Research on Integration Strategies of Green Supply Chains in Cross-Border E-Commerce Oriented Toward Carbon Emission Reduction Targets

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Abstract: *Against the backdrop of deep integration between global carbon emission reduction efforts and digital trade, the construction of green supply chains in cross-border e-commerce has become a central issue in achieving sustainable development. In the face of challenges such as high carbon emissions, multi-node coordination, and information asymmetry, traditional supply chain models can no longer support the realization of carbon neutrality goals. Centering on green integration pathways oriented toward carbon emission reduction, this paper constructs a three-dimensional research framework encompassing theoretical foundations, collaborative structures, and optimization mechanisms. By analyzing the logic of supply chain restructuring, identifying sources of green pressure, and defining system boundaries, it explores green collaboration mechanisms and carbon data feedback systems. On this basis, it designs resource integration strategies and network optimization models. The study shows that carbon performance-driven approaches and data transparency are key pathways to achieving dynamic optimization of green supply chains, providing theoretical support and strategic guidance for building low-carbon and resilient cross-border e-commerce supply chains.*

Keywords: *carbon emission reduction targets; cross-border e-commerce; green supply chain; collaborative mechanism; optimization model; strategy evolution*

Introduction

The increasing stringency of global carbon emission constraints, coupled with the rapid development of digital business models, has imposed systemic pressure on cross-border e-commerce to shift from a “cost-efficiency” paradigm to a “green–low-carbon” collaborative transformation. As a complex network involving multiple entities, nodes, and interaction pathways, cross-border e-commerce inherently exhibits high carbon intensity, intricate coordination, and delayed feedback within its supply chain structure. Against this backdrop, establishing a carbon performance-oriented mechanism for green supply chain integration is not only an internal requirement for improving resource allocation efficiency and environmental performance but also a practical approach to promoting the sustainable reconstruction of international supply chains. Existing research primarily focuses on green optimization strategies in traditional manufacturing or local logistics sectors, while systematic studies on the collaborative restructuring and system evolution of green supply chains in cross-border e-commerce remain insufficient. Anchored in the logic of carbon constraints, this study systematically explores key issues such as structural design, mechanism coordination, and strategy optimization of green supply chains in cross-border e-commerce, aiming to offer theoretical innovation and methodological guidance for green supply chain integration in high-carbon, complex environments.

1. Theoretical Foundation for Green Supply Chain Integration Oriented Toward Carbon Emission Reduction

1.1 Structural Reconstruction Requirements for Supply Chain Systems under Carbon Emission Reduction Targets

Against the backdrop of the continuous advancement of global “carbon neutrality” strategies, supply chain systems are no longer linear structures driven solely by cost efficiency but are gradually evolving into multi-objective optimization systems that emphasize green performance, resilience, and systemic coordination. The incorporation of carbon emission reduction targets compels enterprises to reexamine the organizational logic, spatial layout, and functional division of supply chain nodes, integrating carbon footprint indicators into decision-making variables across the entire process, including site selection, procurement, production, distribution, and recycling. The integration of green performance not only extends the traditional "economic–operational" model but also fundamentally reconstructs the "environment–structure" relationship, marking a strategic shift in supply chain management from functional optimization to structural evolution.

In the complex network system of cross-border e-commerce, characterized by multi-regional, multi-node, and high-frequency interactions, carbon emission paths exhibit pronounced nonlinearity, asymmetry, and multi-dimensional coupling. Lengthened international logistics routes, dispersed supplier distributions, and fluctuating fulfillment cycles render traditional carbon accounting methods and static process models insufficient to meet green strategic objectives. Therefore, it is essential to utilize digital technologies to construct carbon emission mapping models based on multi-source data integration, enabling real-time tracking and traceability analysis of carbon footprints at the node, path, and system levels. On this basis, developing a green network optimization model centered on "carbon performance–responsiveness–collaborative stability" can support the restructuring of network architecture and the redistribution of node functions driven by carbon data, thereby providing a foundational framework with systemic adaptability for supply chain integration [1].

1.2 Analysis of Green Pressure Sources in Cross-Border E-Commerce Operating Models

While the rapid digitalization of global trade has accelerated the development of cross-border e-commerce, it has also exposed significant shortcomings in its green development practices. The operational process of cross-border e-commerce heavily relies on multi-node collaboration and a globalized logistics system, resulting in diverse carbon emission sources, extended emission paths, and considerable challenges in control. From global procurement and warehousing management to last-mile delivery, typical features of cross-border e-commerce—such as dispersed orders, decentralized logistics, and real-time fulfillment—collectively generate multidimensional carbon emission pressure points. Particularly in air transportation, excessive packaging, and distributed warehousing, the carbon intensity is significantly higher than that of localized e-commerce models, forming structural bottlenecks that urgently need to be addressed through green integration.

More critically, significant information asymmetry and the phenomenon of carbon data silos exist within the cross-border e-commerce system. The lack of unified carbon quantification standards and data integration mechanisms across countries and platforms hinders the efficient circulation and sharing of carbon-related information throughout the supply chain. The absence of real-time carbon performance evaluation mechanisms results in a disconnect between resource scheduling and emission reduction decision-making, forming a chain of "data delay–feedback absence–slow response." This structural mismatch in green coordination not only limits integration efficiency but also weakens the effectiveness of carbon optimization strategies. Therefore, it is essential to adopt a systems modeling approach to construct a framework for identifying and regulating carbon emission pressure sources, integrating proactive green risk identification mechanisms into the core of operations. This approach can provide both intervention pathways and data support for green upgrading and facilitate the evolution of cross-border e-commerce from carbon-intensive chains toward low-carbon and flexible network systems [2].

1.3 Functional Positioning and System Boundaries of Green Supply Chain Integration

The essence of green supply chain integration lies not merely in meeting carbon policy compliance requirements, but in establishing an operational system centered on carbon performance as the core metric to achieve the simultaneous generation of environmental and economic value. Its functional scope should encompass full lifecycle carbon control, spanning from upstream green procurement and eco-design, through midstream green manufacturing and low-carbon logistics, to downstream green fulfillment and recycling, thereby forming an end-to-end, closed-loop green management system. In this process, integration strategies focus not only on optimizing technological pathways but also emphasize collaborative mechanisms, data interoperability, and process linkage. By constructing a platform-based system, such integration enables carbon information sharing and real-time interaction among multiple stakeholders, supporting the dynamic coordination of green performance across all system nodes.

Regarding system boundary definition, green supply chain integration must transcend traditional corporate boundaries, functional modules, and operational segments, and instead build an integrated green ecosystem that spans platforms, regions, and systems. This network should cover the entire path from raw material supply, international transportation, and domestic distribution to consumer fulfillment and product recycling, achieving deep embedding of green principles throughout all processes, nodes, and platforms. The system must also possess adaptability to complex environmental disturbances and a self-regulating mechanism that ensures multi-objective coordination—maintaining carbon performance, service levels, and operational costs—under dynamic conditions such as order fluctuations, logistics delays, or sudden shifts in market demand. Ultimately, green supply chain integration not only yields dual benefits in resource optimization and carbon reduction but also provides a structural pathway and systemic support for the strategic upgrading of cross-border e-commerce in the era of "dual carbon" goals.

2. Collaborative Structure and Dynamic Mechanism of Green Supply Chains in Cross-Border E-Commerce

2.1 Value Network Restructuring Mechanism in Green Collaborative Structures

The construction of collaborative capabilities in cross-border e-commerce green supply chains centers on the systemic reorganization of the value network and the reconstruction of coordination mechanisms. Traditional supply chains typically operate under a cost-efficiency-driven linear structure, where the functional roles of nodes are highly specialized and fragmented, resulting in low resource allocation efficiency, obstructed carbon information flow, and a lack of green response mechanisms among nodes. Driven by carbon emission reduction targets, green collaborative structures require a shift from "independent optimization" to "collaborative optimization" among all participating entities, forming an ecologically oriented network system with carbon performance as the dominant variable. Within this system, suppliers, platform operators, cross-border logistics providers, customs clearance and local fulfillment agencies, and end consumers jointly constitute a multilateral cooperative network based on the principles of "shared carbon responsibility, joint green construction, and co-creation of value." By introducing intelligent platforms and centralized data hubs, carbon emission data sharing, fulfillment process transparency, and synchronized green responses are achieved across nodes, effectively supporting multi-dimensional coordination and resilient collaboration within the system.

The restructuring of green collaborative structures not only achieves networked organization in form but also transforms the logic of value creation from "linear value addition" to "circular value enhancement." In this reorganized network, the nature of collaborative relationships shifts from "transactional division of labor" to "strategic co-construction," emphasizing value redistribution mechanisms based on the shared allocation of carbon emission responsibilities. Each node participates in green cooperation agreements and jointly undertakes carbon reduction targets based on carbon performance, while also contributing to the establishment of a green credibility evaluation system under conditions of data transparency, thereby aligning carbon performance with commercial interests. Furthermore, the network incorporates multi-level green incentive mechanisms, such as carbon reduction performance bonuses, green fulfillment index-linked transaction fee rates, and dynamic credit ratings based on carbon footprints, to drive low-carbon behaviors and cooperation willingness among node actors. More importantly, the collaborative structure possesses high adaptability and evolutionary capacity, enabling self-optimization of the network and functional redistribution of nodes in response to market demand fluctuations, carbon policy adjustments, and technological advancements, thus ensuring that the green supply chain system maintains a stable state of high performance and low emissions in dynamic environments [3].

2.2 Process Reengineering and Node Coordination Driven by Green Performance

Under the guidance of carbon neutrality goals, the reengineering of supply chain processes goes beyond merely improving operational efficiency and focuses more on the dynamic optimization of carbon emission performance and coordinated control across multiple stages. Process design should adopt a full-chain perspective, embedding carbon efficiency into key nodes such as logistics route planning, inventory strategy adjustment, order batch consolidation, and packaging optimization. By introducing intelligent algorithms and data-driven models, it is possible to significantly enhance route minimization and load maximization in logistics operations, thereby achieving substantial reductions in carbon emissions per fulfillment unit while maintaining timeliness and cost-effectiveness. In high-frequency, multi-regional delivery scenarios, building a distributed order management system based on green fulfillment rules can improve both the carbon responsiveness and energy efficiency of the fulfillment chain.

The green reengineering of processes relies on refined node coordination mechanisms to address carbon performance disparities caused by node heterogeneity. Nodes vary significantly in carbon sensitivity, energy efficiency levels, and service radii, requiring the construction of functional profiles based on multi-dimensional indicators to enable accurate task matching and dynamic activation. The coordination model should balance carbon performance evaluation, operational response speed, and fulfillment stability across nodes, using weighted composite models or rule-based engines for task allocation and scheduling. By setting carbon sensitivity thresholds and green priority scheduling rules, the supply chain can establish a "low-carbon first, high-carbon compression" scheduling structure, which not only enhances the overall carbon optimization level of the system but also improves structural flexibility and system robustness in the face of sudden order fluctuations and operational disruptions.

2.3 Construction of a Dynamic Feedback System for Carbon Data Transparency

As a foundational element of green supply chain governance, carbon data—its collection completeness, processing capacity, and feedback mechanism—directly determines the implementation quality of integration strategies. The development of a dynamic feedback system must achieve a full-process closed-loop transformation from "static recording" of carbon data to "intelligent sensing–dynamic response–strategic adjustment." The system should integrate heterogeneous carbon emission data from suppliers, logistics providers, platform operators, and consumers, and establish a carbon indicator system and trajectory mapping model to generate an end-to-end carbon flow network. Based on this data, the system can embed dynamic monitoring thresholds and carbon anomaly alert modules to enable real-time identification of abnormal fluctuations in carbon intensity and corresponding strategic adjustments, thereby shifting carbon emission control from post-event tracking to in-process management [4].

Carbon data feedback serves not only for performance evaluation but also as a trigger mechanism for green strategy evolution and a foundation for intelligent decision-making. By integrating edge computing technology, the system enables rapid local responses, while blockchain technology ensures the trustworthiness and traceability of carbon data, preventing ambiguities in carbon responsibility or data tampering. The system should support multidimensional carbon indicator visualization and historical trajectory tracking, and include modules for automatic identification of carbon performance deviations and generation of strategic optimization suggestions, forming a closed-loop feedback chain of "perception–diagnosis–decision–adjustment." The construction of this mechanism not only enhances the execution efficiency and adaptability of green integration strategies but also provides a technological foundation and institutional support for the precise realization of green goals in the complex and ever-changing environment of cross-border e-commerce.

3. Strategic Pathways and Optimization Models for Green Supply Chain Integration in Cross-Border E-Commerce

3.1 Resource Integration Strategy Design Based on Carbon Constraints

In the green transformation process of cross-border e-commerce, carbon emission reduction targets, as a core constraint variable for resource allocation, impose new structural demands on the logic of supply chain resource integration. Traditional resource scheduling models driven by cost and efficiency optimization are no longer adequate to meet the multidimensional environmental performance requirements under the current green and low-carbon strategic context. Green resource integration strategies must adopt "minimization of carbon marginal effects" as a core principle, incorporating carbon performance parameters into key resource elements such as logistics and transportation, warehouse energy use, packaging materials, and information systems. Through dynamic collection and regulation of carbon footprint data, a coordinated scheduling system should be established that accommodates order fluctuations, high-frequency fulfillment, and multi-node distribution, enabling balanced resource allocation across carbon performance, service quality, and operational resilience [5].

The implementation of this strategy should focus on building a multi-level carbon coordination system, including a low-carbon screening mechanism in raw material procurement, route compression and intensive distribution strategies during mid-stage fulfillment, and a circular recycling and reuse network at the final stage. The introduction of a "green resource pool" can integrate low-carbon resources distributed across various nodes, enhancing the regional matching capacity and flexible allocation efficiency of the supply chain system. A carbon quota-sharing mechanism can establish shared responsibility and incentive structures among multiple stakeholders, optimizing the collaborative governance structure of the supply chain. In the context of globalization, the heterogeneity of carbon accounting standards and environmental regulations across countries requires integration strategies to possess cross-regulatory adaptability and compliance control capabilities. Developing a resource matching model based on the composite objectives of carbon intensity, response timeliness, and environmental cost not only improves the operational efficiency of the system but also provides a solid institutional and algorithmic foundation for achieving green performance outcomes.

3.2 Construction of an Optimization Model for Green Supply Chain Network Structure

Optimizing the green supply chain network structure is not merely a logistics allocation issue, but rather a process of structural coordination and performance evolution under multi-objective system alignment. Driven by increasing carbon reduction pressures and evolving customer demands, the network structure must integrate multiple dimensions including green performance, service quality, and cost control to develop a complex optimization system characterized by resilience, adaptability, and predictive capability. The model design should incorporate core variables such as node carbon efficiency assessment, path carbon intensity analysis, and quantitative calculation of transportation carbon factors. Methods such as mixed-integer programming, multi-objective evolutionary algorithms, simulated annealing, or neural network optimization should be employed to establish a carbon performance–driven structural scheduling system that achieves optimal combinations and dynamic reconstruction of nodes and paths.

A key element of green network optimization lies in constructing a dynamic low-carbon priority path mechanism, which manages paths hierarchically via a carbon weighting function, activates nodes or transportation links with superior carbon performance, and suppresses the excessive activation of high-carbon consumption paths. Building on this, task density, adaptive edge weights, and service constraint conditions should be introduced to enable dynamic and flexible adjustment of the network structure. To enhance the model's practicality and foresight, order forecasting algorithms and multi-period rolling optimization strategies can be overlaid, strengthening network stability and response efficiency amid demand uncertainties and fluctuating carbon policies. Moreover, the green network model should function not only as a technical computational platform but also be embedded within strategic decision-making tools, providing theoretical support and structural basis for path planning, risk mitigation, and policy response in green supply chains [6].

3.3 Evolutionary Adaptation–Oriented Green Strategy Adjustment Mechanism

With the continuous refinement of carbon neutrality pathways and increasing uncertainty in the cross-border e-commerce environment, traditional static green strategy models face significant adaptability challenges. The dynamic adjustment mechanism for green supply chain strategies must possess a high degree of evolutionary capability and structural flexibility, enabling real-time fine-tuning or reconstruction of green fulfillment plans under varying market scenarios, policy constraints, and node fluctuations. The core of this mechanism should be based on evolutionary game theory and multi-agent learning frameworks, simulating the strategic behavioral evolution of participants under carbon cost and service performance considerations to drive structural co-evolution within the supply chain system. The strategy adjustment system should also utilize reinforcement learning and feedback correction algorithms to construct strategy adaptation functions, evaluate the effectiveness of node strategy configurations, and restructure pathways to ensure strategy transferability and stability.

The adjustment pathway for green strategies should rely on carbon data–driven and anomaly response mechanisms. By establishing distributed carbon performance monitoring nodes, the system can achieve real-time identification and early warning linkage of abnormal carbon behaviors. Strategy deviations serve as triggers activating adjustment algorithms, guiding iterative processes from local optimization toward global restructuring. Combining system memory functions with a carbon response historical database enables retrospective tracing and path review of strategy adjustment outcomes, providing data support and cognitive models for strategy evolution. Furthermore, the strategy evolution mechanism must adapt to multi-scale changing scenarios, supporting not only flexible micro-level process rescheduling but also serving macro-level green strategic transformation, thereby providing long-term assurance for maintaining low-carbon resilience and systemic adaptability in cross-border e-commerce supply chains amid complex environments.

Conclusion

This study, based on the demand for supply chain transformation driven by carbon emission reduction targets, systematically constructs the theoretical framework, collaborative mechanisms, and strategic models applicable to green integration in cross-border e-commerce. The research indicates that embedding carbon performance will reshape the structural logic and resource allocation methods of supply chain systems, and that green pressure sources in cross-border e-commerce require layered deconstruction and integrated optimization through network restructuring and node coordination. On this basis, the evolution of the green supply chain should be technologically supported by carbon data transparency, achieving structural adaptability and strategic iteration through a dynamic feedback system. Meanwhile, establishing multi-objective optimization models and evolutionary strategy adjustment mechanisms helps maintain system stability and low-carbon collaboration amid fluctuating carbon targets and market uncertainties. Future research may further focus on the standardized construction of carbon emission assessment models, collaborative optimization of multi-agent carbon game mechanisms, and integration pathways of intelligent algorithms in the dynamic evolution of green strategies, thereby providing more extensible theoretical foundations and algorithmic tools for the deep integration and sustainable development of green supply chains under the digital trade context.

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