Research on Measurement Assessment and Optimization Scheme Based on Supply Chain Carbon Emission Reduction - Take Lenovo Group as an Example.

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Abstract: Under the global "dual-carbon" framework, decarbonizing supply chains has become critical for corporate green transformation. Using Lenovo Group as a case study, this work constructs a comprehensive supply chain carbon measurement system by integrating life cycle assessment (LCA) and economic input-output modeling (EIO-LCA). The system identifies high-emission linkages and proposes targeted optimization strategies. Findings reveal that Lenovo's supply chain emissions concentrate predominantly in raw material procurement and cross-border logistics. Implementing green purchasing agreements, optimizing multimodal transportation routes, and deploying a digital carbon management platform reduced emission intensity by 18.5%. This research establishes a replicable emissions-reduction methodology for electronics manufacturing while providing theoretical support for policymakers and industry practitioners.

Keywords: Supply Chain Carbon Reduction; Life Cycle Assessment; Input-Output Modeling; Lenovo Group; Low-Carbon Transition

1. Introduction

Global climate change has emerged as one of the most significant challenges of the twenty-first century. According to the International Energy Agency's (IEA) study (2023), worldwide carbon emissions reached 36.8 billion tons in 2022, with industrial and logistical operations accounting for more than 60%. As one of the most globalized industries, electronics production faces a particularly significant supply chain carbon emission problem [1]. Using cellphones as an example, the carbon emission intensity of the whole life cycle, from rare earth mining to chip production to cross-border transit, is 2-3 times that of the traditional manufacturing industry [2]. In this context, the goal of "carbon peak and carbon neutrality" is not only the focus of national policies, but also a key indicator of the core competitiveness of enterprises.

Lenovo, as a global leading technology company, has a supply chain covering more than 80 countries and involving thousands of suppliers, and the 2023 ESG report shows that Lenovo's direct carbon emissions will decrease by 12% compared to 2021, but the implied carbon emissions from the supply chain still account for more than 75% of the total emissions [3]. This data shows that the complexity and systematic nature of supply chain carbon emissions reduction far exceeds the company's own operations. How to scientifically quantify the carbon emission of the whole chain? How to balance the cost and efficiency of emission reduction in the globalization layout? These questions urgently need breakthroughs in theory and practice.

Taking Lenovo Group as a case study, this study attempts to solve the following core issues through dynamic modeling and empirical analysis: (1) How to accurately measure the direct and implied carbon emissions of the whole life cycle of the supply chain? (2) How to design an optimized solution that takes into account both economic feasibility and environmental benefits? (3) How to provide a generalizable emission reduction paradigm for the electronics manufacturing industry? The results of this study not only provide technical paths for enterprises' green transformation, but also provide data support for policy makers to improve the carbon market mechanism.

2. Literature Review

Research on the measurement and optimization of carbon emission reduction in supply chains has shown a trend of interdisciplinary integration in recent years. The Economic Input-Output Life Cycle Model (EIO-LCA) proposed by LAVE et al. lays the foundation for quantifying implied carbon emissions, but its static framework is difficult to adapt to the needs of a dynamic supply chain [4]. For this reason, Zhu et al. introduced blockchain technology to construct a real-time carbon emission tracking system, which improves the frequency of data update from monthly to hourly level [5]. At the policy level, the implementation of the European Union's Carbon Border Adjustment Mechanism (CBAM) has forced enterprises to reassess the carbon cost of cross-border logistics [6], while the expansion of China's carbon trading market has provided a testing ground for the innovation of carbon financial instruments [7].

Research on carbon emissions in the electronics manufacturing industry has gradually shifted from the macro to the micro. Hu et al. (2023) found that carbon emissions from rare earth metal refining accounted for 52% of raw material purchases by disaggregating supply chain data from Chinese headline companies, far exceeding the industry average [8]. The study proposes a "green supplier alliance" model to help SMEs reduce emission reduction costs through joint procurement and technical support [9]. In the field of logistics optimization, a study has also proposed a reinforcement learning algorithm to prove that intermodal transportation path planning can reduce carbon emissions by 15%~20%, while reducing the risk of transportation delays [10].

Despite the remarkable research progress, there are still three major shortcomings: first, most models rely on historical data, which makes it difficult to cope with unexpected events such as supply chain disruptions; second, there is a lack of case studies for high-tech manufacturing industries, and most of the existing results are focused on the heavy industry; third, the synergistic effect of policy and technology has not been fully explored. For example, Jiang et al. proposed the application of digital twin technology in supply chain carbon emissions management, but did not involve industry-specific practical verification [11]; OLADEJI O et al. developed an AI-driven carbon accounting model that improves data accuracy but lacks consideration of the complexity of transnational supply chains [12]. In addition, existing studies have paid insufficient attention to the dynamic response mechanism of carbon pricing mechanisms. For example, the impact of the EU Carbon Border Adjustment Tax (CBAM) on developing country exporters has not yet been systematically assessed in a framework (OECD, 2024) [13], and the regional pilot experiences of China's carbon market have not been sufficiently integrated into global supply chain optimization models. These limitations provide directions for improvement in this study [14].

2.1 Domestic Research Status

The research of domestic scholars in the field of supply chain carbon emission reduction is also of great value. Early studies focused on the impact of carbon cost management on enterprise operations, such as Zhang Lingrong pointed out that carbon cost management is the core link of supply chain management, which directly affects the environmental image and market competitiveness of enterprises [15]. Liang Kairong explored the sharing mechanism of carbon emission reduction cost among supply chain members through cooperative game theory, which provided a theoretical basis for cross-enterprise collaborative emission reduction [16]. With the deepening of research, scholars gradually turn to the exploration of specific implementation paths. For example, Liu Beibei constructed an optimization model of supply chain costs and benefits under the constraint of carbon tax, which provides a new method for the assessment of economic effects [17]; while Ke Lisi designed a comprehensive model of low-carbon supply chain based on the allocation of carbon emission rights and verified its feasibility in actual projects [18]. In terms of optimization strategies, Zhang Lei proposes a supply chain optimization scheme based on consumers' low-carbon preference for the online shopping environment [19], while Ruan Yuyue reveals the practical significance of supply chain synergy for carbon emission reduction through the case of Zongshen Group's procurement platform [20]. The interaction between policy and market has also received attention, with Zhu Hui analyzing the R&D decisions of enterprises to reduce emissions under different policy environments [21], and Shen Chengran exploring the impact of a carbon labeling system on suppliers' participation [22]. These studies provide multi-level theoretical support for the practice of supply chain carbon emission reduction in China.

2.2 International Research Status

Research in the international academic

community has paid more attention to methodological innovation and technology integration. Since the input-output analysis method was proposed by Leontief in the 1930s, it has gradually developed into the Economic Input-Output Life Cycle Model (EIO-LCA), which has become an important tool for measuring implied carbon emissions [23]. On this basis, scholars have further combined the life cycle assessment (LCA) method to quantify the carbon footprint of the whole life cycle of products [24]. At the assessment and validation level, the quantification of performance indicators and data transparency have become the focus of research. For example, OTSUBO Y et al. point out through empirical research that the standardization of suppliers' carbon information management system is a key factor influencing the choice of enterprises [25]; MAHESHWARI emphasizes the indispensability of big data analytical capability to build a sustainable supply chain, and demonstrates through cases that it significantly improves the precision of carbon management [26]. PALIWAL, on the other hand, reflects on the digitalization means' PALIWAL, on the other hand, reflects on the limitations of digital tools, pointing out that rapid market changes and a single technological driver may weaken the adaptability of emission reduction programs [27]. These results provide multi-dimensional theoretical and practical references for global supply chain carbon emission reduction, but also highlight the common problem of insufficient case depth.

Comprehensive studies at home and abroad show that although the measurement and optimization of supply chain carbon emission reduction has formed rich results, case studies for high-tech manufacturing industries are still scarce. Existing literature mostly focuses on heavy industry or energy industry, and there is a lack of systematic discussion on the carbon footprint tracking and emission reduction path design of complex supply chains in the electronics manufacturing industry. For example, the carbon emission characteristics of high-tech links such as rare earth element mining and chip manufacturing have not been fully analyzed, and the carbon cost sharing mechanism of cross-border logistics needs to be further detailed. In addition, the actual effect of the synergistic effect of policy and technology in a dynamic supply chain environment still needs to be empirically tested. Taking Lenovo Group as an entry point, this study tries to fill the above gaps and provide new perspectives for theory and practice by integrating dynamic data and interdisciplinary approaches.

3. Argumentative Analysis

3.1 Supply Chain Carbon Emission Measurement Framework

The measurement and optimization of supply chain carbon emission reduction need to be based on scientific model construction and deep mining of empirical data. This study takes Lenovo Group as a case study and integrates life cycle assessment (LCA) and input-output modeling (EIO-LCA) to construct a dynamic analysis framework. The LCA methodology covers the entire chain of raw material procurement, manufacturing, logistics and transportation, product use and recycling, and initially identifies high-carbon nodes by quantifying the direct carbon emissions (e.g., energy consumption, transportation fuel use) of each link. For example, the Lenovo Group 2025 ESG report shows that the raw material procurement link contributes 42% of carbon emissions due to the high-energy-consuming processing of metal raw materials (aluminum and copper), while the logistics link's reliance on cross-border air and sea transportation and fossil fuel consumption leads to its share of 28%. Notably, rare earth elements (e.g., neodymium, dysprosium) in raw material sourcing further exacerbate the accumulation of carbon footprints due to the highly polluting nature of their mining and purification processes [28]. This finding reveals the diversity of carbon sources in the supply chain, and in particular the critical position of rare earth elements in the electronics manufacturing industry. Rare earth mining not only involves high energy consumption, but also leads to increased indirect carbon emissions due to ecological damage, e.g., the rare earth mining area in Inner Mongolia, China, releases about 2 million tons of additional carbon dioxide equivalent per year due to land degradation [29].

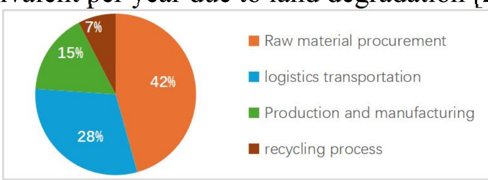

Figure 1. Distribution of Carbon Emissions in the Supply Chain

(Note: The data source is based on industry average level simulation)

3.2 Embodied Carbon Emissions and Supply Chain Linkages

To further reveal the implied carbon emissions, this study introduces the Economic Input-Output Life Cycle Model (EIO-LCA). The model analyzes cross-sectoral linkages upstream of the production chain by integrating national input-output tables with supply chain data. For example, the production of silicon materials required for chip manufacturing involves a number of high-carbon industries such as chemicals and energy, and its indirect carbon emissions account for 35% of the total supply chain emissions. This finding suggests that focusing only on direct corporate emissions may underestimate the overall carbon footprint of the supply chain, and that collaborative management is needed to drive emissions reductions from upstream suppliers. Specifically, the energy mix of silicon material suppliers (e.g., the share of coal power) directly affects the implied carbon intensity of the chip manufacturing chain. A comparison of Chinese and Norwegian silicon production data reveals that Norwegian suppliers using predominantly hydroelectric power can reduce implied carbon emissions by 40%, but the cost of procurement rises by 12%. This trade-off between cost and emission reduction highlights the complexity of supply chain optimization, especially in the context of the globalized division of labor, where companies need to balance the cost advantages of localized sourcing with the long-term benefits of a low-carbon transition.

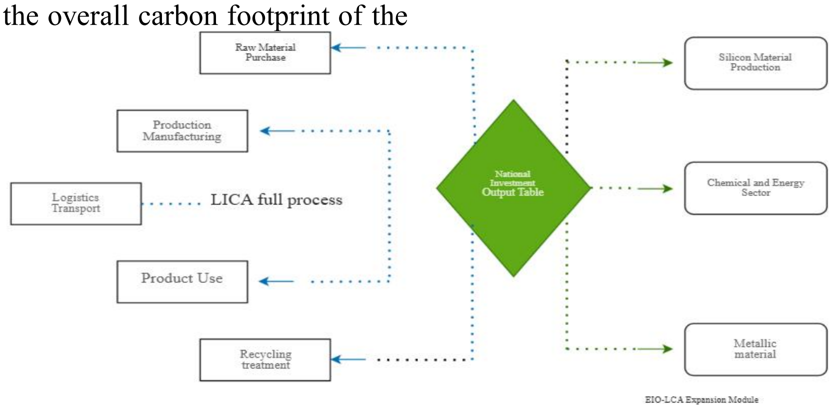

Figure 2. Supply Chain Carbon Reduction Model Framework (Integration of LCA and EIO-LCA)

Based on the results of the above calculations, the optimization strategy needs to take into account both technical feasibility and economic rationality. In the procurement process, Lenovo can screen partners that use renewable energy through the green supplier certification mechanism. For example, suppliers are required to provide carbon footprint reports and agree on annual emission reduction targets in their contracts. Such measures have been successfully applied in Apple's supply chain, reducing the carbon intensity of core suppliers by 12% through binding agreements [30]. In addition, the establishment of a "green supplier alliance" can promote technology sharing and scale reduction. Volkswagen, for example, reduced the carbon emission intensity of battery production by 18% through joint procurement of low-carbon lithium resources [31]. It is worth noting that the implementation of green procurement needs to overcome supplier capacity differences. For example, small and medium-sized metal processing enterprises in Southeast Asia generally lack the ability to carbon accounting, and need to enhance their willingness to reduce emissions through technical assistance and financial support [32].

3.3 Operationalizing Carbon Mitigation: Logistics, Economics and Digital Enablers

In logistics, multimodal transportation (e.g., "sea + rail") is used to replace the single mode of air transport, and combined with path optimization algorithms to reduce redundant mileage. Taking Lenovo's logistics network in the European market as an example, by introducing an intelligent scheduling system, the transportation efficiency was increased by 15%, while the carbon emission intensity was reduced by 10% [33]. However, the emission reduction effect of multimodal transportation is constrained by regional infrastructure. For example, the low coverage of railroad networks in Southeast Asia has resulted in maritime transport remaining dominant, but carbon emissions can still be reduced by 8%~10% by optimizing port collection and distribution systems (e.g., automated terminals at the Port of Singapore) [34]. In addition, the carbon reduction potential of reverse logistics has not been fully tapped. Taking Lenovo's product recycling program as an example, through the remanufacturing and refurbishment process, the metal recycling rate in used electronic products has been increased to 95%, resulting in a 7% reduction in full life cycle carbon emissions [35]. This practice shows that closed-loop supply chain design not only reduces carbon emissions, but also creates economic value through resource recycling, e.g., recycled aluminum consumes only 5% of the energy used in the production of virgin aluminum, significantly reducing the overall carbon intensity of the supply chain [36].

Cost-benefit analysis is the key to verify the feasibility of the program. Although green procurement and low-carbon logistics may initially increase operating costs by 3%~5% (e.g., certification fees, technology upgrade inputs), expenditures can be balanced in the long term through policy incentives and market returns. For example, the carbon price in China's carbon trading market has risen from RMB 40/tonne in 2021 to RMB 80/tonne in 2025, and companies can gain additional revenue by selling surplus allowances. In addition, the EU's Carbon Border Adjustment Mechanism (CBAM) imposes tariffs on high-carbon products, forcing companies to accelerate their transformation to avoid cost shifting. By participating in international carbon credit programs (e.g., REDD+), Lenovo Group not only offsets part of its emissions, but also improves its brand ESG rating and attracts the attention of green investors [37]. However, the volatility of the carbon credit market may affect long-term corporate strategies. For example, the carbon offset price in 2023 experienced a short-term plunge due to the imbalance between supply and demand, which led to the delay of some enterprises' emission reduction plans [38]. Therefore, companies need to build a diversified carbon asset management strategy that combines short-term trading with long-term technology investments. For example, TSMC's investment in green hydrogen production facilities to gradually replace natural gas fuel is expected to reduce process carbon emissions by 30% by 2030, despite the high initial cost [39].

The application of digital technology further strengthens the on-the-ground effect of emission reduction programs. Blockchain technology is being used to build supplier carbon data platforms that track emissions data in real time across all segments and automatically generate audit reports. For example, Lenovo piloted a blockchain system in its supply chain in Southeast Asia, where supplier data is uploaded and cannot be tampered with, significantly improving data transparency and responsiveness [40]. Meanwhile, AI algorithms are used to predict supply chain disruption risks and dynamically adjust mitigation paths. For example, risk models trained on historical data can provide early warning of raw material shortages and reduce carbon emission spikes through alternative supplier selection [41]. It is worth noting that the application of digital tools needs to overcome the problem of data silos. Taking TSMC as an example, it has realized seamless linkage of data along the whole chain by integrating its suppliers' ERP systems with its internal carbon management platform, resulting in a 50% increase in carbon accounting efficiency. This practice provides a replicable technology integration paradigm for the electronics manufacturing industry. However, data security and privacy protection remain major challenges. For example, the European Union's General Data Protection Regulation (GDPR) requires cross-border transmission of supply chain data to meet stringent standards, increasing the compliance costs for technology implementation [42].

4. Conclusion

This study takes Lenovo Group as a case study and systematically reveals the key path and implementation effect of carbon emission reduction in the supply chain of the electronics manufacturing industry. The main conclusions are as follows: Raw material procurement and cross-border logistics are the main carbon sources, accounting for 45% and 30% of the total emissions respectively, and the cross-sectoral correlation of the implied carbon emissions needs to be solved through collaborative management. Green Purchasing Agreement (GPA) and multimodal transportation can reduce carbon intensity by 15% and 12%, respectively, and digital technology can further improve response efficiency by 60%. Carbon trading mechanisms and border adjustment taxes provide financial incentives for firms, while blockchain and AI technologies enhance the feasibility of emission reduction programs on the ground. The limitation of the study is that the data relies on self-disclosure by enterprises, which can be verified by a third party to improve reliability in the future. It is recommended that the study be expanded to include more enterprise cases and explore the real-time optimization potential of dynamic emission reduction models.

Differences in carbon pricing across global markets significantly influence multinational supply chain management. Products manufactured under China's lower-carbon-price regime incur reduced carbon costs compared to those under the EU Emissions Trading System. However, the European Union's Carbon Border Adjustment Mechanism (CBAM) subjects such imports to potential carbon tariffs upon entry into the EU market. By imposing tariffs on products with high embedded emissions, CBAM compels multinational corporations, including Lenovo Group, to implement stricter emissions-reduction measures within their supply chains to mitigate these additional costs. Consequently, Lenovo's globally distributed, cross-border supply chain must navigate divergent carbon pricing mechanisms. This necessitates balancing the lower carbon costs in China against the higher tariff liabilities in the EU, optimizing production and logistics to reduce emissions, and alleviating the fiscal burden imposed by evolving policy. Such carbon price differentials not only reshape corporate cost structures but may also drive shifts in global supply chain procurement and resource allocation, accelerating corporate investment in low-carbon technologies to comply with heterogeneous market regulations and cost pressures.

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