

Strategic Research on Block Chain-Embedded Low-Carbon Closed-Loop Supply Chain

Mao Luo*

College of Business Administration, Guizhou University of Finance and Economics, Guiyang, China

Received: July 14, 2025

Revised: July 18, 2025

Accepted: July 31, 2025

Published online: August 6, 2025

To appear in: *International Journal of Advanced AI Applications*, Vol. 1, No. 5 (September 2025)

* Corresponding Author:
Mao Luo
(luo@mail.gufe.edu.cn)

Abstract. Given the increasing low-carbon awareness among consumers, this study develops a differential game model involving a manufacturer, a retailer, and a blockchain technology service provider to explore low-carbon Closed-Loop Supply Chain (CLSC). By comparing two scenarios in which manufacturers either adopt or refrain from adopting blockchain technology, we examine how its integration influences decision-making, performance, and low-carbon outcome across the supply chain. Analysis and Numerical simulations validate the findings and reveal key insights are as follows: (1) Product pricing, market demand, low-carbon promotional effort, return rate, and overall low-carbon performance are positively correlated with market scale and increase proportionately with consumer environmental consciousness, irrespective of blockchain adoption. (2) Increasing consumer environmental awareness and blockchain service commission rate are found to significantly enhance product pricing, market demand, investment in low-carbon effort, recycling efficiency, overall sustainability level, and the profitability of supply chain members. (3) The low-carbon level exhibits an increasing trend over time and eventually converges to a steady state. (4) As the discount rate increases, firms' incentives for low-carbon investment decline, leading to lower profits. (5) The impact of the low-carbon decay coefficient on profit shows a rise-then-fall pattern, with profits initially increasing and then decreasing, while the rate of decline becomes more gradual at higher decay levels. Through full life-cycle carbon emission monitoring, blockchain technology enhances consumer surplus and can accelerate the achievement of the "dual-carbon" goals. This study provides theoretical support for the application conditions of block chain technology, the dynamic optimization pathways, and policy design within CLSC, thereby contributing to enterprises' low-carbon transitions and the development of circular resource systems.

Keywords: blockchain, low-carbon emission reduction, closed-loop chain, differential game.

1. Introduction

The global electronic waste (e-waste) crisis is exacerbating environmental degradation at an alarming rate. According to the United Nations' Global E-waste Monitor 2024 report, the total volume of e-waste reached 62 million metric tons in 2022, with less than 24% of materials being properly recycled. The remaining 76% entered the environment through landfilling, incineration, or illegal disposal channels, resulting in annual contamination of soil and water resources with approximately 50 million metric tons of heavy metals and hazardous substances (e.g., lead, mercury). If current trends persist, global e-waste generation is projected to exceed 74.7 million metric tons by 2030. Numerous studies and corporate practices demonstrate that recycling and remanufacturing can substantially reduce resource consumption and emissions. Closed-loop recovery can achieve 50% costs savings, 60% energy consumption reduction, 70% raw material conservation, and 80% pollutant emission reduction compared to conventional production methods [1]. In renewable energy equipment sectors, ONE WIND NEW ENERGY Co., Ltd. annually recycles over 500 wind turbines, conserving 3,000 tons of steel and 400 tons of copper while reducing CO₂ emissions by over 1 million metric tons. This initiative concurrently generates 1.8 billion kWh of renewable electricity.

The literature relevant to this study includes three domains: recycling/remanufacturing, low-carbon emissions reduction, and blockchain technology. Currently, recycling and remanufacturing have emerged as a critical research field in modern manufacturing, focusing on costs reduction and dual economic-environmental benefits through circular utilization of end-of-life products. Existing studies predominantly concentrated on recycling channel and incentive mechanism [2-3].

Low-carbon field have become central to global climate change, with extensive scholarly investigations into factors influencing emission reduction in supply chain, including consumer' low-carbon preference, supply chain members' fairness/altruism, and policy interventions. Zhang et al. [4] examined how consumer low-carbon awareness and altruistic preferences impact supply chain dynamics, revealing that members' altruistic behaviors significantly affect carbon reduction investment and recycling performance. Similarly, Gao et al. [5] incorporated consumer low-carbon preferences into their analysis of decision-making patterns among low-carbon supply chain members under varying governmental incentive polices. Li et al. [6] investigated fairness concern between the manufacturer and retailer in low-carbon supply chain, systematically analyzing the impacts of equity preferences on supply chain profitability, carbon reduction level, warranty periods, and revenue-sharing mechanisms. Luo et al. [7] explored the

manufacturer' strategic decisions regarding investments in low-carbon technologies under carbon tax policies, quantifying their cascading effects on conventional manufacturing and remanufacturing operations. Collectively, these studies highlight the critical role of integrating consumer behavioral patterns, policies, and supply chain collaborative mechanisms to enhance both recycling/remanufacturing efficiency and low-carbon outcomes. Such systemic integration facilitates the attainment of multidimensional benefits across economic, social, and environmental dimensions, thereby promoting comprehensive and sustainable value creation.

Blockchain technology is progressively being integrated into supply chain management, introducing transformative solutions and developmental paradigms. A growing number of literatures has explored its multifaceted applications and associated benefits. Chod et al. [8] demonstrated the financial advantages of blockchain-enhanced supply chain transparency, revealing that its adoption significantly reduces financing costs while improving operational efficiency. Ma et al. [9] further investigated blockchain implementation by the manufacturer or retailer in CLSC, identifying its capacity to strengthen brand goodwill, stimulate market demand, and achieve triple sustainability across economy, environment, and society. Jia et al. [10] examined blockchain applications in retired power battery CLSC by constructing decision models under three scenarios: non-blockchain adoption, manufacturer-led costs assumption, and costs-sharing between the manufacturer and distributor. Their analysis quantified blockchain's impacts on information traceability, supply chain member profitability, consumer surplus, environmental footprint, and social welfare. Zhang et al. [11] analyzed quality disclosure strategies in dual-channel supply chain applying price signaling and blockchain technology. They found that while blockchain enhances information transparency and demand, the high-quality manufacturer may not benefit proportionally in the market due to significant channel dominance disparities.

These studies collectively have underlined blockchain's transformative potentials in supply chain management. Its inherent characteristics—transparency, traceability, and decentralization—substantially improve informational visibility across supply networks, strengthen consumer trust, and advance corporate sustainability strategies. By establishing trusted data-sharing platforms, blockchain technology effectively mitigates information asymmetry while incentivizing collaborative low-carbon production and green operations among supply chain members, thereby achieving dual economic-environmental outcomes. The manufacturer can leverage blockchain to implement real-time data tracking and closed-loop management across procurement, production, logistics, and recycling processes. This end-to-

end traceability ensures verifiable operational data, optimizes resource efficiency, and reduces carbon emissions. Notable implementations include: Dell partnered with AntChain (a blockchain service provider) to enhance recycled metal utilization rates, reducing e-waste by over 10,000 metric tons; Volvo collaborated with Circular to trace cobalt and lithium sources in EV batteries, ensuring conflict-free mineral sourcing and compliance with low-carbon standards, thereby improving supply chain emission transparency and return rates.

In summary, the concurrent integration of recycling/remanufacturing and low-carbon emission reduction represents a practical norm in CLSC. However, existing literatures predominantly focus on either return channel or low-carbon reduction investment, with limited attention to the simultaneous optimization of recycling rate decisions and low-carbon reduction strategies. In practice, these two decision-making domains—return rate determination and low-carbon reduction initiatives—often coexist in an interdependent relationship, mutually influencing and constraining one another. Therefore, this study innovatively conceptualizes low-carbon level as dynamic variable and investigates their evolution within a dynamic CLSC framework.

Furthermore, while blockchain technology has garnered increasing attention in CLSC application, few studies have systematically analyzed its dynamic impacts on CLSC operations from a longitudinal perspective. Jia et al. employed a static game-theoretic model to examine blockchain's effects on information traceability and profitability, without accounting for the temporal decay of low-carbon levels. In contrast, this study treated the low-carbon level as a dynamic state variable within a differential game framework to capture the accumulation and attenuation of carbon-reduction benefits and enable a more nuanced analysis of low-carbon investment efficacy evolution. Although Ma et al. examined the effects of the platform-based “blockchain - sales model” combination on platform and member' performances but did not investigate the mechanisms by which consumer low-carbon awareness influences pricing, demand, and profitability. Although the study integrated blockchain into CLSC and analyze its dynamic impact on brand reputation, they neither addressed carbon-reduction issues nor elucidated blockchain's dynamic role in affecting carbon-reduction levels. To bridge these gaps, this paper explicitly incorporates a consumer low-carbon awareness parameter into a dynamic model, quantifying its effects on market demand elasticity, the marginal benefits of low-carbon promotion efforts, and overall supply-chain performance, thereby providing a comprehensive theoretical foundation for stimulating end-consumer green purchases and optimizing coordinated carbon-reduction strategies.

Consequently, this study will address the following research questions: (1) What constitutes the equilibrium decisions of supply chain members in a CLSC system? (2) Under what conditions should manufacturers implement blockchain technology? (3) How does blockchain adoption influence the operation, performance and consumer in CLSC? (4) How does low-carbon level evolve under different operational scenarios? (5) What role does consumers' low-carbon awareness play in shaping CLSC dynamics?

2. Model Description and Assumption

2.1. Model description

This study examines continuous-time dynamics for $t \in [0, \infty]$. Dynamic CLSC system comprising a manufacturer (M), retailer (R), and blockchain technology provider (T), under the premise of consumer low-carbon awareness. The manufacturer can produce and wholesale new products, decide whether to adopt third-party blockchain services, and delegate product recycling operations to the retailer. The retailer engages in product retailing, recycling activities, and invests in dual efforts: low-carbon promotion initiatives and recycling optimization. Should the manufacturer implements blockchain technology, the Blockchain service provider (T) will concurrently allocate technical efforts to support CLSC system integration.

Table 1. Notions for the model

Notion	Meaning
Decision variables	
$w(t)$	Whale price
$p(t)$	Retail price
$r(t)$	Low-carbon promotion efforts
$\tau(t)$	Return rate
$L(t)$	Block chain technology
Stata variable	
$e(t)$	Low carbon level
Parameters	
Q	Demand
a	Market size
β	Consumer's sensitivity coefficient towards price $\beta > 0$
η	Consumers' preference for low-carbon levels $\eta > 0$
Δ	The marginal profit of the manufacturer from recycling and remanufacturing products $\Delta > 0$
A	Marginal profit of retailers in recycling products $A > 0$
f_m	The residual value per unit of remanufactured products derived from used materials.

Notion	Meaning
f_c	The unit transfer payment price paid by the manufacturer to the retailer for acquiring used products.
f_r	The unit recycling costs for used products.
κ	The commission rate paid by the manufacturer to the third-party service provider $\kappa > 0$.
k_r	The costs coefficient for the promotion efforts of low-carbon initiatives $k_r > 0$.
k_e	Costs coefficient of effort invested in recycling $k_e > 0$.
k_i	The costs coefficient of blockchain technology's efforts to be invested $k_i > 0$.
ς	The influence coefficient of the low-carbon publicity efforts on the low-carbon level $\varsigma > 0$.
v	The influence coefficient of blockchain technology on the level of low carbon emissions $v > 0$.
δ	The attenuation coefficient of the low-carbon level over time $\delta > 0$.
ρ	Discount rate $\rho > 0$.
π_M^i	Manufacturer's profit.
π_R^i	Retailer's profit.
π_T	The profits of the technical service providers.
CS^i	Consumer's surplus.
i	$i \in \{N, Y\}$, N indicates without blockchain technology, Y indicates the situation with embedded blockchain technology.

2.2. Model description

Assumption 1. Considering consumers' low-carbon consciousness, their purchasing behavior is influenced not only by price but also by the product's low-carbon level. Consequently, the linear market demand function as:

$$Q = (a - \beta p(t)) + \eta e(t). \quad (1)$$

Assumption 2: The manufacturer's profit originates from product wholesaling and remanufacturing of used products. To highlight the research focus and reduce model complexity, production costs are assumed to be zero, and new and remanufactured products are homogeneous. This assumption, adopted by Shen et al. [12] has been demonstrated to have no material impact on key findings. The manufacturer's unit profit from remanufacturing is denoted as $\Delta = f_m - f_c$. The retailer's profit stems from product sales. The profit per unit of new products is $p(t) - w(t)$, while the profit per unit of recycled products is $A = f_c - f_r$.

The blockchain technology service provider generates revenue primarily through technical services offered to the manufacturer, quantified as $\kappa L(t)$.

Assumption 3: Drawing on the convexity assumptions for general costs in literature[9], the

retailer invests in low-carbon promotion efforts to enhance consumer trust, raise low-carbon awareness, and market sustainable products. The associated costs is modeled as $\frac{1}{2}k_r r^2(t)$. Additionally, the retailer expends recycling efforts to acquire used products, incurring a costs of $\frac{1}{2}k_c \tau^2(t)$. The manufacturer may collaborate with a blockchain technology provider to improve supply chain transparency and traceability, ensuring full lifecycle compliance with low-carbon standards, optimizing production and recycling processes, and further reducing carbon emissions. The blockchain service costs is formulated as $\frac{1}{2}k_l L^2(t)$. All costs functions adhere to the rule of diminishing marginal returns.

Assumption 4: The low-carbon level $e(t)$ is positively correlated with low-carbon promotion efforts and blockchain technology efforts. Its temporal evolution is governed by the differential equation:

$$\dot{e}(t) = \varsigma r(t) + \nu L(t) - \delta e(t), e(0) = 0 \quad (2)$$

When $L(t) = 0$, indicates Without blockchain in CLSC.

Assumption 5: Over the continuous time $t \in [0, \infty]$, the manufacturer, retailer, and blockchain service provider share an identical discount factor. All supply chain members are risk-neutral, operate under symmetric information, and maximize their individual profits.

Assumption 6: Referencing relevant literature[13], and to ensure the practical significance of the study, the following constraints must be satisfied under non-negativity conditions for market demand, profit, state variable, and decision variables:

$$\beta > \frac{\eta^2 \varsigma^2 (2\delta + \rho)}{4\delta(\delta + \rho)^2 k_r}, k_c > \text{Max}\left\{\frac{A\beta^2 (A + 2\Delta)(\delta + \rho)^2 k_r}{2\beta(\delta + \rho)^2 k_r - \eta^2 \varsigma^2}, \frac{2A\beta^2 (A + \Delta)(\delta + \rho)^2 k_r}{3\beta(\delta + \rho)^2 k_r - \eta^2 \varsigma^2}, \frac{1}{2}A\left(A\beta + 2\beta\Delta + \frac{\eta\varsigma}{\delta + \rho}\right)\right\}.$$

These imply that consumer price sensitivity necessitates non-trivial recycling effort costs to sustain CLSC operations. Subsequent analyses are conducted under these constraints.

3. Model development and analysis

3.1 Model development

Based on the above assumptions, this study investigates the impact of blockchain technology adoption by the manufacturer on the decision-making and performance of members within a CLSC. Two models are developed under different scenarios: (1) the scenario without blockchain technology, denoted as the N-mode; and (2) the scenario with blockchain

technology adoption, denoted as the Y mode. Superscripts are used to indicate the scenario, while subscripts M, R, and T represent the manufacturer, retailer, and blockchain technology service provider, respectively.

The profit functions of the supply chain members are defined as:

$$\max_{w(t)} \pi_M^i = \int_0^\infty e^{-\rho t} ((w(t) + \Delta\tau(t))Q - \kappa L(t)) dt \quad (3)$$

$$\max_{p(t), \tau(t), r(t)} \pi_R^i = \int_0^t e^{-\rho t} \left(Q(A\tau(t) + p(t) - w(t)) - \frac{k_c \tau^2(t)}{2} - \frac{k_r r^2(t)}{2} \right) dt \quad (4)$$

$$\max_{L(t)} \pi_T^i = \int_0^\infty e^{-\rho t} (\kappa L(t) - \frac{k_l L^2(t)}{2}) dt \quad (5)$$

$$s.t \dot{e}(t) = \varsigma r(t) + vL(t) - \delta e(t), e(0) = 0. \quad (6)$$

When $L(t)=0$, it represents the scenario without blockchain technology.

The corresponding Hamilton functions as

$$H_M^N = \int_0^\infty e^{-\rho t} ((w(t) + \Delta\tau(t))Q + \lambda_1(t)(\varsigma r(t) - \delta e(t))) dt \quad (6)$$

$$H_R^N = \int_0^\infty e^{-\rho t} \left(\left(Q(A\tau(t) + p(t) - w(t)) - \frac{k_c \tau^2(t)}{2} - \frac{k_r r^2(t)}{2} \right) + \lambda_2(t)(\varsigma r(t) - \delta e(t)) \right) dt \quad (7)$$

$$H_M^Y = \int_0^\infty e^{-\rho t} \left(\int_0^\infty ((w(t) + \Delta\tau(t))Q - \kappa L(t)) + \lambda_3(t)(\varsigma r(t) + vL(t) - \delta e(t)) \right) dt \quad (8)$$

$$H_R^Y = \int_0^\infty e^{-\rho t} \left(\int_0^t \left(Q(A\tau(t) + p(t) - w(t)) - \frac{k_c \tau^2(t)}{2} - \frac{k_r r^2(t)}{2} \right) + \lambda_4(t)(\varsigma r(t) + vL(t) - \delta e(t)) \right) dt \quad (9)$$

$$H_T = \int_0^\infty e^{-\rho t} \left((\kappa L(t) - \frac{k_l L^2(t)}{2}) + \lambda_5(t)(\varsigma r(t) + vL(t) - \delta e(t)) \right) dt. \quad (10)$$

Where $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$ denote the adjoint variables, representing the shadow prices associated with the state variable $e(t)$.

Propositions: Assuming all supply chain members are rational, the equilibrium outcomes under the steady state of the CLSC system ($t \rightarrow \infty$) are shown in the table below.

Table 2. Variables and performance of supply chain

Decision variables and performance	Without blockchain N Model	With blockchain Y Model
Wholesale price	$w_\infty^N(t) = \frac{a\delta k_r B_1}{\beta\delta k_r B_0 + \eta^2 \varsigma^2 k_c}$	$w_\infty^Y(t) = \frac{(D_1(A\beta(A+2\Delta)-2k_c) + D_2 k_c)}{\beta k_i(2\beta\delta D_0 + \eta^2 \varsigma^2(2\delta + \rho)k_c)}$
Retail price	$p_\infty^N(t) = \frac{a\delta k_r B_2}{\beta\delta k_r B_0 + \eta^2 \varsigma^2 k_c}$	$p_\infty^Y(t) = \frac{(D_1(2A\beta(A+\Delta)-3k_c) + D_2 k_c)}{\beta k_i(2\beta\delta D_0 + \eta^2 \varsigma^2(2\delta + \rho)k_c)}$
Low-carbon promotion efforts	$r_\infty^N(t) = \frac{-a\delta\eta\varsigma k_c}{\beta\delta k_r B_0 + \eta^2 \varsigma^2 k_c}$	$r_\infty^Y(t) = \frac{-\eta\varsigma(\delta + \rho)k_c(a\delta k_i + \eta\kappa v)}{k_i(2\beta\delta D_0 + \eta^2 \varsigma^2(2\delta + \rho)k_c)}$

Decision variables and performance	Without blockchain N Model	With blockchain Y Model
Return rate	$\tau_{\infty}^N(t) = \frac{-aA\beta\delta(\delta+\rho)k_r}{\beta\delta k_r B_0 + \eta^2 \zeta^2 k_c}$	$\tau_{\infty}^Y(t) = \frac{-AD_1}{k_l(2\beta\delta D_0 + \eta^2 \zeta^2 (2\delta + \rho)k_c)}$
Low-carbon level	$e_{\infty}^N(t) = -\frac{a\eta\zeta^2 k_c}{\beta\delta k_r B_0 + \eta^2 \zeta^2 k_c}$	$e_{\infty}^Y(t) = \frac{k_c \eta \zeta^2 (a(\delta + \rho)k_l - \eta\kappa\nu) - 2\kappa\nu D_0}{-k_l(2\beta\delta D_0 + \eta^2 \zeta^2 (2\delta + \rho)k_c)}$
Profits	$\pi_M^N = \frac{-a^2 \beta \delta^2 (\delta + \rho) k_c k_r B_1}{(\beta\delta k_r B_0 + \eta^2 \zeta^2 k_c)^2}$ $\pi_R^N = \frac{a^2 \delta^2 k_c k_r B_3}{2(\beta\delta k_r B_0 + \eta^2 \zeta^2 k_c)^2}$	$\pi_M^Y = \frac{-k_c((a\delta k_l + \eta\kappa\nu)D_0 D_1 + D_2(\delta + \rho)^2 k_r k_c)}{k_l^2(2\beta\delta D_0 + \eta^2 \zeta^2 (2\delta + \rho)k_c)^2} - \frac{\kappa^2}{k_l}$, $\pi_R^Y = \frac{-k_c D_1(D_1(A^2\beta - 2k_c) + D_2 k_c)}{2k_l^2 \beta(2\beta\delta D_0 + \eta^2 \zeta^2 (2\delta + \rho)k_c)^2}$, $\pi_r^Y = \frac{\kappa^2}{2k_l}$
Consumer's surplus	$CS^N = \frac{a^2 \beta \delta^2 (\delta + \rho)^2 k_c^2 k_r^2}{2(\beta\delta k_r B_0 + \eta^2 \zeta^2 k_c)^2}$	$CS^Y = \frac{k_c^2 D_1^2}{2k_l^2 \beta(2\beta\delta D_0 + \eta^2 \zeta^2 (2\delta + \rho)k_c)^2}$
Demand	$Q^N = \frac{-a\beta\delta(\delta + \rho)k_r k_c}{\beta\delta k_r B_0 + \eta^2 \zeta^2 k_c}$	$Q^Y = \frac{-k_c D_1}{k_l 2\beta\delta D_0 + \eta^2 \zeta^2 (2\delta + \rho)k_c}$

To streamline the complexity of the formulas, we consolidate the common components of the expressions into the following parameters. Where, $D_0 = (\delta + \rho)^2 k_r (A\beta(A + \Delta) - 2k_c)$,

$$D_1 = (a\delta k_l + \eta\kappa\nu)\beta(\delta + \rho)^2 k_r, \quad D_2 = (a\delta k_l + \eta\kappa\nu)\eta^2 \zeta^2, \quad D_3 = (\delta + \rho)^2 k_r^2 (2\beta(A + \Delta)(\delta + \rho) + \eta\zeta),$$

$$D_4 = \eta^2 \zeta^2 (-\beta(\delta + \rho)(3A\delta + A\rho + 4\delta\Delta + 2\Delta\rho) - \delta\eta\zeta) + 2\beta\delta(\delta + \rho)^2 k_r (2\beta(2A + 3\Delta)(\delta + \rho) + \eta\zeta), \quad D_5 = 2\beta(\delta + \rho)k_r (\eta^2 \zeta^2 (3\delta + \rho) - 4\beta\delta(\delta + \rho)^2 k_r) - \eta^4 \zeta^4,$$

$$D_6 = \eta^2 \zeta^2 (-2\beta(A + \Delta)(\delta + \rho)(2\delta + \rho) - \delta\eta\zeta) + \beta\delta(\delta + \rho)^2 k_r (14\beta(A + \Delta)(\delta + \rho) + 3\eta\zeta), \quad D_7 = \beta(\delta + \rho)k_r (\eta^2 \zeta^2 (7\delta + 3\rho) - 12\beta\delta(\delta + \rho)^2 k_r) - \eta^4 \zeta^4,$$

$$D_8 = \beta\eta\zeta(\delta + \rho)k_c k_r (A(A\beta\delta - \eta\zeta) - 2\delta k_c) + \eta^3 \zeta^3 k_c^2, \quad D_9 = \eta^2 \zeta^2 (-2\beta(A + \Delta)(\delta + \rho)(2\delta + \rho) - \delta\eta\zeta) + 4\beta\delta(\delta + \rho)^2 k_r (4\beta(A + \Delta)(\delta + \rho) + \eta\zeta),$$

$$D_{10} = 4\beta(\delta + \rho)k_r (\eta^2 \zeta^2 (2\delta + \rho) - 4\beta\delta(\delta + \rho)^2 k_r) - \eta^4 \zeta^4.$$

The aforementioned results can be derived by employing methods from differential game theory, optimal control theory, and backward induction. According to the retailer's Hamiltonian

function, the Hessian matrix can be obtained as $\begin{pmatrix} -k_c & -A\beta & 0 \\ -A\beta & -2\beta & 0 \\ 0 & 0 & -k_r \end{pmatrix}$, with the first-order condition

being less than zero, the second-order condition being greater than zero, and the third-order condition being less than zero (as assumption 6). The Hessian matrix is negative definite, and the objective profit functional is a concave function of the decision variables. Equation of the retailer can reach a maximum value with respect to the decision variables. According to the

first-order condition of maximizing the present value Hamiltonian function, $\frac{\partial H_r^N}{\partial p} = 0$, $\frac{\partial H_r^N}{\partial \tau} = 0$,

$$\frac{\partial H_r^N}{\partial r} = 0, \text{ the values of and can be obtained that } a + \beta(w - A\tau - 2p) + e\eta = 0, \lambda_2 \zeta - rk_r = 0, \frac{A(a + e\eta - \beta p) - \tau k_c}{\lambda_2 \zeta - rk_r} = 0,$$

according to the state equation, $\dot{\lambda}_2(t) = \rho\lambda_2(t) - \frac{\partial H_r^N}{\partial e}$, by the transversality condition

$\lim_{t \rightarrow \infty} \lambda_2(t) e^{-\rho t} = 0$ the decision variables of the supply chain members are of finite value, hence

can be obtained $C_1 = 0$; solving the differential equation can yield the shadow price of the state variables: $\lambda_2(t) = \frac{\eta(A\tau + p - w)}{\delta + \rho}$. Substituting the values of into the first-order conditions of

equation of H_R^N , solving the system of equations can yield: $p(t) = \frac{A^2\beta(a + e\eta) - k_c(a + e\eta + \beta w)}{\beta(A^2\beta - 2k_c)}$,

$\tau(t) = \frac{A(a + e\eta - \beta w)}{2k_c - A^2\beta}$, $r(t) = -\frac{\eta\zeta k_c(a + e\eta - \beta w)}{\beta(\delta + \rho)k_c(A^2\beta - 2k_c)}$ and then substituting it into the manufacture's

Hamiltonian function, the manufacturer's reaction function can be obtained. The second derivative of the reaction function is $\frac{2\beta k_c(A\beta(A + \Delta) - 2k_c)}{(A^2\beta - 2k_c)^2}$, which is less than zero, and the equation

can reach a maximum value with respect to the decision variables. According to the first-order condition of maximizing the present value Hamiltonian function: $\frac{\partial H_M^N}{\partial w} = 0$, there is

$\frac{A\beta k_c(-a(A + 2\Delta) - e\eta(A + 2\Delta) + 2\beta w(A + \Delta) - 2\lambda_1\zeta) + 2k_c^2(a + e\eta - 2\beta w) + A^3\beta^2\lambda_1\zeta}{(A^2\beta - 2k_c)^2}$; the sate equation is: $\lambda_1(t) = \rho\lambda_1(t) - \frac{\partial H_M^N}{\partial e}$, by

the transversality condition, $\lim_{t \rightarrow \infty} \lambda_1(t) e^{-\rho t} = 0$, the decision variables of the supply chain members

are of finite value, hence can be obtained $C_2 = 0$; solving the differential equation can obtained

$\lambda_1(t) = \frac{\eta k_c(A(A\beta w - 2\Delta(a + e\eta - \beta w)) - 2w k_c) + (A^2\beta - 2k_c)(A(A\beta(\delta + \rho) + \eta\zeta) - 2(\delta + \rho)k_c)}{(A^2\beta - 2k_c)^2}$. Substituting the values of $\lambda_1(t)$ into the first-

order conditions, and then solving the equation can yield the $w^N(t)$. Substituting it into $p(t), \tau(t), r(t)$, can yield the retail price $p^N(t)$, the recycling rate $\tau^N(t)$, and the efforts of low-carbon publicity $r^N(t)$. Substituting $r^N(t)$ into state variable equation, and then solving the differential equation, can yield e^N . Substituting e^N into $w^N(t), r^N(t), p^N(t), \tau^N(t)$ can yield the steady-state decision solution of Corollary 2. Substituting the steady-state solution into the demand and profit functions can yield the optimal demand and profit, and then substituting into $CS = \int_{p^{\min}}^{p^{\max}} Q dp$ can calculate the consumer surplus.

The proof *Proposition* without blockchain process of Corollary 2 is the same as that of Corollary 1, using the backward solution method. When there is a blockchain technology service provider, first solve the decision variables, substitute them into the retailer's Hamiltonian function, then solve the retailer's decision variables, and finally obtain the manufacturer's decision variables.

3.2 Analysis

3.2.1 Comparative analysis

Corollary1: if $\eta > \max\{\eta_1, \eta_2\}$: when $a > \max\{a_1, a_2\}$, $w_\infty^N > w_\infty^Y$, $p_\infty^N > p_\infty^Y$; when $a < \min\{a_1, a_2\}$,

$$w_\infty^N < w_\infty^Y \quad , \quad p_\infty^N < p_\infty^Y \quad . \quad \text{Among} \quad \eta_1 = \frac{A\eta^2\zeta}{A^2\beta\delta - 2\delta k_c} + \frac{\eta^3\zeta^2 k_c}{\beta\delta(\delta + \rho)k_r(2k_c - A^2\beta)} + \eta_3 \quad ,$$

$$\eta_2 = \frac{A(\beta\delta(\delta + \rho)k_r - \eta^2\zeta^2)}{\delta\zeta k_c} + \frac{\eta^3\zeta^3}{\beta\delta\zeta(\delta + \rho)k_r} \quad , \quad a_1 = \frac{\kappa\nu(A\beta k_c k_r D_4 + k_c^2 D_5 - A^2\beta^3\delta(A + 2\Delta)D_3)}{\delta\zeta k_i(A\beta^3\delta(\delta + \rho)^2 k_r^2(2k_c - A^2\beta) + D_8)} \quad ,$$

$$a_2 = \frac{\kappa\nu(A\beta k_c k_r D_6 + k_c^2 D_7 - 2A^2\beta^3\delta(A + \Delta)D_3)}{\delta\zeta k_c k_i(\eta^2\zeta^2 - \beta\delta(\delta + \rho)k_r)(\eta\zeta k_c - A\beta(\delta + \rho)k_r)} \quad .$$

When consumers' low-carbon awareness is strong ($\eta > \max\{\eta_1, \eta_2\}$) and the market size is sufficiently large ($a > \max\{a_1, a_2\}$), the product price under blockchain adoption becomes lower than that without blockchain integration. In such scenario, the manufacturer and retailer strategically reduce price to attract environmentally conscious consumers, thereby capturing higher market share and profit. This indicates that blockchain adoption grants manufacturer greater pricing flexibility to leverage consumers' sustainability preferences. Conversely, in markets with relatively small size ($a < \min\{a_1, a_2\}$), blockchain implementation imposes additional operational costs (e.g., service fees, technology integration expenses) on the manufacturer. To offset the cost, the manufacturer is compelled to raise product whole price, which may reduce demand and offset potential sustainability gains.

3.2.2 Sensitive analysis

Corollary2: if $\eta > \eta_3$, when $a > \max\{a_3, a_4\}$, $e^N < e^Y$, $Q^N < Q^Y$, $\tau^N < \tau^Y$, $r^N < r^Y$. Among,

$$\eta_3 = \frac{A\beta\delta k_r + A\beta\rho k_r}{\zeta k_c} \quad , \quad a_3 = \frac{\kappa\nu(A\beta k_c k_r D_9 + k_c^2 D_{10} - 2A^2\beta^3\delta(A + \Delta)D_3)}{\delta\eta^2\zeta^3 k_c k_i^2(\eta\zeta k_c - A\beta(\delta + \rho)k_r)} \quad , \quad a_4 = \frac{\kappa\nu(\delta + \rho)(-\beta\delta k_r B_0 - \eta^2\zeta^2 k_c)}{\delta^2\zeta k_i^2(A\beta(\delta + \rho)k_r - \eta\zeta k_c)} \quad .$$

When consumers exhibit strong low-carbon awareness ($\eta > \eta_3$) and the market size is sufficiently large ($a > \max\{a_3, a_4\}$), the adoption of blockchain technology leads to higher low-carbon levels, increased retailer investments in low-carbon promotional efforts, improved recycling rate, and greater market demand compared to scenario without blockchain integration. Blockchain technology enhances low-carbon performance throughout the product lifecycle, fostering trust among environmentally conscious consumers and driving demand growth. This incentivizes the retailer to intensify their low-carbon promotional and recycling effort, thereby further elevating recycling efficiency and boosting both sales revenue and recycling profits.

$$\text{Corollary 3: } \frac{\partial w^i}{\partial \eta} > 0, \frac{\partial p^i}{\partial \eta} > 0, \frac{\partial r^i}{\partial \eta} > 0, \frac{\partial \tau^i}{\partial \eta} > 0, \frac{\partial e^i}{\partial \eta} > 0, \frac{\partial Q^i}{\partial \eta} > 0, \frac{\partial \pi_M^i}{\partial \eta} > 0, \frac{\partial \pi_R^i}{\partial \eta} > 0, \frac{\partial \pi_T^i}{\partial \eta} = 0.$$

Under both scenarios, the decision variables of the manufacturers and retailer, the state variable of the supply chain system, and market demand are positively correlated with consumer low-carbon awareness. As consumers' low-carbon awareness strengthens, market demand increases. The manufacturer, anticipating that consumers are willing to pay a premium for low-carbon products, raise wholesale price to secure profits, particularly when blockchain integration incurs additional operational costs. To align with consumers preferences, the retailer intensify low-carbon promotional efforts and adjust retail price, thereby elevating the low-carbon emission reduction level. Concurrently, heightened consumer low-carbon awareness amplifies market demand, incentivizing the retailer to enhance return rate to capture greater recycling revenues, which further drives improvements in recycling efficiency. The profits of both the manufacturer and retailer increase with heightened consumers' low-carbon awareness. As previously established, stronger consumers' low-carbon awareness drives higher market demand, enabling supply chain members to optimize pricing strategies (e.g., wholesale price, retail price) and capitalize on CLSC efficiencies, thereby achieving greater profitability. In contrast, the profits of the blockchain technology service provider depend solely on delivering technical solutions (e.g., the traceability system, data integrity protocols) to the manufacturer, with no direct linkage to consumer low-carbon awareness. Consequently, regardless of consumers' awareness of low-carbon living, it will not have no significant influence on the blockchain technology service provider.

$$\text{Corollary 4: } \frac{\partial w^y}{\partial \kappa} > 0, \frac{\partial p^y}{\partial \kappa} > 0, \frac{\partial r^y}{\partial \kappa} > 0, \frac{\partial \tau^y}{\partial \kappa} > 0, \frac{\partial L^y}{\partial \kappa} > 0, \frac{\partial e^y}{\partial \kappa} > 0, \frac{\partial Q^y}{\partial \kappa} > 0, \frac{\partial \pi_m^y}{\partial \kappa} > 0, \frac{\partial \pi_r^y}{\partial \kappa} > 0, \\ \frac{\partial \pi_t^y}{\partial \kappa} > 0.$$

Under the scenario with blockchain technology adoption, the decision variables, state variable of in supply chain, market demand, and profits are all positively correlated with the commission rate paid by the manufacturer to the blockchain service provider. An increase in incentivizes the blockchain service provider to enhance its technical efforts, thereby elevating the low-carbon level and strengthening environmentally conscious consumers' trust in product sustainability. This heightened trust drives an increase in market demand. The surge in demand motivates the retailer to intensify low-carbon promotional efforts, while recyclers amplify recycling efforts to capitalize on higher recycling revenues, leading to a corresponding rise in return rates.

Although blockchain adoption increases operational costs for both the manufacturer and retailer, these costs are offset through strategic price adjustments: the manufacturer raises the

wholesale price, and the retailer elevates the retail price, thereby maximizing their respective profits. Consequently, the profits of all supply chain members increase with higher commission rates. Counterintuitively, the manufacturer's profit does not diminish despite the increased commission payments to the third-party service provider.

$$\text{Corollary 5: } \frac{\partial w^y}{\partial k_i} < 0, \frac{\partial p^y}{\partial k_i} < 0, \frac{\partial r^y}{\partial k_i} < 0, \frac{\partial \tau^y}{\partial k_i} < 0, \frac{\partial L^y}{\partial k_i} < 0, \frac{\partial e^y}{\partial k_i} < 0, \frac{\partial Q^y}{\partial k_i} < 0, \frac{\partial \pi_m^y}{\partial k_i} < 0, \frac{\partial \pi_r^y}{\partial k_i} < 0,$$

$$\frac{\partial \pi_s^y}{\partial k_i} < 0.$$

When the blockchain technology costs coefficient is high, the revenue of the blockchain service provider decreases, resulting in lower profits and consequently diminished technological investment efforts. Which leads to a lower low-carbon level, as governed by the dynamic equation, and also weakens market demand, prompting the manufacturer and retailer to lower product prices to stimulate demand and sustain profitability.

However, consumers' strong low-carbon awareness implies that a decline in counteracts the demand-boosting effects of price reductions. Faced with shrinking profit margins, the retailer reduces investments in recycling efforts and low-carbon promotional efforts, further exacerbating the decline in and creating a negative feedback loop. The manufacturer, constrained by lower wholesale prices and reduced recycling efficiency, experience further profit erosion.

Proof of Corollary 1: By taking the difference of the decision variables and combining the constraint conditions of Assumption 6, the results can be obtained.

Proof of Corollary 2, 3, 4, and 5: By taking the derivative of the parameters and combining the constraint conditions of Assumption 6, the results can be obtained.

4 Numerical Simulation

Next, we will investigate and further validate the impacts of consumer' low-carbon awareness, blockchain commission rate, service costs coefficient, the attenuation coefficient of the low-carbon level over time and discount rate on supply chain members' profits under steady-state conditions of the dynamic control system across various scenarios. Additionally, we analyze the temporal evolution of the state variable and the effects of blockchain adoption on supply chain profitability and consumer surplus. This section employs numerical simulations for comparative analysis, with reference [10]. To ensure non-negativity of decision variables, the state variable, and demand, the parameter settings are specified as follows: $a = 5$, $A = 1$,

$\beta = 0.5$, $\eta = 0.8$, $\delta = 0.2$, $\Delta = 2$, $\kappa = 0.3$, $\rho = 0.2$, $v = 0.3$, $\varsigma = 0.2$, $k_c = 3$, $k_l = 2$, $k_r = 2$.

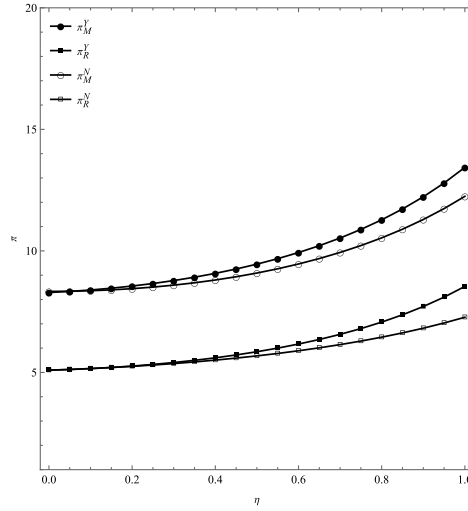


Figure 1. The effect of η on profit

Fig 1, the profit of supply chain members shown growth trend under blockchain adoption becomes more pronounced as consumer low-carbon awareness intensifies, with significantly higher profitability observed compared to scenario without blockchain integration. In both cases, the profits of the manufacturer and the retailer are consistently greater when blockchain technology is implemented. These findings align with the Corollaries 1,2,3, which posit that blockchain-driven transparency and traceability amplify consumer trust in low-carbon statements, thereby can enhance demand elasticity and enabling strategic price adjustments to capture sustainability premiums.

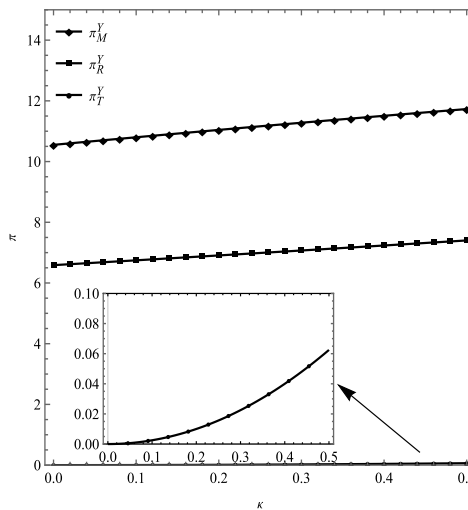


Figure 2. The effect of κ on profit

Fig. 2, it can be concluded that an increasing profits of the manufacturer, the retailer, and the blockchain technology service provider with the commission rate, and that a rising commission rate does not result in a reduction in the profits of manufacturers or the supply chain system. This finding is consistent with Corollary 4.

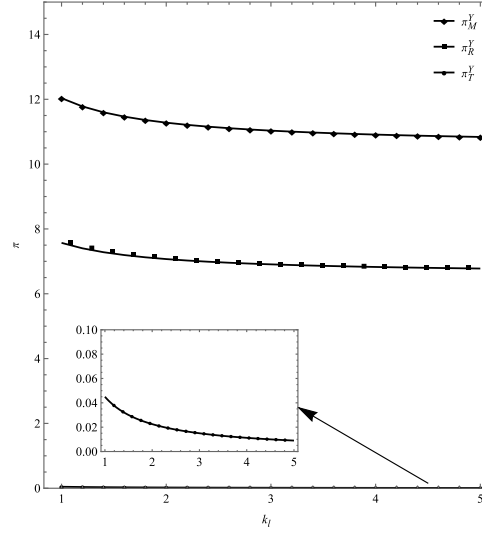


Figure 3. The effect of k_l and on profit

Fig. 3 indicates that as the costs coefficient for blockchain technology services increases, the profits of supply chain members decrease. This outcome is in line with Corollary 5.

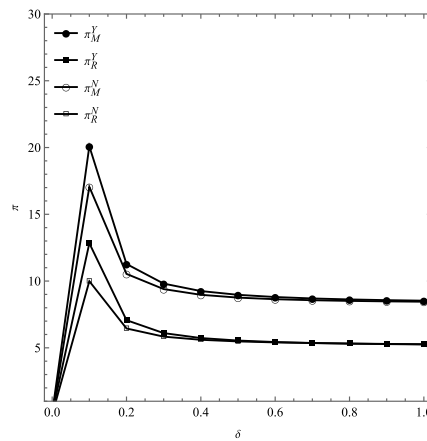


Figure 4. The effect of δ and on profit

Fig. 4 shows that when the decay coefficient of the low-carbon level increases, profits exhibit a hump-shaped response—rising at low decay rates but falling once the decay becomes sufficiently large. A small decay coefficient implies that once achieved, a higher low-carbon level is sustained for longer, allowing firms to capitalize on enhanced reputation and consumer willingness to pay; consequently, product prices can be raised, market demand remains robust, and investments in recycling and carbon-promotion efforts yield positive returns, driving profits

upward. However, as the decay coefficient grows, the persistence of any low-carbon improvements diminishes rapidly, eroding the benefits of upfront investments. Firms consequently scale back recycling efforts and carbon-reduction promotions, and to offset their shrinking future gains, they still raise prices—only to face a contraction in demand. The combined effect of weakened low-carbon persistence, reduced promotional and recycling activities, and suppressed consumer response ultimately leads to a drop in profits once the decay coefficient crosses a critical threshold.

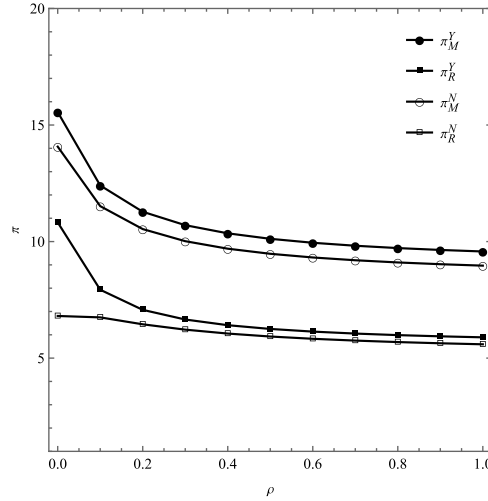


Figure 5. The effect of ρ and on profit

Fig. 5 illustrates that an increase in the discount rate reduces the profits of the supply chain members. The discount rate reflects the extent to which decision-makers value future returns. As the discount rate rises, the present value of future earnings declines, prompting firms to prioritize short-term gains while underestimating the benefits of long-term investments. Under these conditions, the manufacturer and the retailer tend to curtail efforts in low-carbon promotion and product recycling, resulting in lower recycling rates and diminished carbon-reduction initiatives. Meanwhile, to preserve short-term profitability or offset rising costs, they may opt to raise product prices. However, higher prices suppress consumer demand and lead to reduced overall sales. The combined effects of reduced low-carbon investment, contracting market demand, and weakened consumer response ultimately lower profit levels throughout the supply chain. Consequently, a higher discount rate not only erodes the incentive for firms to pursue low-carbon transformation but also impedes the attainment of sustainable development objectives within the supply chain.

Besides, from Figures 4 and 5, it can also be observed that comparing the scenarios with and without blockchain adoption, the manufacturer and the retailer achieve higher profits when

blockchain technology is implemented., the profits of the manufacturer and the retailer are consistently greater when blockchain technology is implemented.

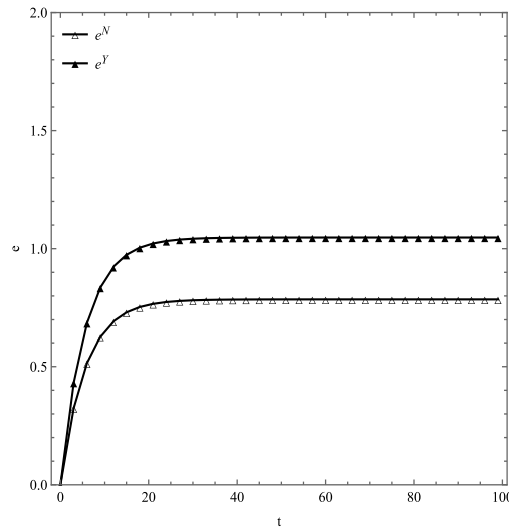


Figure 6. The trajectory of the change in low-carbon levels over time

Fig. 6 demonstrates that over time, the level of low-carbon emission reduction steadily improves, suggesting that the efforts of supply chain members coupled with technological advancements are driving the achievement of environmental protection goals. Moreover, the presence of blockchain technology yields a higher low-carbon level compared to scenario without blockchain. Thus, embedding blockchain technology not only facilitates the attainment of more ambitious low-carbon targets but also constitutes an important technological measure for realizing sustainable development and environmental protection.

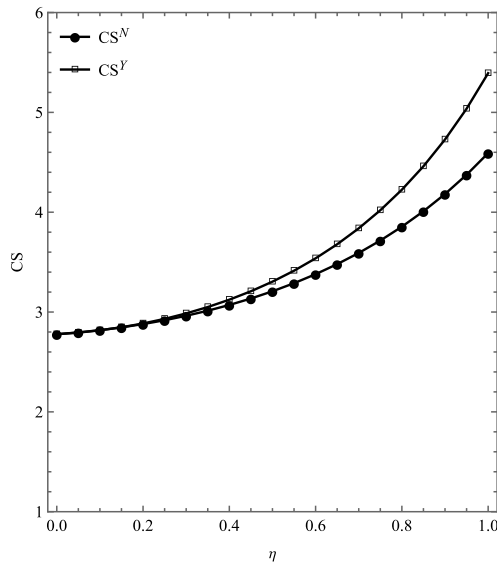


Figure 7. The effect of η on consumer' surplus

Fig. 7 reveals that as consumers' awareness of low-carbon issues increases, consumer surplus also rises, and it is higher when blockchain technology is applied. The low-carbon level increases over time and eventually stabilizes, resulting from increased investments by supply chain members and the willingness of low-carbon-conscious consumers to pay premium prices. Furthermore, the integration of blockchain technology effectively reduces the carbon footprint, thereby enhancing consumer surplus.

5 Conclusion

This study moves beyond the static research framework of forward supply chain by constructing a CLSC dynamic differential game model, thereby revealing the impact of the interaction between low-carbon awareness and market size on the profit transmission mechanism. In an innovative extension, blockchain technology is applied not only in brand goodwill management but also in full-cycle carbon footprint monitoring, leading to the development of a three-dimensional evaluation system based on “transparency-efficiency-emission reduction.” The research conclusions are as follows:

(1) When the market scale is large and consumers exhibit strong low-carbon awareness, blockchain technology can reduce product prices while enhancing low-carbon levels, consumer surplus, and recycling rates. The profits of supply chain members may increase by 15% to 25%, offering a quantifiable implementation pathway toward achieving the “dual-carbon” goals. The technological transparency triggers a “low-carbon premium” effect, accelerating the attainment of a stable low-carbon level in carbon footprint monitoring.

(2) In scenarios where the technology investment costs coefficient of the blockchain service provider is high and consumers have strong low-carbon awareness, reducing technological effort will result in decreased profits for supply chain members.

(3) The level of low-carbon operation rises over time and eventually stabilizes; additionally, when blockchain technology is integrated, the low-carbon level is higher.

(4) As the discount rate increases, the present value of future returns declines, weakening the incentive for firms to invest in low-carbon promotion and recycling. To sustain short-term profitability, companies tend to raise product prices, which in turn suppress market demand. The combined effect of reduced low-carbon investment and diminished demand ultimately leads to a decline in supply-chain member profits.

(5) The decay coefficient of the low-carbon level exhibits an inverted-U effect on profits. At low decay rates, carbon-reduction benefits are sustained over time, enhancing consumers'

willingness to pay premiums and improving recycling efficiency, which drives profit growth. As the decay coefficient increases, however, these benefits dissipate more rapidly, prompting firms to cut back on related investments and raise prices to offset losses—thereby contracting demand and recycling rates, and causing profits to fall. Notably, although profits continue to decrease at higher decay rates, the rate of decline diminishes as the decay coefficient becomes very large.

Overall, under the dual-carbon framework, the manufacturer should comprehensively evaluate the cost-effectiveness of blockchain technology and the level of consumer low-carbon awareness when deciding whether to implement blockchain-enabled full-cycle management. This integrated strategy can effectively balance technological innovation with cost control, thereby facilitating the green and low-carbon transformation of the supply chain and supporting the achievement of dual-carbon objectives. Based on the findings of this study, a key managerial implication is that the retailer should share a portion of the blockchain implementation costs initially borne by the manufacturer. Such a cost-sharing arrangement not only distributes the financial burden more equitably but also enhances joint investment in digital infrastructure, improves supply chain transparency and carbon traceability, and fosters coordinated low-carbon governance—ultimately contributing to improved overall supply chain performance and sustainability.

References

- [1] L. Yang, Y. Hu and L. Huang, "Collecting mode selection in a remanufacturing supply chain under cap-and-trade regulation," *European Journal of Operational Research*, vol. 287, pp. 480-496, 2020.
- [2] P. De Giovanni and G. Zaccour, "A selective survey of game-theoretic models of closed-loop supply chains," *Annals of Operations Research*, vol. 314, pp. 77-116, 2022.
- [3] J. Wei, W. Y. Chen and G. X. Liu, "How manufacturer's integration strategies affect closed-loop supply chain performance," *International Journal of Production Research*, vol. 59, pp. 4287-4305, 2021.
- [4] Z. Zhang and L. Yu, "Altruistic mode selection and coordination in a low-carbon closed-loop supply chain under the government's compound subsidy: A differential game analysis," *Journal of Cleaner Production*, vol. 366, p. 132863, 2022.
- [5] M. Y. Gao, L. X. Xia, Q. Z. Xiao, and M. Goh, "Incentive strategies for low-carbon supply chains with information updating of customer preferences," *Journal of Cleaner Production*, vol. 410, 2023.
- [6] S. Li, S. J. Qu, M. Wahab, and Y. Ji, "Low-Carbon supply chain optimisation with carbon emission reduction level and warranty period: nash bargaining fairness concern," *International Journal of Production Research*, vol. 62, pp. 6665-6687, 2024.

- [7] R. L. Luo, L. Zhou, Y. Song, and T. J. Fan, "Evaluating the impact of carbon tax policy on manufacturing and remanufacturing decisions in a closed-loop supply chain," *International Journal of Production Economics*, vol. 245, 2022.
- [8] J. Chod, N. Trichakis, G. Tsoukalas, H. Aspegren, and M. Weber, "On the Financing Benefits of Supply Chain Transparency and Blockchain Adoption," *Management Science*, vol. 66, pp. 4378-4396, 2020.
- [9] D. Ma and J. Hu, "The optimal combination between blockchain and sales format in an internet platform-based closed-loop supply chain," *International Journal of Production Economics*, vol. 254, p. 108633, 2022.
- [10] J. Jia, W. Chen, Z. Wang, L. Shi, and S. Fu, "Blockchain's role in operation strategy of power battery closed-loop supply chain," *Computers & Industrial Engineering*, vol. 198, p. 110742, 2024.
- [11] Q. Zhang, Y. Li, P. Hou, and J. Wang, "Price signal or blockchain technology? Quality information disclosure in dual-channel supply chains," *European Journal of Operational Research*, vol. 316, pp. 126-137, 2024.
- [12] B. Shen, C. Dong and S. Minner, "Combating Copycats in the Supply Chain with Permissioned Blockchain Technology," *Production and Operations Management*, vol. 31, pp. 138-154, 2022.
- [13] S. C. Zhang and J. X. Zhang, "Contract preference with stochastic cost learning in a two-period supply chain under asymmetric information," *International Journal of Production Economics*, vol. 196, pp. 226-247, 2018.