Game theory analysis of operational decision-making in green supply chain: the impact of consumer preferences

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Abstract. In the current global context of increasing emphasis on sustainable development, high carbon emissions and resource waste in traditional supply chains have become critical factors affecting supply chain efficiency. This paper conducts an in-depth analysis of green supply chain operational decisions from the perspective of consumer green preferences, utilizing game theory. Through the construction of Nash equilibrium, Stackelberg competition, and cooperative game models, this study explores the decision-making behaviors of suppliers and retailers and their interaction mechanisms under different game scenarios. The research findings indicate that as consumer green preferences strengthen, the level of green investment by various supply chain parties significantly increases. Under Nash equilibrium conditions, the optimal wholesale price rises with the increase in consumer green preferences, thereby enhancing the overall profit of the supply chain. Furthermore, cooperative game results demonstrate that supply chain participants can achieve maximized total profits through cooperation, outperforming the performance under Nash equilibrium and Stackelberg competition models. Therefore, the significance and value of this research lie in providing theoretical and practical support for addressing issues of green strategic planning and cooperation mechanisms in supply chains, particularly emphasizing the impact of consumer green preferences on supply chain strategies and operational decisions.

1 Introduction

With the escalating global environmental challenges, the high carbon emissions and resource waste in traditional supply chains have exerted significant pressure on ecosystems and society. In response to these challenges, an increasing number of enterprises are adopting Green Supply Chain Management (GSCM), aiming to optimize environmental performance across all supply chain links to mitigate negative environmental impacts. The core objectives of GSCM are to reduce, reuse, and recycle resources and energy, thereby improving environmental performance and corporate competitiveness [1, 2]. Implementing GSCM not only helps reduce environmental impact but also achieves effective resource utilization and operational cost reduction, enabling enterprises to maintain a competitive edge in the fierce

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market competition [3, 4]. Research indicates that GSSCM implementation can enhance corporate business value and market performance by meeting market demands for sustainable development through the provision of environmentally friendly products, while simultaneously establishing a positive brand image in competition [5]. To achieve these goals, enterprises must systematically integrate environmental standards into their supply chains and effectively manage supplier environmental responsibilities [6]. This integration not only meets stringent regulatory requirements but also promotes the improvement of operational efficiency and market competitiveness, especially in the current context where consumers increasingly value environmental protection, making GSCM a crucial strategy for winning consumer trust and loyalty [7].

This paper first constructs a Nash equilibrium model to analyze the strategy choices of suppliers and retailers under independent decision-making and their impact on supply chain performance. In a static environment without information advantage or cooperation, it examines the strategies of various participants aimed at maximizing benefits and their effects on supply chain operations. Subsequently, through the Stackelberg competition model, it simulates a more complex dynamic game environment, analyzing the strategic interactions between leaders and followers. Finally, through a cooperative game model, it explores the strategy choices of various participants under cooperation and evaluates the possibility of achieving overall benefit maximization through cooperation.

By comparing the results of cooperative and non-cooperative games, this paper comprehensively assesses the significant impact of cooperative strategies on supply chain performance and deeply analyzes the decisive role of decision-making order and information structure on strategy selection. These research findings not only provide a solid theoretical foundation and practical guidelines for enterprises to formulate effective green supply chain strategies but also offer specific insights and guidance on how to optimize economic benefits and design and implement supply chain cooperation strategies in a fiercely competitive market.

2 Literature review

Research shows that consumer preferences for green products have become one of the key factors driving enterprises to implement Green Supply Chain Management (GSCM). This preference prompts consumers to lean towards products that reduce environmental impact during the production process [8]. Consumer preferences influence product design, pricing, brand positioning, and marketing strategies [9].

Some studies have employed the Stackelberg game model to analyze the role of consumer environmental awareness in green supply chain decision-making, finding that consumer environmental awareness significantly influences manufacturers' green innovation decisions and retailers' pricing strategies [10]. Research using the Shapley value model indicates that cooperative mechanisms based on revenue distribution can significantly enhance the environmental and economic performance of the supply chain, helping supply chain members effectively respond to changes in consumer preferences and achieve both economic and environmental benefits [11].

In recent years, with the enhancement of social environmental awareness, especially younger generation consumers' tendency to choose green products, the diversification of information channels has deepened their understanding of products' environmental impact [12, 13]. Therefore, consumer green preferences not only shape market demand but also drive enterprises towards green transformation, influencing the adjustment of their supply chain strategies. This change heralds the enormous potential of the green market in the future.

Existing literature has extensively explored various aspects of GSCM, such as its positive impact on corporate performance and changes in consumer purchasing behavior [14].

Research indicates a significant positive correlation between GSCM implementation and enterprise performance in market, management, and accounting aspects [15, 16]. However, research on the strategy choices of supply chain members and their interaction mechanisms in the face of consumer green preferences remains relatively limited.

Although existing research has extensively discussed the implementation of GSCM, systematic studies on how consumer green preferences specifically influence the operational decisions of supply chain members are still insufficient. This paper aims to integrate consumer preferences with supply chain decisions through game theory analysis, exploring the strategy choices of supply chain members and their interaction mechanisms in the face of consumer green preferences. By employing Nash equilibrium, Stackelberg competition, and cooperative game models, this research aims to provide new perspectives and deepen understanding of green supply chain management theory.

3 Equations and mathematics

This study examines a two-tier green supply chain comprising a single supplier and a single retailer, within which consumer preference for product sustainability is markedly pronounced. The supplier is tasked with production and setting the wholesale price while bearing the costs associated with green technology investments. On the other hand, the retailer decides on the retail pricing and influences consumer perceptions of sustainability through marketing efforts (Table 1).

Table 1. Symbols and notations.

Parameters	
a	Basic market demand
b	Price sensitivity
θ	Consumer preference for green products (exogenous variable)
γ	Outcome of marketing efforts
c	Supplier's unit production cost
k	Supplier's investment cost coefficient
k	Retailer's marketing cost
Decision variables	
w	Supplier's wholesale price
g	Supplier's level of green investment
p	Retailer's retail price
e	Retailer's level of marketing effort

The core inquiry of this research revolves around how supply chain actors can optimize their decisions in light of consumer preferences for green products, and how various strategic choices under different decision-making scenarios impact the overall performance of the supply chain.

$$D = a - bp + \theta g + \gamma e \tag{1}$$

Assuming a linear market demand function influenced by the retail price, the degree of product greenness, and the level of the retailer's marketing efforts, market demand can be represented as follows. To ensure the economic validity of the model, it is assumed that all parameters are integers. Given that price is often the primary factor influencing consumer purchasing decisions in most markets, it is assumed that market demand is more sensitive to price than to the degree of consumer preference for green products and the effectiveness of marketing efforts. Additionally, the model disregards inventory management and logistical costs.

Drawing on the structural costs of green investment products [1], a convex function is used to reflect the increasing marginal costs. Consequently, the profits for the supplier and retailer are calculated as follows:

$$\prod s = (w - c)D - \frac{kg^2}{2} \tag{2}$$

$$\prod r = (p - w)D - \frac{me^2}{2} \tag{3}$$

3.1 Nash equilibrium structure

In a Nash equilibrium structure, suppliers and retailers make simultaneous decisions without a predefined sequence, reflecting the competitive dynamics prevalent in real-world markets. By solving the first-order conditions, the optimal decisions under Nash equilibrium as follows:

$$\begin{cases} w^* = \frac{ak-c\theta^2}{bk-\theta^2} \\ g^* = \frac{(a-bc)\theta^2}{bk-\theta^2} \\ p^* = \frac{ak-c\theta^2}{bk-\theta^2} \\ e^* = 0 \end{cases} \tag{4}$$

Proposition 1: Under Nash equilibrium, the optimal wholesale price w^* increases with the increase of consumer's green preference θ

Proof: Calculation of $\frac{\partial w^*}{\partial \theta}$ shows that since the market demand is positive, i.e., $a > bc$, and both the investment cost coefficient and consumer preference for green products are greater than 0,

$$\frac{\partial w^*}{\partial \theta} = \frac{(-2c\theta)(bk-\theta^2)-(ak-c\theta^2)(-2\theta)}{(bk-\theta^2)^2} \tag{5}$$

it simplifies to,

$$\frac{\partial w^*}{\partial \theta} = \frac{2\theta(k(a-bc)}{(bk-\theta^2)^2} \tag{6}$$

Hence, $\frac{\partial w^*}{\partial \theta} > 0$.

This proposition reveals the significant impact of consumer green preferences on supply chain pricing decisions. As consumer preferences for green products strengthen, suppliers raise wholesale prices, reflecting the market's willingness to pay higher prices for environmentally friendly products. This result emphasizes the key role of consumer preferences in driving the development of green supply chains.

Corollary 1: Under Nash equilibrium, as consumer green preferences increase, the total profit of the supply chain also increases.

Proof: Substituting the Nash equilibrium optimal solution into the total profit of the supply chain $\prod t = \prod s + \prod r$, can get:

$$\prod tn = -\frac{(a-bc)^2 k\theta^2}{2(-bk+\theta^2)^2} \tag{7}$$

Further calculation of $\frac{\partial \prod tn}{\partial \theta}$ yields:

$$\frac{\partial \prod t}{\partial \theta} = -\frac{(a-bc)^2 k\left(bk\theta+\theta^3\right)}{(bk-\theta^2)^3} = \frac{(a-bc)^2 k(bk\theta^2+\theta^3)}{(bk-\theta^2)^2(\theta^2-bk)} \tag{8}$$

Next, using the Hessian matrix:

$$H=\begin{pmatrix}\frac{\partial^2\prod t}{\partial p^2} & \frac{\partial^2\prod t}{\partial p\partial g} & \frac{\partial^2\prod t}{\partial p\partial e}\\ \frac{\partial^2\prod t}{\partial g\partial p} & \frac{\partial^2\prod t}{\partial g^2} & \frac{\partial^2\prod t}{\partial g\partial e}\\ \frac{\partial^2\prod t}{\partial e\partial p} & \frac{\partial^2\prod t}{\partial e\partial g} & \frac{\partial^2\prod t}{\partial e^2}\end{pmatrix}=\begin{pmatrix}-2b & \theta & \gamma\\ \theta & -k & \theta\\ \gamma & \theta & -m\end{pmatrix} \tag{9}$$

The first-order principal minor is $-2b$; the second-order principal minor is $Det(H_{2\times2})=2bk-\gamma^2$; the third-order principal minor is $Det(H)=-2bkm+k\gamma^2+m\theta^2$. For the determinant to be negative, it requires $Det(H)=-2bkm+k\gamma^2+m\theta^2<0$. Because $-2b<0$. Therefore, $-2bk+\theta^2<0$. Hence,

$$\frac{\partial\prod t}{\partial\theta}=\frac{(a-bc)^2k(bk\theta^2+\theta^3)}{(bk-\theta^2)^2(\theta^2-bk)}>0 \tag{10}$$

This corollary further highlights the positive impact of consumer green preferences on the overall performance of the supply chain. It suggests that as consumer awareness of environmental protection increases, not only can suppliers benefit by raising wholesale prices, but the overall economic performance of the supply chain is also enhanced. This result provides economic incentives for businesses to invest in green technologies and develop environmentally friendly products.

3.2 Stackelberg competition structure

In the Stackelberg competition structure, the supplier, acting as a leader, makes decisions first, followed by the retailer, reflecting many practical decision-making sequences in supply chains.

Optimal decisions under Stackelberg competition are derived using backward induction:

$$\begin{cases} w_s^*=\frac{ak(2bm-\gamma^2)+bc(2bkm-k\gamma^2-m\theta^2)}{b(4bkm-2k\gamma^2-m\theta^2)}\\ g_s^*=\frac{(a-bc)m\theta}{4bkm-2k\gamma^2-m\theta^2}\\ p_s^*=\frac{ak(3bm-\gamma^2)+bc(bkm-k\gamma^2-m\theta^2)}{b(4bkm-2k\gamma^2-m\theta^2)}\\ e_s^*=\frac{(-ak+bck)\gamma}{-4bkm+2k\gamma^2+m\theta^2}\end{cases} \tag{11}$$

And the total profit of supply chain is,

$$\prod s+\prod r=\prod ts=\frac{(a-bc)^2km}{2(-4bkm+2k\gamma^2+m\theta^2)^2} \tag{12}$$

Proposition 2: Compared to Nash equilibrium, the green investment level under Stackelberg competition is higher ($g_s^*>g^*$).

Proof: By comparing the expressions for g_s^* and g^*, it can be demonstrated that under the same parameters, $g_s^*>g^*$. Assuming $g_s^*-g^*>0$.

$$g_s^*-g^*=\frac{(a-bc)m\theta}{4bkm-2k\gamma^2-m\theta^2}-\frac{(a-bc)\theta^2}{bk-\theta^2} \tag{13}$$

Simplified as follow:

$$g_s^*-g^*=\frac{(a-bc)k(3bm-2\gamma^2)\theta}{(-bk+\theta^2)(-4bkm+2k\gamma^2+m\theta^2)}=\frac{(a-bc)k(2(\gamma^2-2bm)+bm)\theta}{(-bk+\theta^2)(2k((\gamma^2-2bm)+m\theta^2)} \tag{14}$$

Next, using the Hessian matrix:

$$H=\begin{pmatrix}\frac{\partial^2\prod r}{\partial p^2} & \frac{\partial^2\prod t}{\partial e\partial p}\\ \frac{\partial^2\prod r}{\partial e\partial p} & \frac{\partial^2\prod t}{\partial e^2}\end{pmatrix}=\begin{pmatrix}-2b & \gamma\\ \gamma & -m\end{pmatrix} \tag{15}$$

To determine if the supply chain's profits are maximized locally at (p,e), it need to confirm if this Hessian matrix is negative definite. Thus, the first-order principal minor is $-2b$; the second-order principal minor needs to satisfy $Det(H)<0$:

$$Det(H) = (-2b)(-m) - \gamma^2 = 2bm - \gamma^2 \tag{16}$$

For the determinant to be negative, it requires $2bm - \gamma^2 < 0$.

$$g_s^* - g^* = \frac{(a-bc)k\big(2(\gamma^2-2bm)+bm\big)\theta}{(-bk+\theta^2)(2k((\gamma^2-2bm)+m\theta^2)} > 0 \tag{17}$$

In the Stackelberg competition structure, the supplier, acting as a leader, makes decisions first, followed by the retailer, reflecting many practical decision-making sequences in supply chains. This proposition shows the advantages of the Stackelberg structure in promoting green investments. As a frontrunner, the supplier can guide the retailer's behavior through strategic pricing and green investment decisions, achieving a higher level of green investment. This result highlights the importance of the leader's role in the supply chain and its potential in driving environmental sustainability. Meanwhile, the optimal marketing effort level e_s^* is not zero, indicating that in this structure, the retailer has the incentive to make certain marketing investments. These results collectively reflect the advantages of the Stackelberg structure in coordinating supply chain behavior, promoting green investments, and enhancing market competitiveness.

3.3 Cooperative game theory

In the cooperative game, suppliers and retailers need to make joint decisions to maximize the total profit, reflecting an ideal state of high coordination and information sharing among supply chain members. By maximizing the total profit function:

$$\prod tc = \prod s + \prod r = (p-c)(a - bp + \gamma e + \theta g)) - \frac{kg^2}{2} - \frac{me^2}{2} = \frac{(a-bc)^2 km}{4bkm - 2(k\gamma^2 + m\theta^2)} \tag{18}$$

Since internal transfer prices do not affect total profits in a cooperative game theory structure, retail prices are used instead of wholesale prices. The optimal decisions under a cooperative game are obtained:

$$\begin{cases} p_c^* = \dfrac{a + c(\frac{\gamma^2}{m} + \frac{\theta^2}{k} - b)}{b - \frac{\gamma^2}{m} - \frac{\theta^2}{k}} \\ g_c^* = \dfrac{(a - bc + c\frac{\gamma^2}{m} + c\frac{\theta^2}{k})\theta}{k(b - \frac{\gamma^2}{m} - \frac{\theta^2}{k})} \\ e_c^* = \dfrac{(a - bc + c\frac{\gamma^2}{m} + c\frac{\theta^2}{k})\gamma}{m(b - \frac{\gamma^2}{m} - \frac{\theta^2}{k})} \end{cases} \tag{19}$$

Proposition 3: The level of green investments under cooperative game is higher than under both Nash equilibrium and Stackelberg competition, i.e., $g_c^* > g_s^* > g^*$.

Proof: By comparing the expressions for g_c^*, g_s^*, g^*, it can be demonstrated that under the same parameters, $g_c^* > g_s^* > g^*$. Given that $g_s^* > g^*$ from Proposition 2, it only need to prove $g_c^* > g_s^*$:

$$g_c^* - g_s^* = \frac{(-a+bc)m\theta}{-2bkm + k\gamma^2 + m\theta^2} - \frac{(a-bc)m\theta}{4bkm - 2k\gamma^2 - m\theta^2} \tag{20}$$

it simplifies to,

$$g_s^* - g^* = \frac{(a-bc)km\big(2bm-\gamma^2\big)\theta}{(-2bkm + 2k\gamma^2 + m\theta^2)(2k\gamma^2 - 4bkm + m\theta^2)} > 0 \tag{21}$$

Therefore, $g_c^* > g_s^* > g^*$ holds, proving Proposition 3.

Proposition 3 highlights the significant advantage of cooperative game in promoting green investments. This result indicates that through coordinated collaboration among supply chain members, the highest level of green investments can be achieved, thereby maximizing environmental performance.

Corollary 2: Cooperative game can achieve the highest total profits for the supply chain.

Proof: Since cooperative game considers the maximization of the entire supply chain's profits rather than individual profits, total profits are necessarily higher than in other scenarios. Therefore, it needs to prove $\prod tc > \prod tn$ and $\prod tc > \prod ts$.

First, proving $\prod tc > \prod tn$. Obviously, $\prod tn = -\frac{(a-bc)^2 k\theta^2}{2(-bk+\theta^2)^2} < 0$. Thus, proving $\prod tc > 0$ suffices:

$$\prod tc = \frac{(a-bc)^2 km}{4bkm-2(k\gamma^2+m\theta^2)} = \frac{(a-bc)^2 km}{2(2kbm-k\gamma^2-m\theta^2)} \quad (22)$$

Since $2kbm - k\gamma^2 < 0$, and $2kbm + k\gamma^2 + m\theta^2 < 0$:

$$m\theta^2 < 2bkm - k\gamma^2 < 0 \quad (23)$$

Thus, $2bkm - k\gamma^2 - m\theta^2 > 0$, proving $\prod tc > 0$ and hence $\prod tc > \prod tn$.

Next, proving $\prod tc > \prod ts$: assuming $\prod tc - \prod ts > 0. \prod tc - \prod ts = \frac{(a-bc)^2 km}{4bkm-2(k\gamma^2+m\theta^2)} - \frac{(a-bc)^2 km}{2(-4bkm+2k\gamma^2+m\theta^2)^2} = \frac{(a-bc)^2 k^3 m(-2bm+\gamma^2)^2}{2(2bkm-k\gamma^2-m\theta^2)(-4bkm+2k\gamma^2+m\theta^2)^2}$. Therefore, $\prod tc - \prod ts > 0$.

Corollary 2 further emphasizes the economic value of supply chain coordination. Cooperative game theory not only facilitates the highest level of green investments but also maximizes the overall economic efficiency of the supply chain. This result provides a strong economic incentive for supply chain members to seek cooperative mechanisms.

4 Conclusion

This research systematically analyzes decision-making behaviors in green supply chains through the construction of three models: Nash equilibrium, Stackelberg competition, and cooperative game theory. The study reveals several significant findings: (1) Consumer green preferences emerge as a critical factor driving green investment. These preferences not only influence the strategic choices of supply chain parties but also directly promote the implementation of green investment decisions. Consequently, enhancing consumer environmental awareness and encouraging green consumption represent crucial pathways for advancing green supply chain development. This conclusion provides clear direction for policymakers and corporate managers, suggesting the use of education and incentive mechanisms to strengthen consumer preferences for green products, thereby fostering sustainable development across the entire supply chain. (2) The research highlights the significant impact of decision structures on strategy selection, particularly in promoting green investment, where the Stackelberg structure demonstrates clear advantages over Nash equilibrium. As first movers in the Stackelberg game, suppliers can guide retailer behavior through strategic pricing and green investment, achieving higher levels of green investment. This finding emphasizes the role of supply chain leaders and their potential in driving environmental sustainability. However, it also indicates that supply chain parties must carefully consider the distribution of market power and its effects on overall investment levels when designing and implementing strategies. (3) Results from the cooperative game model underscore the importance of supply chain coordination, demonstrating that cooperation not only enhances economic benefits but also significantly increases levels of green investment.

Based on these conclusions, it is recommended that policymakers and corporate managers strengthen consumer environmental awareness through education and incentive mechanisms, encouraging green consumption to drive sustainable supply chain development. Supply chain leaders should leverage their first-mover advantage in the market, guiding the behavior of other supply chain members through strategic pricing and green investment to achieve higher levels of green investment and environmental sustainability. Furthermore, it is advisable for supply chain parties to establish cooperative mechanisms, such as information sharing, joint investment, or collaborative marketing, to more effectively address environmental challenges and achieve mutual benefits.

Although this research provides valuable insights, the simplified assumptions in the models may limit their comprehensive representation of complex real-world scenarios. For instance, treating consumer green preferences as exogenously given may overlook their dynamic nature. Additionally, the study does not consider the impact of inventory and logistics costs, potentially affecting the practical application of the models. Future research could consider relaxing these assumptions, introducing more complex demand and cost structures, or endogenizing consumer green preferences to provide more precise supply chain management strategies.

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