Research on Green Supply Chain Decision-Making Based on Blockchain to Eliminate the Risk of Energy Efficiency Data Fraud

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ABSTRACT

Abstract: Falsification of product energy efficiency data affects the accuracy of carbon footprint tracking in green supply chain, and is not conducive to the achievement of carbon neutrality goals. Therefore, applying blockchain technology to eliminate the risk of fraudulent product energy efficiency data in the green supply chain, and then investigating its impacts on green supply chain decision-making is a new proposition worth studying. By constructing a Stackelberg game model including a manufacturer and a retailer, this paper analyzes the impacts of applying blockchain technology on green supply chain pricing decisions, carbon emission reduction and profit. We find that the increased risk of product energy efficiency data fraud will have negative impacts on product wholesale price, selling price, carbon emission reduction, and order quantity; Furthermore, the improvement of brand credibility brought about by the application of blockchain is conducive to enhancing the level of carbon emission reduction, and has essential impact on the wholesale price and the selling price, while the impacts of the marginal use cost of blockchain are the opposite. Finally, the triple factors including fixed cost, marginal usage cost and degree of brand credibility improvement jointly affect the profits of enterprises when applying blockchain. Our results have important managerial implications for government and companies who intend to improve their financial and environmental performance by applying blockchain technology in green supply chain.

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CCS CONCEPTS

• **Theory of computation**; • **Models of computation**; • **Computability**;

KEYWORDS

carbon emission reduction, blockchain, energy efficiency data fraud, brand credibility

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1 INTRODUCTION

In order to accelerate the construction of ecological civilization and achieve the common goal of mankind, the Chinese government has made a solemn commitment and taken positive actions to strive to achieve carbon peaking and carbon neutrality goals by 2030 and 2060, respectively. Doing a perfect job in carbon footprint tracking is the key to achieve these goals. In practice, product energy efficiency labeling provides consumers with product energy efficiency information and is also an important measure of government energy conservation management. Even though energy label data fraud is illegal, this phenomenon is common.

In 2015, the U.S. Environmental Protection Agency (EPA) accused Volkswagen of Germany of installing relevant software on some of its diesel vehicles, so that the car can reduce the emission of pollutants in the state of being tested, so as to pass the car inspection, while the exhaust emission of the car is 40 times the standard. In 2018, Tesla was reported by the EPA that the fuel efficiency values of Model 3 were inconsistent with its energy efficiency label data. On June 10, 2019, Gree reported to the State Administration for Market Regulation that Aux produced and sold substandard air-conditioning products. Falsification of energy efficiency data not only damages consumer rights and the market reputation of green products, but also has adversely effects on carbon footprint tracking.

How to solve the falsification of product energy efficiency data and promote carbon emission reduction has become a key issue.

Blockchain technology has significant features such as decentralization, consensus trust, asymmetric encryption, and timestamps, which are the key to the efficient application of the achievements of Industry 4.0 to the supply chain [1]. The application of blockchain enables product-related information to be tracked and verified from the production end to the consumer end, and cannot be tampered with, effectively reducing operational risk and moral hazard and has achieved certain results in practice. IBM proposed to apply blockchain technology to food field, to control the whole process of products from the source of production to the terminal of consumption.

The application of blockchain technology will also generate new costs, including the cost of improving hardware equipment, training relevant personnel, and marginal costs in the process of use. However, blockchain technology can enable the smooth transfer of information between members of the supply chain, help consumers to obtain real information about products, and reduce the cost of consumers' choice. As a result, the brand credibility of the relevant enterprises can be improved, and the firms can benefit. Based on the above theoretical and practical researches, this paper aims to answer the following questions: (1) What impact will the risk of product energy efficiency data fraud have on the green supply chain? (2) What impact does the application of blockchain technology have on green supply chain decision-making? (3) When will it be profitable to apply blockchain technology in green supply chain?

For analyzing the impact of the application of blockchain technology on the green supply chain, this paper constructs a green supply chain benchmark model (T-model) and a green supply chain model based on blockchain technology (B-model). First, we analyze the impact of risk of product energy efficiency data fraud on the green supply chain; Second, we analyze the impact of applying blockchain on carbon emission reduction and pricing decisions. Finally, we analyze the impact of applying blockchain on the profits of manufacturer and retailer.

2 LITERATURE REVIEW

2.1 Blockchain

The blockchain technology invented by Satoshi Nakamoto is a radical innovation that can achieve much more. Kshetri believed that blockchain technology has broad application prospects in the field of logistics and supply chain [2]. The existence of the "bullwhip effect" in supply chain aggravates the uncertainty of the supply chain, and the application of blockchain technology can effectively tackle this problem [3]. Transactions in the supply chain are faced with verification cost and transaction cost, and the application of blockchain technology can effectively reduce these two types of cost [4]. Whitaker and Kräussl found that the transfer of credit between members of the supply chain is smooth [5]. At present, Blockchain technology not only helps to achieve product traceability, but also helps to establish a credit rating system to improve the efficiency of supply chain management [6].

Industry 4.0 provides a broader future for ecological and social sustainability [7]. The technology that enables Industry 4.0 to be effectively applied to the supply chain is the blockchain [2]. According to the research of De Giovanni, the blockchain technology application in supply chain is not always profitable [8]. Min argued that more attention should be paid to the role of blockchain in improving the stability of supply chain [9].

2.2 Green supply chain

Both theoretical and practical research attach great importance to the sustainable development of supply chain [10]. Bazan claimed that reducing energy consumption is the key to reduce carbon emission in supply chain [11]. Adhikari and Bisi applied cost sharing contract and profits sharing contract to coordinate the green supply chain, and further studied the impact of fairness concern on green supply chain [12].

By constructing a Stackelberg game model, Xia studied the influence of cross-shareholding on green supply chain decision [13]. Chen analyzed the impact of cooperation between supply chain members on pricing decisions and carbon emission reduction decisions [14]. Wu found that increasing investment in carbon emission reduction of products by manufacturers can create a win-win situation [15]. Huang investigated the impact of financing decisions on carbon emission reduction under the cap-and-trade policy [16].

In summary, the research of blockchain in supply chain is mainly qualitative, and the quantitative research is less. To the best of our knowledge, this paper is the first to investigate the role of blockchain in eliminate the risk of product energy efficiency data fraud. We construct a green supply chain benchmark model with the risk of falsification of product energy efficiency data and a green supply chain extended model using blockchain technology, and analyze the advantages and disadvantages of applying blockchain technology to the green supply chain, explore the effects of applying blockchain technology on the green supply chain decision and profit. The research results provide decision-making references for supply chain members to complete the carbon emission reduction goal.

3 MODELS

3.1 The green supply chain benchmark model

In this section, we contemplate the green supply chain composed of manufacturer m (he) and retailer r (she). The risk of falsification of product energy efficiency data exists in the green supply chain, and companies may misreport their carbon emission reduction data [17]. The retailer needs to pay a certain cost to find qualified products, including verifying the authenticity of product energy efficiency data. The manufacturer increases the research and development (R&D) investment so that the product can achieve carbon emission reduction level k_T on the basis of the original energy consumption level to enhance the market competitiveness of the product, and determines the wholesale price w_T simultaneously. The retailer orders q_T units of product from the manufacturer and sells them to consumers at price p_T. The benchmark model decision sequence is showed in Figure 1.

Due to the existence of the risk of falsification of product energy efficiency data in the supply chain, consumers are in a relatively weak position and cannot confirm whether the information obtained is accurate, so they do not fully trust the energy efficiency

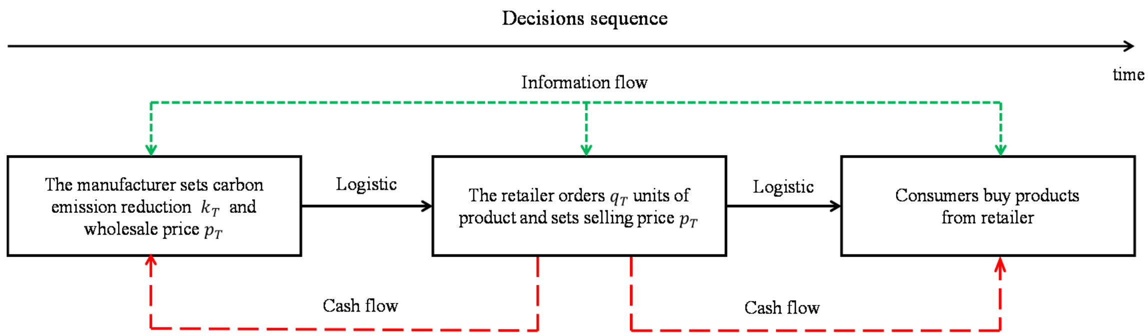

Figure 1: The sequence of decisions in T − model

data of products. The greater the risk of falsification of product energy efficiency data in the supply chain, the lower the consumer's trust in the product. Therefore, the product demand faced by the retailer is affected by the price, the product carbon emission reduction level and the risk of falsification of energy efficiency labeling data, and its order quantity is:

$$q_T = D - \varepsilon p_T + \lambda k_T (1 - \gamma) \tag{1}$$

Without carbon emission reduction investment, $q_T = D - \varepsilon p_T > 0$,and $p_T > w_T > c$. The profit functions for the manufacturer and the retailer are:

$$\Pi_m^T (w_T, k_T) = (w_T - c)\, q_T - \frac{z k_T^2}{2} \tag{2}$$

$$\Pi_r^T (p_T) = (p_T - w_T)\, q_T - \frac{c_A A^2}{2} \tag{3}$$

The relevant variables are explained as follows:

D is the maximum market demand; ε is the price sensitivity of the consumer; λ is the consumers' sensitivity to carbon emission reduction level; c is the unit production cost.

The risk of falsification of energy efficiency label data is characterized by parameter γ, and $0 \le \gamma \le 1$.

$-\frac{z k_T^2}{2}$ is the R&D cost paid by the manufacturer to improve the carbon emission reduction level of the product; z is the unit carbon emission reduction cost.

$-\frac{c_A A^2}{2}$ is the cost paid by the retailer to find a qualified product; A is the retailer's effort level to procure eligible goods, and c_A is the marginal cost of this effort level.

Based on equations 1), (2) and (3), the optimal decision results and profits of the manufacturer and the retailer are shown in Table 1. The risk of falsification of product energy efficiency data has the following impacts on the supply chain:

Proposition 1. In the $T - model$, $\frac{\partial k_T}{\partial \gamma} < 0, \frac{\partial p_T}{\partial \gamma} < 0, \frac{\partial q_T}{\partial \gamma} < 0$ $, \frac{\partial w_T}{\partial \gamma} < 0$.

Proposition 1 shows that as the risk of falsification of product energy efficiency data increases, the carbon emission reduction level k_T and the wholesale price w_T of the manufacturer will decrease, and the order quantity q_T and the selling price p_T of the retailer will decrease. The greater the risk factor of falsification of product energy efficiency data, the higher the consumer's distrust of the manufacturer, which damages the brand credibility of the energy-saving product. If the quality of product cannot be recognized by consumers, the sales volume will inevitably decrease, and the profits of retailer and manufacturer will be affected. The manufacturer is also reluctant to invest more in the research and development of energy-saving products. In order to promote sales, the retailer will choose to lower the price of products, forming a negative feedback loop in the green supply chain.

3.2 The green supply chain model based on blockchain

In the model based on blockchain, the retailer builds a transaction platform based on blockchain technology, and she need to invest a fixed cost F_B to complete related technical transformation and hardware equipment upgrading, including purchasing equipment and hiring professional and technical personnel. In addition, the marginal cost, related to the number of the trading, linked to the use of the blockchain is generated during the transaction process. In practice, blockchain technology has the characteristics of multi-party writing, joint maintenance, public ledger, decentralization, and non-tampering, which makes the transaction process more transparent, removes operational risks and moral risks in the supply chain, and consumers can obtain real data about the product. As transactions are more transparent and reliable, the brand credibility of stakeholders in the supply chain will be enhanced by using blockchain. At the same time, the retailer can obtain accurate data of the product. Same as De Giovanni's hypothesis, we assume that the retailer's price comparison cost is zero [8]. The supply chain decision sequence is showed in figure 2.

When trading in the supply chain based on blockchain technology, the risk of falsification of product energy efficiency data is effectively eliminated, and consumers can obtain real information on product energy efficiency data. Thus, the retailer's order quantity is:

$$q_B = D - \varepsilon p_B + \lambda k_B \tag{4}$$

The profit functions for the manufacturer and the retailer are:

$$\Pi_m^B (w_B, k_B) = (w_B - c - c_B + v)\, q_B - \frac{z k_B^2}{2} \tag{5}$$

$$\Pi_r^B (p_B) = (p_B - w_B - c_B + v)\, q_B - F_B \tag{6}$$

where:

v is the value coefficient of brand credibility, F_B is the allocation of fixed cost in each transaction, and is collectively referred to as

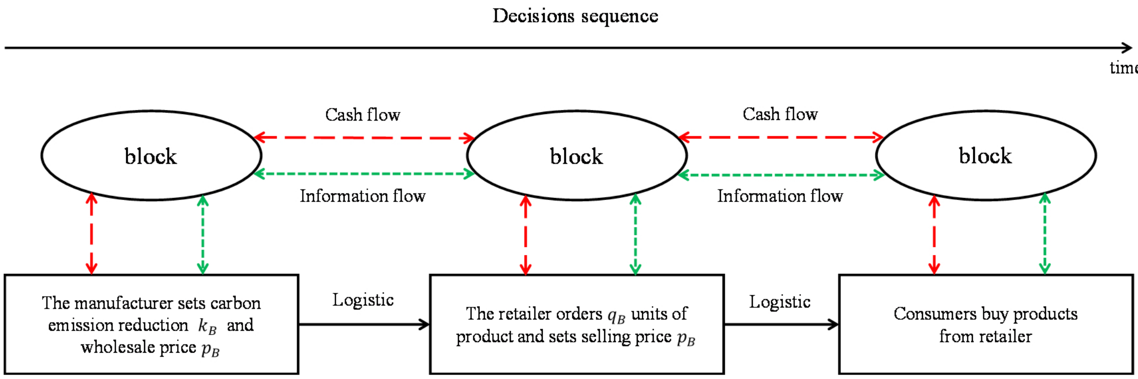

Figure 2: The sequence of decisions in $B - model$

Table 1: Equilibrium analysis

Models	T-model(j=T)	B-model(j=B)
w_j	$\frac{2z(D+\varepsilon c)-c\lambda^2(1-\gamma)^2}{4\varepsilon z-\lambda^2(1-\gamma)^2}$	$\frac{2z(D+\varepsilon c)+\lambda^2(v-c-c_B)}{4\varepsilon z-\lambda^2}$
k_j	$\frac{(D-\varepsilon c)\lambda(1-\gamma)}{4\varepsilon z-\lambda^2(1-\gamma)^2}$	$\frac{[D+\varepsilon(2v-c-2c_B)]\lambda}{4\varepsilon z-\lambda^2}$
p_j	$\frac{z(3D+\varepsilon c)-c\lambda^2(1-\gamma)^2}{4\varepsilon z-\lambda^2(1-\gamma)^2}$	$\frac{3Dz+(\lambda^2-\varepsilon z)(2v-2c_B-c)}{4\varepsilon z-\lambda^2}$
Π_m^j	$\frac{z(D-\varepsilon c)^2}{2[4\varepsilon z-\lambda^2(1-\gamma)^2]}$	$\frac{z[D+\varepsilon(2v-2c_B-c)]^2}{2(4\varepsilon z-\lambda^2)}$
Π_r^j	$\frac{2\varepsilon z^2(D-\varepsilon z)^2-c_A A^2[4\varepsilon z-\lambda^2(1-\gamma)^2]^2}{2[4\varepsilon z-\lambda^2(1-\gamma)^2]^2}$	$\frac{\varepsilon z^2[D+\varepsilon(2v-2c_B-c)]^2-F_B(4\varepsilon z-\lambda^2)^2}{(4\varepsilon z-\lambda^2)^2}$

fixed cost for the convenience of explanation. The interpretations of other related variables in the $B-model$ is the same as the specific interpretations in the $T - model$, and $p_B > w_B > c + c_B - v > 0$. In the $-model$, specifically, the manufacturer broadcast the product wholesale price w_B on the network, and this information is open and transparent. The retailer can obtain the real information about the product, and then decide the order quantity q_B based on the wholesale price published by the manufacturer, and sell them to consumers at the price p_B. Based on equations 4), (5), and (6), the optimal decision results and profits of the manufacturer and the retailer are shown in Table 1.

4 MODEL ANALYSIS

4.1 The effects of cost on firms' decisions in B-Model

This subsection focuses on analyzing the impact of cost on decisions. Details as follows:

Proposition 2. (1) $\frac{\partial k_B}{\partial c} < 0$;
(2) If $\frac{\lambda^2}{4\varepsilon} < z < \frac{\lambda^2}{2\varepsilon}$, then $\frac{\partial w_B}{\partial c} < 0, \frac{\partial p_B}{\partial c} < 0$;
(3) If $\frac{\lambda^2}{2\varepsilon} \leq z < \frac{\lambda^2}{\varepsilon}$, then $\frac{\partial w_B}{\partial c} \geq 0, \frac{\partial p_B}{\partial c} < 0$;
(4) If $\frac{\lambda^2}{\varepsilon} \leq z$, then $\frac{\partial w_B}{\partial c} > 0, \frac{\partial p_B}{\partial c} \geq 0$.

Proposition 2 shows that as the production cost increases, the manufacturer facing the greater cost pressure has to reduce the relevant R&D investment, resulting in a lower level of product carbon emission reduction; If $\frac{\lambda^2}{4\varepsilon} < z < \frac{\lambda^2}{2\varepsilon}$, even if the production cost increases, the manufacturer and the retailer can still use price promotion strategy; If $\frac{\lambda^2}{2\varepsilon} \leq z < \frac{\lambda^2}{\varepsilon}$, due to the cost pressure, the manufacturer must choose to increase the wholesale price to ensure his profit, and the retailer in the downstream of the supply chain still has profit margin to sell at a lower price; If $\frac{\lambda^2}{\varepsilon} \leq z$, the manufacturer's carbon emission reduction cost is high, and the retailer has to raise the selling price in the face of further increasing wholesale price.

4.2 The effects of blockchain technology on firms' decisions in B-model

The application of blockchain technology in the supply chain will have the following effects:

Proposition 3. (1) $\frac{\partial k_B}{\partial v} > 0$, $\frac{\partial w_B}{\partial v} > 0$; (2) If $\frac{\lambda^2}{4\varepsilon} < z < \frac{\lambda^2}{\varepsilon}$, then $\frac{\partial p_B}{\partial v} > 0$; If $\frac{\lambda^2}{\varepsilon} \leq z$, then $\frac{\partial p_B}{\partial v} \leq 0$.

Proposition 3 shows that good brand credit has a positive impact on the carbon emission reduction level k_B and the wholesale price w_B. If $\frac{\lambda^2}{4\varepsilon} < z < \frac{\lambda^2}{\varepsilon}$, from Proposition 2, we know that when the unit production cost c increases, the retailer will reduce the selling price p_B. Under this condition, if the value coefficient of brand credibility v increases, the retailer should increase the selling price p_B. If $\frac{\lambda^2}{\varepsilon} \leq z$, when the unit production cost c increases, the retailer will increase the selling price p_B. When the value coefficient of brand credibility v increases, the retailer should decrease the selling

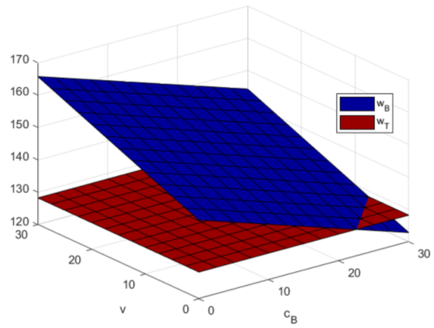

Figure 3: Impacts of v and c_B on the wholesale price

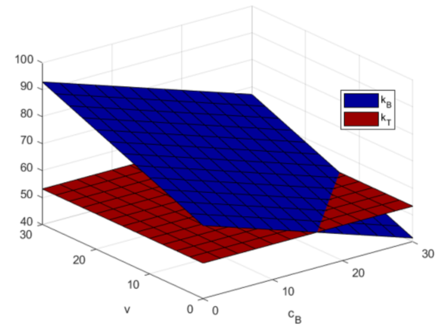

Figure 4: Impacts of v and c_B on the manufacturer's carbon emission reduction level

price p_B. As consumers are price sensitive, the retailer should adjust the pricing decision based on changes in different factors.

Proposition 4. (1) $\frac{\partial w_B}{\partial c_B} < 0$, $\frac{\partial k_B}{\partial c_B} < 0$; (2) If $\frac{\lambda^2}{4\varepsilon} < z < \frac{\lambda^2}{\varepsilon}$, then $\frac{\partial p_B}{\partial c_B} < 0$; If $\frac{\lambda^2}{\varepsilon} \le z$, then $\frac{\partial p_B}{\partial c_B} \ge 0$.

Proposition 4 shows that the marginal blockchain usage cost c_B is also one of the important factors affecting the decision of the supply chain. Comparing Proposition 3, we find that the marginal blockchain usage cost c_B and the value coefficient of brand credibility v have opposite effects.

Proposition 5. (1) If $v - c_B \ge TH_1$, then $w_B \ge w_T$; (2) If $v - c_B \ge TH_2$, then $k_B \ge k_T$;(3) If $v - c_B \ge TH_3$, then $p_B \ge p_T$.

Where $TH_1 = \frac{-2z\gamma(D-\varepsilon c)(1-\gamma)}{4\varepsilon z-\lambda^2(1-\gamma)^2}$, $TH_2 = \frac{-\gamma(D-\varepsilon c)[4\varepsilon z+\lambda^2(1-\gamma)]}{2\varepsilon[4\varepsilon z-\lambda^2(1-\gamma)^2]}$, $TH_3 = \frac{-3z\gamma\lambda^2(D-\varepsilon c)(2-\gamma)}{2(\lambda^2-\varepsilon z)[4\varepsilon z-\lambda^2(1-\gamma)^2]}$.

Proposition 5 shows that the value coefficient of brand credibility v and the marginal blockchain usage cost c_B have important impact on the decision-making level. Three thresholds are given between v and c_B. When the difference between v and c_B is greater than the corresponding threshold, the decision levels of the manufacturer and the retailer in the $B-model$ is greater than those in the $T-model$. Next chapter will use numerical analysis to more intuitively analyze the impact of blockchain technology on the supply chain.

5 NUMERICAL ANALYSIS

This section compares and analyzes the impact of applying blockchain technology on green supply chain decision-making and profits through numerical simulation. The basic parameters are set as follows: $D = 200$, $\varepsilon = 1.2$, $c = 10$, $z = 2$, $\lambda = 2$, $\gamma = 0.1$.

5.1 The impact of blockchain on the wholesale price

Figure 3 shows that the wholesale price w_B decreases with increasing c_B and increases with increasing v, which is consistent with the conclusions of Propositions 3 and 4. Combining Proposition 5, we discover that when the blockchain marginal usage cost c_B is high, and the value coefficient of brand credibility v is low, the wholesale price w_B in the $B - model$ will be lower than the wholesale price w_T in the $T - modle$.

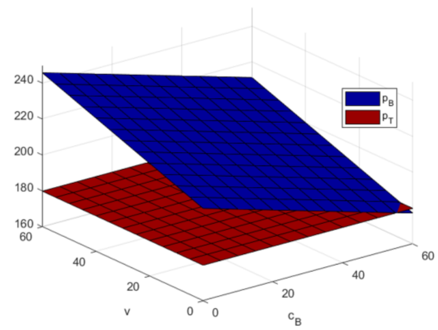

Figure 5: Impacts of v and c_B on the selling price

5.2 The impact of blockchain on the carbon emission reduction

Figure 4 shows that the carbon emission reduction level k_B decreases with increasing c_B and increases with increasing v, which is consistent with the conclusions of Propositions 3 and 4. Combining Proposition 5, when the blockchain marginal usage cost c_B is high, and the value coefficient of brand credibility v is low, the carbon emission reduction level k_B in the $B - model$ will be lower than the carbon emission reduction level k_T in the $T - modle$.

5.3 The impact of blockchain on the selling price

Figure 5 shows that the selling price p_B decreases with increasing c_B and increases with increasing v, which is consistent with the conclusions of Propositions 3 and 4. Combining Proposition 5, when $v - c_B \ge TH_3$, then $p_B \ge p_T$. Figure 5 is plotted under the condition $\frac{\lambda^2}{4\varepsilon} < z < \frac{\lambda^2}{\varepsilon}$. When $\frac{\lambda^2}{\varepsilon} \le z$, the conclusion has been given by propositions 3 and 4, and its graph is no longer drawn here.

5.4 The impact of blockchain on the profits

Figure 6 shows that the manufacturer's profit Π_m^T decreases as the γ increases; When the value coefficient of brand credibility v is greater than the marginal use cost of the blockchain c_B, Π_m^B is always

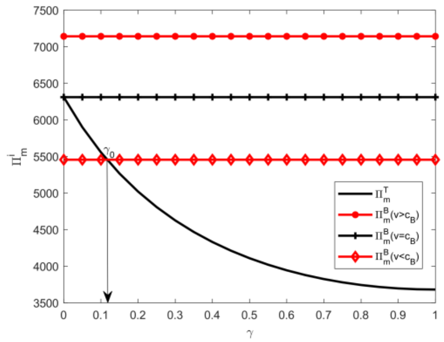

Figure 6: Impacts of blockchain on the manufacturer's profit

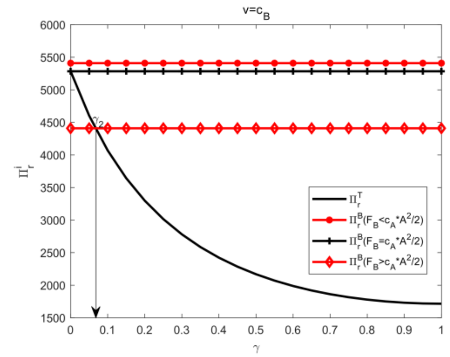

Figure 8: Impacts of blockchain on the retail's profit

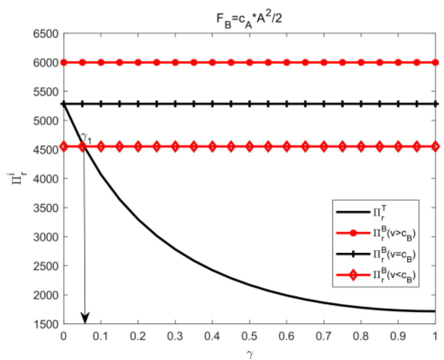

Figure 7: Impacts of blockchain on the retail's profit

greater than Π_m^T; When the value coefficient of brand credibility v is less than the marginal use cost of the blockchain c_B, the risk coefficient γ has a threshold γ_0, so that the manufacturer's profit Π_m^B is equal to Π_m^T; If γ is less(greater) than γ_0, Π_m^B is less(greater) than Π_m^T.

To facilitate analysis, in Figure 7, the fixed investment of the retailer's blockchain construction F_B in the $B - model$ is assumed equal to the cost paid by the retailer to find a qualified product in the $T - modle$. The impact of the fixed cost of the retailer's blockchain construction F_B on the profit is analyzed in Figure 8. As can be seen from Figure 7, the retailer's profit Π_r^T decreases with the increase of the γ; When the value of brand credibility is greater than the marginal use cost of the blockchain, the retailer's profit Π_r^B is always greater than Π_r^T; When the value coefficient of brand credibility v is less than the marginal use cost of the blockchain c_B, we found that if γ is less(greater) than γ_1, Π_r^B is less(greater) than Π_r^T. In Figure 8, the value coefficient of brand credibility v is assumed equal to the marginal use cost of the blockchain c_B. It can be seen from the figure, F_B and c_B have the same effect on the profit. In summary, whether a retailer should adopt blockchain technology is influenced by the triple(v, c_B, F_B).

6 CONCLUSION

This paper studies the impact of applying blockchain technology on the green supply chain decisions. We found that when certain conditions are met, the application of blockchain technology can effectively improve the economic and environmental benefits of the supply chain. The main conclusions are as follows:

- When the risk of falsification of product energy efficiency data increases, the carbon emission reduction level decreases, making products less competitive in the market. The wholesale price, the order quantity and the selling price decrease accordingly, and the profits of the manufacturer and the retailer decrease, too. The falsification of product energy efficiency data seriously affects the healthy development of the supply chain, increases the burden of government supervision, is not conducive to carbon footprint tracking, and affects the realization of carbon peaking and carbon neutrality goals.
- Cost is an important factor influencing decision-making. When unit production cost increases, the manufacturer will reduce the carbon emission reduction level of products, which is not conducive to the realization of carbon peaking goals. The manufacturer and the retailer should make reasonable pricing decisions based on the size of carbon emission reduction cost and the changing trend of unit production cost.
- Applying blockchain technology has an important impact on supply chain decisions. When the value coefficient of brand credibility increases, the manufacturer will increase the product carbon emission reduction level and the wholesale price. However, the impact on the selling price is relatively complicated. When certain condition is met, the selling price of the product will increase (decrease) with the increase (increase) of the brand credibility value coefficient. The impact of the blockchain marginal usage cost on supply chain decisions are opposite to the impact of the brand credibility value coefficient.
- Applying blockchain requires increased fixed investment and marginal usage cost, but it also helps to improve brand credibility. These three factors jointly determine whether the incremental profit brought by the use of blockchain technology can cover its costs, which is also the key to whether supply chain members choose to apply the technology.

This paper provides some managerial implications:

- The improvement of corporate brand credit brought about by the application of blockchain technology deserves attention. From the perspective of regulatory authorities, the government should pay attention to the positive role of blockchain technology in eliminating the risk of falsification of product energy efficiency data.
- Manufacturer should actively improve production technology and increase production efficiency to reduce production costs. The government should introduce relevant policies to create favorable conditions for green product manufacturer to reduce production costs, thereby promoting carbon emission reduction. At the same time, the manufacturer and the retailer should make reasonable price decisions based on the specific circumstances of each cost to maximize profits.
- Whether an enterprise chooses to apply blockchain technology needs to be comprehensively considered. The government should guide and standardize the behavior of market entities, give relevant policies to reduce the cost of construction and use of blockchain technology, and accelerate the promotion and application of blockchain in green supply chain.

This paper investigates the role of blockchain technology in green supply chain, and analyzes the impact of applying blockchain technology on the decision-making and profits of supply chain members. However, this study has certain limitations, and future research can consider the impact of carbon quotas on green supply chain decision-making; The application and impact of blockchain in carbon trading can be further explored.

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APPENDIX

The derivation of Table I.

(a) $T-model$: From equation 3), we obtain $\frac{\partial^2\Pi_r^T(p)}{\partial p^2}=-2\varepsilon<0$, so $\Pi_r^T(p)$ is a concave function of p. Let $\frac{\partial\Pi_r^T(p)}{\partial p}=0$, we obtain $p=\frac{D+\varepsilon w+\lambda k(1-\gamma)}{2\varepsilon}$, replace $p=\frac{D+\varepsilon w+\lambda k(1-\gamma)}{2\varepsilon}$ in $\Pi_m^T(w,k)$, we obtain $\frac{\partial^2\Pi_m^T(w,k)}{\partial w^2}=-\varepsilon<0$, $\frac{\partial^2\Pi_m^T(w,k)}{\partial w\partial k}=\frac{\lambda(1-\gamma)}{2}$, $\frac{\partial^2\Pi_m^T(w,k)}{\partial k^2}=-z<0$, $\frac{\partial^2\Pi_m^T(w,k)}{\partial k\partial w}=\frac{\lambda(1-\gamma)}{2}$. Hessian Matrix $H_1=\left|\begin{matrix}\frac{\partial^2\Pi_m^T}{\partial w^2} & \frac{\partial^2\Pi_m^T}{\partial w\partial k}\\ \frac{\partial^2\Pi_m^T}{\partial k\partial w} & \frac{\partial^2\Pi_m^T}{\partial k^2}\end{matrix}\right|=\varepsilon z-\frac{\lambda^2(1-\gamma)^2}{4}$, to ensure that the model has a solution, we assume $\varepsilon z-\frac{\lambda^2(1-\gamma)^2}{4}>0$, let $\frac{\partial\Pi_m^T(w,k)}{\partial w}=0$, and $\frac{\partial\Pi_m^T(w,k)}{\partial k}=0$, we have $w_T=\frac{2z(D+\varepsilon c)-c\lambda^2(1-\gamma)^2}{4\varepsilon z-\lambda^2(1-\gamma)^2}$,$k_T=\frac{(D-\varepsilon c)\lambda(1-\gamma)}{4\varepsilon z-\lambda^2(1-\gamma)^2}$, and then replace w_T, k_T in $p=\frac{D+\varepsilon w+\lambda k(1-\gamma)}{2\varepsilon}$, we obtain $p_T=\frac{z(3D+\varepsilon c)-c\lambda^2(1-\gamma)^2}{4\varepsilon z-\lambda^2(1-\gamma)^2}$. Replace p_T, k_T in equation 1), we obtain $q_T=\frac{\varepsilon z(D-\varepsilon c)}{4\varepsilon z-\lambda^2(1-\gamma)^2}$, replace w_T, q_T, k_T in equation 2), we obtain $\Pi_m^T(w_T,k_T)=\frac{z(D-\varepsilon c)^2}{2[4\varepsilon z-\lambda^2(1-\gamma)^2]}$. Replace w_T, q_T, p_T in equation 3), we obtain $\Pi_r^T(p_T)=\frac{2\varepsilon z^2(D-\varepsilon z)^2-c_A A^2[4\varepsilon z-\lambda^2(1-\gamma)^2]^2}{2[4\varepsilon z-\lambda^2(1-\gamma)^2]^2}$.

(b) $B-model$: From equation 6), we obtain $\frac{\partial^2\Pi_r^B(p)}{\partial p^2}=-2\varepsilon<0$, so $\Pi_r^B(p)$ is a concave function of p. Let $\frac{\partial\Pi_r^B(p)}{\partial p}=0$, we obtain $p=\frac{D+\varepsilon w+\lambda k-\varepsilon(v-c_B)}{2\varepsilon}$, replace $p=\frac{D+\varepsilon w+\lambda k-\varepsilon(v-c_B)}{2\varepsilon}$ in $\Pi_m^B(w,k)$, we obtain $\frac{\partial^2\Pi_m^B(w,k)}{\partial w^2}=-\varepsilon<0$, $\frac{\partial^2\Pi_m^B(w,k)}{\partial w\partial k}=\frac{\lambda}{2}$, $\frac{\partial^2\Pi_m^B(w,k)}{\partial k^2}=-z<0$, $\frac{\partial^2\Pi_m^B(w,k)}{\partial k\partial w}=\frac{\lambda}{2}$. Hessian Matrix $H_2=\left|\begin{matrix}\frac{\partial^2\Pi_m^B}{\partial w^2} & \frac{\partial^2\Pi_m^B}{\partial w\partial k}\\ \frac{\partial^2\Pi_m^B}{\partial k\partial w} & \frac{\partial^2\Pi_m^B}{\partial k^2}\end{matrix}\right|=\varepsilon z-\frac{\lambda^2}{4}$, to ensure that the model has a solution, we assume $\varepsilon z-\frac{\lambda^2}{4}>0$, let $\frac{\partial\Pi_m^B(w,k)}{\partial w}=0$, $\frac{\partial\Pi_m^B(w,k)}{\partial k}=0$, we have $w_B=\frac{2z(D+\varepsilon c)-c\lambda^2+(v-c_B)\lambda^2}{4\varepsilon z-\lambda^2}$, $k_B=\frac{[D+\varepsilon(2v-2c_B-c)]\lambda}{4\varepsilon z-\lambda^2}$, and then replace w_B, k_B in $p=\frac{D+\varepsilon w+\lambda k-\varepsilon(v-c_B)}{2\varepsilon}$, we obtain $p_B=\frac{3Dz+(\lambda^2-\varepsilon z)(2v-2c_B-c)}{4\varepsilon z-\lambda^2}$. Replace p_B, k_B in , we obtain $q_B=\frac{D\varepsilon z+\varepsilon^2 z(2v-2c_B-c)}{4\varepsilon z-\lambda^2}$. Replace w_B, q_B, k_B in , we obtain $\Pi_m^B(w_B,k_B)=\frac{z[D+\varepsilon(2v-2c_B-c)]^2}{2(4\varepsilon z-\lambda^2)}$. Replace w_B, q_B, p_B in equation 6), we obtain $\Pi_r^B(p_B)=\frac{\varepsilon z^2[D+\varepsilon(2v-2c_B-c)]^2-F_B(4\varepsilon z-\lambda^2)^2}{(4\varepsilon z-\lambda^2)^2}$.

Proof of Proposition 1.
$\frac{\partial k_T}{\partial \gamma} = \frac{-(D-\varepsilon c)\lambda[4\varepsilon z+\lambda^2(1-\gamma)^2]}{[4\varepsilon z-\lambda^2(1-\gamma)^2]^2} < 0, \frac{\partial p_T}{\partial \gamma} = \frac{-6z(D-\varepsilon c)\lambda^2(1-\gamma)}{[4\varepsilon z-\lambda^2(1-\gamma)^2]^2} < 0$,
$\frac{\partial q_T}{\partial \gamma} = \frac{-2\varepsilon z(D-\varepsilon c)\lambda^2(1-\gamma)}{[4\varepsilon z-\lambda^2(1-\gamma)^2]^2} < 0$, $\frac{\partial w_T}{\partial \gamma} = \frac{-4z(D-\varepsilon c)\lambda^2(1-\gamma)}{[4\varepsilon z-\lambda^2(1-\gamma)^2]^2} < 0$.

Proof of Proposition 2. (1) $\frac{\partial k_B}{\partial c} = \frac{-\varepsilon\lambda}{4\varepsilon z-\lambda^2} < 0$;
(2) If $\frac{\lambda^2}{4\varepsilon} < z < \frac{\lambda^2}{2\varepsilon}$, $\frac{\partial w_B}{\partial c} = \frac{2\varepsilon z-\lambda^2}{4\varepsilon z-\lambda^2} < 0$, $\frac{\partial p_B}{\partial c} = \frac{\varepsilon z-\lambda^2}{4\varepsilon z-\lambda^2} < 0$;
(3) If $\frac{\lambda^2}{2\varepsilon} \leq z < \frac{\lambda^2}{\varepsilon}$, $\frac{\partial w_B}{\partial c} = \frac{2\varepsilon z-\lambda^2}{4\varepsilon z-\lambda^2} \geq 0$, $\frac{\partial p_B}{\partial c} = \frac{\varepsilon z-\lambda^2}{4\varepsilon z-\lambda^2} < 0$;
(4) If $\frac{\lambda^2}{\varepsilon} \leq z$, $\frac{\partial w_B}{\partial c} = \frac{2\varepsilon z-\lambda^2}{4\varepsilon z-\lambda^2} > 0$, $\frac{\partial p_B}{\partial c} = \frac{\varepsilon z-\lambda^2}{4\varepsilon z-\lambda^2} \geq 0$.

Proof of Proposition 3. (1) $\frac{\partial k_B}{\partial v} = \frac{2\varepsilon\lambda}{4\varepsilon z-\lambda^2} > 0$, $\frac{\partial w_B}{\partial v} = \frac{\lambda^2}{4\varepsilon z-\lambda^2} > 0$;
(2) If $\frac{\lambda^2}{4\varepsilon} < z < \frac{\lambda^2}{\varepsilon}, \frac{\partial p_B}{\partial v} = \frac{2(\lambda^2-\varepsilon z)}{4\varepsilon z-\lambda^2} > 0$; If $\frac{\lambda^2}{\varepsilon} \leq z$, $\frac{\partial p_B}{\partial v} = \frac{2(\lambda^2-\varepsilon z)}{4\varepsilon z-\lambda^2} \leq 0$.

Proof of Proposition 4. (1) $\frac{\partial w_B}{\partial c_B} = \frac{-\lambda^2}{4\varepsilon z-\lambda^2} < 0$, $\frac{\partial k_B}{\partial c_B} = \frac{-2\varepsilon\lambda}{4\varepsilon z-\lambda^2} < 0$.
(2) If $\frac{\lambda^2}{4\varepsilon} < z < \frac{\lambda^2}{\varepsilon}$, $\frac{\partial p_B}{\partial c_B} = \frac{-2(\lambda^2-\varepsilon z)}{4\varepsilon z-\lambda^2} < 0$; If $\frac{\lambda^2}{\varepsilon} \leq z$, $\frac{\partial p_B}{\partial c_B} = \frac{-2(\lambda^2-\varepsilon z)}{4\varepsilon z-\lambda^2} \geq 0$.

Proof of Proposition 5. From $w_B - w_T \geq 0$, we obtain $TH_1 = \frac{-2z\gamma(D-\varepsilon c)(1-\gamma)}{4\varepsilon z-\lambda^2(1-\gamma)^2}$; From $k_B - k_T \geq 0$, we obtain $TH_2 = \frac{-\gamma(D-\varepsilon c)[4\varepsilon z+\lambda^2(1-\gamma)]}{2\varepsilon[4\varepsilon z-\lambda^2(1-\gamma)^2]}$; From $p_B - p_T \geq 0$, we obtain $TH_3 = \frac{-3z\gamma\lambda^2(D-\varepsilon c)(2-\gamma)}{2(\lambda^2-\varepsilon z)[4\varepsilon z-\lambda^2(1-\gamma)^2]}$.