Research on the Collaborative Emission Reduction Mechanism for Green Supply Chain Management in the Manufacturing Industry under the "Dual Carbon" Goals

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Abstract: Under the backdrop of the "dual carbon" goals, the collaborative emission reduction in the green supply chain of the manufacturing industry has become an important path to achieve the carbon reduction targets. This paper focuses on the issue of the collaborative emission reduction mechanism in the green supply chain of the manufacturing industry under the "dual carbon" goals, and constructs an analytical framework of "driving mechanism - collaborative mechanism - implementation path". It systematically explores the internal mechanism, influencing factors and mechanism design of the collaborative emission reduction in the green supply chain of the manufacturing industry. The study indicates that collaborative emission reduction is driven by multiple factors such as external pressure from policies and market mechanisms, as well as internal driving forces from economic interests. The collaborative emission reduction mechanism should include four dimensions: incentive mechanism, which stimulates emission reduction through revenue sharing, cost sharing and green procurement; constraint mechanism, which prevents opportunistic behavior through contracts, supervision and punishment; coordination mechanism, which resolves conflicts through communication, interests and resource coordination; and guarantee mechanism, which ensures the collaborative operation through technology, funds and systems. Based on this, countermeasures and suggestions such as enterprise strategic transformation, government institutional supply and the bridging role of industry associations are proposed, aiming to provide theoretical references and practical paths for the green transformation of the manufacturing supply chain and carbon emission reduction management.

Keywords: Dual Carbon Goals; Manufacturing Industry; Green Supply Chain; Coordinated Emission Reduction; Mechanism Design

1. Introduction

Climate change is a major challenge facing humanity today. "Carbon peak and carbon neutrality" has become a global consensus and a solemn commitment of China. Manufacturing, as an important sector of carbon emissions, is facing unprecedented pressure for emission reduction and opportunities for transformation. Green supply chain management has become a key leverage for manufacturing to achieve carbon emission reduction goals [1]. Under the traditional supply chain management model, the responsibility for carbon emissions often lies with individual enterprises, making it difficult to form a collaborative force for full-chain carbon emission reduction [2]. How to build an effective collaborative emission reduction mechanism and achieve the collaborative carbon emission reduction of upstream and downstream enterprises in the supply chain has become an important issue that needs to be addressed urgently. The core difference between green supply chain management and traditional supply chain management lies in embedding environmental protection and carbon emission reduction goals throughout the supply chain process. Through green transformation in aspects such as supplier management, material selection, production manufacturing, and logistics transportation, the systematic reduction of carbon emissions throughout the entire chain can be achieved [3]. However, green supply chain collaborative emission reduction faces multiple challenges. There is information asymmetry and conflicts of interest among supply chain enterprises, and "free-rider" behavior occurs from time to time; different

entities have significant differences in carbon emission reduction capabilities and intentions, and the coordination costs are high; carbon emission accounting standards are not unified, making it difficult to form an effective incentive and restraint mechanism [4]. Based on this, this paper focuses on the issue of collaborative emission reduction mechanisms for green supply chain management in the manufacturing industry under the "dual carbon" goals. By using theoretical tools such as collaborative governance and game theory, it deeply analyzes the evolutionary mechanism, influencing factors, and implementation paths of collaborative emission reduction among supply chain enterprises, providing theoretical references and practical guidance for the green transformation of manufacturing enterprises and the carbon emission reduction management of the supply chain.

2. Theoretical Basis

2.1 Green Supply Chain Management Theory

Green supply chain management refers to a management model that comprehensively considers environmental impacts throughout the entire supply chain process. It was first proposed by the University of Michigan in 1996 [5]. Its core concept is to integrate environmental protection and sustainable development goals into all aspects of the supply chain, such as procurement, production, logistics, and recycling, to achieve a win-win situation of economic benefits and environmental protection [6]. Studies have shown that effective green supply chain management can significantly reduce enterprise operating costs, reduce greenhouse gas emissions, enhance market competitiveness and brand value. In the context of the "dual carbon" goals, the connotation of green supply chain management has further deepened. It not only focuses on pollutant emission control, but also emphasizes systematic management of carbon emissions, becoming an important path choice for enterprises to achieve carbon reduction targets [7].

2.2 Collaborative Governance Theory

The theory of collaborative governance emphasizes that multiple entities achieve common goals through coordinated cooperation. In the context of the green supply chain, collaborative governance involves horizontal collaboration between the core enterprises of the supply chain and their upstream and downstream suppliers, as well as vertical collaboration among various entities such as the government, the market, and society [8]. The core of collaborative governance lies in establishing effective coordination mechanisms, benefit distribution mechanisms, and information sharing mechanisms. Through institutional design, it addresses the "free-rider" problem in collective actions and maximizes the overall interests of the supply chain [9]. Studies have shown that collaborative governance can significantly reduce the carbon emission intensity of the supply chain and enhance the efficiency of green transformation [10].

3. Mechanism Analysis of Collaborative Emission Reduction in Green Supply Chain

3.1 The Incentive Mechanism of Collaborative Emission Reduction

The driving force for collaborative emission reduction in the green supply chain stems from the dual influence of external pressure and internal motivation [11]. From the perspective of external pressure, policy regulations are the main driving force [12]. China has set the goals of carbon peak by 2030 and carbon neutrality by 2060. The Ministry of Industry and Information Technology and other departments have set clear requirements for the reduction of carbon emission intensity in key industries. The implementation of the EU's Carbon Border Adjustment Mechanism (CBAM) has imposed carbon tariff pressure on export enterprises, compelling the upstream and downstream of the supply chain to jointly reduce carbon emissions. The improvement of the market mechanism also creates pressure. The expansion of the national carbon market internalizes the cost of carbon emissions, forcing enterprises to pay attention to the carbon footprint of the supply chain. The enhancement of consumers' environmental awareness also brings market pressure, as green consumption preferences prompt enterprises to optimize carbon management in the supply chain. The improvement of consumers' environmental awareness also brings market pressure. The green consumption preferences prompt enterprises to optimize carbon management in the supply chain. From the perspective of internal motivation, economic benefits are the fundamental driving force for enterprises to

participate in collaborative emission reduction [13]. Collaborative emission reduction can generate scale effects, reducing the emission reduction costs of individual enterprises; it can obtain green premiums, enhancing the market competitiveness of products; and it can enjoy policy incentives, receiving fiscal subsidies and tax benefits. Core enterprises in the supply chain can enhance the stability and resilience of the supply chain by assisting suppliers in reducing emissions, and reduce the risk of supply chain disruptions [14].

3.2 Information Sharing and Transparency Mechanism

Information sharing is the fundamental condition for collaborative emission reduction. In traditional supply chains, carbon emission information is mostly limited to the level of individual enterprises, and the transmission of carbon footprints along the supply chain is not smooth, making it difficult to accurately define carbon emission responsibilities [15]. The application of digital technologies has made information transparency possible. Internet of Things sensors can collect energy consumption data in real time, blockchain technology ensures the immutability of data, and artificial intelligence algorithms can accurately calculate carbon footprints. By building a supply chain carbon data platform, full life cycle carbon footprint tracking can be achieved from raw material extraction, component processing, logistics transportation to final product recycling [8]. The establishment of an information sharing mechanism requires addressing two major issues: data standards and privacy protection. In terms of data standards, it is necessary to unify carbon emission accounting methods and data formats to ensure the comparability of carbon data across all supply chain links. In terms of privacy protection, a balance needs to be struck between information transparency and commercial confidentiality. Federated learning and other privacy computing technologies can be adopted to achieve "data availability but not visibility".

3.3 Cost Sharing and Benefit Coordination Mechanism

Cost sharing is the key to maintaining the long-term stability of collaborative emission reduction. Due to the differences in bargaining power and emission reduction capabilities among supply chain enterprises, the design of the cost-sharing scheme directly affects the willingness and sustainability of participation of all parties [16]. Core enterprises usually bear more costs for emission reduction investment and technical support, while suppliers are responsible for the implementation of specific emission reduction renovations. Studies have shown that a reasonable cost-sharing ratio should be matched with the distribution of emission reduction benefits and reflect the principle of fairness [17]. The core of the benefit coordination mechanism lies in establishing a reasonable benefit distribution plan. The benefits brought by collaborative emission reduction include carbon quota savings benefits, green premium benefits, brand value enhancement, and supply chain stability improvement, etc. The distribution of benefits should comprehensively consider the emission reduction investment, risk assumption, and opportunity cost of all parties. A model of "basic distribution + performance rewards" can be adopted, and it can be dynamically adjusted according to the actual emission reduction effects of all parties.

3.4 Influencing Factors and Evolutionary Game Mechanism

The effectiveness of green supply chain collaborative emission reduction is influenced by multiple factors. Large enterprises usually have stronger resource endowments and technical capabilities, and their willingness to reduce emissions is relatively higher [18]. The difference in emission reduction capabilities leads to varying levels of participation by supply chain enterprises in collaborative emission reduction. Enterprises with strong environmental awareness are more inclined to take on the responsibility of emission reduction voluntarily, while short-sighted enterprises may exhibit "free-rider" behavior [17]. The degree of dependence between the core enterprise and its suppliers affects the depth and breadth of collaborative emission reduction, with a higher degree of dependence resulting in a stronger willingness to collaborate. Effective communication mechanisms can reduce information asymmetry and reduce coordination costs [15]. Historical cooperation experience influences enterprises' expectations for the collaborative prospects, and a good cooperative experience helps to establish long-term collaborative relationships. The stricter carbon emission regulations lead to greater emission

reduction pressure on enterprises and a stronger external driving force for collaborative emission reduction. The degree of market competition affects enterprises' motivation to gain competitive advantages through green differentiation. Technological conditions determine the cost and feasibility of emission reduction, and technological progress has lowered the technical threshold for collaborative emission reduction. The institutional environment includes carbon market mechanisms, green financial support, etc. A well-developed institutional environment helps to encourage collaborative emission reduction behavior [19].

The evolutionary game mechanism indicates that the strategic choices of supply chain enterprises for collaborative emission reduction have multiple equilibria [20]. In the absence of effective incentive mechanisms, the supply chain may encounter a "collaborative dilemma", where both parties choose not to collaborate on emission reduction, resulting in a collectively irrational outcome. When there is an appropriate incentive and constraint mechanism, the system may converge to the "collaborative emission reduction" stable strategy. The achievement of the stable strategy depends on initial conditions, parameter settings, and external environmental factors.

4. Collaborative Emission Reduction Mechanism Design

4.1 Design of Incentive Mechanism

The incentive mechanism is the core mechanism for promoting the collaborative emission reduction among supply chain enterprises [21]. An effective incentive mechanism should balance efficiency and fairness, stimulating the emission reduction enthusiasm of all parties. The revenue-sharing incentive mechanism, by reasonably distributing the benefits brought about by collaborative emission reduction, motivates enterprises to continuously participate. The revenue-sharing mechanism can significantly enhance the willingness of suppliers to collaborate and strengthen the stability of the collaborative relationship. The cost-sharing incentive mechanism, by reasonably sharing the emission reduction costs, lowers the participation threshold for enterprises, and reasonable cost-sharing can attract more suppliers to participate in collaborative emission reduction. The green procurement incentive mechanism, through procurement policies to guide suppliers to undergo green transformation, can form positive incentives, guiding suppliers to actively improve their carbon management levels.

4.2 Design of Constraint Mechanism

Constraint mechanism is an important mechanism to prevent opportunistic behavior and ensure collaborative stability [22]. Contractual restraint, by signing clear collaborative emission reduction agreements and stipulating the responsibilities and obligations of all parties, can form a stable expectation of cooperation and reduce the probability of opportunistic behavior. Supervisory restraint, by establishing an effective supervision system to ensure the implementation of emission reduction measures, can promptly identify problems and urge all parties to fulfill their emission reduction commitments. Punitive restraint, through penalties for violations, curbs opportunistic motives. Punitive restraint should be used in conjunction with incentive restraint to form a management system that combines rigidity and flexibility.

4.3 Design of Coordination Mechanism

The coordination mechanism is an important mechanism for resolving collaborative conflicts and enhancing collaborative efficiency [23]. The communication coordination mechanism, by establishing regular communication channels, promotes information exchange and problem-solving. Effective communication and coordination can promptly resolve conflicts and maintain collaborative relationships. The interest coordination mechanism, by reasonably distributing collaborative benefits and resolving interest conflicts, helps to establish a stable interest community. The resource coordination mechanism, by optimizing resource allocation, enhances collaborative efficiency. Resource coordination can generate scale effects and improve the overall efficiency of collaborative emission reduction.

4.4 Design of Guarantee Mechanism

The guarantee mechanism is the institutional arrangement that supports the continuous operation of collaborative emission reduction [24]. The technical guarantee mechanism provides technical support for collaborative

emission reduction. Establishing a carbon management technology service platform for supply chains, conducting academic-industry-research cooperation, and promoting advanced and applicable technologies, etc., are all technical guarantee mechanisms that can reduce emission reduction costs and enhance the effectiveness of emission reduction. The financial guarantee mechanism provides financial support for collaborative emission reduction. The financial guarantee mechanism can solve the financing problems of enterprises and ensure the smooth implementation of emission reduction projects. The institutional guarantee mechanism provides institutional support for collaborative emission reduction, which can standardize the behavior of collaborative emission reduction and create a favorable external environment.

5. Suggestions

Firstly, manufacturing enterprises should attach great strategic importance to the collaborative emission reduction in the green supply chain and incorporate it into the core content of their sustainable development strategies. Establish a green supply chain management system, clearly define the responsibilities and divisions of each department in carbon emission reduction, and specify medium- and long-term emission reduction targets and implementation paths. Increase the intensity of green procurement. Enterprises should use carbon emission reduction performance as an important indicator for evaluating suppliers, establish long-term strategic cooperation relationships with suppliers, and jointly set emission reduction targets and implementation plans. Incorporate carbon emission reduction requirements into the entire process of supplier admission, evaluation, and elimination. Guide the green transformation of the supply chain through green procurement. In addition, enterprises should open up their technological accumulation and provide technical assistance and capacity training to suppliers; jointly build a carbon emission reduction technology research and development platform, carry out key common technology research; promote digital carbon management tools to enhance the transparency of carbon data and the efficiency of carbon accounting in the supply chain.

Secondly, the government should play a role in guiding policies and providing institutional support, creating an external environment conducive to the collaborative emission reduction of the green supply chain. Introduce special policies for collaborative emission reduction in the green supply chain, clearly defining incentives such as tax benefits, financial subsidies, and financial support; establish a special fund for the development of the green supply chain to support core enterprises in carrying out carbon emission reduction demonstration projects in the supply chain; establish a green procurement policy system to guide public institutions to prioritize the purchase of green products. Accelerate the formulation of carbon emission accounting standards for key industries, unify the calculation standards and methods of carbon footprints; improve the evaluation standards for the green supply chain, establish a unified green rating system for suppliers; promote the improvement of the carbon market mechanism, expand the coverage of carbon emission rights trading. Establish a carbon disclosure system for the supply chain, requiring key enterprises to regularly disclose carbon emission data of the supply chain; strengthen the construction of third-party carbon verification institutions to improve the quality and credibility of verification; enhance the coordination and cooperation between the carbon market and other policy tools to form policy synergy. Ensure the effectiveness of the policies through effective supervision.

Thirdly, industry associations should play the role of a bridge and link, promoting the overall improvement of the collaborative emission reduction in the industry's green supply chain. They should formulate industry self-discipline conventions, clearly defining the emission reduction standards and behavioral guidelines for the industry; establish an information sharing platform for carbon emission reduction within the industry to facilitate the exchange and promotion of best practices; conduct performance evaluations and rankings on carbon emission reduction in the industry to motivate the advanced and urge the lagging behind. Organize carbon emission reduction technology seminars to share advanced technologies and successful experiences; establish an industry technical expert database to provide consulting services for enterprises' emission reduction renovations; promote cooperation among industry, academia and research institutions to

facilitate the research and development of carbon reduction technologies and the transformation of achievements. Participate in the formulation of international green supply chain standards to enhance the international influence of Chinese standards; draw on international advanced experience to improve the domestic green supply chain management system; promote international recognition to facilitate international trade in green products and services.

6. Conclusion

This paper focuses on the core issue of collaborative emission reduction of green supply chain in manufacturing industry under the "Dual carbon" goals target, and systematically carries out mechanism analysis and mechanism construction research for the practical pain points of decentralized carbon emission responsibility and insufficient reduction force of the whole chain in traditional supply chain management. The research first summarized the core connotations of green supply chain management theory and collaborative governance theory, clarified the development direction of green supply chain management under the "dual carbon" context, which is the deepening of systematic management of carbon footprints throughout the entire chain from end-point pollution control. This laid a solid theoretical foundation for the subsequent analysis. Based on this, from three dimensions of the driving mechanism, information sharing transparency mechanism, and cost sharing and interest coordination mechanism, the internal operational logic of collaborative emission reduction in the green supply chain was deeply explained. Combined with the evolutionary game method, the multiple equilibrium characteristics of enterprise strategy choices were analyzed, the influence paths of key factors such as external policy regulation, internal economic motives, and differences in subject capabilities on the effect of collaborative emission reduction were clarified, and the evolutionary law that the supply chain is prone to fall into a "collaborative dilemma" when lacking effective institutional design was revealed. Based on the conclusion of mechanism analysis, this article completed the systematic design of the green supply chain collaborative emission reduction mechanism from four dimensions of incentives, constraints, coordination, and guarantees, and constructed a flexible and tough full-chain management framework: through revenue sharing, cost sharing, and green procurement to form a positive incentive system, relying on contracts, supervision, and punishment mechanisms to prevent opportunistic behaviors such as "free-riding", using communication, interests, and resource coordination to resolve conflicts among subjects, and supplemented by technology, funds, and institutional guarantee support mechanisms to ensure the long-term stable operation. Finally, from the three levels of enterprise strategic implementation, government institutional supply, and industry association bridging role, practical countermeasures and suggestions were proposed.

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