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Evolutionary game theoretical approach for reducing carbon emissions in a complex supply chain organization

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Abstract

Purpose – Our research explores the intricate behavior of low-carbon supply chain organizations in an ever-evolving landscape, emphasizing the profound implications of government-mandated low-carbon policies and the growing low-carbon market. Central to our exploration is applying a combined game theory model, merging Evolutionary Game Theory (EGT) with the Shapley Value Cooperative Game Theory Approach (SVCGTA).

Design/methodology/approach – We establish a two-tier supply chain featuring retailers and manufacturers within this novel framework. We leverage an integrated approach, combining strategic Evolutionary Game Theory and Cooperative Game Theory, to conduct an in-depth analysis of four distinct low-carbon strategy combinations for retailers and manufacturers.

Findings – The implications of our findings transcend theoretical boundaries and resonate with a trinity of economic, environmental and societal interests. Our research goes beyond theoretical constructs to consider real-world impacts, including the influence of changes in government low-carbon policies, the dynamics of consumer sensitivities and the strategic calibration of retailer carbon financing incentives and subsidies on the identified ESS. Notably, our work highlights that governments can effectively incentivize organizations to reduce carbon emissions by adopting a more flexible approach, such as regulating carbon prices, rather than imposing rigid carbon caps.

Originality/value – Our comprehensive analysis reveals the emergence of an Evolutionary Stability Strategy (ESS) that evolves in sync with the phases of low-carbon technology development. During the initial

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stages, our research suggests that manufacturers or retailers adopt low-carbon behavior as the optimal approach.

Keywords Complex organization, Low carbon emission, Supply chain organization, Game theory model, Evolutionary model, Sustainability, Management, Manufacturing

Paper type Research paper

1. Introduction

The supply chain collaborates among companies to satisfy marketing authorities like distributors, manufacturers, logistics, retailers, vendors, transportation systems, government regulatory bodies, and end users. In recent days, the efficiency of the supply chain model has increased organizational standards in effective product distribution and consumer services at as low a cost as possible. Globalization makes the supply chain more dynamic, interdependent, and intertwined among business players. The world has encountered climatic change issues like global warming, pollution, etc. It is necessary to transform enterprises into low-carbon emission strategies. Many developing countries suffer from carbon emissions and have recently moved towards low-carbon and clean environmental strategies for sustainable living. The familiar policies on carbon reduction, the carbon cap, and trade policy have been implemented in many regions like California, Tokyo, and Beijing. In this policy, the government set up carbon emission caps for enterprises. This policy allows enterprises to get permits for excess carbon emissions in the trading markets. When consumers prefer low-carbon products, it creates new opportunities for the manufacturers. Low-carbon businesses use carbon financing strategies to make supply chain-based decisions.

Many countries, recognizing the imperatives of a low-carbon future, have taken decisive legislative steps to tighten their low-carbon policies (He *et al.*, 2020; Chenic *et al.*, 2022). These efforts include prioritizing low-carbon industries, embracing clean energy solutions, and an unwavering commitment to eco-friendly environmental practices (Ronoh, 2020). One of the cornerstones of these policies is the carbon cap-and-trade mechanism, a multifaceted strategy that has been rigorously tested and successfully implemented across diverse landscapes. From bustling metropolises like Beijing and Tokyo to entire regions, exemplified by California, this mechanism is at the forefront of the global battle against carbon emissions (Hu *et al.*, 2024). Under this system, governments set emissions caps for carbon-emitting enterprises, introducing a dynamic approach allowing these entities to trade permits for carbon emissions. This mechanism, supported by significant research (Liu *et al.*, 2024; Jin *et al.*, 2024; Hu *et al.*, 2023), not only advances economic objectives but also propels environmental responsibility to the forefront.

Today, enterprises seek to market low-carbon products by responding to government policies. This research aims to help enterprises by analyzing consumer, retailer, and manufacturer demands at various levels, such as investment policies and customizing requirements (Li *et al.*, 2020; Moshood *et al.*, 2021). The enterprise players are considered under the game theory model based on state-of-the-art work performance. This research studied and analyzed various game theoretical models to improve the analysis process. Retailers in China started to process low-carbon products in the market. Reducing carbon policies encourages enterprises to reduce frozen products. For example, animal food products are cold processed instead of using refrigerators (Jiang and Xu, 2023; Mohsin *et al.*, 2021; Kong *et al.*, 2023). Dried and compacting technology uses the energy-saving model in crop product processing. Product packaging and shopping bags are changed to eco-friendly products, which is highly encouraged by retailers. Retailers must support new enterprises that assist in participating in low-carbon production among the farmers and start-ups. Marketing by retailers who promote low-carbon production has greater attention towards sustainable business development (Xing *et al.*, 2023; Xu Xu and Wei, 2023; Moshood *et al.*, 2021). Even though low-carbon products affect economic growth, retailers' interest in low carbon encourages consumers to help with climate change issues and promote sustainable nature. With cooperation on government policies and demands in markets, manufacturers and suppliers must collaborate with retailers to encourage low-carbon products using sustainable materials. Many challenges exist to achieving low carbon usage among enterprises and retailers (Rechsteiner, 2021).

Numerous small businesses or agricultural producers know the prevailing preferences for low-carbon markets and governmental policies to reduce carbon emissions. However, due to financial limitations, they often need help to upgrade their low-carbon production technologies, managing instead to keep their offerings at the current level without enhancements. In this context, carbon financing provided by larger retail entities presents a promising strategy for fostering the development of low-carbon production capabilities among financially restricted upstream manufacturers. Through carbon financing, retailers can tailor their products to be more environmentally friendly while manufacturers gain the means to invest in sustainable production practices. This collaboration enables retailers and manufacturers to adhere to governmental regulations on carbon reduction and satisfy market demand for eco-friendly products, thereby improving the sustainability of the supply chain. Nevertheless, companies can benefit from other partners' low-carbon initiatives within the supply chain without bearing the associated expenses. As a result, exploring evolutionary games related to low-carbon behavior within the supply chain has emerged as an important field of study, aiming to identify effective strategies for the sustainable growth of new low-carbon retail models.

Literature studies have previously investigated evolutionary game theories to help enterprise players make decisions on supply chain-based low carbon strategies. To enhance the cooperation between the enterprise players, this research improves the state-of-the-art by integrating evolutionary and cooperative game theory models to achieve the best low carbon supply chain usage among retailers. In previous work, manufacturers, retailers, and consumers did not have a cooperative communication model. This work uses unified game theory whenever the decision needs to be made with cooperation. The proposed integration model explores the low carbon strategy with the supply chain model and uses an integration of the game theoretical model to examine the effects of government policies. As operational management has more issues in low-carbon situations, this research provides a solution using a supply chain network with a hybrid game theory model to guide ESS.

The research contributes to developing low-carbon businesses and bringing sustainable solutions to the industries' supply chain. The research implications and consideration of situations are,

1. Contract implications: individual efforts towards low-carbon initiatives, low-carbon practices among supply chain entities, including non-engagement in low-carbon activities, collaborative endeavors for carbon reduction
2. This research employs evolutionary and game theory to examine the dynamics of low-carbon actions within enterprises. Evolutionary models lead to the identification of stable strategies known as Evolutionary Stable Strategies (ESS). Cooperative models help foster good cooperation among contract players.
3. These strategies demonstrate a sustained commitment to reducing carbon emissions, enhancing overall social welfare through alignment with low-carbon market demands, adherence to governmental policies on carbon reduction, and bolstering the sustainability of supply chain operations.
4. Furthermore, the ESS highlights enduring strategies for low-carbon adaptation among supply chain companies, considering both external (government policies and consumer preferences for low-carbon products) and internal (carbon finance rates and subsidies) environmental shifts, thereby offering insights into their influence on the supply chain's low-carbon strategic alignment.

The emerging landscape is dynamic and calls for innovative approaches to ensure the sustainable development of low-carbon retailers. Recognizing this, exploring evolutionary low-carbon behavior games has gained prominence in recent research (Chen *et al.*, 2022; Shang and Luo, 2021). These games offer a platform for supply chain enterprises to navigate the complex terrain, thereby enabling viable methods for realizing the vision of a low-carbon future. In this multifaceted landscape, enterprises must navigate an intricate web of government policies, evolving consumer preferences, and the strategic deployment of carbon financing (Luo *et al.*, 2023). This journey calls for a holistic approach that transcends conventional business paradigms and embraces environmental responsibility as a core value. Within this context, we explore, seeking to illuminate the path to a sustainable, low-carbon future, one where economic prosperity aligns seamlessly with environmental preservation.

The main contributions of the paper are as follows

(1) This paper makes a novel contribution by developing the Shapley Value Cooperative Game Theory Approach to Evolutionary Game Theory (SVCGTA—EGT). Such integration fosters an in-depth approach to the study of low-carbon supply chains, stressing the importance of collaboration among stakeholders.

(2) With the help of SVCGTA, the formation of low-carbon strategies in the upper chains of the product supply is made clearer. This analysis also explains how manufacturers and retailers address their decisions regarding the low-carbon market and policy.

(3) The paper pinpoints Evolutionary Stability Strategies (ESS) using SVCGTA, offering vital guidance to organizations navigating various stages of low-carbon technology growth.

(4) Through the proposed, the study evaluates the impacts of alterations in government low-carbon policies and changes in consumer sensitivities on low-carbon supply chain strategies, guiding stakeholders in adapting to these dynamic factors.

This article is organized into five sections: A literature review from various studies in part 2, a main system methodology in part 3, a result evaluation in part 4, and a conclusion in part 5.

2. Literature review

2.1 Carbon emission reduction

The study Sovacool *et al.* (2020) systematically evaluates the historical effects of nuclear power and renewable energy on carbon emissions in 123 countries over 25 years, clarifying their relative effectiveness in emission reduction. Findings indicate that large-scale national nuclear adoption doesn't significantly reduce emissions, while renewables exhibit emission reduction potential. This research work does not suggest any data analysis model at the enterprise level. The study also underscores competition between nuclear and renewable technologies. The study Sun *et al.* (2022) introduces a multi-hierarchy meta-frontier data envelopment analysis (DEA) approach to assess CO2 reduction inefficiency (CRI) and potential in nuclear and renewable power industries across 58 countries, emphasizing the heterogeneities in regions and power industries. The findings reveal variations in carbon reduction efficiency (CRE), with China, the USA, and Russia showing higher average CRE values in clean-energy power. Asia, America, and Europe must address CRI in the nuclear power industry, with management and regional development inefficiencies being primary concerns. This research suggests data analysis for CO2 reduction inefficiency analysis.

2.2 Carbon emission reduction in supply chain management

The paper Sarkar *et al.* (2021) addresses sustainability challenges in supply chain management, emphasizing the significance of improving product quality and reducing carbon emissions. It presents a three-echelon sustainable supply chain model, considering a single supplier, single manufacturer, and multiple retailers, focusing on discrete setup cost reduction and quality control. The model aims to minimize costs while enhancing sustainability by reducing defective products and controlling carbon emissions. This research study does not aim to control real players in the market in carbon reduction analysis.

2.3 Cooperative game theory and evolutionary game theory

The article Eskafi *et al.* (2015) addresses the increasing importance of supply chain management for gaining a competitive edge in recent years. Improved customer service, increased revenue, and cost reduction are advantages of effective supply chain management. Organizations must establish clear goals, define relevant criteria, and continuously measure performance to achieve these benefits. This study introduces a novel approach that combines the balanced scorecard, path analysis, evolutionary game theory, and cooperative game theory to determine company measurement indicators and strategies. By employing this method, the study offers a comprehensive program for future organizational activities and assesses the firm's current status. The proposed approach is applied to a food producer, and the results are rigorously analyzed to guide strategic planning. This research encourages our model to use cooperative game theory in real-player market analysis.

Previous studies have yet to investigate the low-carbon strategies of supply chain enterprises using evolutionary game theory or explore the impacts of government low-carbon policies, consumer low-carbon product preferences, and inter-enterprise carbon financing on the low-carbon strategies of supply chain enterprises from an evolutionary game As complex low carbon situations are becoming an issue in the operations management of certain enterprises, this research seeks to assist supply chain enterprises develop better low-carbon businesses and provide long-term strategies for supply chain enterprises and governments.

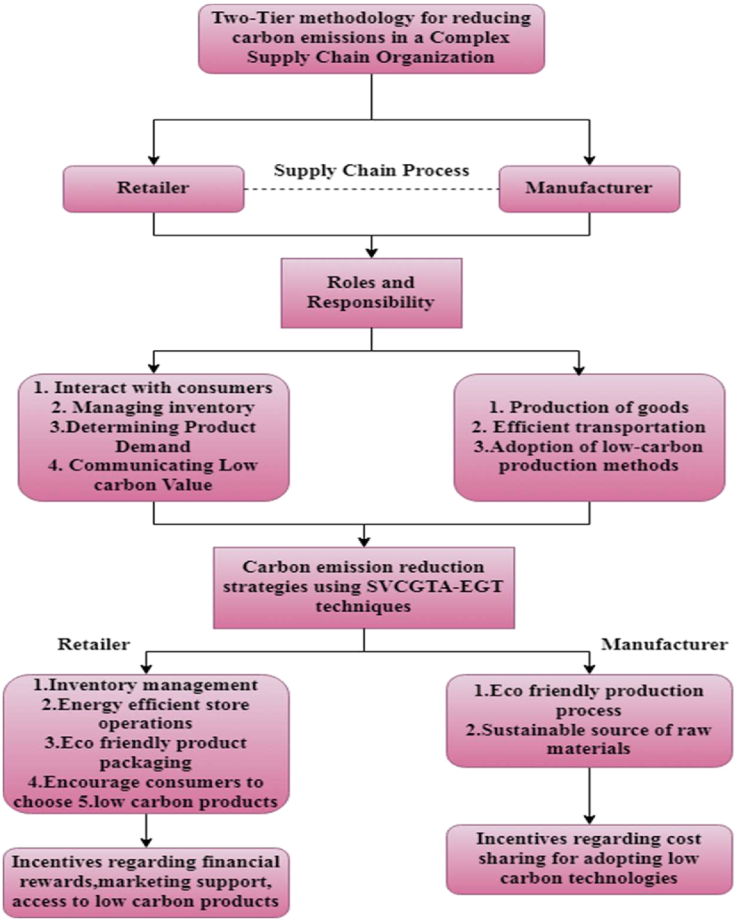
3. Methodology

3.1 Two-tier model overview

The proposed SVCGTA-EGT model for reducing carbon emissions within a supply chain employs a two-tier framework comprising the retailer and the manufacturer. Each tier has a distinct role in pursuing reduced carbon emissions, and the SVCGTA-EGT approach equitably allocates its responsibilities and incentives.

Retailer Tier: The retailer tier assumes the task of interfacing with end consumers, managing inventory, and gauging product demand. Their central function is to bridge the gap between the supply chain and the market. Retailers can adopt a range of low-carbon strategies, such as optimizing inventory management, implementing energy-efficient store operations, advocating for eco-friendly packaging, and promoting the selection of low-carbon products by consumers. The SVCGTA-EGT methodology is instrumental in determining the fair share of responsibilities and incentives for retailers in the context of carbon reduction. This ensures that retailers are motivated to engage in carbon reduction efforts actively and duly rewarded for their contributions.

Manufacturer Tier: The manufacturer tier takes on goods production, product quality maintenance, and product transportation to retailers. Their vital function includes the adoption of low-carbon production methods, utilization of energy-efficient machinery, and sustainable sourcing of raw materials. Figure 1 illustrates how the SVCGTA-EGT methodology effectively allocates responsibilities and incentives to manufacturers



Source(s): Created by author

Figure 1.
Proposed SVCGTA-EGT-Two tier model and its main objectives

according to their contributions to carbon reduction. This approach encourages manufacturers to invest in low-carbon production practices and make consistent efforts to reduce emissions. The SVCGTA-EGT method assesses the marginal contribution of each tier to the overall reduction in carbon emissions by evaluating various combinations of their actions and their impact on emissions reduction. Through the SVCGTA-EGT, responsibilities, and incentives are equally apportioned, ensuring each tier garners recognition for its endeavors. As time progresses and low-carbon technologies evolve, the SVCGTA-EGT model adapts accordingly. During the initial stages of low-carbon technology development, the method may recommend that only one of the two players, the retailer or the manufacturer, embrace low-carbon practices to maximize efficiency. With advancing technology and greater accessibility to low-carbon practices, the model may suggest a shift in responsibilities. This ensures that the supply chain remains adaptable and responsive to evolving environmental and market conditions.

3.2 Evolutionarily stable strategy (ESS) in the retailer-manufacturer supply chain

In this model, four implications are analyzed: (1). Individual efforts towards low-carbon initiatives, (2). Low-carbon practices among supply chain entities, (3). Including non-engagement in low-carbon activities, and (4). Collaborative endeavors for carbon reduction.

1. *Individual efforts towards low-carbon initiatives:* Consumers must appreciate the low-carbon products on the market. Retailers and consumers must cooperate to encourage this.
2. *Low-carbon practices among supply chain entities:* To improve the economy, supply chain entities in the market, such as manufacturers, retailers, and consumers, must practice low-carbon and quality products.
3. *Including non-engagement in low-carbon activities:* Analyze those not interested in low-carbon supply chains and cooperate with them for sustainable practice.
4. *Collaborative endeavors for carbon reduction:* Collaborative endeavors for carbon reduction are strategic partnerships and joint initiatives to decrease carbon emissions and enhance sustainability across various sectors. These efforts are critical in addressing the global challenge of climate change. They are characterized by the participation of multiple stakeholders, including governments, private sector entities, non-governmental organizations (NGOs), and the general public.

3.2.1 Evolutionarily stable strategy (ESS). In the context of a retailer-manufacturer supply chain, the concept of ESS is instrumental in understanding the long-term stability of strategies chosen by retailers and manufacturers, especially concerning low-carbon technology adoption, carbon emissions reduction, and incentives. An Evolutionarily Stable Strategy is a strategy that, once adopted by a significant portion of the population, resists invasion by alternative strategies. The ESS source is adapted from the study Du *et al.* (2021).

3.2.2 Players and strategies. This supply chain game involves two primary players: retailers and manufacturers. Retailers are responsible for interfacing with end consumers, managing inventory, and gauging product demand. On the other hand, manufacturers handle goods production, product quality maintenance, and product transportation to retailers. Various strategy combinations exist between retailers and manufacturers, including Retailer Adopts Low-Carbon Practices, Manufacturer Adopts Low-Carbon Practices, Retailer Adopts Low-Carbon Practices, Manufacturer Does Not Adopt, Retailer Does Not Adopt, Manufacturer Adopts Low-Carbon Practices, and Retailer Does Not Adopt, Manufacturer Does Not Adopt. Both retailers and manufacturers are considered rational economic entities, each having only two mutually exclusive strategies.

3.2.3 Payoffs.

1. Costs and Prices

Manufacturers face costs, denoted as $c1$ and $c0$, when implementing low-carbon production methods and traditional production methods, respectively. It is assumed that $c1 > c0$, indicating that low-carbon production involves higher costs compared to traditional methods. Prices for products produced using low-carbon methods and traditional methods are represented by $p1$ and $p0$, respectively, where $p1 > p0$. These prices reflect the benefits gained by manufacturers and the costs incurred by retailers.

2. Environmental Considerations

Retailers' ecological awareness is captured by the parameter β, where $\beta \in [0, 1]$. It represents the extent to which retailers value low-carbon and environmentally friendly products. The variable E represents the environmental value associated with products produced using low-carbon methods compared to products from traditional production methods. When retailers initially stock traditional products, their awareness of environmental benefits is minimal ($\beta = 0$).

(3) Government Incentives and Carbon Tax

Manufacturers adopting low-carbon production methods receive governmental subsidies, denoted as $s1$, while retailers stocking and promoting low-carbon products can benefit from subsidies, denoted as $s2$. A carbon tax T_i is imposed on manufacturers based on their carbon emissions relative to an acceptable level e_i Manufacturers using low-carbon methods generally have lower emissions compared to e_0, while those employing traditional methods have emissions exceeding e_0.

(4) Carbon Tax Calculation

The carbon tax T_i for manufacturers is computed based on the carbon emissions they generate during production, considering an acceptable level e_0

$$T_i = \begin{cases} (e_i - e_0) \times c_t \, e_i \geq e_0 \\ 0 \, e_i \geq e_0 \end{cases} \quad i = CB, LCB$$

(5) Tax Transfer to Retailers

A proportion of the carbon tax αT is transferred to retailers, increasing their costs when stocking and promoting traditional products. This adapted framework applies the concept of ESS to the long-term stability of strategies chosen by retailers and manufacturers in response to environmental awareness, governmental incentives, and carbon tax policies within a supply chain context. ESS analysis can help identify strategies that resist invasion by alternative strategies, contributing to a deeper understanding of the evolution of low-carbon practices and carbon emissions reduction strategies within supply chains.

3.2.4 ESS-based carbon emission reduction in various sectors. Yu *et al.* (2022) utilizes multi-agent models with evolutionary game theory and scenario simulation to evaluate the impact of carbon quota trading on emissions. It emphasizes the collaborative role of enterprises and governments, with initial willingness affecting convergence speed. Policy recommendations include reducing emission costs, fostering corporate reduction initiatives, and enhancing government regulation for more effective carbon market development. The authors in Wang *et al.* (2023), Perera (2018) address carbon emissions reduction in prefabricated buildings, emphasizing the need for low-carbon production techniques. It constructs an evolutionary game model involving manufacturers and the government to analyze strategy evolution. Key factors include low-carbon production costs, incentives, sanctions, and government performance assessments. Recommendations involve exploring low-carbon technologies, introducing carbon emission accounting subsidies, and enhancing regulatory frameworks for a more efficient low-carbon economy. Using game theory, the paper Eskafi *et al.* (2015) explores a government's role in promoting environmental sustainability in the competitive electricity market. It focuses on Stackelberg's leadership and the evolutionarily stable equilibria. A bimatrix coordination game with multiple equilibria is analyzed, emphasizing power plants' behavior to reduce carbon emissions and avoid tariffs. Using quantal response equilibrium (QRE) for bounded rationality leads to a unique Nash equilibrium, aiding policymakers in setting incentives and tariffs to meet environmental obligations in the electricity market. Evolutionary game theory (EGT) (Du *et al.*, 2021) is applied to analyze the interactions among multiple participants, revealing the evolution of their strategies and the emergence of evolutionary stable strategies (ESS). The study underscores dynamic strategy adjustments can lead to system convergence under certain conditions. It also highlights the role of investment in environmental protection, emissions trading, and emission reduction incentives in motivating polluting enterprises and local governments to fulfill their ecological duties. The findings provide valuable insights into ecological regulation and emission reduction strategies, suggesting ways to enhance environmental policy in China.

3.3 SVCGTA approach

In this research, we employ SVCGTA to manage carbon emissions in a supply chain (Chong and Sun, 2020; Veeramsetty, 2021). SVCGTA starts by creating coalitions, groups of distribution generation units (DGs), to reduce carbon emissions and improve power generation efficiency. This cooperative approach is akin to a team effort in game theory, where DGs work together for mutual benefit. Key to SVCGTA is the concept of Shapley values, a core element in cooperative game theory. Shapley values assign a value to each DG based on their contribution to the coalition's objectives. In our case, Shapley values determine how much each DG contributes to lowering emissions and enhancing power generation efficiency. We do this by considering all possible combinations of DG participation and assessing the impact on emissions and efficiency. This ensures that each DG is fairly rewarded based on their actual contributions. Shapley values also form the basis for financial incentives tailored to each DG. These incentives align with their efforts to reduce carbon emissions and optimize power generation, motivating DGs to meet supply chain goals of reduced carbon footprint and efficient power generation. The strategic allocation of incentives keeps DGs motivated. Moreover, Shapley's values help efficiently distribute resources, in this case, financial incentives. They are directed toward DGs who have substantially contributed to emissions reduction and efficiency improvement, ensuring fairness. SVCGTA operates iteratively, adapting to changing conditions and recalculating Shapley values, promoting ongoing improvement in carbon reduction and power generation.

3.3.1 Algorithm for reducing carbon emission in a supply chain using SVCGTA. 3.3.1.1 Inputs. Hour T of the day D,

Forecasted Load $L\,(T,D)$
Shapley values λ^T
Carbon pricing parameters $(\in_1, \in_2)$
3.3.1.2 Initialization.

```
Step 1: Calculate base case loss with forecasted load $L\,(T,D)$ by using the distribution load
Step 2: Set iteration $j = 1, (\prod_a^T)_i^j = \lambda^T \, and \, (PG^T)_i^0 = 0 \, where \, i = 1, 2, \ldots N_{DG}$
Step 3: $i = 1$
Step 4: while $i \neq N_{DG} + 1 \, do$
    Compute carbon emission using equation $\left(PG^T\right)_i^j = \frac{\left(\left(\prod_a^T\right)_I^j - B_i\right) L\,(T,D)\Big)}{2_{a_i}}$   (1)
Step 5: $i \leftarrow i + 1$
Step 6: end while
Step 7: Calculate the total carbon emissions and losses for loss $V^L(C)$, emission c due to the coalition $C$ based on the carbon emission computed in Step 4.
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Step 8: Calculate $\Delta benifit_j^T$ using $\Delta benifit_j^T = (PLoss_0^T - PLoss_j^T)\lambda^T - \sum_{i=1}^{N_{DG}} (PG^T)_i^j * \prod_a^T)_I^j - \lambda^T - \sum_{i=1}^{N_{DG}} (QG^T)_i^j \prod_R^T)_I^j + (EC_0^t - EC_j^t)\omega_e$ and set $\Delta Pmax = \max((PG^T)_i^j - (PG^T)_i^{j-1})$ where i = 1,2, . . .. $N_{DG}$.
Step 9: if $\Delta benifit_j^T \leq \in_1 or \Delta Pmax \leq \in_2$ then
Step 10: GoTo ⇝ Step 19
Step 11: else
Step 12: GoTo ⇝ Step 14
Step 13: end if
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(where ϵ_1 *and* ϵ_2 are small values).

Step 14: Calculate share of each distribution generation *DG* in change in carbon emissions $\Phi_i(L)$ and change emission $\Phi_i(e)$ using Shapley Values *SV*

Step 15: Compute financial incentives of each *DG* unit for its contribution in carbon emission reduction using

$$DGgain_{loss}^{i} = \omega_1 \frac{(PLoss_0^T - PLoss_j^T\big)\lambda^T + \big(\big(\big(EC_0^t - EC_j^t\big)\omega_e\big)xLoss(i)}{(PLoss_0^T - PLoss_j^T\big)} \tag{2}$$

$$DGgain_{Emn}^{i} = \omega_2 \frac{(PLoss_0^T - PLoss_j^T\big)\lambda^T + \big(\big(\big(EC_0^t - EC_j^t\big)\omega_e\big)xEmn(i)}{(PEmn_0^T - Emn_j^T\big)} \tag{3}$$

where $xLoss(i) - \Phi_i(L)$ *and* $xEmn(i) = \Phi_i(e)$

Step 16: Compute incentive for active and reactive power prices of each DG as shown in

$$\begin{gathered} DGgain_P^i = DGgain_{Loss}^i * \left(cosdg^i\right)^2 + DGgain_{Emn}^i \\ DGgain_Q^i = DGgain_{Loss}^i * \left(1 - \left(cosdg^i\right)^2\right) \end{gathered} \tag{4}$$

Step 17: Compute active and reactive power price for next iteration using

$$\left(\left(\prod_a^T\right)_i^{j+1} - \lambda^T\right) \frac{\left(\left(\prod_a^T\right)_i^{j+1} - B_i\right)}{2a_i} = DGgain_P^i \tag{5}$$

$$\left(\left(\prod_R^T\right)_i^{j+1} - \lambda^R + \frac{DGgain_Q^i}{\left(QG^T\right)_i^j} \tag{6}$$

Increment iteration $j = j + 1$ and go to step 3.

Step 18: Stop iterative algorithm for hour T and take the print out of required data.

The algorithm operates within the framework of the SVCGTA-EGT and aims to effectively manage carbon emissions within a supply chain organization. It takes into account several inputs, such as the time of day T, forecasted load $(L(T,D))$, Shapley values λ^T, and carbon pricing parameters $(\in_1, \in_2)$. At the outset of the algorithm, the baseline loss is calculated using the forecasted load $(L(T,D))$,. This serves as the reference point for assessing the effectiveness of subsequent strategies. Furthermore, an iteration counter j is established along with the initialization of Shapley values λ^T, and power generation levels PG^T at zero (Step 2). The algorithm proceeds with iterative evaluations, focusing on each distribution generation unit DG in turn (Step 3). Within this iterative loop, the carbon emissions for each DG are computed using an equation $(PG^T)_i^j = \frac{\left(\prod_a^T\right)_I^j - B_i)L(T,D)\Big)}{2_{a_i}}$ that considers Shapley values, the load forecast, and various parameters. The process is repeated for all DG units, sequentially advancing to the next i and continuing until all DGs are assessed. At each iteration, the total carbon emissions $V^L(C)$ and losses $V^L(C)$ for the coalition C are calculated based on the carbon emissions determined in the previous steps. The algorithm proceeds by quantifying the change in benefits $\Delta benefit$ through an equation $(PLoss_0^T - PLoss_j^T)\lambda^T - \sum_{i=1}^{N_{DG}} (PG^T)_i^j * \prod_a^T)_I^j - \lambda^T - \sum_{i=1}^{N_{DG}} (QG^T)_i^j \prod_R^T)_I^j + (EC_0^t - EC_j^t)\omega_e$ that factors in carbon losses, Shapley values, and other relevant parameters. A pivotal decision point is reached as the algorithm evaluates whether the change in benefits falls below the predefined threshold $\in_1$ or if the change in power generation is less than $\in_2$. If either condition is met, the algorithm proceeds to its termination (Step 9). Conversely, if neither condition is satisfied, the analysis continues with steps 11 to 13. Within this phase, the algorithm calculates the share of each DG in driving changes in carbon emissions (carbon emissions $\Phi_i(L)$ and change emission $\Phi_i(e)$) through the application of Shapley values SV (Step 14). Furthermore, it calculates financial incentives for each DG based on their contributions to carbon emission reduction

$$DGgain^i_{loss} = \omega_1 \frac{(PLoss_0^T - PLoss_j^T\Big)\lambda^T + \Big(\Big(\Big(EC_0^t - EC_j^t\Big)\omega_e\Big)xLoss(i)}{\Big(PLoss_0^T - PLoss_j^T\Big)}$$

$DGgain^i_{Emn} = \omega_2 \frac{(PLoss_0^T - PLoss_j^T)\lambda^T + (((EC_0^t - EC_j^t)\omega_e)xEmn(i)}{(PEmn_0^T - Emn_j^T)}$. These incentives are determined through a combination of the original carbon losses $PLoss$, the updated Shapley values λ^T, and additional parameters, incorporating both losses and emissions. Active and reactive power incentives for each DG are also computed using equation

$$DGgain^i_P = DGgain^i_{Loss} * \Big(cosdg^i\Big)^2 + DGgain^i_{Emn}$$
$$DGgain^i_Q = DGgain^i_{Loss} * \Big(1 - \Big(cosdg^i\Big)^2\Big)$$

(Step 16). The algorithm proceeds by recalculating the active and reactive power prices for the next iteration, considering the adjusted Shapley values and other relevant factors. Following this, the iteration counter j is incremented, and the algorithm returns to the outset of the loop, prepared for the next iteration. Ultimately, the algorithm concludes when the conditions specified in Step 9 are met (Step 18). This algorithm presents a comprehensive approach to managing carbon emissions within a supply chain organization. Rooted in cooperative game theory and Shapley values, it leverages carbon pricing, load forecasts, and Shapley values to make informed decisions. This facilitates the reduction of carbon emissions while acknowledging the financial incentives for different actors within the system, contributing to more sustainable and environmentally conscious supply chain practices.

4. Results and experiments

4.1 Simulation setup

In this section, we started to evaluate our proposed SVCGTA-EGT by adapting the dataset from the source Luo *et al.* (2024). For the evaluation of the proposed SVCGTA-EGT model, data has been referenced from the China Carbon Emissions Trading Network, the China Carbon Market Review and Outlook (2022), and the 2021 Study on Domestic Carbon Price Formation Mechanism to assign values to essential parameters. These parameter values align with real-world conditions and practicality. In 2022, the average daily transaction price of carbon emissions in China's national market fluctuated within the range of RMB 40–60 per ton. As a result, for the SVCGTA-EGT evaluation, a carbon price of 50 has been set. In addition to carbon price, other crucial parameters have been assigned values per the practical context. These values are informed by empirical data sources, enhancing the evaluation's reliability and authenticity. The dataset also accounts for the initial probabilities associated with upstream and downstream supply chain firms. In this context, a probability of 0.5 has been assumed for supplier technological innovation (x) and manufacturer subsidy (y). This simplification is consistent with the focus of the SVCGTA-EGT evaluation, which prioritizes the dynamics of carbon trading and reduction efforts while acknowledging initial probabilities in the supply chain. By employing this dataset, the proposed SVCGTA-EGT model can be rigorously assessed within the framework of real-world carbon emissions trading in China, contributing to a more comprehensive understanding of its practical utility and impact.

4.2 Evaluation criteria

In this section, we conduct a comprehensive comparative analysis between our proposed SVCGTA-EGT model and existing game-theoretic models, including Stackelberg (Xu *et al.*, 2021), ESS (Li *et al.*, 2022), and Non-Cooperative approaches (Zhou *et al.*, 2019) in terms of carbon emission reduction and cost reduction efficiency. Our evaluation encompasses several critical dimensions, including carbon pricing effectiveness, Shapley values, incentives, subsidies, and active and reactive power prices. This rigorous comparison allows us to assess the performance and impact of each model across these vital parameters.

4.2.1 Carbon pricing effectiveness. Figure 2 consists of two sets of carbon pricing parameters, ε1 and ε2, and their corresponding effectiveness values. Carbon pricing parameters represent the pricing mechanisms or costs associated with carbon emissions. In this context, ε1 and ε2 are two different parameters, and their values are varied to assess how they impact the effectiveness of a carbon pricing model in incentivizing carbon reduction. ε1 encompasses a range of values that likely represent distinct levels or rates of carbon pricing. These values provide a spectrum of pricing parameters, reflecting varying degrees of cost associated with carbon emissions. Parallel to ε1, ε2 presents a series of values related to the carbon pricing parameter ε2. These values could signify alternative pricing mechanisms, potentially different from ε1, offering a diverse set of parameters to analyze. The effectiveness list quantifies the performance of the carbon pricing model when exposed to different combinations of ε1 and ε2. The values directly signify the model's effectiveness in driving carbon reduction under the specified ε1 and ε2 pairs. Effectiveness serves as a

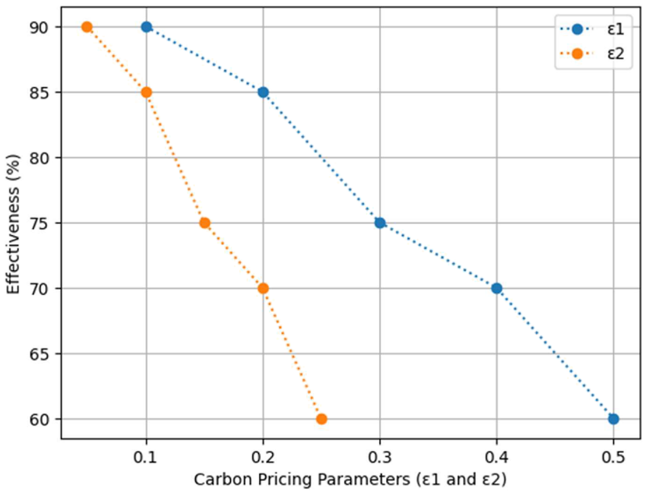

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Figure 2.
Carbon pricing effectiveness

measure of the model's capacity to stimulate carbon emissions reduction. In this context, the data suggests that heightened values of both ε1 and ε2 decrease effectiveness. These play a crucial role in evaluating and fine-tuning the parameters of a carbon pricing model. The objective is to identify the optimal combination of ε1 and ε2 values that maximize effectiveness, ensuring robust incentives for carbon emissions reduction while maintaining economic feasibility.

4.2.2 Shapley values for DG units. Shapley values, originating from cooperative game theory, are a mechanism for attributing value to participants in a collaborative context based on their respective contributions to the overall outcome. In the specific context of carbon emission reduction and the involvement of DG units, Shapley values offer valuable insights into the contributions of each DG unit toward lowering carbon emissions, as illustrated in Figure 3. Within this framework, DG symbolizes distinct distribution generation units, each charged with generating or distributing electrical power within a given system. In pursuing carbon emission reduction, these DG units employ diverse energy sources and technologies to supply electricity while striving to minimize carbon emissions. The Shapley values assigned to DGs represent quantified estimations of each unit's role in reducing carbon emissions. For instance, DG2's Shapley value of 0.3 signifies that DG2 substantially contributes to reducing carbon emissions. This suggests that the actions or technologies implemented by DG2 are instrumental in attaining the emission reduction objective. In contrast, DG4's Shapley value of 0.1 indicates a smaller but meaningful influence on emissions reduction. Overall, Shapley values offer a numerical measure of each DG unit's significance and effectiveness in reducing carbon emissions. They aid decision-makers in recognizing the units that play more substantial roles in accomplishing environmental objectives, thereby facilitating the development of targeted strategies and resource allocation.

4.2.3 Performance evaluation in terms of incentives and subsidies, active and reactive power prices and iteration efficiency. SVCGTA-EGT excels in incentives and subsidies, power pricing, and iteration efficiency, which are presented in Figure 4. In incentives and subsidies, the financial support provided to DG units stands out for its remarkable effectiveness. These incentives have effectively spurred the DG units to take meaningful actions to reduce carbon emissions. The model successfully fosters active engagement of DG

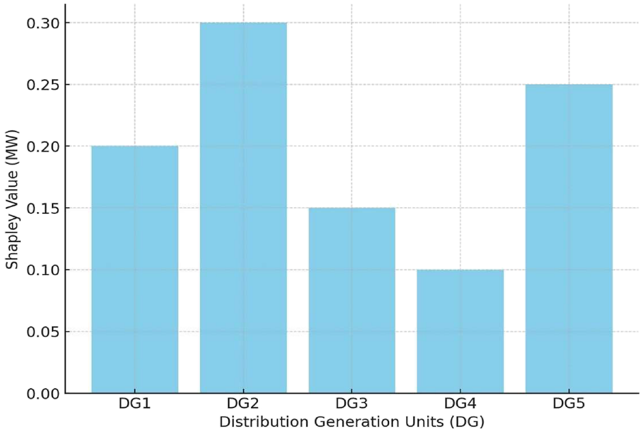

Figure 3.
Shapley values DG units for carbon emission reduction

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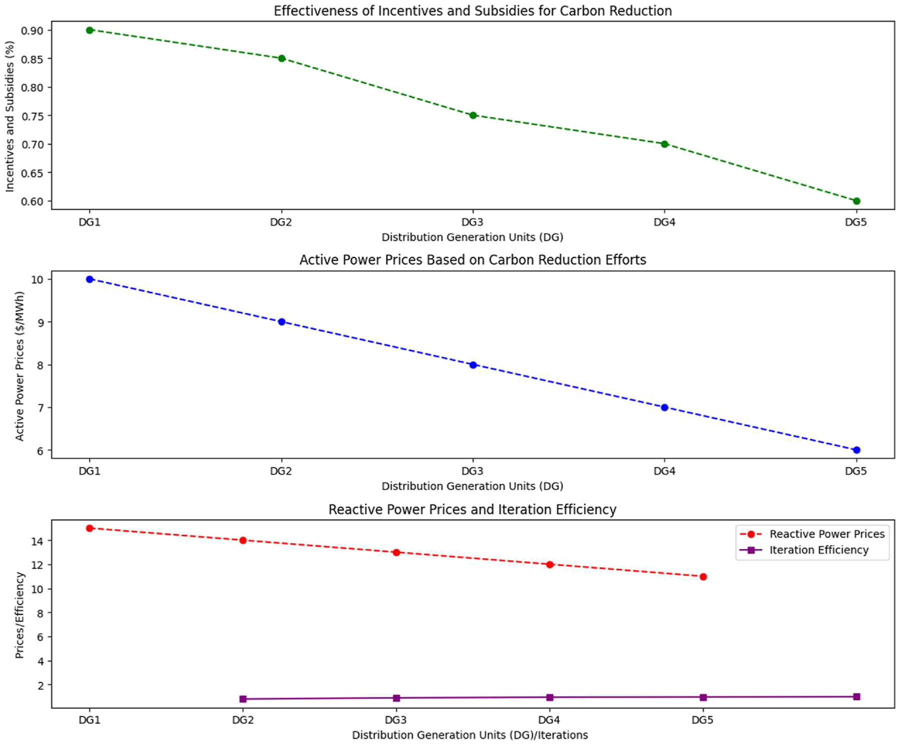

Figure 4.
Incentives and subsidies, active and reactive power prices and iteration efficiency

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units in carbon reduction initiatives, yielding substantial and impactful contributions in line with the model's emission reduction objectives. Regarding active and reactive power pricing, it aligns seamlessly with its overarching goals of curbing carbon emissions and enhancing economic efficiency. The pricing strategies employed within the model are designed to encourage energy consumption that is not only environmentally responsible but also economically prudent. This harmonious blend of environmental sustainability and economic viability underscores the model's success in achieving the supply chain organization's dual objectives. Furthermore, it demonstrates outstanding efficiency in its iterative processes. The model's iterative algorithm is notable for its swift convergence to stable outcomes, requiring a relatively small number of iterations. This efficiency translates into resource savings and reduced computational time, adding to the model's practicality. Its consistent ability to quickly reach meaningful solutions underscores the reliability of the iterative algorithm integrated into SVCGTA-EGT.

4.3 Comparison analysis

4.3.1 Carbon emission reduction. Figure 5 offers a comprehensive insight into the effectiveness of SVCGTA concerning carbon emission reduction, which serves as a focal point for comparing various models. The distinctive efficacy of SVCGTA becomes strikingly evident as the iterations progress. This model consistently achieves lower levels of carbon emissions, marking a resounding success in fulfilling its emission reduction objectives. The data depicts a continuous and significant decline in emissions over time, firmly establishing SVCGTA as a high-impact performer. In contrast, the Stackelberg model showcases a reduction in emissions, although its values remain marginally higher than those achieved by SVCGTA across all iterations. While Stackelberg proves to be a valid approach for emissions control, it falls short when it comes to matching SVCGTA's superior performance in emission reduction. The ESS model exhibits even higher emissions compared to both SVCGTA and Stackelberg. Though it does contribute to reducing emissions as time progresses, its journey

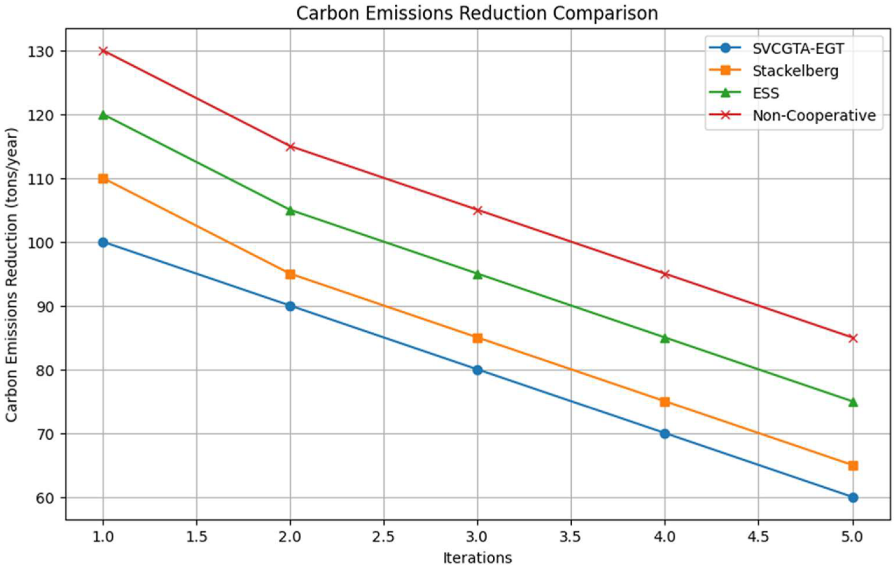

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Figure 5.
Comparison of carbon emission reduction

commences with higher initial emission levels and consistently trails behind the other models. This highlights a certain level of inefficiency on ESS's part in achieving emission reduction compared to SVCGTA and Stackelberg. Conversely, the non-cooperative model kicks off with the highest initial carbon emissions and remains stuck in this unfavorable position throughout the iterations, marking it as the least effective model for emissions reduction. Overall, SVCGTA consistently emerges as the frontrunner, succeeding in curbing carbon emissions to a greater extent than its counterparts. It surpasses not only the Stackelberg model but also the ESS and non-cooperative models regarding emissions reduction. This notable performance gap underscores SVCGTA's dominance, maintaining the lowest emissions levels throughout the iterations. The data thus confidently positions SVCGTA-EGT as an exceptionally proficient approach for mitigating carbon emissions, offering a valuable solution for tackling environmental sustainability concerns and managing low-carbon supply chains.

4.3.2 Cost reduction effectiveness. SVCGTA-EGT stands out with its impressive efficacy in cost reduction, as demonstrated in Figure 6. Across five iterations, this approach consistently exhibits a remarkable ability to optimize cost-saving strategies. The cost experiences a notable reduction, plummeting from 5,000 to 3,000 (USD) during this timeframe, accentuating the model's effectiveness. Each iteration consistently delivers significantly lower cost reduction values compared to the Stackelberg, ESS, and non-cooperative models. This enduring excellence underscores the model's resilience and trustworthiness. Critical to SVCGTA-EGT is its role in enhancing cost efficiency. The data accentuates the model's capacity to realize substantial cost savings, an imperative consideration for supply chain organizations aiming to boost their cost-effectiveness. By reaping financial benefits from the integration of low-carbon practices, SVCGTA-EGT makes a substantial contribution to curtailing operational expenses. Moreover, SVCGTA-EGT maintains a continuous competitive advantage in cost reduction throughout the iterations. This competitiveness proves invaluable for organizations with aspirations of cost minimization while concurrently preserving or improving their operational efficiency. The model's unwavering edge in cost reduction positions it as an appealing choice for supply

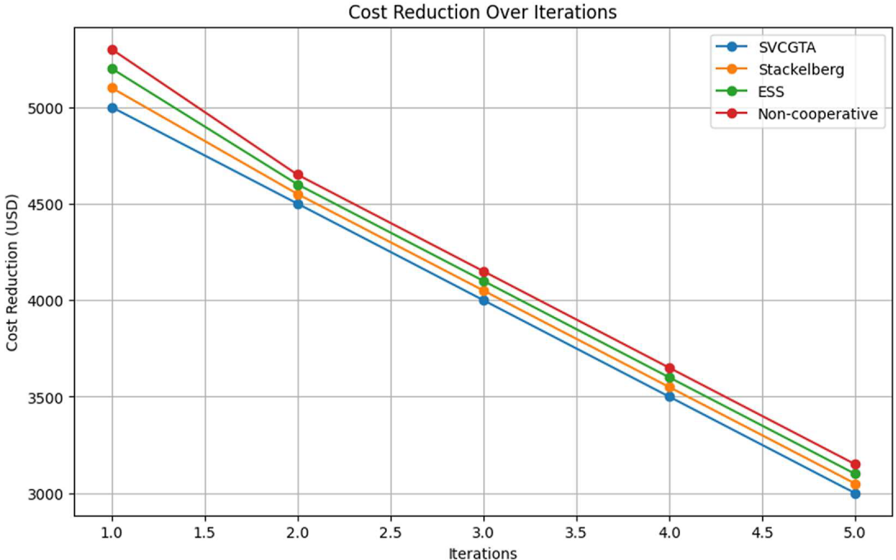

Figure 6.
Comparison of cost reduction efficiency

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chain management. Crucially, SVCGTA-EGT's effectiveness in cost reduction aligns seamlessly with economic goals. It efficiently curtails operational costs related to carbon emissions, providing vital support to supply chain organizations striving for heightened economic resilience. This alignment underscores SVCGTA-EGT as an exceptionally efficient and beneficial approach for organizations keen on optimizing cost savings and reinforcing overall economic efficiency within intricate supply chain operations.

5. Conclusion

In conclusion, our research introduces a novel and integrated approach by combining EGT with the SVCGTA to investigate low-carbon supply chain behavior. Throughout this study, we've successfully addressed several key objectives and provided valuable insights into the complex landscape of low-carbon practices in supply chain organizations. Our findings reveal the emergence of an ESS that adapts to various phases of low-carbon technology development. During the initial stages, we've shown that manufacturers and retailers can effectively adopt low-carbon behavior. However, as we progress into advanced phases of low-carbon technology, retailers emerge as the most efficient champions of low-carbon practices. This signifies the model's adaptability and underscores its alignment with evolving environmental, economic, and societal goals. Our research extends beyond theoretical constructs to explore real-world impacts. We've examined the influence of government low-carbon policies, consumer sensitivities, and the strategic calibration of retailer carbon financing incentives and subsidies on the identified ESS. Crucially, our work highlights that governments can incentivize organizations to reduce carbon emissions by adopting a more flexible approach and regulating carbon prices instead of imposing rigid carbon caps. Furthermore, our findings underscore the substantial influence of consumer sensitivities in driving lasting reductions in operational carbon emissions. Within the intricate ecosystem of the evolutionary supply chain, retailers have emerged as pivotal agents. Their strategic flexibility in adjusting carbon financing interest rates is critical in stabilizing the evolving supply chain system. Our combined SVCGTA and EGT model not only charts a transformative path through the complex landscape of low-carbon supply chain behavior but also offers profound insights into strategic transitions and collaborative dynamics. Our research is a valuable contribution to the field in a world increasingly focused on environmental sustainability, economic efficiency, and societal well-being. It provides a framework for supply chain organizations to navigate the ever-evolving low-carbon landscape effectively. Ultimately, our work paves the way for a more sustainable and harmonious future for low-carbon supply chains, resonating with a diverse range of stakeholders. In future, dynamic models that account for time-varying behaviors and strategies of supply chain participants, considering the evolving nature of policies, market demands, and technological advancements.

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