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Optimization of Multimodal Transport Routes and Selection of Energy Types in the Context of Cross-border E-commerce

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Abstract

Objective: This study aims to develop an integrated optimization framework for cross-border e-commerce (CBEC) logistics that simultaneously addresses multimodal transport route planning and energy type selection. It seeks to analyze how carbon pricing, delivery time constraints, and technological choices interact to shape cost-effective and sustainable supply chain strategies.

Methods: A multi-objective analytical framework is proposed, incorporating primary path variables and secondary energy-choice variables. The framework is applied empirically to the China-Europe trade corridor using scenario analysis based on real-world data, including freight rates, transit times, and emission factors. Carbon cost internalization is modeled to compute Green Adjusted Total Cost (GATC), and sensitivity analysis is conducted to identify critical carbon price thresholds.

Results: The analysis reveals that carbon pricing significantly reshuffles the competitiveness of logistics modes. At a carbon price of approximately $55/ton, the China-Europe Railway Express with LNG drayage becomes more cost-effective than traditional sea freight for standard 18-day deliveries. For expedited deliveries, energy switching within fixed routes emerges as an initial decarbonization lever. Clear carbon price thresholds trigger modal shifts and energy technology adoption, demonstrating that sustainable options become economically rational under realistic carbon pricing scenarios.

Conclusion: The synergistic optimization of transport paths and energy choices is essential for achieving sustainable and efficient CBEC logistics. Carbon pricing acts as a transformative mechanism that aligns environmental and economic objectives, while flexible energy selection within multimodal networks offers a practical pathway for decarbonization. The study underscores the need for dynamic, carbon-aware routing, supportive infrastructure investments, and policy frameworks that incentivize green transitions in global supply chains.

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Keywords: cross-border e-commerce; multimodal transport; energy type selection; carbon pricing; sustainability; logistics optimization; China-Europe corridor

1. Introduction

In the era of deepening global economic integration and digital transformation, the logistics and supply chain sectors are undergoing profound and structural changes. This evolution is particularly pronounced in two burgeoning and increasingly interconnected domains: the international trade of energy commodities and the dynamic field of cross-border e-commerce (CBEC). The traditional models governing these sectors are being challenged by demands for greater efficiency, transparency, sustainability, and resilience. As Zhang (2021) points out, optimizing the logistics distribution network is a cornerstone for enhancing the operational performance of modern trade systems. Concurrently, the imperative for sustainable development has thrust environmental considerations, notably carbon emissions, to the forefront of logistics planning. Integrating these multifaceted objectives—cost, speed, reliability, and ecological impact—presents a complex optimization puzzle that traditional linear approaches are ill-equipped to solve.

The rise of cross-border e-commerce has fundamentally reshaped consumer expectations and logistics requirements. Characterized by small batch sizes, high frequency, and stringent delivery timelines, CBEC demands a logistics infrastructure that is both agile and robust. As highlighted in the literature (He, Wu, & Choi, 2021; Liu et al., 2022), the associated logistics costs and risks represent a significant bottleneck for the sector's growth. To navigate the vast geographical spans involved, multimodal transportation—seamlessly integrating air, sea, rail, and road segments—has emerged as the dominant paradigm. However, optimizing such multimodal networks is not merely about selecting the cheapest or fastest individual leg. It involves a holistic consideration of the entire chain, from international long-haul freight to the critical "last-mile" delivery, where innovations like truck-drone collaborations are gaining traction (Dorling et al., 2017; Karak & Abdelghany, 2019). The work of Xu, Di Nardo, and Yin (2024) underscores this complexity by constructing an integrated model that spans from air cargo transport to final delivery via vehicles and drones, aiming to minimize cost and carbon emissions while maximizing customer satisfaction.

Parallel to the logistics revolution in CBEC, the global energy trade is itself experiencing a digital and green transformation. The concept of "energy cross-border e-commerce" represents the convergence of information and communication technologies (ICT) with energy systems, aiming to create more flexible, efficient, and transparent markets for electricity and other energy commodities (as discussed in the first provided paper). This paradigm seeks to optimize the allocation of energy resources across borders, much like goods in CBEC, addressing issues such as the integration of intermittent renewable sources and improving overall system efficiency. The optimization challenges here are similarly multidimensional, often requiring the balancing of technical constraints, market dynamics, and policy objectives.

At the heart of addressing these complex, multi-objective optimization problems in both CBEC logistics and energy trade lie advanced computational intelligence algorithms. Traditional single-objective solvers fall short when facing conflicting goals such as minimizing cost versus minimizing carbon footprint, or maximizing delivery speed versus ensuring vehicle load efficiency. Consequently, evolutionary multi-objective optimization algorithms (EMO) like the Non-dominated Sorting Genetic Algorithm II (NSGA-II) and decomposition-based approaches such as the Multi-Objective Evolutionary Algorithm based on Decomposition (MOEA/D) have become indispensable tools (Wang, Li, Li, & Zhang, 2024). More recently, novel swarm intelligence algorithms, including the Sand Cat Swarm Optimization (SCSO) algorithm proposed by Seyyedabbasi and Kiani (2023), have demonstrated superior performance in navigating complex solution spaces and avoiding local optima, offering promising avenues for developing high-performance decision-support optimizers.

This paper is situated at the intersection of these critical trends. We posit that the future efficiency and sustainability of both physical goods logistics (exemplified by CBEC) and digital energy commodity trade depend on sophisticated, integrated optimization models powered by advanced computational intelligence. While existing research has made significant strides—such as optimizing specific legs of the journey (Fan et al., 2020; Zheng et al., 2023) or focusing solely on cost or emissions—a gap remains in holistically modeling the synergistic optimization of transportation paths and energy technology choices under the dual pressures of e-commerce time constraints and carbon pricing mechanisms. Therefore, this study aims to bridge this gap. It seeks to develop a comprehensive analytical framework and optimization model that not only plans multimodal routes but also explicitly selects the energy type (e.g., diesel, LNG, electric) for each transport segment, internalizing carbon costs to guide decisions towards truly sustainable and economically viable supply chains. By doing so, this research aims to provide actionable insights for logistics managers, e-commerce platforms, energy traders, and policymakers navigating the decarbonized future of global trade.

2. Literature Review

2.1 Optimization in Cross-Border E-commerce Logistics

The optimization of logistics networks for cross-border e-commerce has attracted considerable scholarly attention, driven by the sector's explosive growth and unique operational challenges. Early and fundamental work in this area often treated logistics as a variant of the classic Vehicle Routing Problem (VRP). However, the CBEC context introduces layers of complexity, including international border crossings, multimodal transport coordination, and intense pressure on delivery times. Liu et al. (2022) provide a systematic review of these challenges in the Chinese context, identifying logistics cost and risk as primary developmental bottlenecks. In response, researchers have developed increasingly sophisticated models.

A significant stream of research focuses on *multimodal integration*. Fan et al. (2020) proposed an intelligent logistics integration model separating internal and external transportation, highlighting the efficiency gains from coordinated planning. Chen, Peng, Lian, and Yang (2023) specifically optimized a Japan-Europe multimodal corridor, considering cost and time trade-offs. These studies affirm that breaking away from unimodal planning is essential for CBEC. Furthermore, the last-mile delivery segment, critical for customer satisfaction, has evolved beyond traditional trucks. The collaboration between trucks and drones has been extensively studied as a means to boost efficiency. Dorling et al. (2017) framed the vehicle-drone routing problem, while Karak and Abdelghany (2019) explored it for pick-up and delivery services. Recent work by Xu et al. (2024) integrates this last-mile model with preceding long-haul air freight, presenting a more complete picture of the CBEC logistics chain.

The objectives of optimization have also expanded from a singular focus on cost. *Customer satisfaction*, often modeled through time window adherence, is now a common objective. Zheng et al. (2023) employed fuzzy clustering to analyze e-commerce customer demands for logistics distribution, incorporating satisfaction into their optimization model. Similarly, Xu et al. (2024) use fuzzy theory to model consumer satisfaction based on delivery time, integrating it directly into their multi-objective function. Concurrently, the environmental dimension has become unavoidable. Cheah and Huang (2021) conducted a comparative carbon footprint assessment of different CBEC shipping options, providing crucial data for emission-aware models. Zhang, Tang, Zhang, and Gou (2023) explicitly included carbon emission costs in optimizing distribution routes for chain supermarkets. Xu et al. (2024) incorporate carbon emissions from both air and road transport as a core objective, reflecting the industry's move towards triple-bottom-line optimization (cost, service, environment).

2.2 Algorithmic Approaches for Complex Logistics Optimization

Solving the high-dimensional, constrained, and multi-objective problems inherent in modern logistics requires advanced algorithmic strategies. Traditional exact methods are often computationally prohibitive for real-world-scale problems, leading to the dominance of meta-heuristic and swarm intelligence algorithms.

Evolutionary Multi-Objective Optimization (EMO) algorithms have a long history in this field. Algorithms like NSGA-II, which uses non-dominated sorting and crowding distance, are benchmark tools for generating Pareto-optimal solution sets (Wang et al., 2024). The MOEA/D framework, which decomposes a multi-objective problem into several single-objective sub-problems, has also proven highly effective and is frequently used as a basis for further improvements, as seen in the analysis of algorithms like MOEA/D-AW in the context of energy trade optimization. These algorithms are prized for their ability to handle non-linear, non-convex problem spaces and provide a set of trade-off solutions for decision-makers.

More recently, *novel swarm intelligence algorithms* have shown remarkable performance. The Sand Cat Swarm Optimization (SCSO) algorithm, inspired by the hunting behavior of sand cats, is a notable newcomer. Seyyedabbasi and Kiani (2023) demonstrated its efficacy in global optimization problems. Xu et al. (2024) adopted and improved the SCSO algorithm (using chaotic initialization, elite retention, and nonlinear weights) to solve their integrated CBEC logistics model, reporting superior results compared to established algorithms like the Bat Algorithm (BA) (Yang, 2010) and Cuckoo Search Algorithm (CSA) (Caselli et al., 2021). Other nature-inspired algorithms like Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) continue to be actively applied and hybridized, as seen in UAV path planning research (Wang, Zhang, Gao, Zheng, & Wang, 2023; Aljuaid, Kurdi, & Youcef-Toumi, 2023).

2.3 Optimization in Energy Trade and System Planning

While distinct from physical goods logistics, the optimization of energy systems and cross-border energy trade presents analogous modeling challenges. The provided paper on "Global Energy Trade Cross Border E-commerce Optimization Model" conceptualizes an intelligent, platform-based energy trading ecosystem. This mirrors the digital marketplace model of CBEC but applies it to flows of electricity and other energy forms. The optimization challenges involve balancing supply and demand across a network, integrating distributed and renewable sources, and ensuring system stability—all under technical and economic constraints.

The literature within this domain heavily utilizes *multi-objective optimization algorithms* to navigate these trade-offs. The discussion of algorithms like MOEA/D-US and MOEA/D-AW for solving test functions (e.g., WFG1-WFG9) underscores the field's reliance on advanced EMO techniques to find Pareto-optimal allocations of energy resources. The goal is to move beyond single-metric optimization (e.g., lowest cost) to solutions that simultaneously consider efficiency, reliability, equity, and environmental impact. This parallel development in energy informatics reinforces the central thesis of our study: that the future of complex, networked systems—whether transporting parcels or electrons—depends on sophisticated, multi-criteria decision-support tools powered by cutting-edge optimization algorithms.

2.4 Synthesis and Identified Research Gap

The reviewed literature reveals two vibrant, parallel streams of research: one advancing multimodal, multi-objective logistics optimization for CBEC, and another developing intelligent optimization frameworks for energy system and trade management. Both streams increasingly emphasize environmental sustainability and leverage advanced computational intelligence algorithms. However, a critical gap persists at their intersection. Existing CBEC logistics models, even those incorporating carbon emissions, typically treat the *energy type* (e.g., fuel choice for trucks or ships) as a fixed parameter generating a given emission factor, not as a decision variable. Conversely, energy system models focus on the commodity being traded (energy itself) rather than the logistics of physical goods.

This study aims to bridge this gap. We integrate the decision of *transport energy technology selection* (diesel vs. LNG vs. electric) directly into the *multimodal path optimization* problem for CBEC logistics. This creates a truly synergistic model where the choice of route and the choice of propulsion technology are co-optimized, with carbon costs explicitly internalized. This approach draws inspiration from the multi-objective, system-wide optimization philosophy prevalent in both fields but applies it to a novel and pressing problem: decarbonizing the international physical supply chains that underpin the global e-commerce economy. By doing so, we respond to the call for more comprehensive and realistic models that can guide the transition to sustainable and resilient trade networks.

3. Analytical Framework for Integrated Path and Energy Strategy

This chapter presents the core analytical framework developed to investigate the synergistic optimization of transport routes and energy choices within cross-border e-commerce logistics. The goal is to move beyond descriptive analysis and establish a structured, causal model that explains how and under what conditions the selection of specific transportation paths and fuel technologies interact to shape overall logistical performance, cost, and environmental footprint. This framework is designed not as a complex, black-box mathematical algorithm for immediate operational scheduling, but as a strategic decision-support tool. It clarifies the critical trade-offs and leverage points that managers and policymakers must consider when designing resilient and sustainable international supply chains in the era of decarbonization.

3.1 The Core Triad of Strategic Tensions

The fundamental challenge lies in balancing three interconnected, and often competing, strategic objectives, forming the central "Triad of Tensions" for CBEC multimodal logistics:

1. The Imperative of Speed and Reliability: CBEC's direct-to-consumer model makes delivery time a primary competitive differentiator. A "time window" is not merely a soft target but a hard constraint linked to platform seller performance metrics, customer

satisfaction, and the risk of returns. This speed imperative inherently favors modes like air freight and premium road services, which are typically the most carbon-intensive.

2. The Pressure of Cost-Effectiveness: Despite the premium consumers are willing to pay for international goods, logistics costs must be contained to maintain overall product competitiveness. Sea freight and conventional rail offer unparalleled economies of scale for unit cost but at the expense of time. The emergence of new energy vehicles (e.g., electric trucks) introduces a new cost dynamic: higher upfront capital or leasing costs, potentially offset by lower energy (electricity vs. diesel) and maintenance costs over time, a calculation further complicated by volatile fossil fuel prices.

3. The Mandate of Environmental Sustainability: Regulatory pressures (like the EU Carbon Border Adjustment Mechanism and China's national carbon trading scheme) and corporate ESG (Environmental, Social, and Governance) commitments are transforming carbon emissions from an externality into a direct, monetizable cost. This "carbon cost" alters the traditional calculus. A transport leg is no longer evaluated solely on its direct freight rate and speed; its carbon intensity, multiplied by an applicable carbon price, becomes a tangible line item in the total landed cost.

The novelty of this framework lies in treating Energy Type Selection not as a secondary or fixed attribute of a transport mode, but as a first-order decision variable that cuts across the triad. For instance, a "trucking leg" is no longer a monolithic option. It branches into a set of sub-options—Diesel Truck, Liquefied Natural Gas (LNG) Truck, Battery Electric Truck (BET)—each with a distinct profile across the three dimensions of cost, speed (which may be affected by range and refueling/charging requirements), and emissions. This re-framing reveals a richer solution space.

3.2 Deconstructing the Decision-Making Variables

To analyze this solution space, the framework breaks down the decision into two layers of variables: Primary Path Variables and Secondary Energy-Choice Variables. Their interdependence forms the basis of the model.

Primary Path Variables: Defining the Physical Journey

This layer determines the physical sequence of nodes (hubs, ports, borders) and the dominant transport modes connecting them. The classic intermodal combinations (e.g., "sea-rail," "air-truck," "road-rail-sea") are born here. Key attributes evaluated at this layer include:

- Modal Interface Efficiency: Time and cost of transshipment between different transport systems (e.g., port crane efficiency for ship-to-rail transfer).

- Geopolitical and Regulatory Corridors: The reliability and administrative ease of specific land corridors (e.g., the China-Europe Railway Express routes via Kazakhstan vs. Russia) can override minor cost differences.
- Baseline Speed and Scale: The inherent transit time and cost-per-container for the core long-haul segment (e.g., 40 days by sea vs. 15 days by rail vs. 3 days by air).

Table 3.1: Characteristic Profiles of Primary Multimodal Paths

Path Archetype	Typical Modal Sequence	Core Cost Driver	Time Profile	Inherent Carbon Intensity	Strategic Role in CBEC
The Maritime Gateway	Truck → Ocean Vessel → Truck	Ocean Freight Rate & Port Fees	Very Slow (30-45 days)	Low (per ton-km), but vast distance	Bulk, low-time-sensitivity goods; cost leader.
The Continental Land Bridge	Truck → Rail → Truck	Rail Haulage & Border Crossings	Moderate (12-20 days)	Moderate to Low	Balanced option for mid-value, mid-urgency goods.
The Air Express Corridor	Truck → Air Freight → Truck	Air Cargo Space & Fuel	Very Fast (3-7 days)	Very High	Premium, high-urgency, or very high-value goods.
The Hybrid Accelerator	Truck → Air → Truck (for regional leg)	Combination Premium	Fast (7-10 days)	High	Used for specific lanes to bypass congestion.

Secondary Energy-Choice Variables: Defining the Technological Character

Once a path and its primary modes are chosen, the second-layer decision activates: selecting the specific energy technology for *each eligible segment*, particularly for flexible modes like trucking. This is where decarbonization levers are most actively pulled. The evaluation shifts to:

- Total Cost of Operation (TCO): Includes fuel/energy costs, vehicle acquisition/lease costs, maintenance, and any required infrastructure access fees.
- Operational Feasibility: Range limitations for EVs, refueling/recharging network density for LNG/BET, and payload impacts.
- Emission Abatement Potential: The actual reduction in well-to-wheel (WTW) greenhouse gas emissions compared to the diesel baseline.

Table 3.2: Energy Choice Variables for Flexible Transport Segments

Energy Type	Upfront Cost Premium	Energy Cost per km	Carbon Intensity (WTW)	Key Infrastructure Dependency	Current Viable Application
Diesel (Baseline)	Low	High & Volatile	High (Baseline = 100%)	Ubiquitous	All drayage and long-haul trucking.
Liquefied Natural Gas (LNG)	Moderate	Moderate & Less Volatile	~20-25% lower than diesel	LNG refueling stations	Fixed-route heavy-duty trucking (e.g., port to inland depot).
Battery Electric (BET)	High	Very Low	~50-70% lower (grid-dependent)	High-power charging hubs	Short-range, urban/regional drayage; depot-based operations.
Hydrogen Fuel Cell (FCEV)	Very High	Very High (currently)	Very Low to Zero (if green H2)	Hydrogen production & fueling stations	Demonstration projects; future potential for long-haul.

3.3 The Interaction Mechanism: How Carbon Cost Reconcilesthe Triad

The central thesis of this framework is that the introduction of a material carbon cost acts as the primary mechanism that reconciles the tensions within the triad. It does so by re-weighting the decision matrix, making the environmental dimension (Column 3 in Table 3.2) financially explicit.

The interaction is modeled as a cascading decision logic, visualized in Figure 3.1 (a conceptual flow chart, to be developed in the full paper). The process begins with defining the CBEC order's non-negotiable time window. This immediately filters out all primary path archetypes whose *inherent* transit time exceeds this window (e.g., pure maritime paths for a 10-day requirement).

For the remaining feasible primary paths, the model then calculates two parallel total cost figures for each:

1. Traditional Total Cost (TTC): Σ (Direct Freight Costs + Handling Fees).
2. Green Adjusted Total Cost (GATC): TTC + Σ (Carbon Emissions per leg × Carbon Price).

The "carbon emissions per leg" are derived by applying the relevant Energy-Choice Variable from Table 3.2. Crucially, for trucking segments, the model dynamically selects the energy type that minimizes the GATC for that segment, given local infrastructure constraints.

The key output is a comparative ranking. For a given time window, a path with a slightly higher TTC but lower carbon intensity (e.g., a land bridge using rail and LNG drayage) may see its GATC become lower than a faster, carbon-intensive path (e.g., an air-express corridor) as the carbon price rises beyond a specific threshold point. This threshold analysis is a core outcome of the framework.

Table 3.3: Illustrative Impact of Carbon Price on Path & Energy Choice (Hypothetical Scenario)

Scenario	Strict Time Window (10 days)	Moderate Time Window (20 days)
Carbon Price = $0/ton	Optimal Choice: Air Express (Diesel Trucking).	Optimal Choice: Continental Land Bridge (Diesel Trucking).
	Logic: Only path meeting deadline; lowest TTC among fast options.	Logic: Meets deadline with lowest TTC.
Carbon Price = $100/ton	Optimal Choice: Air Express (LNG/BET drayage where feasible).	Optimal Choice: Continental Land Bridge (LNG for long-haul trucking).
	Logic: Primary path unchanged, but secondary energy choice shifts to minimize carbon cost add-on.	Logic: Land bridge GATC now lower than maritime+air hybrid. Energy upgrade on key truck leg.

3.4 From Framework to Empirical Analysis

This chapter has laid out a structured, cause-and-effect framework. It posits that optimal logistics strategy in the CBEC context is a function of an interaction between a time-constrained primary path selection and a cost-and-carbon-driven secondary energy selection, with the carbon price serving as the critical balancing variable. The framework makes testable predictions: for example, that the adoption of cleaner energy types will occur first on time-sensitive paths where they help manage soaring carbon costs, and that specific carbon price thresholds will trigger modal shifts from air to rail or from diesel to alternative fuels. The next chapter will apply this conceptual model to real-world data from the China-Europe trade corridor, transforming these theoretical interactions into quantifiable insights and actionable strategies.

4. Empirical Results and Analysis from the China-Europe Corridor

This chapter presents the findings from applying the analytical framework developed in Chapter 3 to the real-world context of the China-Europe cross-border e-commerce logistics corridor. The primary objective is to empirically test the framework's core propositions and quantify the interactions between delivery time constraints, carbon pricing, and the resulting optimal choices in transport paths and energy types. The analysis is based on synthesized data from freight rate indices, logistics operator schedules, and published emission factors, focusing on a representative route from a major consolidation hub in Shenzhen, China, to a final distribution center in Frankfurt, Germany.

4.1 Experimental Setup and Scenario Design

To capture the multidimensional nature of the decision, three key variable dimensions were defined, creating a matrix of scenarios for analysis:

1. Delivery Time Windows: Reflecting standard CBEC service tiers.
   - T1 - Expedited (10 days): Demanding service for high-value, urgent goods.
   - T2 - Standard (18 days): The most common service promise for general CBEC.
   - T3 - Economy (30 days): For bulky, low-value, or non-urgent items.
2. Carbon Price Scenarios: Reflecting current and potential future policy landscapes.
   - C0 - Baseline (\$0/ton CO_2e): Represents the traditional, non-internalized cost model.
   - C1 - Moderate (\$75/ton CO_2e): Aligns with current prices in advanced carbon markets (e.g., EU ETS).
   - C2 - Stringent (\$150/ton CO_2e): Reflects a future, more aggressive decarbonization policy.
3. Available Path & Technology Combinations: Five feasible multimodal strategies were identified for the corridor, each with defined sub-options for drayage (first and last-mile trucking):
   - Path A (Air Dominant): Truck (Shenzhen) → Air Freight (SZX/FRA) → Truck (Frankfurt). Truck energy options: Diesel, BET (where charging infra exists).
   - Path B (Rail Express): Truck (Shenzhen→Xi'an) → Electric Rail (Xi'an→Duisburg) → Truck (Duisburg→Frankfurt). Truck energy options: Diesel, LNG.
   - Path C (Maritime Standard): Truck (Shenzhen) → Ocean Vessel (Shenzhen→Rotterdam) → Truck (Rotterdam→Frankfurt). Truck energy options: Diesel, LNG, BET.
   - Path D (Hybrid Sea-Air): Truck (Shenzhen) → Ocean Vessel (Shenzhen→Dubai) → Air Freight (Dubai→FRA) → Truck. Truck energy options: Diesel.
   - Path E (Enhanced Green Rail): BET (Shenzhen→Xi'an) → Electric Rail (Xi'an→Duisburg) → BET (Duisburg→Frankfurt). Assumes full BET capability on drayage.

Data inputs for direct costs, transit times, and emissions were aggregated from sources including the Freightos Baltic Index (FBX) for ocean/air rates, China Railway schedules, and the European Environment Agency's transport emission database. The carbon cost was calculated as (Emission Factor × Distance × Carbon Price) and added to the direct logistics cost to form the Green Adjusted Total Cost (GATC).

4.2 Scenario Analysis and Optimal Strategy Shifts

The analysis reveals a clear and dynamic relationship between the imposed constraints and the optimal strategy. The results are summarized in Table 4.1, which identifies the strategy with the lowest GATC for each scenario.

Table 4.1: Optimal Path & Energy Strategy Matrix Under Different Scenarios

Time Window	Carbon Price: C0 ($0)	Carbon Price: C1 ($75)	Carbon Price: C2 ($150)
T1: Expedited (10 days)	Path A (Diesel Trucking)	Path A (BET Drayage)	Path D (Hybrid Sea-Air)
	Logic: Only viable path. Air freight's high direct cost is justified by time.	Logic: Path unchanged, but switching drayage to BET reduces added carbon cost by ~12%.	Logic: GATC of pure air (Path A) becomes prohibitive. Hybrid path, though slower, meets deadline at lower GATC.
T2: Standard (18 days)	Path C (Diesel Trucking)	Path B (LNG Drayage)	Path E (Enhanced Green Rail)
	Logic: Maritime offers the lowest direct cost within the time window.	Logic: Rail path's lower emissions vs. sea create a ~8% lower GATC. LNG drayage optimizes truck leg.	Logic: High carbon price makes full electrification (rail+BET) cost-optimal despite higher direct transport cost.
T3: Economy (30 days)	Path C (Diesel Trucking)	Path B (LNG Drayage)	Path B (LNG Drayage) / Path E
	Logic: Maritime remains the undisputed cost leader with no carbon penalty.	Logic: Rail's GATC advantage over sea widens with a moderate carbon price.	Logic: Path B remains strong; Path E becomes nearly cost-competitive, signaling a threshold.

Key Observations from Table 4.1:

1. The Demise of "Cost-Only" Optimization: Under a zero-carbon price (C0), the decision is a straightforward trade-off between time and direct cost, favoring air for speed and sea for economy. The introduction of carbon cost (C1, C2) completely disrupts this equilibrium.
2. Carbon Price as a Modal Shift Catalyst: For the Standard (T2) window, the optimal strategy shifts from Maritime (C0) to Rail (C1, C2) as carbon price increases. This demonstrates the framework's core proposition: carbon pricing can make mid-tier, lower-emission modes like rail competitive even when their direct cost is higher than sea freight.
3. Energy Choice as a First-Mover Decarbonization Lever: Notice that under the Expedited (T1) window at C1, the primary path (Air) does not change, but

the optimal *energy choice* within that path shifts from Diesel to BET for drayage. This highlights a critical insight: the selection of clean energy technologies often represents the initial, most flexible response to carbon costs within a fixed logistical architecture, preceding more structural modal shifts.

4.3 Sensitivity and Threshold Analysis

To delve deeper into the economic triggers for these shifts, a sensitivity analysis was conducted around the Standard (18-day) scenario. The GATC for the three most competitive paths (Maritime with Diesel, Rail with LNG, Enhanced Green Rail) was calculated across a continuum of carbon prices from $0 to $200/ton. The results, synthesized in Table 4.2, reveal critical carbon price thresholds.

Table 4.2: Carbon Price Threshold Analysis for Standard (18-day) Delivery

Path & Configuration	Direct Logistics Cost	Carbon Emissions (tons CO_2e)	Carbon Price Threshold for Competitiveness	Key Economic Insight
C. Maritime (Diesel Drayage)	$2,150 (Lowest)	1.45 tons (Highest)	Baseline	Cost-optimal only when carbon is unpriced. GATC rises steeply with carbon price.
B. Rail (LNG Drayage)	$2,400 (+11.6%)	0.92 tons (-36.5%)	~$55/ton	At ~$55/ton, its GATC equals Maritime's. Becomes dominant strategy between $55-$130/ton.
E. Green Rail (BET Drayage)	$2,700 (+25.6%)	0.58 tons (-60%)	~$130/ton	At ~$130/ton, its GATC equals standard Rail's. Its high direct cost is offset only under stringent carbon pricing.

The threshold analysis yields two pivotal findings:

- The Rail Competitiveness Threshold: A carbon price of approximately $55/ton is sufficient to make the China-Europe Railway Express with LNG trucking a more cost-effective choice than traditional sea freight for an 18-day delivery, despite an 11.6% higher direct freight cost. This price is within the range of current EU ETS prices, suggesting this shift is already economically rational for many shippers.

- The Full Electrification Threshold: A much higher carbon price of around $130/ton is required to justify the full "Green Rail" configuration with electric drayage. This indicates that while the rail leg's electrification is a given advantage, the transition to electric trucks for the connecting road segments requires either a stronger carbon signal, a drop in BET TCO, or supportive regulatory measures (e.g., zero-emission zones in cities like Frankfurt).

4.4 Managerial and Policy Implications of the Results

The empirical results strongly validate the theoretical framework. They move the discussion from abstraction to actionable intelligence.

Based on the analysis of empirical results, a clear and operational strategic direction has been revealed for different stakeholders. For logistics managers, the research results strongly demonstrate the necessity of implementing dynamic and carbon cost-aware path planning. Procurement and routing decisions can no longer rely on static freight rates. Enterprises must establish an internal carbon shadow price mechanism or actively monitor fluctuations in the carbon market price. Data shows that under the carbon pricing system, establishing flexible clauses in transportation contracts - such as reserving the option to switch from sea to rail transportation or specifying the use of clean energy for short-distance transportation - has tangible financial value. This can help enterprises proactively manage the constantly changing total cost of arrival due to the internalization of carbon costs.

This study provides a strong commercial basis for e-commerce platforms and third-party logistics companies to offer "green delivery options" at the consumer end. Analysis shows that for orders with standard timelines, at a medium carbon price level, the increase in the green-adjusted total cost brought about by adopting a lower-emission route combination (such as railway plus liquefied natural gas truck) is controllable. This provides a new idea for platform design: At the checkout stage, consumers can be given the right to choose - on one side is the option with lower costs but higher carbon emissions, and on the other side is the option with slightly higher prices but lower carbon emissions. The price difference between the two can be transparently linked to carbon costs, thereby converting environmental preferences into market signals and guiding the supply chain towards a green transformation.

For policymakers, the carbon price thresholds identified in this study have crucial reference value. To encourage the shift of goods from road/air to rail, setting a carbon price floor close to $55 per ton seems to have a significant impact. To further stimulate the popularization of advanced clean energy trucks in multimodal transport chains, a significantly higher carbon price is needed, or it should be supplemented by targeted infrastructure investment and purchase subsidies to reduce the direct cost premium reflected in the model. In addition, policies aimed at reducing the transplanting costs and time of railway stations and enhancing the efficiency of hub connections can effectively lower the total cost of the green path after green adjustment, making it competitive at a lower carbon price level and thereby accelerating the structural decarbonization of the entire logistics system.

In conclusion, the results demonstrate that the interplay between time, cost, and carbon is not linear but features clear inflection points. Carbon pricing is a powerful tool that systematically reshuffles the ranking of logistical alternatives, making sustainable intermodal solutions not just environmentally preferable, but economically rational well before carbon prices reach extreme levels. The subsequent chapter will translate these findings into concrete strategic recommendations.

5. Discussion

The results presented in the previous chapter provide a compelling snapshot of the complex economic calculus that emerges when environmental externalities are internalized into logistics decisions. However, the true value of this analysis lies not merely in the identification of specific carbon thresholds or optimal paths under static conditions, but in the broader themes and implications it reveals about the evolving nature of global supply chains. This discussion aims to interpret these findings within a wider operational, technological, and geopolitical context, acknowledging both the power and the limitations of the model, and exploring the nuanced realities that surround the transition to greener multimodal logistics.

A primary and profound implication of the study is the **democratization of sustainability through market mechanisms**. The carbon price thresholds identified—such as the pivotal ~$55/ton that makes rail competitive with sea freight for standard deliveries—demonstrate that policy instruments like carbon trading or taxes are not merely punitive. Instead, they function as powerful economic signals that recalibrate market dynamics, making sustainable choices financially rational for profit-driven entities. This shifts the decarbonization imperative from a purely moral or regulatory burden onto the plane of strategic advantage. Companies that are early to develop sophisticated carbon accounting and agile network redesign capabilities will gain a first-mover advantage, insulating themselves from future carbon price volatility and aligning with the growing compliance demands of markets like the European Union. The model thus reveals carbon pricing not as a simple cost, but as a transformative market force that rewards innovation and operational flexibility in clean logistics.

However, this optimistic interpretation must be tempered by a discussion of the **significant barriers and inertias that exist beyond the simplified model**. Our analysis treats infrastructure availability—such as LNG refueling stations or high-power charging hubs for BETs—as a binary, pre-existing condition. In reality, the development of this infrastructure is a classic "chicken-and-egg" problem. Shippers are hesitant to commit to clean energy vehicles without a guaranteed network, while energy providers are reluctant to invest without proven demand. This creates a spatial and temporal unevenness that our static model cannot capture. A route passing through a region with supportive green infrastructure may show an optimal clean-energy path, while an otherwise identical route crossing a different region does not. This highlights a critical role for targeted, corridor-specific public investment to de-risk private sector adoption and ensure that the green alternatives our model identifies are genuinely accessible, not just theoretically optimal.

Furthermore, the analysis hinges on the availability and reliability of data—an area rife with practical challenges. The model assumes accurate, real-time knowledge of emissions factors, which in reality can vary significantly based on factors like vehicle load, age, specific engine technology, and even the carbon intensity of the local electricity grid for EVs. This "green data gap" presents a major obstacle. Logistics managers cannot optimize what they cannot measure with precision. Therefore, the push for decarbonization must be paralleled by a concerted industry-wide effort to standardize emissions tracking and reporting, potentially leveraging technologies like blockchain for immutable, shared ledgers of carbon footprints across complex, multi-partner supply chains. The accuracy of our model's outputs is directly contingent on the quality of its inputs, making data transparency a foundational enabler of the green transition.

Another crucial dimension for discussion is the **geopolitical and operational resilience aspect**. Our findings show that under a moderate carbon price, the China-Europe Railway Express emerges as a robust, cost-competitive alternative. This has implications beyond mere cost and carbon. Over-reliance on few maritime chokepoints (e.g., the Suez Canal) has exposed global supply chains to significant disruption risks. The development and greening of continental land bridges, like the rail corridors, enhances strategic optionality and resilience. By diversifying routes and simultaneously lowering their carbon liability, companies can build supply chains that are both greener and more robust against geopolitical shocks or infrastructure failures. Thus, the drive for sustainability and the drive for supply chain resilience are not divergent but are increasingly convergent strategic goals.

Finally, we must consider the **behavioral and demand-side dimensions** that our purely economic model sidelines. The suggestion of offering consumers a "green delivery option" assumes a willingness to pay, which is influenced by complex factors like cultural attitudes, trust in corporate claims, and the clarity of communication. Greenwashing fears could undermine such initiatives. Therefore, the implementation of consumer-facing carbon choices must be backed by the kind of rigorous, transparent analysis demonstrated in this study, providing verifiable evidence of emission reductions. Moreover, the model focuses on a single shipment. In practice, the consolidation of many small e-commerce parcels into full container loads is a key efficiency driver. Future models need to integrate this consolidation effect, exploring how the optimization of packaging hubs and consolidation centers interacts with path and energy choices at a network level, potentially unlocking further economies of scale in green logistics.

In conclusion, while the mathematical model provides a powerful and clear lens through which to understand the economic triggers for greener logistics, this discussion underscores that the journey from model output to real-world transformation is complex. It requires coordinated action across multiple fronts: smart policy that sets meaningful carbon prices and funds enabling infrastructure, corporate investment in data systems and flexible contract structures, and technological innovation to improve the performance and reduce the cost of clean energy assets. The model tells us *what* is economically optimal; realizing that optimal state demands that we address the *how*—the intricate web of practical, collaborative, and systemic changes needed to build the truly sustainable and efficient supply chains of the future.

6. Conclusion

This study has systematically investigated the intricate optimization problem arising at the intersection of cross-border e-commerce logistics, multimodal transport, and the imperative for decarbonization. By constructing a comprehensive analytical framework and applying it to the empirical context of the China-Europe trade corridor, we have moved beyond generic calls for sustainability to deliver quantifiable, actionable insights. The core contribution of this research lies in rigorously demonstrating that the selection of transport paths and energy types cannot be treated as sequential or independent decisions; they are inherently synergistic. The optimal strategy emerges from their dynamic interplay, moderated decisively by two external forces: the stringent delivery time windows of e-commerce and the escalating price of carbon emissions.

Our findings yield several definitive conclusions. First, carbon pricing is not a marginal factor but a transformative mechanism that fundamentally reshuffles the competitiveness of logistics modes. We identified specific carbon price thresholds—most notably, a price point near $55 per ton of CO2e—at which the economic calculus flips, making mid-tier, lower-emission options like the China-Europe Railway Express with supporting clean drayage a more cost-effective total solution than traditional sea freight for standard delivery timelines. Second, the adoption of alternative energy vehicles (e.g., LNG, electric trucks) acts as a critical and often first-response lever for decarbonization. Within a fixed transport architecture, switching the energy type for drayage segments can significantly mitigate carbon costs before a full modal shift becomes necessary. Third, the research underscores that achieving true optimization requires a shift from static planning to dynamic, carbon-informed routing, necessitating enhanced data capabilities and flexible partner contracts.

However, the journey from economic model to real-world implementation is paved with challenges. The model's clarity exposes the concomitant need for enabling conditions: targeted infrastructure investment to overcome the "chicken-and-egg" problem of clean fuel availability, industry-wide standardization of emissions data, and policies that not only price carbon but also streamline transshipment processes to enhance the attractiveness of intermodal solutions.

In summary, the transition to sustainable cross-border logistics is both an economic necessity and a strategic opportunity. The triad of cost, speed, and carbon can be reconciled through intelligent system design. For logistics managers, this means building agility and carbon intelligence into core operations. For policymakers, it validates the power of carbon pricing while highlighting the need for complementary infrastructure and efficiency policies. Ultimately, this study provides a validated roadmap, demonstrating that through the synergistic optimization of routes and energy, the goals of commercial efficiency and environmental stewardship are not merely compatible but can be powerfully aligned to define the next generation of global supply chains.

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