T_1}^2T_3^2}$, $A_2=\frac{U^2K_2({T_2}^2-{T_4}^2)}{{T_2}^2T_4^2}$, $B_1=\frac{UK_1T_2-UK_2T_1+2T_1T_2C_b}{2T_1T_2m(\beta-1)}$ and $B_2=\frac{UK_1T_4-UK_2T_3+2T_3T_4C_b}{2T_3T_4m(\beta-1)}$.

Corollary 6. *When $C_b>\max(A_1,A_2)$ and $e_s>\max(B_1,B_2)$, the evolutionary stability strategy of the system is (N,N).*

When the cost of introducing blockchain technology is high, and the allocation of carbon allowances is also high, the implementation of blockchain technology results in lower reductions in carbon trading for manufacturers and increased sales for retailers compared to the cost of the blockchain itself, as shown in Figure 2a. In this case, the optimal evolutionary stabilization strategy for the system is for manufacturers and retailers not to introduce blockchain technology.

Corollary 7. *When $C_b>\min(A_1,A_2)$ and $e_s>\max(B_1,B_2)$, the evolutionary stability strategy of the system is (N,Y).*

When the cost of introducing blockchain technology is low, and the allocation of carbon allowances is high, retailers are more likely to invest in blockchain technology as the increase in sales outweighs the cost of introduction. On the other hand, manufacturers may choose not to introduce blockchain technology as the decrease in carbon turnover resulting from its introduction is less than the cost of the technology itself. It is important to note that this decision is influenced by the allocation of carbon allowances and the restrictions placed on manufacturers. As shown in Figure 2b, the final evolutionary game strategy is for the retailer to introduce blockchain technology while the manufacturer does not.



(a) (b) (c)

(d) (e) (f)

FIGURE 2. Dynamic phase diagram of system evolution.

Corollary 8. *When* $C_b > \max(A_1, A_2)$ *and* $e_s > \min(B_1, B_2)$*, the evolutionary stability strategy of the system is* (Y, N)*.*

When the cost of introducing blockchain technology is high, but the allocation of carbon quotas is low, the manufacturer is more constrained by the carbon quota. The reduction in carbon trading volume brought about by the manufacturer through blockchain technology exceeds the introduction cost of the technology. At this point, the manufacturer chooses to introduce blockchain technology. However, the increase in sales brought about by the retailer's introduction of blockchain technology is not as high as the introduction cost. Therefore, the retailer chooses not to introduce it. In this scenario, the final evolutionary game strategy of the system is for the manufacturer to introduce blockchain technology while the retailer does not, as stated in Figure 2c.

Corollary 9. *When* $C_b > \min(A_1, A_2)$ *and* $e_s > \min(B_1, B_2)$*, the evolutionary stability strategy of the system is* (Y, Y)*.*

When the cost of introducing blockchain technology is low, and the allocation of carbon allowances is low, implementing blockchain technology results in a more significant reduction in carbon transactions for manufacturers and an increase in sales for retailers than the cost of the blockchain itself. This is demonstrated in Figure 2d. In this case, the optimal evolutionary stabilization strategy for the system is the introduction of blockchain technology by both manufacturers and retailers.

Corollary 10. *When* $A_2 < C_b < A_1$ *and* $B_2 < e_s < B_1$*, the evolutionary stabilization strategy of the system is* (N, Y) *and* (Y, N)*.*

When the cost and carbon quota of blockchain introduction satisfy $A_2 < C_b < A_1$ and $B_2 < e_s < B_1$, the profit increase brought by the introduction of either the manufacturer or the retailer alone is greater than the introduction cost but less than the profit increase brought by the introduction of the other party. Therefore, a binary equilibrium exists, as shown in the figure. Figure 2e is divided into two parts by the unstable and saddle point regions. The OABD region is below the fold line, where the manufacturer introduces blockchain technology and the retailer does not, with a higher probability. The OCBD region is above the fold line, where the retailer introduces blockchain technology and the manufacturer does not, with a higher probability.

Corollary 11. *When $A_1 < C_b < A_2$ and $B_1 < e_s < B_2$, the evolutionary stabilization strategy of the system is (N, N) and (Y, Y).*

When the cost of introducing blockchain technology and the carbon quota fall satisfy $A_1 < C_b < A_2$ and $B_1 < e_s < B_2$, the profit increase resulting from the unilateral introduction of blockchain technology by the manufacturer and retailer is less than the cost of introducing the technology, as illustrated in figure. To ensure clarity, technical abbreviations will be explained upon first use. In Figure 2f, the region is divided into two parts: the unstable point and the saddle point. The lower part, OADC, is below the fold line, and it is more likely that neither the manufacturer nor the retailer will introduce blockchain technology. The upper part, ABCD, is above the fold line, and there is a higher probability that both the manufacturer and the retailer will choose to introduce blockchain technology. In regions with a higher probability that manufacturers and retailers will not introduce blockchain technology, there is also a higher probability that they will choose to introduce it in the ABCD region above the fold line.

4.3. Influence of parameters on binary equilibrium strategy

This paper analyses the evolution of strategies $(1, 1)$ and $(0, 0)$ in the case of binary equilibrium. The final evolutionary strategy is determined by the area of region OADC and region ADCB, denoted by S_1 and S_2, respectively. The probability of the system evolving a stable strategy $(0, 0)$ is greater than that of evolving a stable strategy $(1, 1)$, if $S_1 > S_2$ and *vice versa*. The probability of the system evolutionary stabilisation strategy being $(1, 1)$ is greater than the probability of it being $(0, 0)$. For instance, in the analysed region ADCB, the probability of the system evolutionary stabilisation strategy being $(1, 1)$ can be calculated as $S_2 = 1 - \frac{1}{2}(x^* + y^*) = 1 - \frac{1}{2}(\frac{\pi_r^{NY} - \pi_r^{NN}}{\pi_r^{NY} + \pi_r^{YN} - \pi_r^{NN} - \pi_r^{YY}} + \frac{\pi_m^{YN} - \pi_m^{NN}}{\pi_m^{NY} + \pi_m^{YN} - \pi_m^{NN} - \pi_m^{YY}})$.

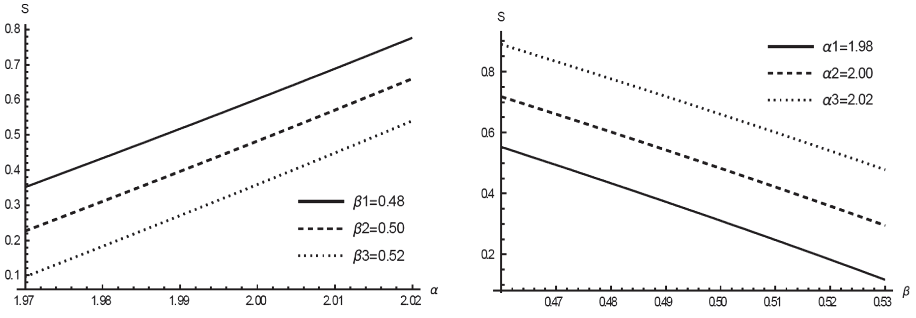
Corollaries 10 and 11 show that factors such as α, β, λ, U and others influence the evolutionary stabilization strategy. Due to the complexity of binary equilibrium conditions [44]. In this paper, we employ a numerical simulation method to analyse each parameter's influence on the system's evolutionary outcome. Expressly, set $a = 100$, $c = 5$, $C_b = 190$ and $e_s = 80$.

(1) Analysis of the influence of blockchain technology on consumers' low-carbon preferences and carbon trading costs α and β on area S_2.

Setting $U = 100$, $\lambda = 4$, $e = 10$, $m = 5$, $\alpha \in [1.97, 2.02]$ and β takes the values of 0.48, 0.50, and 0.52, respectively, and obtains Figure 3a. In addition, setting $\beta \in [0.46, 0.53]$, α takes the values of 1.98, 2.00, and 2.02, respectively, and obtains Figure 3b.

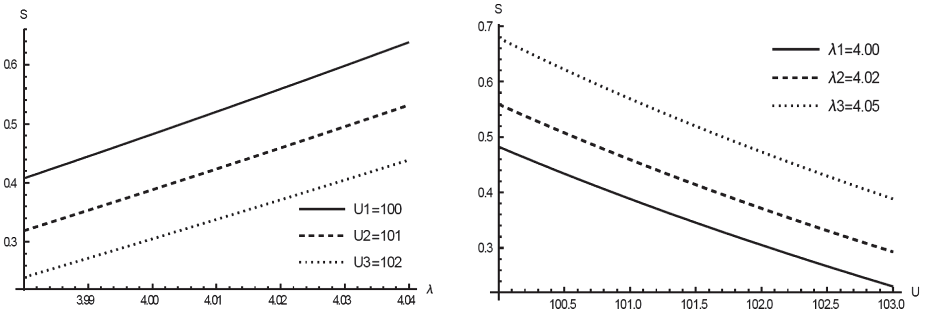
Corollary 12. *The likelihood of both parties adopting blockchain technology increases with its positive impact on consumers' low-carbon preferences. Conversely, as blockchain technology's impact on carbon transaction costs grows, the probability of adoption by either party decreases.*

When blockchain technology significantly enhances consumers' low-carbon preferences, the resulting increase in product demand boosts profits for both manufacturers and retailers, encouraging them to adopt the technology. However, if blockchain's impact on reducing carbon transaction costs diminishes, manufacturers become less inclined to implement it. In such cases, the profit gains for retailers from unilaterally adopting blockchain technology are insufficient to offset the associated costs, leading both parties to forgo adoption. To enhance the influence of blockchain technology on consumers' low-carbon preferences, retailers should actively promote blockchain's decentralized and trustless nature. Additionally, manufacturers and research institutes can improve the operational convenience of blockchain-based carbon trading and reduce transaction costs by developing more efficient and user-friendly intelligent contracts.



(a) (b)

FIGURE 3. Impact of β and α on S_2.



(a) (b)

FIGURE 4. Impact of λ and U on S_2.

(2) Analysis of the impact of consumers' low-carbon preferences λ and the difficulty factor of reducing emissions in the area S_2.

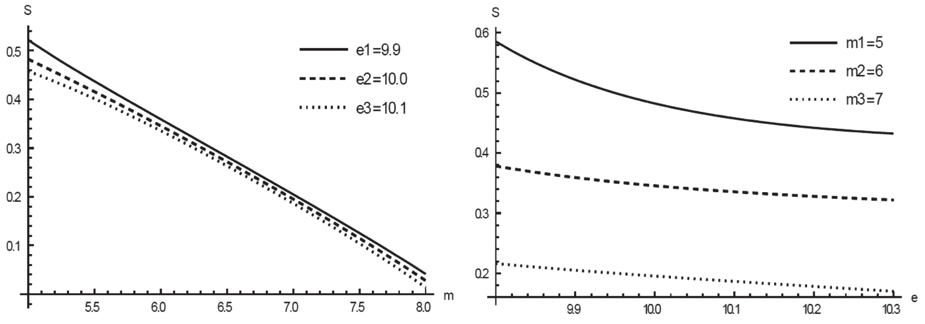
Setting $e = 10$, $m = 5$, $\alpha = 2$, $\beta = 0.5$, $\lambda \in [3.98, 4.06]$ and U takes the values of 100, 101, 102, respectively, and obtains Figure 4a. In addition, setting $U \in [100, 103]$ and λ takes the values of 4.00, 4.02, and 4.05, respectively, and obtains Figure 4b.

Corollary 13. *As consumers' preference for low-carbon products increases, so does the likelihood that both manufacturers and retailers will adopt blockchain technology. Conversely, as the difficulty of reducing emissions rises, the probability that neither party will implement blockchain technology also increases.*

When consumer preference for low-carbon products grows, demand increases, leading to higher profits for manufacturers and retailers, incentivising them to adopt blockchain technology. However, as the difficulty of emission reduction increases, the cost for manufacturers to reduce emissions also rises. Consequently, the likelihood of manufacturers adopting new technology decreases. Simultaneously, the benefits for retailers to unilaterally adopt blockchain technology become lower than the associated costs, leading the system to evolve towards a state where neither manufacturer nor retailer adopts blockchain technology.

(3) Analysis of unit carbon trading costs and initial carbon emissions per unit of product on area S_2.

Setting $U = 100$, $\lambda = 4$, $\alpha = 2$, $\beta = 0.5$, $m \in [4.7, 8.0]$ and U takes the values of 9.9, 10.0, 10.1, respectively, and obtains Figure 5a. In addition, setting $e \in [9.8, 10.3]$ and λ take the values of 4.00, 4.02, and 4.05, respectively, and obtain Figure 5b.



(a) (b)

Figure 5. Impact of m and e on S_2.

Corollary 14. *When unit carbon transaction costs and initial carbon emissions are high, the likelihood that neither party will adopt blockchain technology increases.*

As unit carbon transaction costs rise, the savings from blockchain technology for manufacturers become smaller than the costs of implementing it. This drives manufacturers away from adopting blockchain technology. Simultaneously, the benefits for retailers to independently introduce blockchain technology outweigh the associated costs, leading the system to evolve toward a scenario where neither party adopts blockchain technology. Additionally, when initial carbon emissions per product unit are high, the manufacturer faces lower carbon trading volumes and costs, reducing the need for new technologies to assist with carbon trading. Consequently, neither the manufacturer nor the retailer adopts blockchain technology in this situation.

5. Conclusion

5.1. Conclusions and managerial implications

Reducing supply chain emissions is crucial for achieving carbon neutrality in the context of dual-carbon targets. However, challenges like consumer mistrust of low-carbon products and inefficiencies in the carbon trading market have impeded companies' efforts to reduce emissions. Blockchain technology is viewed as an effective solution to these challenges as a decentralised and trustless innovation. While China actively promotes the development of blockchain technology, its high costs remain a significant barrier to enterprises' adoption. In response to this issue, this paper examines a secondary low-carbon supply chain consisting of a single supplier and retailer. First, it establishes an emission reduction decision model using the Stackelberg game theory, considering four strategies based on whether manufacturers and retailers adopt blockchain technology. Next, it constructs an evolutionary game model to explore the sufficient conditions for each blockchain adoption strategy. Finally, the paper uses Mathematica to analyse the effects of consumers' low-carbon preferences, carbon transaction costs, and blockchain benefit parameters on the selection of dual equilibrium strategies.

Applying blockchain technology in emissions reduction exhibits significant differences across supply chain segments. In the retail segment, blockchain technology greatly enhances supply chain transparency and traceability, prompting all stakeholders to take a more active and responsible role in reducing emissions. This effect has been demonstrated in cases like Walmart's collaboration with IBM on agricultural product traceability, which not only improves supply chain efficiency but also indirectly reduces carbon emissions by minimising food waste. In contrast, in the manufacturing segment, the primary benefit of blockchain technology lies in reducing carbon transaction costs rather than directly fostering innovation in emission-reduction technologies. For instance, the BMW Group has utilised blockchain to track cobalt sourcing to ensure ethical practices. However, in terms of direct emissions reduction, blockchain's role is mainly in optimising transaction costs rather than driving technological advancements. This phenomenon suggests that when under pressure to reduce carbon emissions, manufacturers often prefer to rely on the carbon trading market to purchase allowances for compliance rather than actively pursuing emission reduction initiatives. As a result, introducing blockchain technology may significantly impact overall supply chain emissions reduction only when carbon transaction costs reach a substantially high level, and blockchain's role in reducing these costs is limited.

Strategies for introducing blockchain technology in supply chains are intricately linked to implementation costs and carbon quotas' availability. Four distinct equilibrium strategies emerge as these factors fluctuate. When the cost of introducing blockchain technology is low, and carbon quotas are scarce, manufacturers and retailers are incentivised to adopt the technology. This enhances overall supply chain efficiency and promotes significant emission reductions. If blockchain introduction costs remain low but carbon allowances are plentiful, retailers are likelier to adopt the technology. They are directly impacted by consumer pressure and regulatory requirements, making blockchain adoption more critical for them. In scenarios where blockchain costs are high and carbon quotas are limited, manufacturers may implement blockchain technology to mitigate the high carbon transaction costs associated with insufficient emission reductions. Conversely, neither manufacturers nor retailers will likely adopt the technology when blockchain introduction costs and carbon quotas are high.

These scenarios suggest that promoting and applying blockchain technology in supply chains is not solely a technical challenge but rather a complex decision-making process influenced by market structure, policy environment, and economic considerations. The broader market environment, consumer behaviour, and regulatory landscape also play a crucial role in shaping these decisions. For example, IKEA's initiative to introduce blockchain technology for enhanced product traceability aligns with consumer demand for low-carbon and sustainable practices. When blockchain introduction costs and carbon allowances fall within certain thresholds, manufacturers and retailers may simultaneously adopt or reject the technology, indicating a potential binary equilibrium. Furthermore, consumer preference for low-carbon products is a strong driver for blockchain adoption, while high carbon trading costs and the difficulty of reducing emissions serve as deterrents. Therefore, enterprises must carefully evaluate blockchain introduction costs, the policy and market environment, and consumer demand to formulate an optimal strategy for adopting blockchain technology.

The following management insights are recommended: The government should actively encourage retailers to adopt blockchain technology to enhance supply chain emissions reduction. To facilitate this, the government can lower the cost of blockchain implementation and reduce carbon quotas by providing technical subsidies and increasing investment in technology. Retailers should focus on educating consumers about blockchain technology, emphasising its decentralised and trustless features. This will help increase consumer preference for low-carbon products and amplify the impact of blockchain technology on emissions reduction and enterprise profitability. Carbon transaction costs significantly influence manufacturers' decisions regarding emission reduction and blockchain adoption. Therefore, manufacturers, research institutions, and related entities should work on improving the operational efficiency of blockchain-based carbon trading. This can be achieved by designing more user-friendly and effective intelligent contracts to reduce transaction costs.

5.2. Future directions

This paper focuses on a secondary supply chain involving a single manufacturer and retailer. However, real-world supply chains often include multiple manufacturers, retailers, and additional layers of suppliers. Future research should extend the analysis to multi-layered supply chains involving various stakeholders. This can be achieved by selecting representative enterprises or industries for case studies and validating the theoretical model through field research and data analysis. Moreover, consumer behaviour and market structures are undergoing significant transformations as product technology continues to evolve – particularly with the shift from traditional high-carbon products to low-carbon or even carbon-free alternatives [45]. In a market where low-carbon products coexist with conventional ones, consumer green trust becomes a critical factor influencing emission reduction decisions [46]. Future research should develop theoretical models that incorporate variables such as consumer green trust, enterprise emission reduction inputs, and the application level of blockchain technology.

Researchers can reveal the underlying connections and mechanisms through empirical analysis by examining these variables in scenarios where low-carbon and conventional products coexist.

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