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Theoretical Framework for Greening Air Logistics A Perspective Based on Low-Carbon Technology and Supply Chain Collaboration

Xiaoli Liu
[1]Jiangsu Aviation Technical College, Aviation Service Institute, Zhenjiang 212134, Jiangsu, China
Corresponding author: Xiaoli Liu (e-mail: 15051143390@163.com)

ABSTRACT Green transformation of air logistics requires coordinated optimization of low-carbon technology deployment and supply-chain collaboration, especially under high-frequency and time-sensitive freight scenarios. This study develops a three-dimensional theoretical and analytical framework consisting of a technology-driven layer, collaborative operation layer, and value objective layer. Sustainable aviation fuel, new-energy ground equipment, carbon-footprint monitoring, information sharing, process integration, and resource collaboration are modeled as interacting system components. Multi-factor variance analysis, system-dynamics simulation, and multi-case comparison are used to test the interaction effect between low-carbon technology and collaboration. Results show that the high-technology and high-collaboration configuration reduces carbon-emission intensity by 43.4% and improves operational efficiency by 41.9% compared with the low-technology and low-collaboration configuration. The proposed framework reveals the dynamic coupling between technology embedding and collaborative operations and provides decision support for low-carbon air logistics, IoT-based carbon monitoring, and sustainable transport-system optimization.

INDEX TERMS air logistics, low-carbon technology, supply chain collaboration, system dynamics, iot monitoring

I. INTRODUCTION

As a vital engine for the global movement of industrial materials, the air logistics industry faces increasingly urgent emission reduction challenges while balancing rapid economic growth with sustainable manufacturing demands. This necessity for decarbonization requires a seamless integration of green transport solutions with the high-frequency logistics requirements of the modern sector. ICAO has put forward the target of net-zero emissions in 2050. It is necessary for air logistics industry to speed up the process of green development. In practice, most of the air logistics companies are trapped in the dilemma of "high cost of low-carbon technology investment" and "slow improvement of operational efficiency" : on the one hand, low-carbon technologies like sustainable aviation kerosene and new energy ground handling equipment need to invest huge amount of money, and it is impossible to recover cost by applying these technologies alone in the short term; on the other hand, due to the information isolation and process separation in upstream and downstream of supply chain, it is hard to create synergic effect in whole chain for the application of low-carbon technology, which further reduces the economic efficiency and sustainability of green investment [1-3]. How to coordinate low-carbon technology and supply chain collaboration to achieve the goals of emission reduction and efficiency improvement becomes a key issue that needs to be solved in the process of greening air logistics.

Existing research has explored the greening of air logistics extensively. Wu and Yang identified key factors and main driving mechanisms in air logistics through two-stage data-driven analysis to screen the most feasible sustainable development solutions [4]. Baxter pointed out through case studies that air cargo companies are promoting the decarbonization of their business by adopting a variety of measures such as energy-saving aircraft, sustainable aviation fuel, equipment electrification and circular economy[5]. Calvet pointed out through a review study that the need to address air congestion and environmental pressures requires the optimization of flight and ground operations through advanced technologies[6]. Griffiths et al. pointed out that by building green flight paths and strengthening international cooperation and financing mechanisms, the large-scale application of sustainable aviation fuel can be promoted, thereby helping the aviation industry achieve its decarbonization goals[7]. Koç pointed out through analysis of relevant airline documents that green marketing strategies help address the challenges of climate change and sustainable development and promote the practice of environmental responsibility in the aviation industry[8]. Alharasees et al. used a multicriteria decision-making framework to evaluate and select sustainable aviation fuel solutions by integrating environmental, economic, technological and social factors[9]. Beškovnik took the East Adriatic region as an example to analyze the comprehensive performance and complex operation characteristics of the regional air transport chain in terms of cost, timeliness and carbon emissions[10]. However, the aforementioned studies mostly treat technology and collaboration as independent paths, failing to systematically reveal the interaction mechanism between them, and have not yet constructed a unified theoretical framework integrating low-carbon technologies and supply chain collaboration. This results in fragmented greening research, making it difficult to provide systematic transformation guidance for enterprises.

In response to the limitations of previous studies, this paper incorporates resource-based view and dynamic capability theory, takes low-carbon technologies as strategic resources of enterprise and supply chain collaboration as the key level of dynamic capability, establishes a theoretical framework of low-carbon technologies and supply chain collaboration from three levels of "technology embedding—process reengineering— organizational adaptation". In terms of methods, this paper fully uses interdisciplinary deductive reasoning, multi-case analysis and system dynamics simulation. This framework validates its explanatory power through multi-case comparisons of industrial logistics, while identifying the evolutionary regularity of technology-collaboration interactions via dynamic simulation. Such an approach overcomes existing deficiencies in theoretical integration and dynamic analysis by effectively bridging the gap between advanced material flow requirements and sustainable transport logistics.

II. CORE CONNOTATION AND DIMENSIONAL DEFINITION

The greening of air logistics is driven by the logic of "technology embedding—process reengineering—organizational adaptation." Specifically, technology embedding refers to the integration of low-carbon hardware into existing assets; process reengineering involves the fundamental redesign of workflows to align with technological capabilities; and organizational adaptation is the structural alignment of stakeholders to sustain these changes. From the resource-based view, low-carbon technology is the strategic material resource to realize green transformation for air logistics company. Specifically, the popularization and application of sustainable aviation fuel, replacement of new energy ground handling equipment, implementation of carbon footprint monitoring system and optimization of airport energy management system all belong to low-carbon technology. Furthermore, the decarbonization efficacy of an isolated technology is often localized at specific operational nodes, failing to achieve systemic impact without cross-sector integration. From the viewpoint of dynamic capability theory, supply chain collaboration is the enterprise's core organization capability to integrate internal and external resources and respond to the changes in external environment. It is reflected in the construction of cross-enterprise information sharing mechanism, implementation of joint planning and collaborative decision-making, process integration and standardization, and establishment of risk sharing mechanism.

Based on the above theoretical basis, this paper defines the dual connotation of greening air logistics from two distinct dimensions: technological greening and operational greening. Technological greening is defined as the material state of an enterprise characterized by the adoption of low-carbon resources (e.g., sustainable fuels and electrified equipment) to lower the ceiling of carbon emission intensity. In contrast, operational greening is defined as the result of organizational capability, where supply chain collaboration acts as the mechanism to optimize the conversion efficiency of these technological resources. By distinguishing these, greening is viewed as a dynamic coupling process where technology provides the environmental potential and collaboration ensures the operational realization of that potential. It can be seen from the above definition that, technology and collaboration are not simply added up, but have a two-way interactive coupling relationship. Specifically, on the one hand, the implementation of low-carbon technology can provide the goal of quantified emission reduction and data support for the collaboration of whole supply chain, and the carbon footprint information is more transparent, which makes the collaborative decision-making more accurate; on the other hand, the collaboration of whole supply chain creates the organizational conditions for the release of technological value, and the cross-enterprise process integration can effectively reduce the transaction cost of technology application, and the joint planning and collaborative decision-making can maximize the benefits of technology investment.

III. ANALYZING THE INTERACTION MECHANISM

Low-carbon technology drive and supply chain collaboration drive are not simply one-way drive or linear superposition, but "two-way interaction" and "cross-effect" deep coupling relationship. From the view of dynamic capability theory, low-carbon technology is strategic material base to support aviation logistics company realize green transformation, and the supply chain collaboration is the core enterprise organization capability to coordinate internal and external resources and realize cooperation and coordination among various stakeholders. The interaction mechanism between two can be analyzed from following two directions: "technology drive collaboration" and "collaboration drive technology". From the view of technology driven collaboration, the deep application of low-carbon technology can provide quantitative emission reduction target and specific data support for supply chain collaboration. Facing with the sustainable aviation fuel's application and promotion, airline, airport and fuel supplier need to build closer procurement and allocation collaboration relationship; The application and promotion of carbon footprint monitoring system, realize open carbon emission data transmission between carbon footprint upstream and downstream of supply chain, and provide an objective basis for collaborative decision-making; The promotion of new energy ground handling equipment, airport, ground service company and airline need to carry out unified planning and coordinated cooperation on charging facility layout and equipment allocation. The data and physical flow changes induced by the application of low-carbon technology force all parties in the supply chain to break the existing information isolation and build closer collaborative relationship.

From the view of technology driven by collaboration, the deep collaboration of supply chain can build organizational premise and scale economy to release the value of low-carbon technology. The establishment of information sharing platform, effects of technology investment can be perceived and evaluated in real time by upstream and downstream of supply chain, and the risk of technology application can be reduced due to information asymmetry; The implementation of cross-enterprise joint plan, can reduce the unit price of sustainable aviation fuel procurement by bulk purchase and long-term contract, and make the technology application more economical and practical; Process integration and standardization, make cross-enterprise scheduling of new energy ground support equipment possible, and avoid the problem of equipment idleness caused by interface incompatibility. The existence of collaborative mechanism can reduce the transaction cost and organizational friction in the application of low-carbon technology, and accelerate the diffusion of technology from pilot project to large-scale application.

Moreover, the interaction between technology and collaboration is not a static equilibrium, but a dynamically evolutionary process. Technological investment plays the role of triggering factor in the formation of collaborative mechanism; the demand for carbon data transparency motivates all the subjects in supply chain to build initial basis for information sharing. With the maturity of collaborative mechanism, the amplifying effect of technological benefits gradually becomes evident; the higher collaborative density, the larger marginal effect of technological investment; when the degree of collaboration reaches a certain level, the positive interactive effect between technology and collaboration appears. On one hand, the data dividends brought by the application of technology optimize the collaborative decision-making mechanism; on the other hand, the improvement of collaboration effect provides basis for larger scale technological application. This process of dynamic evolution is the intrinsic logic of the transformation of green aviation logistics from quantitative change to qualitative change.

IV. CONSTRUCTING A THEORETICAL FRAMEWORK

Based on the above definition of core connotations and analysis of interaction mechanisms, this paper follows the logical hierarchy of "technology embedding—process restructuring—organizational adaptation" and constructs a three-dimensional theoretical framework comprising a "technology-driven layer, collaborative operation layer, and value objective layer," as shown in Figure 1.

The technology-driven layer, positioned at the bottom of the framework, is the material basis and driving force for the greening of air logistics. This layer includes the application of low-carbon technologies in all links of air logistics, which can mainly be manifested in three forms: first, substitution of sustainable aviation fuels at the aircraft level. By increasing the blending ratio, the carbon emission intensity during flight can be reduced, which is manifested in the carbon emission of each kilometer flown; second, new energy equipment are applied at the level of ground operations, which includes electrified ground support vehicles, airport energy management system, and green conversion of cargo handling equipment; third, a carbon footprint monitoring system is applied at the data collection level, which can achieve real-time tracing and public accounting of the carbon emission of the whole chain through IoT sensors and blockchain technology. The core function of the technology-driven layer is to provide feasible emission reduction methods and quantitative basis for greening; the application level of technology layer determines the technological ceiling for greening. The collaborative operation layer, positioned in the middle layer of the framework, is the organizational bridge and mechanism guarantee linking technology and value. This layer focuses on establishing cooperative relationships among all parties involved in the supply chain, which can be manifested in three forms: First, information collaboration, which breaks the information isolation between airlines, airports, freight forwarders and cargo owners by jointly building a carbon data sharing platform, achieving real-time sharing and joint accounting of carbon emission data among all parties; Second, process collaboration, which optimizes key links such as flight scheduling, ground services and cargo transshipment across enterprises through joint planning and collaborative decision-making mechanism, thereby reducing the carbon emissions caused by process fragmentation; Third, resource collaboration, which enhances the utilization rate of green resources such as sustainable aviation fuels and new energy ground handling equipment through infrastructure sharing and cross-enterprise equipment scheduling, improving the balance of green resource distribution. The core function of the collaborative operation layer is to provide organizational conditions for releasing technological value, and the application level of collaborative operation layer determines the conversion efficiency of greening investment.

The value objective layer, positioned in the top of the

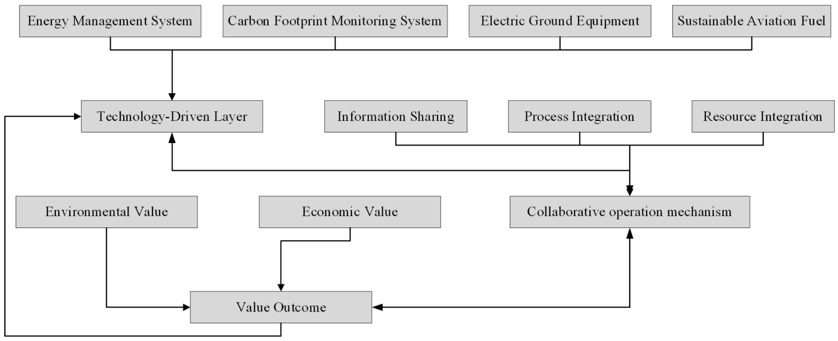

FIGURE 1. Three-Dimensional Theoretical Framework for Green Aviation Logistics

framework, is the final goal and evaluation standard for the greening of air logistics. This layer includes two types of objectives achieved by the cross-industry cooperation and technology empowerment: First, environmental value, namely, continuous reduction of carbon emission intensity in the whole chain, including fuel consumption reduction in air transport link and energy structure optimization in ground operation link; Second, economic value, namely, continuous improvement of operation efficiency, including increased flight load factor, reduced ground turnaround time and unit cost. It is worth noting that the value objective layer is not simply the sum of technology and collaboration, but a systematic result achieved by their interaction, reflecting the conversion of green development from technological input to performance output.

The three layers are not isolated but exhibit a dynamic connection of layer-by-layer transmission and bidirectional feedback. The technology-driven layer provides the collaborative operation layer with a data foundation and emission reduction tools, making collaborative decision-making evidence-based; the collaborative operation layer creates organizational conditions and economies of scale for the technology-driven layer, amplifying the marginal benefits of technological investment; both jointly promote the realization of the value objective layer, and the achievement of the value objective, in turn, provides positive incentives for continued investment in technology and collaboration. This framework breaks away from the traditional research that separates technology and collaboration, revealing the inherent logic and implementation path of greening air logistics from a system integration perspective.

V. APPLICABILITY TESTING OF THE THEORETICAL FRAMEWORK

A. EXPERIMENTAL SETUP

To validate the effectiveness of the constructed theoretical framework, a multi-method fusion testing method is adopted in this study, and a progressive experiment is designed from three dimensions: "interaction effect verification, dynamic evolution simulation, and real-world scenario explanation". The evaluation index of carbon emission intensity (CO_2 emissions per unit turnover) and operational efficiency (freight volume per unit cost) are taken as the main evaluation indicators. The carbon emission intensity is calculated based on the ICAO (International Civil Aviation Organization) recommended carbon calculation method, taking into account the influence of sustainable aviation fuel blending ratio and ground operation electrification rate. The operational efficiency is comprehensively evaluated based on DEA model considering flight load factor, ground turnaround time, information sharing times.

B. INTERACTION EFFECT TESTING OF LOW-CARBON TECHNOLOGY AND SUPPLY CHAIN COLLABORATION

To test the interaction effect of low-carbon technology and supply chain collaboration on the greening of air logistics, this study employs 2×2 inter-group comparison design and classifies 20 air logistics companies into high/low low-carbon technology level group and high/low supply chain collaboration level group. The data of carbon emission intensity and operation efficiency in the past three years were collected from corporate annual report and questionnaire. Multivariate analysis of variance (ANOVA) is employed to test whether there exists significant interaction effect between the two groups of variables.

The ANOVA results showed that the interaction effect between low-carbon technology and supply chain collaboration was significant ($F=8.72$, $p<0.01$). Group 1 (high technology + high synergy) had a carbon emission intensity of 0.86 kg CO_2/t·km, a 43.4% reduction compared to Group 4 (low technology + low synergy); its operational efficiency was 3.42 t·km/yuan, a 41.9% improvement compared to Group 4. Further comparison revealed that Group 2 (high technology + low synergy) and Group 3 (low technology + high synergy) showed similar performance, indicating that advantages in a single dimension are insufficient to achieve a breakthrough in green development; only synergy between the two can produce a significant "multiplier effect."

C. DYNAMIC SIMULATION EXPERIMENT OF THEORETICAL FRAMEWORK

In order to show the evolution process of low-carbon technology and supply chain collaboration, this paper takes air logistics greening as the research object and uses system dynamics to establish the simulation model of green supply chain collaboration. To avoid circularity in validation, the

TABLE 1. Evaluation of the Interaction Effect between Low-Carbon Technology and Supply Chain Collaboration

Group	Low-Carbon Technology Adoption Level	Supply Chain Collaboration Level	Sample Size (Firms)	Mean Carbon Emission Intensity (kg CO_2/t·km)	Mean Operational Efficiency (t·km/CNY)
Group 1	High	High	5	0.86	3.42
Group 2	High	Low	5	1.23	2.85
Group 3	Low	High	5	1.15	2.93
Group 4	Low	Low	5	1.52	2.41

simulation model is calibrated using historical industry baseline data rather than the framework's internal theoretical assumptions. While the framework identifies technology investment and collaboration density as core drivers, the simulation parameters—such as the technological decay rate and organizational friction coefficients—were derived from independent longitudinal datasets of the global air cargo industry. The simulation employs these external empirical constraints to test whether the framework's predicted "multiplier effect" holds true under varying time-lag scenarios (Year 1, 3, and 5) of collaborative intervention. Then, the dynamic changes of carbon emission intensity and operational efficiency in the process of simulation are tracked.

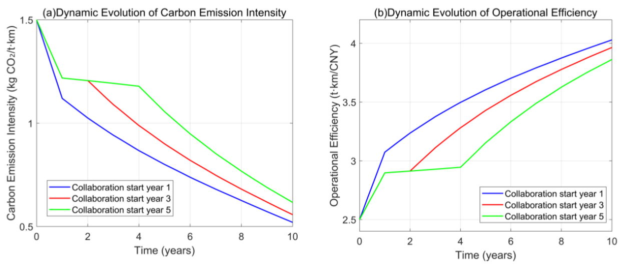

FIGURE 2. Comparison of Dynamic Simulation Experiments of Theoretical Framework: (a) shows the dynamic evolution curves of carbon emission intensity under different collaboration activation times; while (b) presents the corresponding trend of operational efficiency over time

In the first year of collaborative implementation, the carbon emission intensity at the end of the simulation period was 0.52 kg CO2/t·km, a 15.6% decrease compared to 0.62 kg CO2/t·km in the fifth year. In terms of operational efficiency, it reached 4.03 t·km/yuan in the first year, a 4.3% increase compared to 3.86 t·km/yuan in the fifth year. The simulation results indicate that the interaction effect is most pronounced when the collaborative mechanism is synchronized with the Technology Readiness Level (TRL) of low-carbon assets. While earlier intervention generally widens the performance gap, the model recognizes that synergy is contingent upon technological viability. Specifically, the "Year 1" scenario assumes that the technology has reached a commercial threshold; if technology remains in the pilot stage, the "collaboration density" acts primarily as an informational foundation, with the full multiplier effect only manifesting once the technology reaches industrial scale.

D. LONGITUDINAL CASE STUDY OF CAPACITY TRANSFER AND TEACHING BEHAVIOR

To verify the effectiveness of the theoretical model in explaining the relevant phenomena in practical applications, this study randomly chose three typical enterprises for multi-case comparative studies. According to the levels of low-carbon technology and supply chain collaboration levels, we defined three target companies as Company A (High Technology + High Collaboration), Company B (High Technology + Low Collaboration), and Company C (Medium Technology + High Collaboration). Finally, based on semi-structured interviews and public information disclosed by the three companies, the green performance of the three companies were acquired and the differences of carbon emission intensity and company performance with different combinations of models were compared. The data are shown in Figure 3:

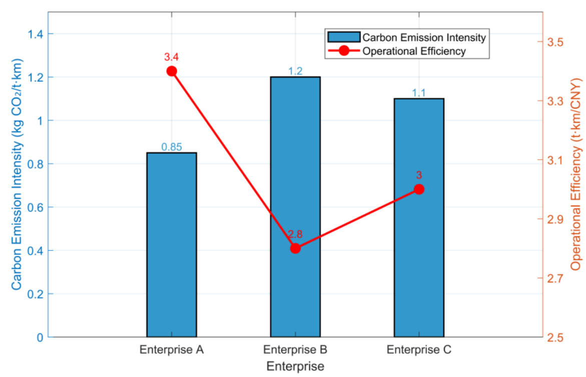

FIGURE 3. Longitudinal Case Comparison of Competency Transfer and Teaching Behavior

The results of the multi-case comparison show that Company A (high technology + high collaboration) performed best, with a carbon emission intensity of 0.85 kg CO2/t·km and an operating efficiency of 3.40 t·km/yuan. Company B (high technology + low collaboration) had a carbon emission intensity of 1.20 kg CO2/t·km and an operating efficiency of only 2.80 t·km/yuan. Although Company C (medium technology + high collaboration) utilized less advanced low-carbon hardware than Company B, its carbon emission intensity (1.10 kg CO2/t·km) was lower. This demonstrates a mechanistic compensatory effect: through high-density supply chain collaboration, Company C optimized its load factors and reduced empty-leg repositioning, thereby lowering the "per unit" carbon intensity despite using less efficient fuel. In contrast, Company B's advanced technology was undermined by "organizational friction," where sub-optimal routing and fragmented ground handling led to higher energy waste per ton-kilometer, proving that collaborative optimization can bridge the performance gap of moderate technology.

VI. CONCLUSION

This paper aims to address the fundamental issues of green air logistics by integrating the unique material flow requirements and low-carbon transformation needs of the industry. By synchronizing manufacturing logic with sustainable transport strategies, the study seeks to optimize the ecological efficiency of the entire industrial transport process. Starting from the synergistic integration of low-carbon technology and supply chain perspective, a three-dimensional theoretical framework is constructed from technology-driven layer, collaborative operation layer and value objective layer. The validity of the three-dimensional theoretical framework is verified by multi-case comparison and system dynamics simulation. The research results show that there exists a certain interactive effect between low-carbon technology and supply chain collaboration. Their collaborative relationship can effectively bridge the technology and operation, and build a virtuous cycle of mutual enhancement. Still, this study also has certain limitations. The sample size of multi-case studies is limited, and the parameters of system dynamics model are based on the experience data of industry experience. In the future, the scope of case studies can be expanded further, and the actual enterprise operation data can be used to calibrate and verify the parameters of system dynamics model. Furthermore, the dynamic adaptation mechanism between technology and collaboration under varying policy scenarios, alongside the promotion effect of digital technology on their integration within the industrial logistics framework, warrants further investigation. Such studies can elucidate how digital twin fusion and smart manufacturing parameters drive the deep synchronization of green transport initiatives and cross-sector operational efficiency.

AUTHOR CONTRIBUTIONS

Xiaoli Liu designed, collected and analyzed the data, and drafted the manuscript. Xiaoli Liu conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Xiaoli Liu participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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