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Dynamic Collaborative Mechanism of Cross-Border E-Commerce Dual-Channel Supply Chain Under Carbon Quota Constraints

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Abstract

In the context of the accelerated global carbon neutrality initiative and the formal enactment of the European Union's Carbon Border Adjustment Mechanism (CBAM), the low-carbon transformation of cross-border e-commerce supply chains has become an inevitable trend. This study examines a dual-channel supply chain comprising manufacturers, e-commerce platforms, logistics service providers—including overseas warehouses and direct shipping—and consumers, all constrained by carbon quotas. Considering heterogeneity in consumer preferences for price sensitivity and environmental sustainability, demand functions are developed to differentiate between price-sensitive and green-preference consumers. A three-stage Stackelberg game model is constructed, with the platform as the leader and manufacturers as followers, to analyze optimal pricing and production strategies under carbon quota constraints. The model is solved via backward induction to obtain equilibrium solutions, which are validated through numerical case analysis. The findings indicate that: (1) Carbon quota constraints significantly influence supply chain pricing strategies and channel selection, compelling firms to internalize carbon costs into their decision-making processes; (2) Enhancing consumers' green preferences effectively incentivizes manufacturers to invest in emission reductions and provides a market foundation for platforms to implement green premium strategies; (3) As the leader, the platform's pricing and channel allocation strategies play a decisive role in the overall profitability and carbon emission performance of the supply chain. These insights offer theoretical contributions and strategic guidance for cross-border e-commerce enterprises aiming to optimize economic and environmental outcomes in alignment with the "dual carbon" objectives.

Keywords: cross-border e-commerce, dual-channel supply chain, carbon quota, Stackelberg game, consumer preference

1. Introduction

With the acceleration of global climate governance processes, carbon quota policies are significantly transforming the landscape of international trade. Entering a transitional period in 2023 and scheduled for full implementation in 2026, CBAM's comprehensive accounting requirements for product lifecycle emissions exert direct pressure on cross-border e-commerce supply chains characterized by extensive networks and multiple stages [1]. As the world's largest trading nation, China recorded a cross-border e-commerce transaction volume of 17.66 trillion RMB in 2024 [2]. It has become an essential strategic priority to establish a green, low-carbon, and efficient cross-border e-commerce supply chain system.

Currently, cross-border e-commerce predominantly employs a dual-channel model combining "overseas warehouses" and "direct shipping" [3]. The disparity in carbon efficiency between channels, coupled with the increasing heterogeneity of consumer preferences—some consumers are highly price-sensitive, while others are willing to pay a premium for low-carbon products—complicates the dynamics of conflict and cooperation among channels under carbon regulations [4].

Existing research exhibits notable limitations in addressing these challenges. Many studies focus on static optimization within single channels [5] or traditional supply chain emission reduction strategies [6], failing to adequately capture the dynamic strategic interactions inherent in cross-border e-commerce dual-channel systems.

Furthermore, although some literature examines the impact of carbon policies on supply chain decision-making [7], they often overlook the critical role of consumer heterogeneity in demand-driven preferences, particularly lacking quantitative analyses of cross-entity coordination mechanisms within specific policy frameworks such as CBAM.

Therefore, this paper constructs a four-tier supply chain model comprising manufacturers, e-commerce platforms, dual-channel logistics, and two types of heterogeneous consumers. By establishing a platform-led Stackelberg game framework, the study investigates how supply chain participants dynamically determine pricing and production decisions under carbon quota constraints to balance profit maximization with emission compliance. The research aims to deepen the theoretical understanding of supply chain coordination under carbon restrictions and to provide strategic insights for enterprises seeking scientifically grounded low-carbon operational strategies.

2. Model Construction

2.1 Problem Description

This study examines a four-tier dual-channel supply chain system (as shown in Figure 1) comprising a single manufacturer (M), an e-commerce platform (P), and two categories of consumers (C). The supply chain faces stringent total carbon quota constraints E_{max} imposed by CBAM. If total emissions exceed the allocated quota, additional allowances must be purchased at a carbon price c_e. The manufacturer produces a homogeneous product sold through the platform, which offers two fulfillment options for consumers to choose from:

(1) Overseas Warehouse Channel (W) with rapid delivery times (t_W);

(2) Direct Shipping Channel (D) with slower delivery times ($t_D > t_W$).

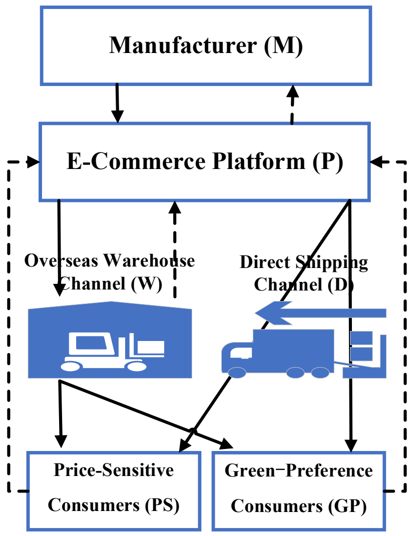

Figure 1. Four-tier dual-channel supply chain system

The consumer market is segmented into two groups:

(1) Price-Sensitive Consumers (PS): accounting for a proportion θ, highly sensitive to price and delivery time.

(2) Green-Preference Consumers (GP): accounting for a proportion 1-θ, willing to pay a premium for low-carbon products.

The game follows a platform-led Stackelberg sequence:

Stage 1: The platform, as the leader, sets the sales prices for both channels, denoted as p_W and p_D.

Stage 2: The manufacturer, as the follower, determines its total production quantity Q, based on the platform's pricing decisions.

2.2 Model Assumptions

(1) The total potential market demand is normalized to 1; the sizes of the two consumer segments are stable.

(2) The unit production cost of manufacturer is c_m ; the unit order processing cost of platform is negligible.

(3) The unit logistics and warehousing cost for Overseas Warehouse Channel is c_W, with unit carbon emission e_W. The unit logistics cost for the Direct Shipping Channel is c_D, with unit carbon emission e_D. Typically, $c_W > c_D$, $e_D > e_W$.

(4) All supply chain entities are risk-neutral and pursue profit maximization.

2.3 Demand Function

For price-sensitive consumers, the demand for the two channels is affected by price and timeliness. A linear demand function with cross-price elasticity is adopted:

$$D_W^{PS} = \theta\left[\alpha_1 - \beta p_W + \gamma p_D + \delta\left(t_D - t_W\right)\right] \tag{1}$$

$$D_D^{PS} = \theta\left[\alpha_2 - \beta p_D + \gamma p_W - \delta\left(t_D - t_W\right)\right] \tag{2}$$

where α_1, α_2 represents the market's fundamental capacity; β and γ denotes the price sensitivity coefficient and the channel substitution coefficient, respectively, and $\beta > \gamma > 0$; δ is the time sensitivity coefficient.

For green-preference consumers, the demand function incorporates perceptions of product carbon emissions. It is assumed that consumers perceive differences in carbon emissions through the platform's carbon footprint label [8], with the strength of green preference denoted as η.

$$D_W^{GP} = (1-\theta)\left[\alpha_1 - \beta p_W + \gamma p_D + \delta\left(t_D - t_W\right) + \eta\left(e_D - e_W\right)\right] \tag{3}$$

$$D_D^{GP} = (1-\theta)\left[\alpha_2 - \beta p_D + \gamma p_W - \delta\left(t_D - t_W\right) - \eta\left(e_D - e_W\right)\right] \tag{4}$$

Consequently, the total demand for the two channels is given by:

$$D_W = D_W^{PS} + D_W^{GP} = \alpha_1 - \beta p_W + \gamma p_D + \delta\left(t_D - t_W\right) + (1-\theta)\eta\left(e_D - e_W\right) \tag{5}$$

$$D_D = D_D^{PS} + D_D^{GP} = \alpha_2 - \beta p_D + \gamma p_W - \delta\left(t_D - t_W\right) - (1-\theta)\eta\left(e_D - e_W\right) \tag{6}$$

The manufacturer's total production volume is $Q = D_W + D_D$.

2.4 Profit Function

The manufacturer's profit Π_M equals sales revenue minus production cost. Assuming a simple wholesale-price contract between the platform and manufacturer, with the wholesale price w:

$$\Pi_M = \left(w - c_m\right)\left(D_W + D_D\right) \tag{7}$$

To simplify the model, this game assumes that the platform and manufacturer form a profit-sharing alliance, jointly determining the production plan and profit distribution, thereby internalizing the decision-making of manufacturer. The platform (supply chain system) aims to maximize total profit.

The platform's profit Π_P equals sales revenue minus total costs and carbon emission penalty fees, and the total costs include procurement costs (simplified as production costs) and logistics/warehousing costs.

$$\Pi_P = p_W D_W + p_D D_D - c_m\left(D_W + D_D\right) - c_W D_W - c_D D_D - C_e \tag{8}$$

The total carbon emissions are:

$$E = e_W D_W + e_D D_D \tag{9}$$

The carbon emission penalty fees:

$$C_e = c_e \cdot \max\left(E - E_{max}, 0\right) \tag{10}$$

To facilitate derivation, we treat $\max\left(E - E_{max}, 0\right)$ as a penalty term. As the total carbon emissions E is a function of p_W and p_D, the objective function of Π_P can be expressed as:

$$\Pi_P\left(p_W,p_D\right)=\left(p_W-c_m-c_W\right)D_W+\left(p_D-c_m-c_D\right)D_D-c_e\cdot\max\left(e_WD_W+e_DD_D-E_{max},0\right) \tag{11}$$

3. Model Solution

Given that this research presumes a collaborative decision-making framework between the platform and manufacturer, the game is simplified to the platform making unilateral decisions to maximize the total profit of the supply chain. This constitutes a nonlinear programming problem, with the solution divided into two cases: carbon quota not exhausted ($E \le E_{max}$) and carbon quota exhausted ($E > E_{max}$).

Case 1: Carbon quota not exhausted ($E \le E_{max}$)

In this case, the carbon penalty term is 0. The platform's objective function is:

$$\Pi_P\left(p_W,p_D\right)=\left(p_W-c_m-c_W\right)D_W+\left(p_D-c_m-c_D\right)D_D \tag{12}$$

Substitute Equations (5) and (6) into Equation (12), Π_P becomes a quadratic function of p_W and p_D . To find its maximum, we take the first-order partial derivatives with respect to p_W and p_D , and set them to 0:

$$\frac{\partial\Pi_P}{\partial p_W}=\alpha_1-2\beta p_W+2\gamma p_D+\delta\left(t_D-t_W\right)+\left(1-\theta\right)\eta\left(e_D-e_W\right)+\beta\left(c_m+c_W\right)-\gamma\left(c_m+c_D\right)=0 \tag{13}$$

$$\frac{\partial\Pi_P}{\partial p_D}=\alpha_2-2\beta p_D+2\gamma p_W-\delta\left(t_D-t_W\right)-\left(1-\theta\right)\eta\left(e_D-e_W\right)+\beta\left(c_m+c_D\right)-\gamma\left(c_m+c_W\right)=0 \tag{14}$$

To ensure the profit function has a unique maximum value, the Hessian matrix must be negative definite, i.e., $4\beta^2-4\gamma^2>0$, which holds constantly since $\beta>\gamma$.

By solving Equations (13) and (14) simultaneously, the optimal prices p_W^* and p_D^* can be obtained. Substitute the optimal prices into the demand function and carbon emission function to verify whether $E\left(p_W^*,p_D^*\right)\le E_{max}$ is satisfied. If yes, this is the optimal solution; otherwise, turn to Case 2.

Case 2: Carbon quota exhausted ($E > E_{max}$)

In this case, the platform aims to maximize its profit subject to the carbon quota constraint $e_WD_W+e_DD_D=E_{max}$. This leads to an optimization problem with equality constraints. The Lagrangian function $L\left(p_W,p_D,\lambda\right)$ is constructed as follows:

$$L\left(p_W,p_D,\lambda\right)=\Pi_P\left(p_W,p_D\right)-\lambda\left(e_WD_W+e_DD_D-E_{max}\right) \tag{15}$$

where λ is the Lagrange multiplier, representing the marginal cost of carbon reduction.

Substitute D_W and D_D into the function, calculate the partial derivatives with respect to p_W , p_D and λ , and set them to 0, forming the Karush-Kuhn-Tucker (KKT) conditions:

$$\frac{\partial L}{\partial p_W}=\frac{\partial\Pi_P}{\partial p_W}-\lambda\left(-\beta e_W+\gamma e_D\right)=0 \tag{16}$$

$$\frac{\partial L}{\partial p_D}=\frac{\partial\Pi_P}{\partial p_D}-\lambda\left(\gamma e_W-\beta e_D\right)=0 \tag{17}$$

$$\frac{\partial L}{\partial\lambda}=e_WD_W+e_DD_D-E_{max}=0 \tag{18}$$

By solving the above equations simultaneously, the optimal price p_W^{**}, p_D^{**} and the value of λ under carbon quota constraint can be obtained.

4. Numerical Analysis

4.1 Parameter Setting

Market potential: $\alpha_1=200,\alpha_2=180$

Cost parameters: $c_m=10,c_W=8,c_D=5$

Time parameters: $t_W=3,t_D=10,\delta=2$

Demand elasticity: $\beta=5,\gamma=2$

Carbon emission parameters: $e_W = 1, e_D = 3$ (unit: kg CO_2 per unit)

Consumer structure: $\theta = 0.6$

Green preference: $\eta = 4$

Carbon quota and price: $E_{max} = 300$ kg, $c_e = 2$ RMB/kg

4.2 Solution of Numerical Example

Case 1: Carbon quota not exhausted

Solving Equations (13) and (14) simultaneously, obtaining:

$p_W^* \approx 42.1, p_D^* \approx 39.8$

$D_W \approx 111.9, D_D \approx 89.1$

$\Pi_P^* \approx 4258.9$

$E^* \approx 111.9 \times 1 + 89.1 \times 3 = 379.2$ kg

Due to the total carbon emissions exceeding the quota, i.e., $E^* > E_{max} = 300$, the solution proceeds to Case 2.

Case 2: Carbon quota exhausted

Solving Equations (16) , (17) and (18) simultaneously, obtaining the new equilibrium solution:

$p_W^{**} \approx 44.8, p_D^{**} \approx 40.5$

$D_W \approx 127.5, D_D \approx 57.5$

$\Pi_P^{**} \approx 4085.6$

$E^{**} = 127.5 \times 1 + 57.5 \times 3 = 300$ kg (Quota fully utilized.)

4.3 Results Analysis

(1) Price and channel shift effects: It can be observed from the comparison between the two cases that the platform significantly increased the selling prices across both channels under carbon constraints.Additionally, through strategic price adjustments, the platform directed demand from the high-carbon direct shipping channel (D_D decreasing from 89.1 to 57.5) toward the low-carbon overseas warehouse channel (D_W increasing from 111.9 to 127.5). This exhibits an active, market-oriented emission reduction behavior.

(2) Profit loss: The implementation of carbon constraints resulted in an approximate 4.1% decrease in total supply chain profit (from 4258.9 to 4085.6).This loss constitutes the "carbon compliance cost" for the enterprise, reflecting the economic expense associated with internalizing environmental externalities.

(3) Sensitivity analysis of consumer green preference: Holding other parameters constant, the impact of green preference intensity (η) changing from 0 to 10 on the equilibrium outcomes was examined. The results indicate that as η intensifies, both the demand and pricing of the overseas warehouse channel show an upward trend, while the direct shipping channel exhibits the opposite trend. This indicates that cultivating consumer green awareness can effectively incentivize the supply chain to tilt towards the low-carbon channel, and even realize profit recovery under carbon constraints.

5. Conclusion

This study addresses the problem of low-carbon coordination in cross-border e-commerce dual-channel supply chains. By constructing demand functions distinguishing price-sensitive and green-preference consumers and establishing a platform-led Stackelberg game model, it reveals the dynamic decision-making mechanism of the supply chain under carbon quota constraints.The following research conclusions and managerial implications are obtained:

(1) Carbon tariff policies such as CBAM effectively internalize environmental costs into corporate economic costs. Enterprises will respond to carbon constraints by proactively adjusting pricing strategies and guiding channel demand shifts, rather than passively accepting penalties. For cross-border e-commerce platforms, a dynamic pricing model linked to carbon emissions should be established to transmit carbon costs to channel selection and final sales prices in a refined manner.

(2) Consumer green preferences serve as an endogenous driver for supply chain transition toward low-carbon models. Platforms should enhance the visibility of low-carbon attributes through carbon footprint labels and green marketing, fostering and guiding consumers' green consumption habits. This not only alleviates the burden of corporate emission reduction, but also creates new brand value and profit growth opportunities.

(3) As the organizational core of the supply chain, e-commerce platforms play a crucial role in low-carbon transformation. Platforms need to not only optimize their own operations but also design reasonable coordination mechanisms (e.g., traffic allocation, green certification subsidies) to incentivize upstream manufacturers to invest in process improvements and emission reduction, thereby achieving systemic emission reduction across the entire supply chain ecosystem.

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