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Scenario-Driven Innovation Empowering High-Quality Development Path for Zero-Carbon Supply Chains in Liaoning Manufacturing Enterprises

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Abstract: Under the dual context of the carbon neutrality and carbon peak goals and the Northeast China revitalization strategy, Liaoning province is actively promoting the low-carbon, green, and high-quality development of manufacturing enterprises supply chains. This study employs scenario-driven innovation as the core strategy to propel high-quality development of zero-carbon supply chains in manufacturing enterprises. Through an elaboration of theories pertaining to scenario-driven innovation and high-quality development of carbon-neutral supply chains, this study examines key challenges faced by manufacturing enterprises in Liaoning province during their transition toward high-quality development in carbon-neutral supply chains. These challenges include data gaps in carbon footprint accounting, inadequate attention to carbon supply chain management, and weak carbon supply chain collaboration capacity. Building on these insights, the study proposes three scenario-driven innovation approaches: (1) developing process-adaptive real-time tracking and monitoring scenarios to strengthen carbon footprint data systems; (2) integrating visualization tools into supply scenarios to enhance carbon-focused supply chain governance; and (3) creating goal-penetrating scenarios to unlock collaborative potential in carbon supply chains. These recommendations aim to provide both theoretical foundations and actionable guidelines for Liaoning's manufacturing enterprises to achieve high-quality zero-carbon supply chain transformation.

Keywords: Scenario-Driven Innovation; Zero-carbon Supply Chains; High-Quality Development.

1. Introduction

As a pivotal manufacturing hub in China, Liaoning province boasts industrial clusters spanning automotive, aerospace, equipment manufacturing, and chemical sectors, supported by a well-established supply chain network. "Measures for accelerating the establishment of a green, low-carbon, and circular economic development system in Liaoning province (2021)" (No. 29) emphasized the imperative to promote the manufacturing sector to expedite the construction of green supply chains. Subsequently, "Implementation plan for carbon peak in Liaoning province" issued in 2023, further clarified the necessity for advancing carbon peak goals within the manufacturing domain. Most recently, in 2024, "Implementation rules for gradient cultivation and management of green manufacturing in Liaoning province" (No. 119), which explicitly requires manufacturing enterprises to integrate green and low-carbon development principles throughout the entire product life cycle, highlighting the pivotal role of leading enterprises in driving green transformation across entire supply chains. These successive policy documents underscore a consistent and determined effort by Liaoning province to steer manufacturing supply chains toward low-carbon operation, green transformation, and high-quality development.

In a complementary national policy direction, "Guiding opinions on accelerating scenario innovation to promote high-level application of artificial intelligence for high-quality economic development" released in August 2022, defines scenario innovation as an approach oriented toward the creative application of new technologies and characterized by supply-demand interaction, which facilitates iterative technological upgrading. Scenario-driven innovation operates within a paradigm that

integrates scenario-specific demands with techno-economic considerations, focusing particularly on enhancing the capability of leading enterprises to mitigate carbon emission risks throughout their supply chains. Therefore, this study adopts "scenario-driven innovation" as a conceptual foundation to explore pathways for achieving high-quality development in carbon-neutral supply chains among manufacturing enterprises in Liaoning province from a novel perspective and strategic direction. The study aims to provide practical evidence and reference value for promoting the transition of manufacturing enterprises and their associated supply chains in Liaoning toward low-carbon, sustainable, and high-quality development.

2. Theoretical Basis

2.1 Scenario-Driven Innovation

Scholars widely recognize scenario-driven innovation as a transformative paradigm in the digital economy era[1,2]. This approach utilizes specific application scenarios as operational platforms to orchestrate the collaborative integration of technological, organizational, and market-demand innovation elements, thereby co-creating novel ecosystems[3]. Through comprehensive resource, information, and data integration, it enables deep absorption and scientific utilization of these elements, subverting traditional value creation logic by transcending boundaries among technologies, products, services, processes, business models, and management practices to deliver innovative ecosystems with distinct core value propositions[4,5]. The core elements of scenario-driven innovation encompass scenarios, strategy, demand, and technology. From a strategic development perspective, this approach involves identifying key issues, strengthening the design of scenario-based tasks, and integrating technology R&D with application to unlock greater value[6]. The scenario-driven system is composed of policy guidance, industrial transformation, innovation enablement, and demand-driven forces[4]. By constructing demand scenarios as a carrier, it facilitates problem identification, scenario-based task design, and technological innovation. This process helps enterprises overcome existing development bottlenecks and explore new technologies, products, business models, and management boundaries[7]. Emerging digital technologies, such as big data, cloud computing, artificial intelligence, and the Internet of Things, are enabling diverse scenario elements and extending specific demands across broader enterprise supply chain platforms. These technologies facilitate the construction of a dynamic digital system that is strategy-led, scenario-driven, technology-based, and management-supported[3].

2.2 High-Quality Development of Zero-Carbon Supply Chains

The term zero-carbon supply chain refers to a state where an entire supply chain, anchored by a core enterprise, achieves either zero carbon dioxide emissions or fully offsets its emissions through artificial or natural means, as interpreted by Mao[8]. High-quality development of zero-carbon supply chains involves core enterprises implementing low-carbon (or zero-carbon) management across product life cycles and among supply chain partners, thereby driving energy conservation and emission reductions across upstream and downstream enterprises. This process continuously reduces the supply chain's overall carbon footprint, ultimately achieving carbon neutrality or even net-zero emissions across the entire chain. "High-quality development of zero-carbon supply chains" represents an innovative industrial model that operates within supply chain structures composed of diverse enterprises. It meets stringent green, environmentally sustainable, and low-carbon requirements while balancing critical factors such as supply chain stability, quality, and cost. This approach achieves a dual win by integrating social and economic value creation[9], propelling industries toward sustainable, high-quality growth. By leveraging technological innovation, management optimization, and collaborative partnerships, it transcends traditional efficiency-driven supply chain paradigms, embedding zero-carbon objectives into supply chain risk management frameworks. This integration fosters synergy between modern supply chain ecosystems and China's dual circulation development paradigm[10].

Scenario-driven innovation, guided by the core logic of "strategy leadership - scenario design - factor synergy - value closure"(e.g., Figure 1), constructs a precise empowerment pathway for

high-quality development of zero-carbon supply chains. From an operational perspective, the process begins with leveraging the "dual carbon" strategy as the overarching guide, setting the goal of achieving "full-chain carbon neutrality or even net-zero emissions" for zero-carbon supply chains. This involves identifying high-carbon pain points and green demands across all supply chain links, and constructing concrete application scenarios such as green procurement, low-carbon warehousing, and full lifecycle carbon footprint traceability. Subsequently, relying on in-depth research and application of digital technologies like big data-based carbon accounting and IoT-enabled carbon monitoring, as well as low-carbon technologies such as carbon capture and green power substitution, the initiative integrates policy guidance including carbon quotas and green subsidies, industrial transformation support from new energy and circular economy sectors, and collaborative demands from upstream and downstream supply chain enterprises. This multi-dimensional integration of strategy, scenario, technology, demand, and policy elements breaks down traditional barriers in supply chains, such as high-carbon technology dependence, carbon information silos, and the imbalance between green costs and efficiency. It propels zero-carbon supply chains towards high-quality development by balancing environmental sustainability with economic efficiency, ultimately achieving a win-win outcome in terms of both social and economic value.

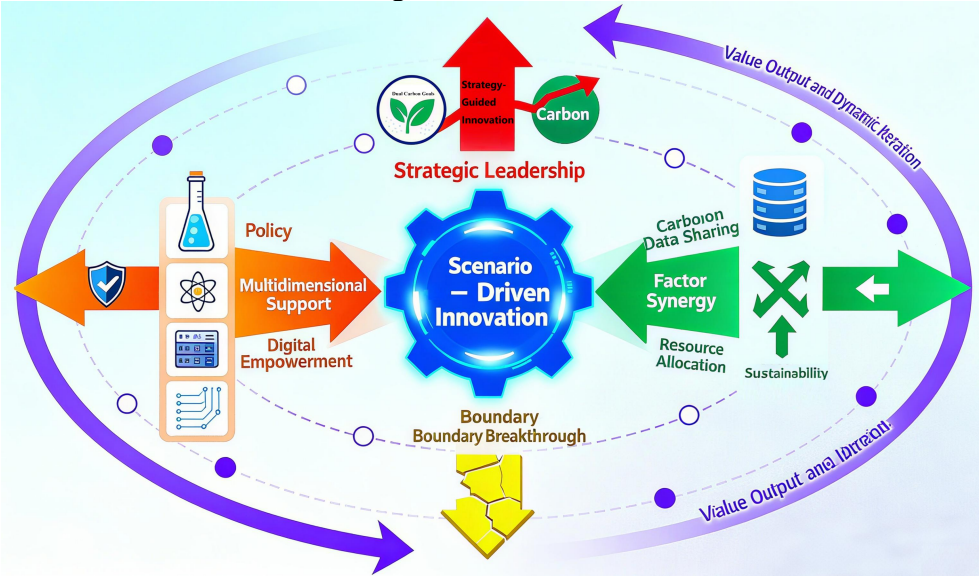

Figure 1. Operational Logic Underlying Scenario-Driven Innovation in Empowering High-Quality Development of Zero-Carbon Supply Chains

3. Challenges in High-Quality Development of Zero-Carbon Supply Chains for Manufacturing Enterprises in Liaoning Province

3.1 Data Gaps in Carbon Footprint Accounting

Liaoning's manufacturing enterprises have long relied heavily on traditional high-carbon energy sources such as coal and petroleum. Taking large-scale steel enterprises like Ansteel as an example, coal constitutes a significant proportion of their energy consumption structure, resulting in relatively high carbon emissions. Manufacturing enterprises are unable to accurately and real-time track and calculate carbon emissions data across all stages of the procurement-production-warehousing-logistics-recycling supply chain. For instance, in production workshops, real-time monitoring and precise regulation of equipment energy use remain inadequate, leading to substantial energy waste. The transition to zero-carbon operations places critical reliance on the completeness, accuracy, and timeliness of carbon footprint data. However, the absence of carbon footprint information and standardized emission monitoring systems across manufacturing processes hinders enterprises' ability to generate disaggregated product-level carbon footprint data compliant with international accounting standards (e.g., ISO 14067). This deficiency undermines precise calculation of

actual emissions and dynamic tracking of life-cycle carbon footprints at end-of-life stages. Consequently, carbon data gaps manifest as fragmented and estimated accounting practices within Liaoning's manufacturing supply chains, obstructing collaborative carbon reduction efforts among upstream and downstream enterprises in zero-carbon supply networks.

3.2 Inadequate Attention to Carbon Supply Chain Management

In Liaoning's pursuit of zero-carbon supply chain development, manufacturing enterprises demonstrate widespread neglect of carbon supply chain management capabilities, a systemic deficiency permeating strategic planning, organizational structures, and operational execution. This gap has emerged as a critical bottleneck hindering high-quality zero-carbon supply chain transformation. Many enterprises still treat carbon supply chain management as a compliance-driven add-on rather than a strategic lever for value creation. In Liaoning, pillar industries such as steel, heavy machinery, and petrochemicals seldom incorporate carbon supply chain optimization into their core objectives, which often relegates carbon management to a peripheral task. During supplier carbon management processes, only 30% of leading enterprises incorporate carbon footprint metrics and emission reduction capabilities into supplier qualification and evaluation frameworks. The majority continue to prioritize price and delivery timelines as primary selection criteria, enabling energy-intensive, high-emission suppliers to maintain dominant positions across critical supply chain nodes. Furthermore, limited awareness and acceptance of green manufacturing products among consumers and downstream enterprises in Liaoning weaken market-driven incentives for zero-carbon supply chain development. This lack of market pull undermines enterprises' ability to achieve synergistic economic and environmental benefits through market mechanisms, ultimately perpetuating a vicious cycle of "lagging awareness → weak capabilities → suboptimal outcomes".

3.3 Weak Carbon Supply Chain Collaboration Capacity

Liaoning's manufacturing sector predominantly relies on heavy industries such as steel, heavy machinery, and petrochemicals to construct supply chains characterized by multi-tiered structures and extensive stakeholder participation. However, systemic weaknesses in carbon supply chain collaboration persist across all stages, forming a critical bottleneck for high-quality zero-carbon supply chain development. Despite dual-carbon policy mandates, Liaoning's manufacturing enterprises have primarily set individual emission reduction targets without extending zero-carbon objectives to upstream service providers and downstream suppliers. Data gaps in carbon footprint accounting exacerbate fragmentation, as inconsistent measurement standards and statistical methodologies prevail among supply chain entities. Upstream suppliers of auxiliary materials predominantly adopt localized simplified calculation methods, while midstream core enterprises align with ISO 14064 standards, and downstream logistics firms rely on industry-default emission factors. This lack of standardized metrics renders inter-entity data incomparable and non-interoperable. Moreover, Liaoning's manufacturers have largely failed to establish collaborative benefit-sharing mechanisms for carbon reduction. Upstream small-and-medium-sized suppliers (SMEs) resist participation in joint emission reduction initiatives due to high upfront costs and delayed returns on investment. Core enterprises, in turn, neither provide financial incentives such as emission reduction subsidies or preferential procurement terms nor guarantee long-term contractual stability to secure supplier revenue streams. Consequently, the supply chain lacks integrated mechanisms to coordinate collective carbon mitigation efforts.

4. Recommendations for Scenario-Driven Innovation in Liaoning's Manufacturing Sector to Promote High-Quality Development of Zero-Carbon Supply Chains

4.1 Construct Process-Adaptive Real-Time Tracking and Monitoring Scenarios to Strengthen Carbon Footprint Data Systems

To address gaps in carbon footprint data across Liaoning's manufacturing zero-carbon supply chains, enterprises should develop scenario-technology aligned real-time tracking solutions tailored to the unique characteristics of each supply chain stage. For instance, in the raw material procurement scenario, where upstream suppliers are fragmented and data acquisition

remains challenging, enterprises can establish an "IoT-enabled supplier-side + direct data connectivity scenario". This system utilizes 5G networks to transmit real-time operational data - such as mining energy consumption and processing hours - to core enterprises' central data platforms. These platforms integrate embedded carbon emission conversion models to automatically generate implicit carbon footprint data for raw materials, resolving procurement-stage data latency issues. Leading enterprises should be encouraged to share monitoring scenarios, whereby core manufacturing enterprises provide open access to proprietary monitoring resources for supporting suppliers. These suppliers can then freely view and supplement carbon footprint data pertaining to their operations, thereby contributing to the formation of a standardized monitoring ecosystem. Emphasis should be placed on low-cost, scalable scenario-driven innovation, with the design of simplified monitoring protocols adapted to regional needs. For example, an energy consumption-to-carbon footprint conversion scenario could be implemented via WeChat mini-programs, enabling automated carbon footprint calculations while providing standardized data templates to eliminate fragmentation and estimation-based inaccuracies.

4.2 Embed Visualization into Supply Scenarios to Strengthen Carbon Supply Chain Management Capabilities

Liaoning's manufacturing enterprises, particularly in steel and heavy machinery sectors, often underestimate the strategic value of carbon supply chain management due to a lack of visible linkages between carbon reduction efforts and operational performance metrics such as production capacity, cost efficiency, and market competitiveness. To address this, carbon management should be integrated into core operational scenarios, including production, procurement, and cost accounting, to make its value tangible. For instance, in steel production scenarios, enterprises can develop cost-benefit comparison frameworks for low-carbon processes. By embedding carbon cost calculation modules into production and procurement control systems, firms can real-time quantify differences in energy consumption costs and carbon footprint-related liabilities between traditional and low-carbon manufacturing methods across product life cycles. These optimized scenario outcomes should be incorporated into key performance indicators (KPIs) for high-quality development, aligning supply chain-wide zero-carbon objectives with corporate decision-making. This approach creates reverse pressure on suppliers to prioritize carbon supply chain optimization as a core business goal. To amplify market-driven incentives, enterprises should design low-carbon product marketing scenarios through government procurement and regional collaboration initiatives. Specifically, governments can establish low-carbon procurement alignment platforms, prioritizing suppliers that meet predefined carbon reduction standards. By formalizing supply chain low-carbon procurement criteria, policymakers and enterprises can jointly elevate carbon supply chain management capabilities, fostering a competitive ecosystem where sustainability drives market access.

4.3 Establish Goal-Penetrating Scenarios to Unlock Carbon Supply Chain Synergy Potential

At present, although manufacturing enterprises in Liaoning have set zero-carbon targets internally, their supply systems lack an extended carbon governance framework, failing to achieve a net-zero carbon neutrality effect where core enterprises reduce emissions while supporting suppliers increase theirs. To address this, a goal-scenario linkage mechanism can be implemented through zero-carbon goal-binding scenarios. For instance, in procurement scenarios, suppliers' zero-carbon targets should be integrated into procurement contracts, with suppliers classified into tiers based on their emission reduction capabilities and assigned carbon management compliance deadlines accordingly; suppliers failing to meet carbon emission standards will face penalty measures such as order volume reductions, incentivizing upstream service providers to proactively adopt zero-carbon objectives. Simultaneously, designing standardized accounting scenarios is crucial to breaking down data silos in Liaoning's manufacturing supply chains by establishing data interaction interfaces that mandate the use of ISO 14064-compliant carbon accounting standards (aligned with core enterprises' protocols) and converting disparate data formats into a unified reporting framework via

a centralized data control platform. Furthermore, creating profit-sharing scenarios involves developing cost-allocation compensation mechanisms, where core manufacturing enterprises in Liaoning co-invest in emission reduction projects with suppliers and distribute low-carbon premiums proportionally based on contribution levels, fostering a virtuous cycle of shared investment returns and driving joint emission reductions across the entire value chain. Finally, constructing public-private partnership (PPP) scenarios enables the establishment of supply chain synergy incentive mechanisms for Liaoning's manufacturing sector, encouraging enterprises to jointly apply for low-carbon policy subsidies through collaborative projects and thereby activating collective decarbonization momentum.

5. Conclusion

Grounded in the policy orientation of Liaoning province toward leveraging scenario-driven innovation to promote high-quality development of zero-carbon supply chains among manufacturing enterprises, this study systematically examines the theoretical connotations of scenario-driven innovation and zero-carbon supply chain quality enhancement. It provides an in-depth analysis of three major challenges faced by manufacturing enterprises in Liaoning in the construction of such supply chains: data gaps in carbon footprint accounting, inadequate attention to carbon supply chain management, and weak carbon supply chain collaboration capacity. To address these issues, targeted solutions are proposed, including the development of process-adaptive tracking and monitoring scenarios, visualized supply chain integration scenarios, and goal-penetrating scenarios. Theoretically, this study deepens the logical relationship between scenario-driven innovation and industrial zero-carbon supply chain transformation, while practically, it offers actionable pathways for Liaoning's manufacturing enterprises to overcome zero-carbon transition barriers and provides local governments with evidence-based references for refining scenario-innovation policy frameworks. These contributions hold significant relevance for advancing high-quality zero-carbon supply chain development in Liaoning's manufacturing sector and supporting the low-carbon revitalization of Northeast China's traditional industrial base.

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