International Journal of Emerging Trends in Social Sciences
ISSN: 2521-3539
Vol. 16, No. 1, pp. 13-21, 2024
DOI: 10.55217/103.v16i1.727

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Blockchain-driven dual-channel green supply chain game model considering government subsidies

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Abstract

In order to improve the performance of green supply chain and promote the adoption of blockchain, this paper establishes a dual-channel green supply chain consisting of a green manufacturer and a retailer, and builds Stackelberg game model considering different scenarios. We analyze the impact of blockchain operating costs and consumer uncertainty about the product greenness. Furthermore, we study the government subsidy for manufacturers' green costs and its impact on supply chain performance and blockchain adoption. Findings reveal that without blockchain technology, government subsidy can improve manufacturers' and retailers' profits. However, when blockchain is adopted, the subsidy effect depends on the blockchain operating costs. In case of higher blockchain operating cost, the product prices and greenness decrease as the green cost subsidies increase; In case of lower blockchain operating cost, the increase in green cost subsidies will lead to increased product prices and greenness; Green cost subsidies can raise profits and lower the blockchain adoption threshold.

Keywords:
Blockchain
Dual-channel green supply chain
Government subsidies
Stackelberg game.

Publisher:
Scientific Publishing Institute

Received: *19 October 2023*
Revised: *21 December 2023*
Accepted: *8 January 2024*
Published: *16 January 2024*

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Funding: This study received no specific financial support.
Institutional Review Board Statement: Not applicable.
Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: Performed the data analysis, Y.X.; wrote the manuscript, K.Z. Both authors have read and agreed to the published version of the manuscript.

1. Introduction

With the ongoing rapid socio-economic development, environmental pollution and resource scarcity issues have become increasingly prominent. However, the pursuit of new development models and the reconciliation of economic and environmental considerations cannot be accomplished by individual companies. This requires collaborative efforts among companies within the supply chain to enhance economic performance, mitigate environmental pollution, and optimize resource utilization. Green supply chain management emerges as a crucial mechanism to achieve this goal.

Besides governmental efforts to promote green development, consumers' willingness to buy eco-friendly products is on the rise, with more consumers having green preference. According to PwC's 2019 Global Consumer Insights Survey, 35% of respondents were inclined to choose green products in order to protect the environment, whereas 37% of respondents expressed a preference for eco-friendly packaged products, and 41% said they would try to avoid using plastic bags and other pollutants.

In light of the above-mentioned government policies supporting green production, consumer awareness of environmental protection, and the development of information technology, e-commerce platforms are emerging. More and more green manufacturers are selling through both online and offline channels, aiming to build a dual-channel green supply chain and realize the coordinated development of economy, environment and society.

However, in the field of green supply chain, there are still numerous challenges, even though more and more manufacturers are producing environmentally friendly products, launching low-carbon green campaigns, and educating consumers about the difference between green products and traditional products. Information asymmetry and the challenge of authenticating green data affect consumer trust in products. Consumer uncertainty about the greenness of products may inhibit consumers' green preferences and willingness to pay, thus having a significant impact on the sales of green products. In this context, the incorporation of emerging technologies like blockchain and the Internet of Things (IoT) to tackle specific challenges in the advancement of green supply chains becomes a vital subject.

In recent years, blockchain has been increasingly applied in green supply chain management and is considered a disruptive technology that fosters the development of green supply chains. Blockchain, with its distributed data storage structure, enables shared decentralized digital ledger among participants. Unlike earlier centralized information-sharing mechanisms, blockchain, as an innovative distributed and decentralized technology, adeptly tackles the complexities of multi-party and bilateral information exchange (2021). With the advantages of data immutability, traceability, and the establishment of trust, the application of blockchain technology could help promote consumer's green behavior, enhance visibility into product lifecycles, boost operational efficiency of supply chains, and fortify green monitoring and information dissemination. For example, BYD New Energy Vehicle Company uses blockchain technology to establish carbon credit circulation platforms and third-party exchange systems, incentivizing environmentally conscious consumer conduct and augmenting transparency in green credentials.

However, due to the additional operating costs associated with blockchain technology, not all companies choose to implement it. To promote the application of blockchain technology and the development of green supply chains, governments have introduced series of policies and measures, such as government subsidy policies.

In this context, the paper establishes a dual-channel green supply chain comprising green manufacturer and retailer. It intends to investigate the government green cost subsidies to manufacturers. The study will explore the impact of green cost subsidies on the application of blockchain technology and the impact on the performance of the green supply chain. It aims to offer decision recommendations to manufacturers regarding the application of blockchain and serve as a reference for government subsidy policies.

The remainder of the paper is structured as follows: Section II presents the related literature. Section III introduces the model formulation. Section IV analyzes different scenarios, examining the influence of government subsidies and blockchain technology. Section V conducts comparisons and numerical analysis. Section VI concludes the paper with managerial insights and future research opportunities.

2. Literature Review

The paper reviews the relevant literature in the following three areas: dual-channel green supply chain, blockchain technology application, and government subsidy.

2.1. Dual-Channel Green Supply Chain

In recent years, the research of dual-channel green supply chain has received the attention of many scholars. Liang and Zhang (2020) taking consumer preferences into account, explored optimal pricing and emission reduction decisions within a low-carbon dual-channel supply chain. Zhang, Liu, and Han (2021) studied dynamic pricing and green strategies in a dual-channel supply chain, emphasizing the impact of reference price on supply chain performance. Wu, Lin, and Xu (2022) established a dual-channel supply chain model comparing both centralized and decentralized decision making and found that manufacturers and retailers tend to participate in a dual-channel supply chain when specific conditions related to dual-channel market share are satisfied. Wang, Jiang, and Yu (2020) examined a dual-channel closed-loop green supply chain considering product customization and three models for collecting used products and found that the retailer collection model was the most effective for the entire supply chain. Rahmani and Yavari (2019) explored demand disruption management in dual-channel green supply chains, comparing centralized and decentralized approaches, emphasizing the impact of disruptions on green product pricing and production. Wu et al. (2022) incorporated consumers' green preferences into their study to explore the impact of retailer fairness concerns on pricing strategies and coordination within dual-channel green supply chains.

To summarize, research on pricing and coordination mechanisms of dual-channel green supply chain has gained much attention in recent years, but little literature has considered the impact of blockchain technology on green supply chain decisions.

2.2. Blockchain Technology Application

Due to the advantages of its technical features, blockchain has made its debut in scenarios such as anti-counterfeiting and traceability and green supply chain management. Wang, Zheng, Jiang, and Tang (2021) designed and implemented a blockchain-enabled data sharing marketplace for supply chains, and showed how blockchain could be used to overcome some of the barriers in supply chain data sharing. Chen, Hu, Wang, and Wu (2023) utilized a quasi-natural experiment to study how blockchain technology can solve the problems due to incomplete supply chain contracts. Lin, Liu, and Wang (2022) leveraged the unique attributes of blockchain to establish a Stackelberg game model for green supply chains, analyzing the prerequisites for implementing blockchain technology within sustainable supply chains. Xu, Zhang, Dou, and Yu (2023) considered network effects in a supply chain where manufacturers adopt blockchain, and found that blockchain technology could improve product greenness and profitability of manufacturers and platforms. Li, Ma, Shi, and Zhu (2022) examined green investment in sustainable supply chains, considering blockchain adoption by manufacturers and fairness concerns of retailers. Wang and Zhang (2023) harnessed blockchain technology to enhance transparency in quality information, while considering the added advantages and associated costs. They also investigated the circumstances in which retailers embrace blockchain technology. Shen, Dong, and Minner (2022) investigated the application of blockchain technology in countering counterfeiting, and explored its implications on brand companies' profits, consumer surplus, and product quality. Hu, Cao, and Li (2022) scrutinized the adoption of blockchain strategies by enterprises in the context of four competitive models, encompassing both strong and weak brand competition. They assessed the effects of these strategies on quality and pricing decisions through the transmission of information.

In general, little literature considered the operating costs of blockchain technology and consumer uncertainty about product greenness.

2.3. Government Subsidy Mechanism

In promoting green development policies, many scholars have conducted in-depth studies on government subsidy strategies. Feng, Wang, Zhang, and Feng (2022) examined the impact of government subsidies on secondary green supply chains based on consumers' green preferences and investigated how manufacturers' social responsibility affects their operations. Li, Geng, Xia, and Qiao (2021) employed game theory to assess government subsidies' impact on the low-carbon supply chain. Meng, Li, Liu, Li, and Zhang (2021) analyzed a dual-channel green supply chain using Stackelberg game theory based on the consideration of consumer preferences and government subsidies. Cao, Zhou, and Hu (2020) discussed the impact of government subsidies on optimal production and social responsibility investment decisions within the supply chain. Pan, Wang, and Tian (2023) constructed a three-stage Stackelberg game model to investigate the effects of retailer fairness concerns and government subsidies on pricing strategies and greenness. Zhang, Peng, and Cheng (2023) studied the influence of consumer low-carbon preference coefficients and green trust coefficients on government subsidy strategies in low-carbon supply chains.

The aforementioned research primarily focuses on the impact of government subsidies on supply chain performance and the green effort of supply chain entities. However, there is limited literature that studied the effects of government subsidies on the adoption of blockchain in a dual-channel green supply chain, considering its operating costs and consumers' uncertainty regarding greenness. Therefore, this paper will comprehensively analyze the impact of government subsidies and the blockchain technology on the dual-channel green supply chain.

3. Model Description and Assumption

3.1. Model Description

This paper analyzes a dual-channel green supply chain composed of one manufacture and one retailer, denoted as subscripts "M" and "R", respectively. The manufacturer produces a green product, which, in the traditional retail channel (Denoted as "t"), is sold to retailer at a wholesale price "w", and the retailer subsequently sells to consumers at a retail price "p_t", where it is evident that "$p_t \geq w$". In the online direct sales channel (denoted as "d"), the manufacturer directly sells the product to consumers at a price "p_d". It is assumed that the retailer can only purchase products from the manufacturer through wholesale channels and cannot acquire products via the online channel. This paper discusses the scenario where the government provides a green cost subsidy "τ" $(0 \leq \tau \leq 1)$ to the manufacturer. The supply chain structure with government subsidies is illustrated in Figure 1.

For many green products, such as new energy electric vehicles and sustainable fashion, manufacturers typically possess significant bargaining power over retailers due to their ownership of key technologies for green production. In these scenarios, manufacturers often play a leadership role in the green supply chain, with retailers acting as followers. As a result, the decision sequence follows a Stackelberg game led by the manufacturers in the green supply chain. The government first decides on its subsidy parameters(coefficient), represented as τ. The event sequence of the dual-channel green supply chain under government subsidies is shown in Figure 2.

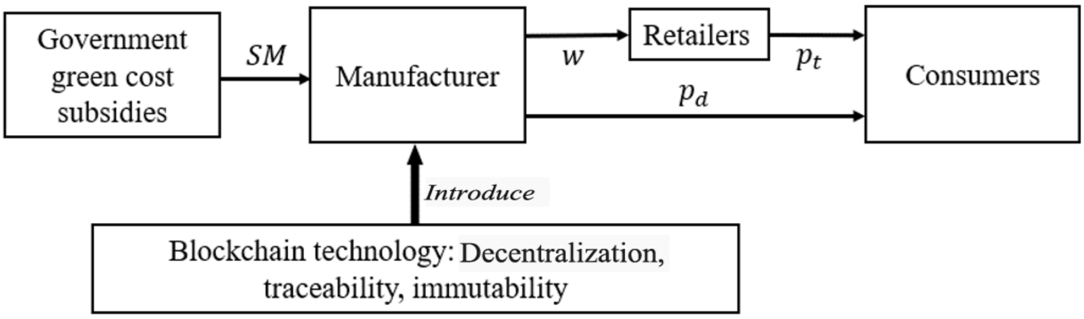


Figure 1. Green supply chain structure diagram with government subsidies.

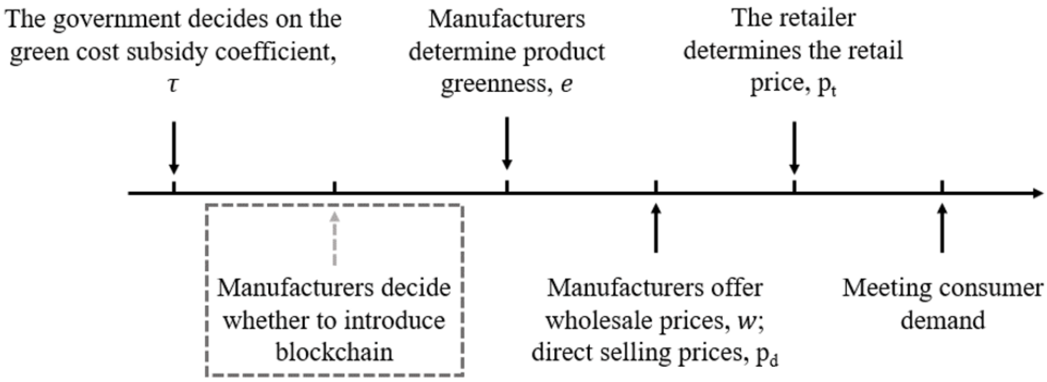


Figure 2. The event sequence of green supply chain under government subsidies.

3.2. Model Assumption

The game model parameters and decision variables are described in Table 1:

Table 1. Game model symbol and description.

Symbol	Description
β	Consumer green preference
a	Potential market size for green products
b	Price elasticity coefficient of green products
α	Consumer sensitivity to cross-channel price
c_b	Unit operating cost of blockchain
k	Cost coefficient for manufacturer's green effort
γ	Degree of uncertainty of consumer perception of product greenness
τ	Government subsidy coefficient for manufacturer's green effort cost
$D_i(i = d, t)$	The direct marketing and distribution market demand
π_i	The profit functions of government-subsidized manufacturers
N、B	Traditional supply chain / Blockchain-supported supply chain
Symbol	Decision variable description
w	Wholesale prices
p_d	Manufacturer's direct sales price
p_t	Retail price
e	Product greenness level

The following basic assumptions are made to facilitate the subsequent solution analysis:

Assumption 1: The unit production cost of manufacturers does not impact research results, and the unit production cost of green products is assumed to be zero for model simplification.

Assumption 2: Manufacturers produce green products with a greenness level "e" and sell them to retailers at a wholesale price "w". The green effort cost for manufacturers is expressed as $C(e) = \frac{1}{2}ke^2$, where "k" is the cost coefficient for green production.

Assumption 3: Consumers encounter a uniform potential market for green products with a market size denoted as "a." Consumers autonomously choose between online and offline channels for green product purchases.

Assumption 4: The introduction cost of blockchain technology is considered a fixed sunk cost and is not integrated into the model. The unit operating cost of blockchain is denoted as "c_b."

Assumption 5: Without the introduction of blockchain, due to information asymmetry, consumers lack full trust in product greenness, resulting in uncertainty denoted as "γ."

Assumption 6: Without blockchain, the direct and distribution market demands for green products are formulated as: $D_d^N = a - bp_d + \alpha p_t + (1-\gamma)\beta e$ and $D_t^N = a - bp_t + \alpha p_d + (1-\gamma)\beta e$, respectively. Blockchain implementation reduces γ to zero, leading to market demands: $D_d^B = a - bp_d + \alpha p_t + \beta e$ and $D_t^B = a - bp_t + \alpha p_d + \beta e$, respectively.

Assumption 7: The government provides a green cost subsidy "τ" ($0 \le \tau \le 1$) to manufacturers. Superscripts "SM" represent government subsidies to manufacturers.

4. Model Construction and Solution

4.1. The Subsidy Model of Green Cost without Blockchain

In the absence of blockchain technology, the government implements a subsidy program for manufacturers, assuming a portion of manufacturer's green production costs. The subsidy ratio is denoted as τ ($0 \le \tau \le 1$). In this scenario, the manufacturer's profit function is as follows:

$$\pi_M^{NSM} = wD_t^N + p_d D_d^N - \frac{1}{2}(1-\tau)ke^2 \tag{1}$$

The retailer's profit function is as follows:

$$\pi_R^{NSM} = (p_t - w)[a - bp_t + \alpha p_d + (1-\gamma)\beta e] \tag{2}$$

Lemma 1. In the absence of blockchain technology, and under a government subsidy program for manufacturers, there exists a unique set of values that maximize the profits of both manufacturer and retailer. In this scenario, the optimal decisions of the supply chain, including the wholesale price w^{NSM*}, the direct sales price p_d^{NSM*}, the product greenness level e^{NSM*}, the optimal retail price p_t^{NSM*}, as well as the manufacturers' optimal profit $\pi_M^{NSM*}$and retailers' optimal profit π_R^{NSM*}, are as follows:

$$w^{NSM*} = \frac{2abk(-1+\tau)}{3b\beta^2(-1+\gamma)^2 + \alpha\beta^2(-1+\gamma)^2 + 4b^2k(-1+\tau) - 4bk\alpha(-1+\tau)} \tag{3}$$

$$p_d^{NSM*} = \frac{2abk(-1+\tau)}{3b\beta^2(-1+\gamma)^2 + \alpha\beta^2(-1+\gamma)^2 + 4b^2k(-1+\tau) - 4bk\alpha(-1+\tau)} \tag{4}$$

$$e^{NSM*} = \frac{a(3b+\alpha)\beta(-1+\gamma)}{3b\beta^2(-1+\gamma)^2 + \alpha\beta^2(-1+\gamma)^2 + 4b^2k(-1+\tau) - 4bk\alpha(-1+\tau)} \tag{5}$$

$$p_t^{NSM*} = \frac{ak(3b-\alpha)(-1+\tau)}{3b\beta^2(-1+\gamma)^2 + \alpha\beta^2(-1+\gamma)^2 + 4b^2k(-1+\tau) - 4bk\alpha(-1+\tau)} \tag{6}$$

$$\pi_M^{NSM*} = \frac{a^2k(3b+\alpha)(-1+\tau)}{6b\beta^2(-1+\gamma)^2 + 2\alpha\beta^2(-1+\gamma)^2 + 8b^2k(-1+\tau) - 8bk\alpha(-1+\tau)} \tag{7}$$

$$\pi_R^{NSM*} = \frac{a^2bk^2(b-\alpha)^2(-1+\tau)^2}{(3b\beta^2(-1+\gamma)^2 + \alpha\beta^2(-1+\gamma)^2 + 4b^2k(-1+\tau) - 4bk\alpha(-1+\tau))^2} \tag{8}$$

Proof: To solve this model, inverse induction is used for the analysis. First, we calculate the first-order partial derivative of Equation 2 with respect to p_t,we get $\frac{\partial \Pi_R^{NSM}}{\partial p_t} = a + b(-2p_t + w) + p_d\alpha + e\beta - e\beta\gamma$. Next, by setting $\frac{\partial \Pi_R^{NSM}}{\partial p_t} = 0$, then we get $p_{t1}^{NSM*} = \frac{a + bw + p_d\alpha + e\beta - e\beta\gamma}{2b}$.

Subsequently, we substitute p_{t1}^{NSM*} into the manufacturer's profit function Equation 1 to derive π_{M1}^{NSM}. We then compute the first-order partial derivatives of π_{M1}^{NSM} with respect to w, p_d, and e. Since the objective function involves multiple variables, we need to compute the Hessian matrix $H(\pi_M^{NSM})$ to judge the extremum. We find that to make the Hessian matrix a negative definite matrix, ensuring the existence of an optimal solution, it is necessary for $H(\pi_M^{NSM})_{33} = \frac{(b+\alpha)(3b\beta^2(-1+\gamma)^2 + \alpha\beta^2(-1+\gamma)^2 + 4b^2k(-1+\tau) - 4bk\alpha(-1+\tau))}{2b}$, $H(\pi_M^{NSM})_{22} = 2(b^2 - \alpha^2) > 0$, This condition must be met for the existence of an optimal solution.

With these results, we set the first-order partial derivatives to zero, enabling us to determine the optimal wholesale price w^{NSM*}, the optimal direct selling price p_d^{NSM*}, and the optimal product greenness level e^{NSM*}. Finally, we calculate p_t^{NSM*}, π_M^{NSM*}, and π_R^{NSM*} accordingly, concluding the proof.

Proposition 1. w^{NSM*}, p_d^{NSM*}, p_t^{NSM*}, e^{NSM*}, π_M^{NSM*}, and π_R^{NSM*} exhibit an upward trend as the green cost subsidy coefficient τ increases. Therefore, the optimal wholesale price, optimal greenness level, and optimal profits are positively correlated with the government's green cost subsidy coefficient τ.

Proof: By calculating their first-order partial derivatives concerning the green cost subsidy coefficient τ, we ascertain that $\frac{\partial w^{NSM*}}{\partial \tau} > 0$, $\frac{\partial p_d^{NSM*}}{\partial \tau} > 0$, $\frac{\partial p_t^{NSM*}}{\partial \tau} > 0$, $\frac{\partial e^{NSM*}}{\partial \tau} > 0$, $\frac{\partial \pi_M^{NSM*}}{\partial \tau} > 0$, and $\frac{\partial \pi_R^{NSM*}}{\partial \tau} > 0$.

4.2. The Subsidy Model for Green Cost with Blockchain

With the implementation of blockchain technology, the consumer uncertainty γ about the product greenness is eradicated, resulting in $\gamma = 0$. Moreover, the implementation of blockchain incurs a unit operating cost c_b. The government subsidies a portion of the manufacture's green production cost, represented as τ $(0 \le \tau \le 1)$. Thus, the manufacture's profit function is as follows:

$$\pi_M^{BSM} = (w - c_b)D_t^B + (p_d - c_b)D_d^B - \frac{1}{2}(1-\tau)ke^2 \quad (17)$$

The retailer profit function is as follows:

$$\pi_R^{BSM} = (p_t - w)(a - bp_t + \alpha p_d + \beta e) \quad (18)$$

Lemma 3. In the blockchain subsidy model for manufacturers' green effort costs, there exists a unique set of values that maximize the profits of manufacturers and retailers. In this case, the supply chain decisions, including the optimal wholesale price w^{BSM*}, the optimal direct sales price p_d^{BSM*}, the optimal product greenness level e^{BSM*}, the optimal retail price p_t^{BSM*}, as well as the optimal profits for manufacturers π_M^{BSM*} and retailers π_R^{BSM*}, are as follows.

$$w^{BSM*} = \frac{c_b(3b\beta^2 + \alpha\beta^2 + 2b^2k(-1+\tau) - 2bk\alpha(-1+\tau)) + 2abk(-1+\tau)}{3b\beta^2 + \alpha\beta^2 + 4b^2k(-1+\tau) - 4bk\alpha(-1+\tau)} \quad (19)$$

$$p_d^{BSM*} = \frac{c_b(3b\beta^2 + \alpha\beta^2 + 2b^2k(-1+\tau) - 2bk\alpha(-1+\tau)) + 2abk(-1+\tau)}{3b\beta^2 + \alpha\beta^2 + 4b^2k(-1+\tau) - 4bk\alpha(-1+\tau)} \quad (20)$$

$$e^{BSM*} = -\frac{(3b+\alpha)(a + c_b(-b+\alpha))\beta}{3b\beta^2 + \alpha\beta^2 + 4b^2k(-1+\tau) - 4bk\alpha(-1+\tau)} \quad (21)$$

$$p_t^{BSM*} = \frac{ak(3b-\alpha)(-1+\tau) + c_b(3b\beta^2 + b^2k(-1+\tau) + \alpha(k\alpha + \beta^2 - k\alpha\tau))}{3b\beta^2 + \alpha\beta^2 + 4b^2k(-1+\tau) - 4bk\alpha(-1+\tau)} \quad (22)$$

$$\pi_M^{BSM*} = \frac{k(3b+\alpha)(a + c_b(-b+\alpha))^2(-1+\tau)}{6b\beta^2 + 2\alpha\beta^2 + 8b^2k(-1+\tau) - 8bk\alpha(-1+\tau)} \quad (23)$$

$$\pi_R^{BSM*} = \frac{bk^2(b-\alpha)^2(a + c_b(-b+\alpha))^2(-1+\tau)^2}{(3b\beta^2 + \alpha\beta^2 + 4b^2k(-1+\tau) - 4bk\alpha(-1+\tau))^2} \quad (24)$$

Proof: Similar to the proof of Lemma 1, we find the conditions for the existence of an optimal solution, which is $k > -\frac{(3b+\alpha)\beta^2}{4b(b-\alpha)(-1+\tau)}$.

Proposition 3. In the presence of blockchain technology, when the blockchain operating cost $c_b > \frac{a}{b-\alpha}$, different from the prior research, the optimal wholesale price w^{BSM*}, the optimal direct sales price p_d^{BSM*}, the optimal retail price p_t^{BSM*}, and the optimal greenness e^{BSM*}, are negatively correlated with the green cost subsidy coefficient τ. When the blockchain operating cost $c_b < \frac{a}{b-\alpha}$, w^{BSM*}, p_d^{BSM*}, p_t^{BSM*}, e^{BSM*} are positively correlated with the green cost subsidy coefficient τ.

Proof: In the game model that involves the implementation of blockchain and the subsidization of manufacturers' green costs, when $c_b > \frac{a}{b-\alpha}$, the following relationships hold: $\frac{\partial w^{BSM*}}{\partial \tau} < 0$, $\frac{\partial p_d^{BSM*}}{\partial \tau} < 0$, $\frac{\partial p_t^{BSM*}}{\partial \tau} < 0$, and $\frac{\partial e^{BSM*}}{\partial \tau} < 0$. However, when $0 < c_b < \frac{a}{b-\alpha}$, the following relationships hold: $\frac{\partial w^{BSM*}}{\partial \tau} > 0$, $\frac{\partial p_d^{BSM*}}{\partial \tau} > 0$, $\frac{\partial p_t^{BSM*}}{\partial \tau} > 0$, and $\frac{\partial e^{BSM*}}{\partial \tau} > 0$.

Proposition 4. When $0 < c_b < \frac{a}{b-\alpha}$ or $c_b > \frac{a}{b-\alpha}$, an increase in the green cost subsidy coefficient τ leads to higher π_M^{BSM*} and π_R^{BSM*}. This demonstrates a positive correlation between the optimal profits of manufacturers and retailers and the government's green cost subsidy coefficient τ.

Proof: As long as $c_b \neq \frac{a}{b-\alpha}$, we have: $\frac{\partial \pi_M^{BSM*}}{\partial \tau} > 0$ and $\frac{\partial \pi_R^{BSM*}}{\partial \tau} > 0$.

5. Numerical Analysis and Discussion

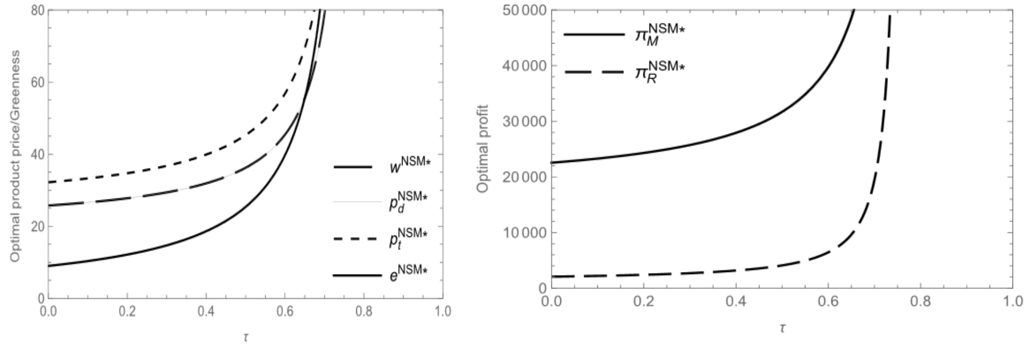
In order to explore deeper into the interplay of pricing, greenness, and profitability among the supply chain members in our model, and to provide a more lucid presentation of these transformations and their corresponding implications, we undertake a numerical analysis in the subsequent section. This analysis aims to elucidate the impact of government subsidy on supply chain performance and their implications for the introduction of blockchain. It serves as a reference for the government and green manufacturers in promoting green development and the adoption of blockchain.

To ensure the coherence of the numerical analysis, we establish the following assumptions regarding the market characteristics of the dual-channel green supply chain system, while taking into consideration the previously mentioned assumptions and parameter ranges, as well as the practical realities of green supply chain operations: $a = 1000$, $b = 50$, $\alpha = 25$, $\beta = 40$, $c_b = 20$, $0 \le \gamma \le 1$, and $k = 160$.

5.1. Impact of Green Cost Subsidy

5.1.1. Without Blockchain Implementation

Based on Figure 3, in the absence of blockchain technology, the optimal wholesale price w^{NSM*}, optimal direct sales price p_d^{NSM*}, optimal retail price p_t^{NSM*}, optimal product greenness level e^{NSM*}, as well as the optimal profits for manufacturers π_M^{NSM*} and retailers π_R^{NSM*} all increase with the government subsidy for manufacturers τ. The government green cost subsidy τ encourages manufacturers to invest more in green production, resulting in cost increases. Consequently, w^{NSM*}, p_d^{NSM*}, and p_t^{NSM*} also increase. Due to the rise of product greenness level, demand also increases. Even with price increases, both manufacturers and retailers' optimal profits increase. This confirms the conclusion of Proposition 1.

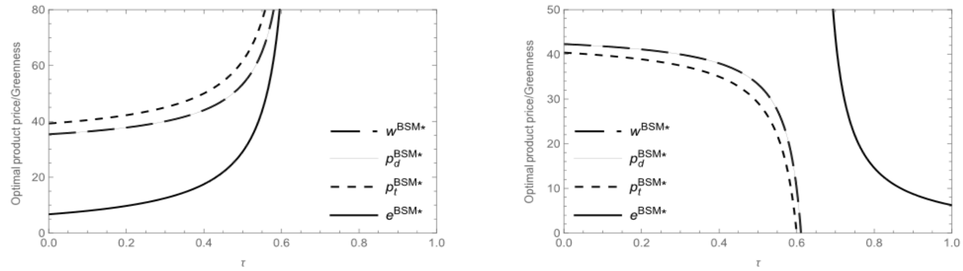


(a) Impact of τ on w^{NSM*}, p_d^{NSM*}, p_t^{NSM*}, and e^{NSM*} *(b) Impact of τ on π_M^{NSM*} and π_R^{NSM*}*

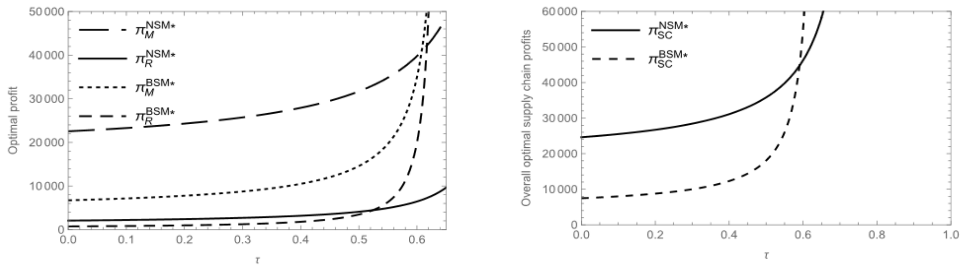
Figure 3. Impact of τ on optimal product price, greenness and profits.

5.1.2. With Blockchain Implementation

Based on Figure 4 a and Figure 4 b, it can be seen that when $c_b < \frac{a}{b-\alpha}$, with the increase in the green cost subsidy τ, manufacturers tend to invest more in green production due to the relatively low operating cost of blockchain technology c_b, leading to increase in e^{BSM*}, w^{BSM*}, p_d^{BSM*}, and p_t^{BSM*}. However, when $c_b > \frac{a}{b-\alpha}$, with higher operating cost of blockchain, manufacturers tend to reduce or even choose not to adopt blockchain technology. Even if green cost subsidy τ increases, manufacturer decreases its investments in green production, resulting in decreased greenness e^{BSM*}. Manufacturer chooses to lower price to stimulate market demand, and retailer subsequently lowers the price p_t^{BSM*}.



(a) Impact of τ on w^{BSM*}, p_d^{BSM*}, p_t^{BSM*}, and e^{BSM*} ($c_b < \frac{a}{b-\alpha}$) *(b) Impact of τ on w^{BSM*}, p_d^{BSM*}, p_t^{BSM*}, and e^{BSM*} ($c_b > \frac{a}{b-\alpha}$)*



(c) Impact of τ on π_M^{NSM*}, π_R^{NSM*}, π_M^{BSM*}, and π_R^{BSM*} *(d) Impact of τ on π_{SC}^{NSM*} and π_{SC}^{BSM*}*

Figure 4. Impacts of τ on the product price, greenness and profits under blockchain.

Examining Figure 4 c and Figure 4 d, it becomes evident that an increase in the green production cost τ leads to an upward trend in profits for both green manufacturers and retailers, as well as the overall supply chain. Additionally, the figures illustrate that as the green cost subsidy τ increases, initially, the optimal profit without blockchain implementation exceeds that with blockchain implementation. Nevertheless, when the government's green cost subsidy τ reaches a sufficiently high level, the optimal profit with blockchain implementation surpasses that without blockchain implementation. This highlights that significant government green cost subsidies τ incentivize green manufacturers to adopt blockchain technology, reducing the entry barrier for blockchain implementation, and facilitating the convergence of blockchain technology and green supply chains.

6. Conclusion

This paper has established a leading manufacturer and a subordinate retailer within a dual-channel green supply chain system. It takes into account the impact of blockchain and government subsidy on pricing, greenness, and profits of supply chain members. Furthermore, it explores their effects on the implementation of blockchain technology. The following conclusions were reached:

(1) In the green cost subsidy model, when blockchain technology is not introduced, product prices and greenness increase with the rise in the green cost subsidy τ. However, when blockchain technology is introduced, the effectiveness of the green cost subsidy also depends on the operating cost of blockchain c_b. When the operating cost is high, manufacturers tend to reduce blockchain usage, decrease green investments, and lower product greenness.

(2) Without blockchain, the optimal profit of green manufacturers and retailers will rise with the increase of government subsidy. However, with the introduction of blockchain, the effect of government subsidy is affected by the operating cost of blockchain. When the operating cost $c_b \neq \frac{a}{b-\alpha}$, the optimal profit of the manufacturers and retailers increases with the rise of the subsidy coefficient τ. When the operating cost of blockchain technology is relatively low, the green cost subsidies can result in enhanced optimal profits, consequently promoting the adoption of blockchain technology.

This study includes managerial insights for supply chain stakeholders, particularly green manufacturers and government policymakers, aiming to promote green innovation and reform within the supply chain. However, this study has certain limitations as it primarily considers a single government subsidy strategy and does not account for the effects of mixed subsidy strategies. This could be explored as a potential direction for future research.

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