Robust Multimodal Routing for Cross-Border Logistics under Travel Time Uncertainty: A Case Study of the China-Vietnam Corridor

Xiaojuan Huang, Meng Tan*
Guangxi Vocational Normal University, Nanning, Guangxi, China
**Corresponding Author*

Abstract: **The implementation of the Regional Comprehensive Economic Partnership (RCEP) and the upgrading of China-ASEAN Free Trade Area have boosted bilateral trade, straining cross-border logistics. The China-Vietnam (Nanning-Hanoi) corridor, relying on road, rail, and maritime multimodal transport, faces inefficiencies from volatile border clearance times, making traditional deterministic models ineffective and raising service level agreement (SLA) violation risks. To address this, we propose a cardinality-constrained Robust Mixed-Integer Linear Programming (RMILP) model with a "budget of uncertainty" parameter, balancing cost and schedule reliability without requiring precise probability distributions. Greater Mekong Subregion (GMS) empirical experiments show rail becomes the robust optimum beyond uncertainty thresholds, providing decision support for logistics providers in transnational supply chains.**

Keywords: Multimodal Transport; Robust Optimization; Cross-border Logistics; Interval Uncertainty; Route Selection.

1. Introduction

1.1 Research Background

In the context of global supply chain reconfiguration and the high-quality development of the Belt and Road Initiative (BRI), cross-border logistics has evolved from a peripheral support function into a strategic determinant of regional economic integration. The economic symbiosis between China and Vietnam, particularly in sectors such as electronics manufacturing, textiles, and cold-chain agriculture, has generated a logistics demand pattern characterized by high frequency, fragmentation, and time sensitivity. However, cross-border logistics is fundamentally distinct from domestic transport due to the prevalence of "border effects"—a compound friction consisting of administrative barriers, infrastructure discontinuities, and regulatory heterogeneity.

The China-Vietnam corridor exemplifies these challenges. Freight traversing the border must undergo rigorous processes including customs declaration, security screening, sanitary and phytosanitary (SPS) inspection, and, in the case of rail transport, transshipment due to gauge differences (standard vs. meter gauge). Empirical observations at key gateways, such as the Youyiguan (Friendship Pass) for road transport and Pingxiang for rail, reveal that processing times are highly volatile. Influenced by geopolitical dynamics, shifting bilateral policies, and seasonal surges, clearance durations can fluctuate from hours to several days. For Logistics Service Providers (LSPs), the primary objective has shifted from minimizing static distance to managing the temporal risks associated with these bottleneck nodes.

1.2 Problem Statement

Traditional literature on the Multimodal Transport Problem (MTP) predominantly relies on deterministic assumptions, treating link travel times and nodal processing times as fixed parameters or expected values. Such approaches, while computationally tractable, fail to capture the "heavy-tailed" nature of border delays. In reality, extreme delay events are not merely statistical outliers but systemic risks inherent to cross-border operations.

Consequently, LSPs operating under deterministic planning frameworks face a critical dilemma. Plans optimized for "average" conditions are fragile; a single disruption at the border can cascade into severe delivery delays, incurring penalty costs and reputational damage.

Conversely, a worst-case scenario approach—assuming maximum delay on all links—leads to overly conservative routing, such as the unnecessary utilization of expensive air freight or underutilization of road capacity, thereby eroding cost competitiveness. The core research problem, therefore, is to determine an optimal routing strategy that minimizes total logistics costs while guaranteeing delivery reliability under a bounded level of uncertainty. This necessitates an optimization methodology capable of explicitly handling parameter uncertainty without the stringent data requirements of Stochastic Programming (SP).

1.3 Contributions

This study addresses the aforementioned gaps through the following contributions:

1.3.1 Context-specific network modeling

We formulate a multimodal network model tailored to the topology of the Guangxi-Vietnam corridor, explicitly incorporating mode-specific operational constraints (e.g., rail transshipment) and modeling border crossings as nodes with interval uncertainty.

1.3.2 Methodological innovation

We adapt the robust optimization framework of Bertsimas and Sim (2004)[1] to the cross-border logistics context. By introducing the parameter Γ (budget of uncertainty), we transform the robust counterpart of the routing problem into a tractable Mixed-Integer Linear Programming (MILP) model. This approach avoids the complexity of probability distribution estimation required by SP.

1.3.3 Managerial implications

Through extensive numerical experiments, we quantify the "price of robustness" and identify critical thresholds for mode switching (e.g., from Road to Rail). These insights provide actionable guidelines for LSPs to dynamically adjust routing strategies based on real-time risk assessments.

2. Literature Review

2.1 Multimodal Transport Network Design

Multimodal transport—where goods are transported under a single contract using at least two modes—has been a subject of research since Crainic (2000)[2] stratified decisions into strategic, tactical, and operational layers. Early studies focused on variants of the shortest-path problem and the Vehicle Routing Problem with Time Windows (VRPTW) in static networks. SteadieSeifi et al. (2014)[3] later emphasized that modern models must balance cost, time, reliability, and CO_2 emissions; yet most studies on the China-Europe Railway Express (CRE) overlook short-haul, high-frequency China-ASEAN corridors, where border congestion—not distance—serves as the primary bottleneck. Wang, Zhang, & Nguyen (2023)[4] demonstrate that stochastic clearance times at Youyiguan result in a road transit time variance 24 times higher than that of rail, reversing the deterministic ranking for perishable fruit shipments. Zhang & Ge (2024)[5] illustrate that synchronodal corridors shorter than 600 km are unviable unless cross-dock slots at Friendship Pass are reserved in advance. Liu, Lim, & Tan (2025)[6] find that a 5% CO_2 emission cap diverts 38% of Nanning–Hanoi freight tonnage to rail, highlighting the inadequacy of traditional CRE-oriented models for the China-Vietnam context.

2.2 Uncertainty in Logistics

Transport uncertainty is typically categorized into supply-side (capacity) and demand-side (volume) types. This study focuses on operational (time) uncertainty. Stochastic Programming (SP) treats travel times as random variables with known distributions (Jiang et al., 2020)[7], but rare, high-impact border delays result in scarce data and nonlinear formulations. Fuzzy Programming (FP) addresses linguistic ambiguity but lacks probabilistic interpretability for SLA enforcement. Chen, Wang, & Cheng (2023)[8] fitted a heavy-tailed Weibull distribution to 28 months of clearance data from Youyiguan, concluding that at least 400 observations per season are required to stabilize SP estimates—data rarely available to small and medium-sized enterprises (SMEs). Kim, Lee, & Cheong (2024)[9] compared SP, distributionally robust SP, and FP in the context of cross-border e-commerce, finding that FP underestimates tail risk by 12–17% when penalty clauses are legally enforceable. Smith, Büyüktahtakın, & Elal (2025)[10] show that even advanced data-driven SP solvers require more than 30 minutes to solve 200-arc, three-mode instances, confirming the need for linear robust optimization (RO) in real-time tools.

2.3 Robust Optimization Applications

Soyster (1973)[11] pioneered worst-case feasible solutions, which are often overly conservative. Ben-Tal & Nemirovski (1998)[12] refined the ellipsoidal set approach but introduced second-order cone complexity. Qiang, Nagurney, & Li (2023)[13] applied cardinality-constrained RO to the Myanmar-China crude oil pipeline and identified a knee point at $\Gamma = 3$, which matches the threshold we observed for the Nanning–Hanoi rail corridor. Park, Kook, & Kim (2024)[14] integrated real-time border queue API data into an RO framework, reducing SLA violations from 14% to 4% for Korean exporters. Ren, Xie, & Liu (2025)[15] incorporated carbon pricing into RO for the China-Laos railway; once the CO_2 cost exceeds 45 RMB per tonne, the “price of robustness” becomes negative—robust routes are both more cost-effective and environmentally friendly. These findings motivate our adoption of the Bertsimas-Sim model to quantify the cost-reliability trade-off under border-induced interval uncertainty in the China-Vietnam corridor.

3. Methodology

3.1 Problem Description and Assumptions

We model the cross-border multimodal network as a directed acyclic graph $G=(N,A)$, where N is the set of nodes and A is the set of arcs. The node set includes origin points (e.g., Nanning), transshipment hubs (e.g., Pingxiang Logistics Park, Qinzhou Port), border checkpoints (e.g., Youyiguan, Dong Dang), and destinations (e.g., Hanoi). The set of available transport modes is denoted by $M=\{\text{Road, Rail, Sea}\}$.

Key Assumptions:

Single Commodity Flow: We consider the transport of standard containers (TEU) where the cargo is homogeneous.

Interval Uncertainty: The travel time on arc (i,j) via mode m is not fixed. It is modeled as a symmetric interval $[\bar{t}_{ij}^m-\hat{t}_{ij}^m, \bar{t}_{ij}^m+\hat{t}_{ij}^m]$, where $\bar{t}_{ij}^m$ is the nominal (expected) time and $\hat{t}_{ij}^m$ is the maximum deviation.

Independence: Delay events on disjoint arcs are assumed to be independent, although the robust model effectively handles correlated delays by bounding the total deviation.

Transshipment: Mode transfer is allowed only at designated hub nodes, incurring both transfer cost and time.

3.2 Mathematical Formulation

Parameters:

- c_{ij}^m : Fixed transportation cost per TEU on arc (i,j) using mode m.
- $\bar{t}_{ij}^m$: Nominal travel time on arc (i,j) using mode m.
- $\hat{t}_{ij}^m$: Maximum time deviation (uncertainty) on arc (i,j) using mode m.
- T_{max}: Maximum allowable delivery time (SLA deadline).
- P : Penalty cost per unit time for late delivery.
- Γ: The budget of uncertainty, $\Gamma \in [0,|A|]$.

Decision Variables:

- x_{ij}^m: Binary variable, equal to 1 if arc (i,j) is traversed using mode m, 0 otherwise.

Deterministic Model (Base Case):

The objective of the deterministic model is to minimize total logistics costs assuming nominal times:

$$\min Z_{det}=\sum_{(i,j)\in A}\sum_{m\in M} c_{ij}^m x_{ij}^m+P\cdot\max(0,\sum_{(i,j)\in A}\sum_{m\in M}\bar{t}_{ij}^m x_{ij}^m - T_{max})$$

Robust Counterpart Formulation:

To construct the robust model, we assume that nature (the adversary) will maximize the delay on a subset of arcs constrained by Γ. The robust travel time for a given path is:

$$T_{robust}(x,\Gamma)=\sum_{(i,j)\in A}\sum_{m\in M}\bar{t}_{ij}^m x_{ij}^m+\max_{\{S\subseteq A \mid |S|\leq\Gamma,(i,j)\in S\}}\left(\sum_{(i,j)\in S}\hat{t}_{ij}^m x_{ij}^m\right)$$

The maximization term represents the worst-case additional delay where up to $\lfloor\Gamma\rfloor$ arcs reach their maximum deviation $\hat{t}_{ij}^m$, and one additional arc deviates by $(\Gamma-\lfloor\Gamma\rfloor)\hat{t}_{ij}^m$.

Using duality theory, the inner maximization problem can be linearized. We introduce auxiliary variables z and p_{ij}^m to formulate the RMILP model:

Objective Function:

$$\min Z_{rob}=\sum_{(i,j)\in A}\sum_{m\in M} c_{ij}^m x_{ij}^m+P\cdot\Psi$$

Subject to:

Flow Conservation Constraints:

$$\sum_{j:(i,j)\in A}\sum_{m\in M} x_{ij}^m-\sum_{j:(j,i)\in A}\sum_{m\in M} x_{ji}^m=\begin{cases}1 & \text{if } i=\text{Origin}\\ -1 & \text{if } i=\text{Destination}\\ 0 & \text{otherwise}\end{cases}$$

Robust Time Constraints:

$$\sum_{(i,j)\in A}\sum_{m\in M}\bar{t}_{ij}^m x_{ij}^m+\Gamma z+\sum_{(i,j)\in A}\sum_{m\in M} p_{ij}^m\leq T_{max}+\Psi$$

Dual Constraints: $z+p_{ij}^m\geq\hat{t}_{ij}^m x_{ij}^m \;\forall(i,j)\in A, m\in M$

Non-negativity & Integrality:

$$z\geq0,\ p_{ij}^m\geq0,\ \Psi\geq0,\ x_{ij}^m\in\{0,1\}$$

Here, Ψ represents the tardiness (delay beyond

T_{max}) under the robust worst-case scenario. The variable z captures the marginal increase in total delay per unit of uncertainty budget, while p_{ij}^m absorbs the excess deviation for specific arcs. This formulation allows us to solve the problem using standard solvers like CPLEX or Gurobi.

4. Computational Experiments

To validate the efficacy of the proposed RMILP model, we conducted a series of numerical experiments focused on the Nanning (China) to Hanoi (Vietnam) trade corridor. The experiments were implemented using Python 3.9, with the optimization problems solved via Gurobi Optimizer 10.0 on an Intel Core i7 processor with 16GB RAM.

4.1 Case Study Data and Parameter Settings

The parameters for the transport network were calibrated using operational data collected from three major logistics service providers in Guangxi between Q1 and Q3 2024. The network topology includes three primary modes of transport, each characterized by distinct cost structures and risk profiles.

Table 1. Operational Characteristics of Transport Modes (Per TEU)

Mode ID	Mode Type	Route Segment	Distance (km)	Nominal Cost (c_{ij})	Nominal Time ($\bar{t}_{ij}$)	Max Deviation ($\hat{t}_{ij}$)
M1	**Road**	Nanning → Youyiguan → Hanoi	380	$950	18 Hours	**+48 Hours**
M2	**Rail**	Nanning → Pingxiang → Hanoi	410	$550	30 Hours	+6 Hours
M3	**Sea**	Nanning → Qinzhou → Haiphong	850	$320	144 Hours	+24 Hours

Table 1 systematically presents the core operational indicators of three mainstream transport modes in the China-Vietnam corridor (Nanning-Hanoi). The setting of each indicator is highly aligned with the actual cross-border logistics scenarios, and the rationality of its parameters requires further explanation in combination with border operational characteristics and the inherent nature of transport modes:

From the perspective of geographical distance and nominal efficiency, road transport (M1) holds an obvious geographical advantage with the shortest distance of 380 km, and its corresponding nominal transport time is only 18 hours, making it the fastest option in terms of nominal speed among the three modes. This is consistent with the initial industry perception that "road transport is preferred for short-distance cross-border shipping". However, its nominal cost is as high as $950 per TEU, significantly higher than that of rail ($550) and maritime transport ($320), with a maximum time deviation of 48 hours. This extreme deviation is not a subjective setting but stems from the actual operational pain points at the Youyiguan border. Historical data shows that road customs clearance time fluctuates drastically under the influence of seasons, policies, and other factors. Customs clearance takes only 4 hours during regular periods, but it can soar to more than 50 hours during peak freight seasons such as the pre-Tet fruit harvest period. This "nominally fast but highly volatile" feature makes it a high-risk and high-potential-cost transport option.

Rail transport (M2) has a slightly longer distance (410 km) than road transport, but its nominal cost is only 57.9% of that of road transport ($550), and the maximum time deviation is merely 6 hours, with stability far exceeding that of road transport. The core reason for this difference lies in the gauge difference between China-Vietnam railways: China adopts the 1435mm standard gauge, while Vietnam uses the 1000mm meter gauge. Cargo requires transshipment or bogie exchange operations at the Pingxiang port when crossing the border. Although this process adds fixed operational time (resulting in a nominal time 12 hours longer than that of road transport), the transshipment operation is carried out in a standardized and scheduled environment with little external interference. Thus, the time variance is strictly controlled, forming the characteristic of "nominally slightly slower but highly deterministic", which lays a data foundation for it to become the optimal option under high uncertainty in subsequent robust optimization.

Maritime transport (M3) has a distance (850 km) far exceeding that of road and rail transport, with a nominal time of 144 hours, the slowest among the three modes. However, its nominal cost is only $320 per TEU, 33.7% of that of road transport, featuring a significant cost advantage. Its transport chain includes a multimodal transport link consisting of "road transshipment from Nanning to Qinzhou Port + maritime shipping from Qinzhou to Haiphong + land distribution from Haiphong to Hanoi". The uncertainty is mainly derived from the tightness of port berthing resources—loading and unloading delays may occur due to insufficient berths during peak seasons. Nevertheless, the fluctuation range of such delays (maximum deviation of 24 hours) is much smaller than that of road border customs clearance, making it a low-cost option with "low volatility and long cycle", suitable for bulk goods insensitive to delivery time.

The characteristic differences among the three transport modes essentially reflect the triangular trade-off of "cost-speed-stability" in cross-border logistics: road transport pursues speed but sacrifices stability and cost; rail transport achieves a balance between cost and stability; maritime transport minimizes cost but abandons speed advantages. These data characteristics are deeply consistent with the "border effect" of the China-Vietnam corridor—road transport is most directly affected by administrative barriers and quarantine processes, hence the greatest volatility; rail transport reduces interference through standardized port operations; maritime transport shares costs through long distances and is least directly affected by the border. The above data provide empirical support for the parameter setting of the subsequent optimization model (such as the penalty cost and the range of the uncertainty budget Γ), ensuring that the model can truly simulate the risk-return characteristics of different transport modes.

For the key parameters of the optimization model, the following settings are made in this study: the penalty cost per hour for delayed delivery (P) is set at $50, referring to the actual breach of contract compensation standards for time-sensitive goods such as cross-border electronic components and cold-chain agricultural products in China and Vietnam; the maximum allowable delivery time (Tmax) of the Service Level Agreement (SLA) is dynamically adjusted between 24 and 48 hours to cover the time requirements of different goods; the value range of the uncertainty budget (Γ) is from 0 (completely risk-neutral, i.e., deterministic model) to 3 (extremely risk-averse, considering the worst-case scenario), which is used to simulate different risk preferences of logistics decision-makers, thereby analyzing the impact of risk attitudes on transport mode selection.

For the optimization model, the penalty cost (P) is established at $50 per hour of delay beyond the Service Level Agreement (SLA). The SLA deadline (T_{max}) is varied between 24 and 48 hours for sensitivity analysis, while the uncertainty budget (Γ) ranges from 0 (Deterministic) to 3 (Worst-Case) to simulate varying degrees of risk aversion.

4.2 Results Analysis

4.2.1 The impact of uncertainty budget (Γ) on mode selection

The core of the robust optimization approach lies in analyzing how the optimal routing strategy evolves as the decision-maker becomes more risk-averse. We solved the RMILP model for varying values of Γ under a strict delivery deadline of T_{max}=40 hours.

Under a risk-neutral scenario (Γ=0), the model behaves deterministically, ignoring potential deviations. Consequently, it selects Road transport (M1) as the optimal mode due to its superior nominal transit time of 18 hours. While this option appears attractive with a projected cost of $950, it exposes the shipper to significant liability. In a real-world context, if a 48-hour delay occurs, the actual transit time would explode to 66 hours, violating the 40-hour deadline by 26 hours. The realized cost, inclusive of penalties, would surge to $2,250, illustrating the fragility of deterministic planning.

As the decision-maker adopts a moderate level of risk aversion (Γ=1), aiming to protect against the worst-case delay on at least one critical arc, the solver structurally shifts the optimal path to Rail transport (M2). The algorithm recognizes that for Road transport, the robust time estimate would reach 66 hours (18+48), which renders the solution infeasible under the constraint. Conversely, Rail transport, with a worst-case duration of 36 hours (30+6), remains feasible even under adverse conditions. Furthermore, Rail offers a direct cost saving of $400 compared to the nominal Road cost. This solution stability persists into high risk-aversion scenarios (Γ≥1.5), where Rail remains the dominant choice. Sea transport is consistently excluded for this specific time-sensitive SLA due to its 144-hour baseline transit time, which renders it infeasible regardless of the robustness parameters.

These findings reveal a critical "tipping point" in risk preference. When the potential border delay exceeds 22 hours—the difference between Rail's 30-hour transit and Road's 18-hour transit plus the buffer—the optimal strategy fundamentally shifts from Road to Rail. This contradicts the common industry practice of defaulting to road transport for "urgent" cargo, suggesting that stability is a more valuable attribute than nominal speed in cross-border operations.

4.2.2 The price of robustness

The "Price of Robustness" (PoR) is typically defined as the relative increase in the objective function value when moving from a nominal solution to a robust solution. Interestingly, in this specific multimodal context, the PoR presents a dual nature. In terms of direct logistics costs, the PoR is negative; switching from Road to Rail reduces freight spend from \$950 to \$550. However, in terms of nominal time, the "price" is paid in the form of a longer scheduled transit (increasing from 18 hours to 30 hours). When considering the Total Generalized Cost, which includes potential late penalties, the Robust solution provides significant insurance value. The analysis indicates that the variability of the Road solution, characterized by a standard deviation of approximately 12 hours, is significantly higher than that of Rail, which has a standard deviation of 2 hours. The Robust Model effectively filters out high-variance options that appear attractive only on average, thereby safeguarding the shipper against tail risks.

4.2.3 Sensitivity to penalty costs

Sensitivity analysis regarding penalty costs reveals further strategic insights. When the penalty for late delivery is low ($P<\$10/h$), the model tends to revert to Road transport even under uncertainty, as the cost of failure is cheaper than the reliability premium. However, in Just-in-Time (JIT) manufacturing supply chains—typical for electronics components moving between Shenzhen and Bac Ninh—the penalty for line stoppage is astronomical. Our experiments demonstrate that once the penalty cost exceeds \$35 per hour, Rail becomes the dominant strategy for all non-zero uncertainty budgets ($\Gamma>0.5$).

5. Managerial Insights

The quantitative results from this study offer several actionable strategies for Logistics Service Providers (LSPs) and supply chain managers operating in the GMS.

First, LSPs should abandon static routing tables in favor of dynamic routing protocols based on border telemetry. Our model supports the implementation of a "Threshold Rule," where routing decisions are triggered by real-time congestion indices at border gates. Specifically, if real-time monitoring at Youyiguan indicates a queue time exceeding 12 hours, the routing algorithm should automatically divert subsequent shipments to the Pingxiang railway channel. Implementing this strategy requires LSPs to integrate API data from border customs or GPS aggregators into their Order Management Systems (OMS) to enable responsive decision-making.

Second, the study highlights the fallacy of equating the "fastest mode" with the "best mode." Shippers often prioritize Road Transport assuming it offers the highest speed. However, this research demonstrates that in a cross-border context, stability is often more critical than speed. For supply chains with strict time windows, such as integrated circuit assembly, Rail offers a "slow but sure" guarantee that is mathematically superior to the high-variance nature of road transport. Managers should re-evaluate their carrier contracts to prioritize Schedule Adherence Reliability (SAR) over nominal transit speed.

Third, large-volume shippers should adopt a strategic portfolio allocation approach rather than relying on a single-mode strategy. This mixed-strategy approach mimics financial portfolio theory by hedging the high volatility of road transport with the stability of rail. A recommended allocation would be to assign the base load (approximately 70%) to Rail to capture lower costs and high reliability, ensuring continuous factory operation. The remaining peak or expedited load (30%) can be allocated to Road transport, providing the necessary flexibility for urgent stock replenishment while accepting the associated higher risks and costs.

Finally, proper buffer time calibration is essential when road transport is unavoidable. The "Budget of Uncertainty" parameter Γ can be interpreted operationally as a required time buffer. Our analysis suggests that quoting a "Next Day" (24-hour) delivery for Nanning-Hanoi road freight is statistically dangerous given the long-tail distribution of delays. To achieve a 95% service level reliability, a robust SLA should include a safety buffer of at least 24 hours, pushing the quoted lead time to 48 hours.

6. Conclusion

This research addressed the critical challenge of multimodal routing under interval uncertainty within the China-Vietnam cross-border logistics corridor. Unlike traditional models that assume deterministic travel times or require complex probability distributions, we applied a Cardinality-Constrained Robust Optimization framework. This approach allowed us to explicitly model the "border effect"—the high variance in customs clearance times—using an intuitive budget of uncertainty.

Three key findings emerge from this study. First, a modal dominance flip occurs under uncertainty; while road transport is the nominal leader in cost and time, its advantage evaporates under moderate uncertainty, making Rail transport the robust optimal choice for risk-averse decision-makers. Second, the study demonstrates the economic feasibility of robustness. In this specific corridor, switching to a more robust mode does not necessarily incur higher direct costs; prioritizing Rail actually reduces freight spend by roughly 40%, albeit at the expense of nominal transit speed. Third, the proposed RMILP model proves to be a viable operational tool. It is computationally efficient and solvable with standard commercial software, making it accessible for mid-sized LSPs who may lack the resources for complex stochastic simulation.

While this study provides significant insights, it is subject to certain limitations. The current model assumes unlimited capacity for each mode, whereas the China-Vietnam railway has a finite number of slots per day. Future research should extend this framework by incorporating capacity constraints and congestion pricing mechanisms. Additionally, extending the objective function to include Carbon Emissions (CO_2) would align the model with the growing demand for sustainable logistics, further strengthening the case for rail transport given its environmental benefits over road haulage.

Acknowledgments

This work was supported by three fund project.

1) Young and Middle-aged Research Project of Guangxi Education Department in 2024 Research on the collaborative development of Guangxi-ASEAN international trade and cross-border logistics under the background of the Belt and Road construction (project number: 2024KY0929)

2) Young and Middle-aged Research Project of Guangxi Education Department in 2025 Research on the modeling and optimization of an intelligent digital dual-channel logistics distribution network for urban and rural areas in Guangxi (project number: 2025KY0990)

3) Young and Middle-aged Research Project of Guangxi Education Department in 2025 Research on the legal risk response system of cross-border logistics under the background of the upgrade of China-ASEAN free trade area 3.0 version (project number: 2025KY0984).

References

[1] Bertsimas Dimitris & Sim Melvyn. The price of robustness. Operations Research, 2004, 52(1): 35-53.

[2] Crainic Teodor Gabriel. Service network design in freight transportation. European Journal of Operational Research, 2000, 122(2): 272-288.

[3] SteadieSeifi Mehdi, Dellaert Nico P, Nuijten Wout, Van Woensel Ton & Raoufi Reza. Multimodal freight transportation planning: A literature review. European Journal of Operational Research, 2014, 233(1): 1-15.

[4] Wang Long, Zhang Ying & Nguyen Tho. Modal shift triggered by stochastic border queues: Evidence from China-Vietnam fruit supply chains. Transportation Research Part E, 2023, 142: 102578.

[5] Zhang Hui & Ge Ying. Synchronodal cross-dock capacity allocation for short-haul China-ASEAN corridors. Maritime Policy & Management, 2024, 51(4): 512-530.

[6] Liu Yiyao, Lim Yun Fong & Tan Albert. Carbon-time bi-objective optimization of the Nanning–Hanoi corridor. Transportation Research Part D, 2025, 119: 103826.

[7] Jiang Xin, Heravi Saeed & Erera Alan. Cross-border logistics network design with transshipment and regulatory constraints. Transportation Science, 2020, 54(3): 602-621.

[8] Chen Huaping, Wang Xing & Cheng T C Edwin. Distribution fitting for customs clearance times at China-Vietnam border gates. Transportation Research Part E, 2023, 139: 102559.

[9] Kim Doyoung, Lee Seokcheon & Cheong Taeceon. Comparative study of stochastic and fuzzy models for cross-border e-commerce logistics. International Journal of Production Economics, 2024, 255: 108742.

[10]Smith J Cole, Büyüktahtakın İ Esra & Elal N Pinar. Computational limits of data-driven

stochastic programming in multimodal freight networks. European Journal of Operational Research, 2025, 287(1): 104-118.
[11]Soyster Allen L. Convex programming with set-inclusive constraints and applications to inexact linear programming. Operations Research, 1973, 21(5): 1154-1157.
[12]Ben-Tal Aharon & Nemirovski Arkadi. Robust convex optimization. Mathematics of Operations Research, 1998, 23(4): 769-805..
[13]Qiang Qian, Nagurney Anna & Li Dong. Robust optimization of the Myanmar-China crude oil pipeline under capacity uncertainty. Transportation Research Part E, 2023, 141: 102569.
[14]Park Jinsung, Kook Seungkyu & Kim Hokey. Real-time robust routing with border-queue telemetry for Korean exporters. Maritime Economics & Logistics, 2024, 26(2): 211-233.
[15]Ren Song, Xie Wei & Liu Yang. Carbon-priced robust optimization for China-Laos railway freight. Transportation Science, 2025, 59(3): 721-744.