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Blockchain-Enabled Coordination and Pricing Optimization in Closed-Loop Supply Chains under Information Asymmetry

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Abstract. This paper examines the effects of blockchain technology on pricing, recycling, and coordination decisions in a closed-loop supply chain under information asymmetry. A two-echelon model consisting of one manufacturer and one retailer is constructed, with the manufacturer acting as the Stackelberg leader. The main decisions concern the wholesale price, retail price, recycling transfer price, and consumer buy-back price, while market demand and return quantity are determined endogenously. By comparing four models—traditional decentralized decision-making, centralized decision-making, blockchain information sharing, and blockchain-enabled coordination—the study finds that recycling-information asymmetry reduces the buy-back price and return quantity, while decentralized decision-making causes double marginalization. Blockchain enhances the transparency and verifiability of recycling information, but information sharing alone cannot eliminate incentive conflicts between supply chain members. Introducing a coordination contract can reproduce the centralized optimal decisions. Blockchain-enabled coordination increases total supply chain profit only when its implementation cost does not exceed the critical value K^*. Under this condition, a fixed transfer payment can achieve a Pareto improvement. These findings provide practical guidance for firms in evaluating blockchain investment, designing coordination contracts, and allocating coordination gains.

Keywords: Closed-loop supply chain, Blockchain, information asymmetry, supply chain coordination, Stackelberg game

1. Introduction

The closed-loop supply chain (CLSC) integrates forward sales with reverse activities such as product recycling and remanufacturing to promote resource reuse and recover residual value [1]. However, information on the quality and quantity of returned products and market demand may not be fully observed and verified by the supply chain members, resulting in information asymmetry and affecting pricing and recycling decisions [1, 2]. At the same time, manufacturers and retailers pursue their own profit objectives under decentralized decision-making, which may cause individual decisions to deviate from the system-wide optimum.

The transparency, traceability, and verifiability of blockchain provide a new technological foundation for addressing these problems [3]. Existing studies have shown that blockchain can increase buy-back prices and recycling quantities and can improve supply chain coordination by

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combining cost-sharing, revenue-sharing, and other contract mechanisms [4-6]. Existing studies have mainly examined either the information-sharing benefits of blockchain or the coordinating effects of supply chain contracts. However, few studies have clearly distinguished the "information gap" caused by information asymmetry from the "incentive gap" resulting from decentralized decision-making within a unified closed-loop supply chain framework and simultaneously examined the relationship between the two. Moreover, the economic feasibility of the coordination model empowered by blockchain at what cost threshold and whether it can achieve Pareto improvement through reasonable profit distribution, still requires further research.

This paper constructs a two-echelon closed-loop supply chain consisting of a single manufacturer and a single retailer and adopts a manufacturer-led Stackelberg game to compare four modes: traditional information asymmetry, centralized complete information, blockchain information sharing, and blockchain coordination. It distinguishes between "information gap" and "incentive gap": blockchain alleviates the former by improving information verifiability, and coordination contracts improve the latter by adjusting the incentives of members, it further analyzes the implementation cost of blockchain and the conditions for achieving Pareto improvement.

2. Literature review

2.1. Information asymmetry, pricing, and closed-loop supply chain coordination

The closed-loop supply chain involves both forward sales and reverse recycling, so its members not only need to set product prices but also need to determine buy-back prices, recycling quantities, and related decisions for remanufacturing. Information asymmetry further complicates these decisions. Li et al. identified uncertainty in returned-product quality and demand, together with information differences among supply chain members, as important sources of information asymmetry in closed-loop supply chains [1]. Beranek and Buscher further demonstrated that the information available to different members can affect pricing, recycling, and profit distribution outcomes [2].

Decentralized decision-making also causes supply chain efficiency losses. When manufacturers and retailers independently maximize their own profits, individual optimal decisions may deviate from the overall optimum of the system. Existing studies typically compare centralized models with decentralized models and use mechanisms such as two-part contracts to improve coordination. Wu et al. found that improving traceability helps increase the recycling volume and system profits, and improved two-part contracts can further improve the coordination performance of supply chain members [3]. Therefore, information asymmetry and incentive conflicts constitute the two core issues addressed by this model simultaneously.

2.2. Blockchain information sharing and supply chain coordination

Blockchain can improve information sharing in the closed-loop supply chain by enhancing information transparency, traceability, and verifiability [4]. Existing studies have shown that blockchain can increase buy-back prices and recycling quantities and improve the recycling rate of waste products [5, 6]. At the same time, the impact of blockchain on supply chain performance is not solely determined by information improvement, its implementation costs and incentive alignment among supply chain members are also important.

Therefore, recent studies combined blockchain with supply chain coordination mechanisms. Xu et al. pointed out that in the blockchain environment, corresponding profit distribution mechanisms are still needed to achieve supply chain coordination and Lin et al. further analyzed the coordinating

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role of cost-sharing and revenue-sharing contracts in the blockchain closed-loop supply chain [7, 8]. Other recent studies have also shown that the economic value of blockchain is influenced by implementation costs, cost-sharing structures, and supply chain organizational structures [9, 10].

Based on these studies, this paper distinguishes the information improvement effect of blockchain from the incentive coordination effect of contracts and incorporates both mechanisms into the closed-loop supply chain model.

3. Model development under information asymmetry and blockchain adoption

3.1. Model setting

This paper considers a two-echelon closed-loop supply chain consisting of a single manufacturer M and a single retailer R. In the forward channel, the manufacturer sells products to the retailer at a wholesale price w, and the retailer then sells them to consumers at a retail price p. In the reverse channel, the retailer recovers used products from consumers at a buy-back price r, and obtains a unit recycling transfer price from the manufacturer. This structure is consistent with the common manufacturer-retailer model found in existing studies on closed-loop supply chains [1]. Let and denote the unit costs of new production and remanufacturing, respectively, and let c_R denote the retailer's unit recycling cost.

The sequence of decisions is as follows. First, as the Stackelberg leader, the manufacturer determines the wholesale price and the unit recycling transfer price b. After observing these decisions, the retailer determines the retail price and the consumer buy-back price r. Market demand and return quantity are then determined by the corresponding demand and return functions. Thus, and are the decision variables, whereas and are endogenous outcomes.

The remanufacturing cost saving is:

$$\Delta = c_n - c_m > 0 \tag{1}$$

Market demand and return quantity are respectively

$$Q = a - \beta p \tag{2}$$

$$R = \gamma r \tag{3}$$

where $a > 0$, $\beta > 0$, and $\gamma > 0$. Information asymmetry in this study concerns the quality and remanufacturing value of returned products. The retailer directly collects used products and therefore has more accurate information about returned products, whereas the manufacturer cannot fully verify it. Let represent the degree of recycling-information asymmetry, where indicates complete information and a larger indicates more severe information asymmetry. Accordingly, the manufacturer's effective remanufacturing value under the traditional system is:

$$(1 - \phi)\Delta \tag{4}$$

To ensure a positive return quantity, assume $(1 - \phi)\Delta - c_R > 0$. Under blockchain, recycling information is fully verifiable, so

$$\phi_B = 0 \tag{5}$$

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3.2. Traditional decentralized model

The traditional CLSC is modeled as a manufacturer-led Stackelberg game. The retailer's profit is

$$\pi_R^T = (p - w)(a - \beta p) + (b - r - c_R)\gamma r \tag{6}$$

Backward induction gives the retailer's best-response functions:

$$\mathrm{p(w)} = \frac{\mathrm{a} + \beta \mathrm{w}}{2\beta} \tag{7}$$

$$\mathrm{r\,(b)} = \frac{\mathrm{b} - \mathrm{c_R}}{2}$$

The manufacturer's profit is

$$\pi_{\mathrm{M}}^{\mathrm{T}} = (\mathrm{w} - \mathrm{c_n})\mathrm{Q} + [(1 - \phi)\Delta - \mathrm{b}]\mathrm{R} \tag{8}$$

Solving the manufacturer's problem gives

$$\mathrm{w_{T^*}} = \frac{\mathrm{a} + \beta \mathrm{c_n}}{2\beta} \tag{9}$$

$$\mathrm{b_T^*} = \frac{[(1 - \phi)\Delta + \mathrm{c_R}]}{2}$$

Therefore,

$$p_{T^*} = \frac{3a + \beta c_n}{4\beta} \tag{10}$$

$$\mathrm{Q_{T^*}} = \frac{\mathrm{a} - \beta \mathrm{c_n}}{4}$$

and

$$\mathrm{r_{T^*}} = \frac{[(1 - \phi)\Delta - \mathrm{c_R}]}{4} \tag{11}$$

$$\mathrm{R_{T^*}} = \frac{\gamma[(1 - \phi)\Delta - \mathrm{c_R}]}{4}$$

Hence,

$$\frac{\partial \mathrm{r_T}}{\partial \phi} = -\frac{\Delta}{4} < 0 \tag{12}$$

$$\frac{\partial \mathrm{R_T}}{\partial \phi} = -\frac{\gamma \Delta}{4} < 0$$

Proposition 1. Greater recycling-information asymmetry reduces both the consumer buy-back price and return quantity. Define

$$X = a - \beta c_n,\ Y = (1 - \phi)\Delta - c_R \tag{13}$$

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$$\Pi_T = \frac{3X^2}{16\beta} + \frac{3\gamma Y^2}{16}$$

The traditional total supply chain profit is

3.3. Centralized benchmark

Under centralized full-information decision-making, the supply chain maximizes

$$\Pi_C = (p - c_n)(a - \beta p) + (\Delta - r - c_R)\gamma r \tag{14}$$

The optimal outcomes are

$$p_C^* = \frac{a + \beta c_n}{2\beta} \tag{15}$$

$$Q_C^* = \frac{a - \beta c_n}{2}$$

$$r_C^* = \frac{\Delta - c_R}{2} \tag{16}$$

$$R_C^* = \frac{\gamma(\Delta - c_R)}{2}$$

Let Then

$$\Pi_C = \frac{X^2}{4\beta} + \frac{\gamma Z^2}{4} \tag{17}$$

Since

$$p_{T^*} > p_{C^*},\ Q_{T^*} < Q_{c^*}$$

$$r_{T^*} < r_{C^{\wedge}*},\ R_{T^*} < R_{C^*}$$

the traditional system suffers from both forward-channel double marginalization and reverse-channel recycling inefficiency.

3.4. Blockchain information-sharing model

Blockchain is assumed to verify information only in the reverse recycling channel, without changing market demand, production costs, or the decentralized pricing structure in the forward channel. Therefore, blockchain affects the recycling decisions by eliminating information asymmetry, while the forward decisions remain unchanged.

$$w_I^* = w_T^*, \quad p_I^* = p_T^* \tag{18}$$

However, setting = 0 yields

$$b_I^* = \frac{\Delta + c_R}{2} \tag{19}$$

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$$r_I^* = \frac{\Delta - c_R}{4}$$

$$R_I^* = \frac{\gamma(\Delta - c_R)}{4}$$

Thus,

$$r_I^* - r_T^* = \frac{\phi\Delta}{4} > 0$$

$$R_I^* - R_T^* = \frac{\gamma\phi\Delta}{4} > 0 \tag{20}$$

Proposition 2. Blockchain information sharing strengthens recycling incentives and increases the return quantity but does not eliminate decentralized pricing inefficiency. This is consistent with evidence that blockchain can increase buy-back prices and collection rates [4, 5].

3.5. Blockchain-enabled coordination

To eliminate the remaining incentive distortion, a two-part coordination contract is introduced:

$$w_B = c_n, \quad b_B = \Delta \tag{21}$$

together with a fixed transfer F. The retailer's coordinated profit is

$$\pi_R^B = (p - c_n)Q + (\Delta - r - c_R)R - F \tag{22}$$

Because F does not affect marginal decisions, the retailer chooses the centralized optimum:

$$p_B^* = p_C^*, \quad Q_B^* = Q_C^* \tag{23}$$

$$r_B^* = r_C^*, \quad R_B^* = R_C^*$$

Proposition 3. The blockchain-enabled coordination contract reproduces the centralized first-best solution. Thus, blockchain reduces the information gap, while the contract reduces the incentive gap. Similar coordination roles of cost-sharing, revenue-sharing, and two-part tariff mechanisms are found in recent studies [6, 8].

3.6. Blockchain adoption threshold

Let $K > 0$ denote the total blockchain implementation cost. The total supply chain profit under blockchain coordination is

$$\Pi_B = \Pi_C - K \tag{24}$$

Blockchain coordination is economically preferable when

$$K \leq K^*$$

Where

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$$K^* = \Pi_C^* - \Pi_T^* = \frac{X^2}{16\beta} + \frac{\gamma[4Z^2 - 3Y^2]}{16} \tag{25}$$

Equivalently,

$$K^* = \frac{(a - \beta c_n)^2}{16\beta} + \frac{\gamma\left\{4(\Delta - c_R)^2 - 3[(1-\phi)\Delta - c_R]^2\right\}}{16}$$

Proposition 4. Blockchain-enabled coordination improves total CLSC profit only when $K \le K^*$. Moreover,

$$\frac{\partial K^*}{\partial \phi} = \frac{3\gamma\Delta Y}{8} > 0, \quad \text{if } Y > 0 \tag{26}$$

Blockchain becomes more valuable when the original information asymmetry is more severe.

3.7. Profit allocation and pareto improvement

Suppose the manufacturer bears and the retailer bears $(1-\lambda)K$. Their coordinated profits are

$$\pi_M^B = F - \lambda K, \tag{27}$$

$$\pi_R^B = \Pi_C - F - (1-\lambda)K$$

Both members participate when

$$F \ge \pi_M^T + \lambda K \tag{28}$$

And

$$F \le \Pi_C - (1-\lambda)K - \pi_R^T \tag{29}$$

A feasible F therefore exists if and only if

$$K \le K^* \tag{30}$$

Proposition 5. When $K \le K^*$, an appropriate fixed transfer can make both members at least as well off as under the traditional system, thereby achieving a Pareto improvement. Overall, the model separates two sources of inefficiency: information asymmetry weakens recycling incentives, while decentralized decision-making causes incentive misalignment. Blockchain addresses the former through verifiable information sharing, whereas coordination contracts address the latter. Blockchain adoption is economically justified only when the resulting efficiency gains exceed blockchain implementation costs.

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4. Comparison results and discussion

4.1. The impact of information asymmetry

The traditional model indicates that under the assumptions of this model, information asymmetry primarily affects supply chain decisions through the reverse recycling channel:

$$\frac{\partial r_T^*}{\partial \phi} < 0, \quad \frac{\partial R_T^*}{\partial \phi} < 0$$

As increases, the manufacturer's judgment of the value of recycled products becomes more conservative, thereby reducing the reverse transfer price paid to retailers and further leading to a decrease in the consumer's buy-back price and the return quantity. This result is consistent with the conclusion of Li et al., which shows that information uncertainty and information screening ability significantly affect recycling decisions in the closed-loop supply chains [1]. At the same time, $p_T^* > p_C^*$, $Q_T^* < Q_C^*$. This indicates that decentralized decision-making also creates double marginalization in the forward sales channel, causing retail prices to be higher than the level determined by centralized decision-making, while market demand is lower than the optimal level of the system. Therefore, traditional closed-loop supply chains simultaneously suffer from two types of efficiency losses: the "information gap" caused by information asymmetry and the "incentive gap" caused by decentralized decision-making. The former primarily affects reverse-channel recycling decisions in the present model, whereas the latter leads to inefficient decentralized pricing and demand decisions.

4.2. The information improvement effect and coordination effect of blockchain

When blockchain enhances the transparency and verifiability of recycling information, while the supply chain still maintains its original decentralized decision-making structure, $r_I^* > r_T^*$, $R_I^* > R_T^*$. This indicates that blockchain can enhance the credibility and verifiability of recycling information, thereby improving the recycling decisions in the reverse channel. This result is consistent with existing research, which shows that blockchain can increase buy-back prices and promote the recycling of waste products [4, 5]. However,

$$p_I^* = p_T^* > p_C^*$$

It should be noted that blockchain-based information sharing alone cannot eliminate the double marginalization effect in the forward channel or fully coordinate decentralized decisions. In other words, the blockchain mainly contributes to narrowing the "information gap" by improving information transparency and verifiability, while the "incentive gap" generated by decentralized decision-making still needs to be resolved through contract coordination mechanisms.Under the coordination model supported by the blockchain,

$$p_B^* = p_C^*, Q_B^* = Q_C^*, r_B^* = r_C^*, R_B^* = R_C^*$$

Therefore, in the modeled setting, effective supply chain coordination requires both reliable information sharing and appropriate incentive design. The research by Lin et al. also indicates that in

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a blockchain-supported closed-loop supply chain, contract mechanisms such as cost sharing and revenue sharing can further improve supply chain coordination [6].

4.3. Blockchain adoption cost and pareto improvement

The system-level economic condition for adopting blockchain coordination is as follows $K \leq K^*$.

This indicates that blockchain does not always have an economic advantage. Only when the efficiency gains brought about by information improvement and supply chain coordination are sufficient to cover the implementation costs of blockchain, is the adoption of blockchain economically reasonable. This conclusion is consistent with the research of Chen et al., which states that only when the traceability and operational benefits brought by blockchain exceed the access and operation costs can supply chain members achieve mutual benefits [4]. Furthermore, $\frac{\partial K^*}{\partial \Phi} > 0$, indicates that the higher the degree of information asymmetry in the traditional supply chain, the greater the potential economic value that blockchain can create. Therefore, the supply chain can bear a higher implementation cost of blockchain.

Finally, when $K \leq K^*$, by setting an appropriate fixed transfer payment F, it is possible to make

$$\pi_M^B \geq \pi_M^T, \quad \pi_R^B \geq \pi_R^T$$

so as to reasonably distribute the additional benefits generated by coordination between manufacturers and retailers, ensuring that the profits of both parties are not lower than in the traditional model, and thereby achieving Pareto improvement.

In conclusion, the optimization of the closed-loop supply chain supported by blockchain is not solely dependent on information transparency at the technical level but is jointly determined by information improvement, incentive coordination, implementation cost, and profit distribution. Blockchain provides a technical foundation for trusted information sharing, while the contract mechanism is responsible for coordinating the economic incentives among members.

5. Managerial implications and research limitation

5.1. Managerial implications

The research results of this paper can provide the following managerial implications for enterprises considering the adoption of blockchain in closed-loop supply chains. Firstly, enterprises should assess the degree of information asymmetry in the existing recycling system. When the quality, quantity, and transaction records of returned products are difficult to verify, blockchain can create greater value by improving information transparency and enhancing recycling incentives. However, if the relevant information is already relatively reliable, the marginal benefits brought by the adoption of blockchain may be relatively limited.

Secondly, blockchain should not be regarded as a solution that can independently achieve supply chain coordination. Although information sharing can improve the reverse recycling channel, it cannot eliminate the dual marginalization and incentive conflicts under decentralized decision-making. Therefore, enterprises should combine blockchain with coordination mechanisms such as cost-sharing, revenue-sharing, or two-part pricing contracts to align the individual decisions of supply chain members with the overall goals of the supply chain.

Finally, enterprises should decide whether to adopt blockchain based on cost-benefit analysis. Only when the implementation cost satisfies is the blockchain investment economically reasonable.

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Even if the total supply chain profit is increased, appropriate fixed transfer payments should be set to distribute the coordination benefits and ensure that manufacturers and retailers have the willingness to participate.

5.2. Research limitations and future directions

This paper only considers a two-echelon closed-loop supply chain consisting of a single manufacturer and a single retailer and uses linear demand functions and linear recycling functions. Future research can further analyze multi-member supply chains, market competition, stochastic demand, and differences in returned-product quality. In addition, since the blockchain systems in reality may still be affected by inaccurate off-chain data, future models can consider partial information verification and technology-dependent implementation costs.

6. Conclusion

This study examines the impact of blockchain technology on pricing, recycling, and coordination decisions in a closed-loop supply chain under conditions of information asymmetry. By constructing a two-echelon closed-loop supply chain consisting of a single manufacturer and a single retailer and using the manufacturer-led Stackelberg game, this paper compares four modes: traditional decentralized decision-making, centralized decision-making, blockchain information sharing, and blockchain coordination.

The research results show that an increase in the degree of recycling information asymmetry will reduce the consumer recycling price and the number of recycled products, while the dual marginalization effect produced by decentralized decision-making will cause the retail price to be higher than the optimal level under centralized decision-making. Blockchain can improve reverse channel decision-making by enhancing the transparency and verifiability of recycling information, but simple information sharing cannot eliminate the incentive conflicts among supply chain members. By further introducing coordination contracts, decentralized decision-making can reproduce the centralized optimal pricing and recycling outcomes under centralized decision-making.

In addition, blockchain coordination is not always economically beneficial. This mode can increase the total profit of the supply chain only when the implementation cost satisfies $K \leq K^*$. Under this condition, appropriate fixed transfer payments can reasonably distribute coordination benefits, ensuring that the profits of the manufacturer and the retailer are not lower than those under the traditional mode, thereby achieving Pareto improvement. Overall, blockchain primarily narrows the information gap, while supply chain coordination still relies on corresponding contracts and profit distribution mechanisms.

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