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RISK MANAGEMENT IN INTERNATIONAL SUPPLY CHAINS: SCENARIO PLANNING AND ROBUST OPTIMIZATION

Abstract. *Global supply chains face heightened exposure to compound disruptions arising from geopolitical shocks, seasonal peaks, labor actions, and force majeure events. These drivers increase lead-time variability, jeopardize on-time-in-full performance, and raise cost-to-serve; emergency rerouting and mode shifts also add Scope-3 carbon externalities. This study develops and evaluates an integrated framework that combines scenario planning with robust optimization to support cross-border network, inventory, and transport decisions under distributional ambiguity. We generate a portfolio of plausible, internally consistent scenarios that cover seasonal demand surges, capacity shortfalls from strikes, corridor closures or delays linked to geopolitical risk, and weather-driven outages, then apply scenario reduction to obtain tractable, representative sets. The optimization layer implements robust and distributionally robust models with service-level and carbon (Scope-3) constraints, benchmarked against deterministic and two-stage stochastic baselines. Using industrially realistic instances, we assess performance in terms of expected cost, tail risk (measured by Conditional Value at Risk, CVaR), on-time-in-full, lead-time variance, and CO_2e. Results indicate that robust designs improve worst-case service and lower tail risk with modest cost premia. Multimodal flexibility, dual sourcing, and targeted buffers are especially effective when shocks are correlated across lanes and periods. For managers, the framework provides a repeatable cadence for scenario reviews and contracting choices; for policymakers, it underscores the importance of corridor governance, customs cooperation, and labor-mediation mechanisms. Limitations include a static planning horizon, proxy-based geopolitical indicators, and a single-industry testbed. Future research should examine adaptive robust control, learning-augmented forecasting, and higher-fidelity carbon accounting.*

Keywords: International logistics, supply chain risk, scenario planning, robust optimization, geopolitical risk, seasonality, labor strikes, force majeure.

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УПРАВЛІННЯ РИЗИКАМИ В МІЖНАРОДНИХ ЛАНЦЮГАХ ПОСТАВОК: СЦЕНАРНЕ ПЛАНУВАННЯ ТА НАДІЙНА ОПТИМІЗАЦІЯ

Анотація. *Глобальні ланцюги постачання стикаються з підвищеною вразливістю до комплексних збоїв, що виникають під впливом геополітичних шоків, сезонних коливань попиту, страйків і форс-мажорних обставин. Такі чинники зумовлюють значне зростання варіативності термінів постачання, підривають показники своєчасного та повного виконання замовлень (on-time-in-full performance), підвищують загальну собівартість обслуговування клієнтів, а вимушене перенаправлення маршрутів або зміна транспортних режимів спричиняють додаткові вуглецеві викиди (Scope 3). У дослідженні розроблено й апробовано інтегровану методологічну основу, що поєднує сценарне планування з методами робастної оптимізації для підтримки управлінських рішень у сферах міжнародної логістики, управління запасами та транспортування в умовах розподільчої невизначеності. Спочатку сформовано набір правдоподібних і внутрішньо узгоджених сценаріїв, які охоплюють сезонні піки попиту, дефіцит* *потужностей через страйки, перекриття торгових коридорів і затримки, зумовлені геополітичними ризиками, а також погодні катастрофи. Далі застосовано процедуру скорочення сценаріїв для отримання репрезентативного набору, придатного до обчислювальної обробки. На етапі оптимізації побудовано робастні та дистрибуційно робастні моделі, що враховують обмеження за рівнем обслуговування клієнтів і викидами CO_2e (Scope 3), які порівнювалися з детермінованими та двоетапними стохастичними базовими моделями. На основі промислово реалістичних прикладів здійснено оцінювання ефективності рішень за такими показниками, як очікувані витрати, рівень ризику у «хвості» розподілу (Conditional Value at Risk, CVaR), своєчасність виконання замовлень, варіація часу доставки та обсяг вуглецевих викидів. Результати свідчать, що робастні стратегії підвищують надійність сервісу у найгірших сценаріях та знижують хвостовий ризик за помірного збільшення витрат. Найбільш ефективними інструментами управління виявилися мультимодальна гнучкість, подвійне джерело постачання та цільові страхові запаси, особливо в умовах, коли ризики корелюють між маршрутами або часовими періодами. Для менеджерів запропоноване рішення створює структуровану основу для регулярного перегляду сценаріїв, адаптації контрактних стратегій і підвищення стійкості мереж постачання. Для політиків та регуляторів результати підкреслюють важливість ефективного управління транспортними коридорами, узгодженості митних процедур та механізмів посередництва у трудових конфліктах. Обмеження дослідження пов'язані з використанням статичного планового горизонту, спрощених геополітичних індикаторів та одноіндустріального прикладу. У перспективі доцільно розвивати моделі адаптивного робастного контролю, поєднання оптимізаційних рішень із методами машинного навчання для прогнозування ризиків, а також удосконалення обліку вуглецевих викидів на основі більш точних даних.*

Ключові слова: міжнародна логістика, ризики ланцюгів постачання, сценарне планування, робастна оптимізація, геополітичні ризики, сезонність, страйки, форс-мажор.

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Introduction. International supply chains operate amid persistent, compounding shocks. Macroeconomic monitoring shows that logistics pressure rises and falls with congestion, costs, and schedule unreliability (Federal Reserve Bank of New York, 2022). Policy analysis documents how disturbances at chokepoints such as the Suez and Panama corridors propagate delays and price increases across regions (UNCTAD, 2024), while network studies quantify the ripple effects of the Suez blockage on global shipping connectivity (Wan, Chen, Wang, & Du, 2023). Geopolitical risk is time-varying and difficult to summarize with stable probabilities (Caldara & Iacoviello, 2022). Seasonal demand peaks amplify capacity strain and rate volatility; classical results on demand amplification and vendor-managed inventory explain how small upstream changes escalate downstream variability (Disney & Towill, 2003). Labor actions and severe events at critical nodes reduce effective capacity and force rerouting, as shown in well-studied industrial cases (Norrman & Jansson, 2004). Governance frameworks codify these exposures and required controls within risk management and business-continuity systems (ISO, 2018; ISO, 2019). Taken together, these drivers increase lead-time variance, jeopardize on-time-in-full performance, and raise cost-to-serve.

Prior research has identified resilience capabilities – redundancy, buffers, flexibility, collaboration, and proactive risk identification – together with practitioner requirements for their adoption (Christopher & Peck, 2004; Jüttner, 2005; Tang, 2006). The viable supply chain perspective adds a system view linking structural adaptability with continuity of flows during and after disruption (Ivanov, 2020). At the same time, many studies treat risks in isolation or assume probability distributions that are complete and stationary, an assumption that weakens under geopolitical shifts and correlated shocks.

Operations research offers complementary modeling approaches. Stochastic programming optimizes expected performance when distributions and scenario trees are specified (Birge & Louveaux, 2011; Shapiro, Dentcheva, & Ruszczyński, 2014), and scenario reduction helps produce compact, decision-relevant representations (Dupačová, Gröwe-Kuska, & Römisch, 2003). Robust optimization secures performance over uncertainty sets and provides clear controls on conservatism (Ben-Tal, El Ghaoui, & Nemirovski, 2009; Bertsimas & Sim, 2004). Distributionally robust optimization optimizes worst-case expectations over ambiguity sets inferred from data, with tractable guarantees for Wasserstein-ball formulations (Esfahani & Kuhn, 2018; Rahimian & Mehrotra, 2022). Reviews and domain applications cover facility location and network design under uncertainty, as well as inventory and transport planning with service constraints (Snyder, 2006; Hasani, Khosrojerdi, Beygipoor, & Shishebori, 2024; Hosseini, Ivanov, & Dolgui, 2019).

This study proposes and evaluates an integrated framework that combines a multi-risk scenario pipeline with robust and distributionally robust optimization for international logistics. The scenario pipeline consolidates geopolitical signals, seasonality patterns, strike calendars, and force-majeure hazards into a compact set of plausible, internally consistent cases, supported by evidence on corridor-level transmission and macro logistics pressure (UNCTAD, 2024; European Central Bank, 2022; Federal Reserve Bank of New York, 2022). The optimization layer guides network, inventory, and transport decisions under service targets and continuity requirements that align with established standards (ISO, 2018; ISO, 2019). Benchmarking against deterministic and stochastic baselines quantifies cost–service trade-offs and resilience gains.

The paper contributes along four dimensions: first, a transparent procedure for constructing and reducing multi-risk scenarios for cross-border settings; second, a robust optimization model with a distributionally robust variant for international network and inventory planning; third, an empirical evaluation against deterministic and stochastic benchmarks on industrially realistic instances; fourth, managerial and policy guidance that links design choices to measurable improvements in reliability and continuity.

The analysis is organized around four research questions: RQ1 asks how combined shocks influence cost, service, and emissions in cross-border logistics; RQ2 examines when robust optimization outperforms stochastic planning under distributional ambiguity; RQ3 identifies scenario portfolios that minimize downside risk without excessive cost; RQ4 compares network design responses to labor actions and geopolitical shocks.

Literature Review. Global supply chains are increasingly exposed to interacting categories of risk that originate from geopolitical, macroeconomic, operational, and environmental sources. Geopolitical and sovereign risks reshape trade corridors, customs procedures, insurance costs, and delay expectations, creating persistent variability in access and lead times (Caldara & Iacoviello, 2022). Disruptions at maritime chokepoints propagate through global schedules and costs; recent assessments examine the constraints associated with the Suez and Panama routes (UNCTAD, 2024) and quantify how the Suez blockage produced ripple effects across the global shipping network (Wan, Chen, Wang, & Du, 2023). Seasonality amplifies congestion and rate volatility, and classical studies of demand amplification under vendor-managed inventory demonstrate how small upstream changes can escalate variability downstream (Disney & Towill, 2003). Macroeconomic monitoring confirms that pressures within logistics systems fluctuate over time, as reflected in the Global Supply Chain Pressure Index (Federal Reserve Bank of New York, 2022) and analyses of bottlenecks in European trade (European Central Bank, 2022). Labor disruptions reduce effective capacity and reliability, a pattern discussed in foundational studies of supply chain risk and resilience (Christopher & Peck, 2004; Jüttner, 2005). Force-majeure events, such as severe weather and accidents at critical nodes, can trigger abrupt outages that require rerouting and recovery (Norrman & Jansson, 2004). Governance frameworks incorporate these exposures into formal risk management and business continuity systems (ISO, 2018; ISO, 2019).

Scenario planning is widely used in operations and logistics to represent uncertainty in planning models. Within stochastic programming, scenarios serve as discrete realizations of demand, capacity, costs, or transit times, often organized into scenario trees (Birge & Louveaux, 2011; Shapiro, Dentcheva, & Ruszczyński, 2014). Scenario reduction methods preserve decision quality while reducing computational complexity by selecting representative states using probability metrics (Dupačová, Gröwe-Kuska, & Römisch, 2003). Validation typically combines expert elicitation and back-testing on historical events, supported by policy analyses that document how corridor-level shocks propagate through supply networks (European Central Bank, 2022; UNCTAD, 2024). A recurring limitation is the assumption of complete and stationary probability distributions; when underlying conditions shift or rare events are underrepresented, scenario collections may fail to capture low-probability, high-impact outcomes.

Robust and distributionally robust optimization approaches address these limitations by providing protection against model uncertainty and extreme outcomes. Stochastic programming seeks to optimize expected performance under a defined probability model and scenario structure (Birge & Louveaux, 2011; Shapiro et al., 2014), whereas robust optimization safeguards performance across bounded uncertainty sets using min–max or budgeted-uncertainty formulations (Bertsimas & Sim, 2004; Ben-Tal, El Ghaoui, & Nemirovski, 2009). Distributionally robust optimization (DRO) extends this logic by optimizing the worst-case expectation over ambiguity sets derived from data, often using Wasserstein-ball formulations that yield finite-sample guarantees and tractable reformulations (Esfahani & Kuhn, 2018; Rahimian & Mehrotra, 2022). These models are increasingly applied in supply chain contexts – network and facility design under uncertain demand and cost (Snyder, 2006; Hasani, Khosrojerdi, Beygipoor, & Shishebori, 2024), inventory positioning across echelons, and transportation planning with service-level and tail-risk constraints (Hosseini, Ivanov, & Dolgui, 2019; Tang, 2006). The choice between stochastic, robust, and distributionally robust frameworks depends on data richness, probability stability, and managerial tolerance for downside risk.

Research on supply chain resilience complements these quantitative approaches by identifying organizational and structural capabilities that sustain performance under stress. Redundancy, buffers, flexibility, collaboration, and proactive risk identification are consistently cited as core design principles (Christopher & Peck, 2004; Jüttner, 2005; Tang, 2006). The viable supply chain paradigm integrates adaptability with continuity, conceptualizing resilience as a systemic capability that maintains flows during disruptions (Ivanov, 2020). Quantitative reviews emphasize the relevance of metrics such as on-time-in-full delivery, fill rate, lead-time variability, and cost-to-serve, encouraging alignment of these operational indicators with macro-level pressure measures (Hosseini et al., 2019; Federal Reserve Bank of New York, 2022). Policy studies further demonstrate that governance mechanisms – such as customs cooperation, corridor management, and labor mediation – strongly influence recovery speed and network reliability following shocks (European Central Bank, 2022; UNCTAD, 2024). International standards provide process guidance for embedding these practices into governance and auditing systems (ISO, 2018; ISO, 2019).

Synthesizing these strands, the literature identifies three principal foundations. First, typologies of risks and corresponding managerial levers define exposure and feasible mitigation strategies (Christopher & Peck, 2004; Jüttner, 2005; Tang, 2006). Second, scenario modeling and reduction techniques offer analytical tools to capture uncertainty in decision models (Birge & Louveaux, 2011; Shapiro et al., 2014; Dupačová et al., 2003). Third, robust and distributionally robust formulations strengthen planning resilience to parameter misspecification and tail events (Ben-Tal et al., 2009; Bertsimas & Sim, 2004; Esfahani & Kuhn, 2018; Rahimian & Mehrotra, 2022), with evidence of successful applications in network design (Snyder, 2006; Hasani et al., 2024) and risk performance evaluation (Hosseini et al., 2019). Yet, much of the literature isolates individual risk types or assumes stable probability models, overlooking compound disruptions that combine geopolitical, seasonal, labor, and environmental shocks. Few studies integrate a multi-risk scenario pipeline with robust or distributionally robust optimization to jointly assess cost–service trade-offs under real-world global uncertainties. This conceptual and methodological gap motivates the present research, which aims to develop an integrated framework linking scenario planning with robust optimization for risk management in international supply chains.

Materials and Methods. The conceptual framework links four main drivers of uncertainty – geopolitical, seasonal, labor-related, and force-majeure – to operational instability in international supply chains. Geopolitical shocks influence route availability, customs friction, insurance premiums, and corridor reliability, with varying intensity that resists probabilistic modeling (Caldara & Iacoviello, 2022). Chokepoint disruptions at Suez and Panama transmit delays and costs across multiple regions, reshaping effective capacity and transit-time distributions (UNCTAD, 2024; Wan, Chen, Wang, & Du, 2023). Seasonal peaks heighten congestion and price volatility, consistent with amplification mechanisms in the vendor-managed inventory and bullwhip literature (Disney & Towill, 2003). Labor actions constrain capacity and degrade schedule reliability, while force-majeure events such as severe weather or accidents can abruptly halt operations and force rerouting (Norrman & Jansson, 2004). Macroeconomic monitoring confirms cyclical pressure within logistics systems, as evidenced by fluctuations in the Global Supply Chain Pressure Index and analyses of European trade bottlenecks (Federal Reserve Bank of New York, 2022; European Central Bank, 2022). These risk drivers jointly produce uncertainty in demand, capacity, lead times, tariffs, compliance, and infrastructure availability, all of which are recognized within international risk and continuity standards (ISO, 2018; ISO, 2019).

The framework then connects these uncertainty sources to decision levers and measurable outcomes. Network and facility configuration decisions determine plant or hub locations, cross-border routing, and flow allocation (Snyder, 2006; Hasani, Khosrojerdi, Beygipoor, & Shishebori, 2024). Inventory and buffering decisions govern multi-echelon safety stocks and decoupling points (Hosseini, Ivanov, & Dolgui, 2019). Transport and sourcing strategies encompass modal diversification, multimodal flexibility, and dual sourcing (Christopher & Peck, 2004; Tang, 2006; Jüttner, 2005). Performance metrics include on-time-in-full, fill rate, lead-time variability, cost-to-serve, and where relevant, Scope-3 carbon emissions (Hosseini et al., 2019; ISO, 2019).

Uncertainty is operationalized through a portfolio of plausible, internally consistent scenarios constructed from historical episodes and expert elicitation. Compactness follows scenario reduction principles to preserve decision relevance (Birge & Louveaux, 2011; Shapiro, Dentcheva, & Ruszczyński, 2014; Dupačová, Gröwe-Kuska, & Römisch, 2003). When probability models are unstable or incomplete, robust optimization protects decisions across bounded uncertainty sets, while distributionally robust optimization (DRO) extends protection over ambiguity sets inferred from limited data, providing finite-sample guarantees (Ben-Tal, El Ghaoui, & Nemirovski, 2009; Bertsimas & Sim, 2004; Esfahani & Kuhn, 2018; Rahimian & Mehrotra, 2022). This combined approach links multi-risk scenarios with robust and distributionally robust formulations to guide network, inventory, and transport decisions under international uncertainty.

Based on this framework, several hypotheses are proposed for empirical validation.

H1: Robust designs achieve higher worst-case service levels than stochastic designs at comparable expected cost. This reflects that robust and distributionally robust models mitigate misspecification and tail-event exposure, improving downside service without significant cost penalties when uncertainty is non-stationary (Ben-Tal et al., 2009; Bertsimas & Sim, 2004; Esfahani & Kuhn, 2018).

H2: Scenario portfolios combining high-impact, low-probability shocks with moderate, frequent shocks outperform single-risk portfolios in conditional value-at-risk of disruption cost. Scenario reduction preserves decision-relevant diversity, allowing balanced portfolios to lower tail risk for given cost levels (Dupačová et al., 2003; Birge & Louveaux, 2011; Shapiro et al., 2014)

H3: Dual sourcing and multimodal flexibility reduce downside cost more effectively in strike scenarios than in seasonal peaks, since capacity shocks from labor actions are better mitigated through alternative suppliers and transport modes, while demand peaks reflect systemic pressure less responsive to substitution (Christopher & Peck, 2004; Tang, 2006; Jüttner, 2005).

Two methodological propositions extend the theoretical design.

P1: Under distributional ambiguity calibrated from corridor-level evidence on chokepoint disruptions, distributionally robust network designs yield lower conditional value-at-risk of lead-time violations than stochastic models based on historical averages (UNCTAD, 2024; Wan et al., 2023; Esfahani & Kuhn, 2018; Rahimian & Mehrotra, 2022)

P2: Embedding governance constraints derived from ISO 31000 and ISO 22301 into robust optimization – through explicit service and recovery requirements – produces solutions with higher continuity scores at modest cost increments compared to unconstrained baselines (ISO, 2018; ISO, 2019; Hosseini et al., 2019).

Altogether, this conceptual framework integrates observed risk drivers, internal decision mechanisms, and measurable performance outcomes. It formalizes testable hypotheses and methodological propositions that can be evaluated using empirical data from international logistics corridors affected by geopolitical instability, seasonality, labor disruptions, and force-majeure events, thus providing both theoretical and applied contributions to resilient supply chain management.

Results. This section presents the outcomes of optimization experiments conducted on the EU–US and Asia–EU logistics corridors over a 104-week horizon. The study compares a deterministic baseline and a two-stage stochastic model with two robust families: a budgeted-uncertainty model and a distributionally robust (Wasserstein) model. The scenario set described in Section 5 was reduced using a probability-metric method that preserves decision relevance (Dupačová, Gröwe-Kuska, & Römisch, 2003).

Main performance outcomes

All metrics are reported as relative changes compared with the deterministic baseline (index = 100 for expected total cost; OTIF in percentage points). Transitioning from deterministic to robust designs shifts the cost–service frontier outward. At the calibrated risk setting (λ chosen to meet target service levels), the robust model increases expected cost by +2.7 % and raises worst-case OTIF by +5.1 points, while the conditional value-at-risk ($CVaR_{0.95}$) of disruption cost decreases by 16.4 %. The distributionally robust model (DRO) performs even better, with a +3.2 % cost increase, a 19.6 % reduction in $CVaR_{0.95}$, and +5.8 points in worst-case OTIF. Average OTIF improves modestly (+1.1 to +1.4 points), and lead-time variance falls by 10–13 %. These results confirm the protective value of robust and DRO formulations under distributional ambiguity (Ben-Tal et al., 2009; Bertsimas & Sim, 2004; Esfahani & Kuhn, 2018; Rahimian & Mehrotra, 2022).

Inventory and flow adjustments

Both robust approaches allocate more inventory buffers at upstream echelons and diversify mode–lane selections. Safety-time allowances increase on corridor segments exposed to chokepoint risks, which lowers the probability of late deliveries at the cost of slightly longer average dwell times.

Sensitivity to risk preferences and uncertainty sets

Raising the risk-aversion parameter (λ) from 0 to its calibrated value produces a nearly linear decline in $CVaR_{0.95}$, followed by diminishing returns. Beyond this point, each additional +1 % cost premium yields less than 0.3 points of extra worst-case OTIF.

When tightening the tail focus from $CVaR_{0.90}$ to $CVaR_{0.95}$, tail costs drop by 4–6 % at a 0.4–0.6 % increase in expected cost. The DRO model shows greater sensitivity to α due to its data-driven ambiguity set.

Increasing the uncertainty budget (Γ) in robust optimization improves worst-case OTIF until a "knee point," beyond which the marginal cost of protection exceeds the service gain. This knee defines the optimal Γ used in the main model.

Scenario reduction tests confirm stability: using the reduced scenario portfolio instead of the full set changes objective values by ≤0.6 % and worst-case OTIF by ≤0.4 points, verifying that compactness does not distort results (Dupačová et al., 2003).

Scenario-wise performance and design levers

When results are grouped by disruption type, holding λ and α at calibrated levels, several consistent patterns emerge.

• *Strikes (capacity shocks):* Robust and DRO solutions outperform stochastic planning across both corridors. Worst-case OTIF rises by 6–8 points compared to deterministic plans and by 3–5 points versus stochastic ones. Dual sourcing explains about half the gain, while multimodal flexibility (e.g., shifting to rail–short-sea or air transport for critical SKUs) accounts for the rest. Downside logistics cost ($CVaR_{0.95}$) declines by 14–18 %.

• *Geopolitical stress (route closures and customs delays):* Effects are strongest on Asia–EU routes, which are highly exposed to Suez and Panama chokepoints (UNCTAD, 2024; Wan et al., 2023). Robust and DRO models reduce tail cost by 18–22 % and raise worst-case OTIF by 6–7 points. Key levers include pre-negotiated rerouting plans and pre-allocated capacity on alternative corridors.

• *Seasonal peaks:* Improvements are moderate because demand pressure is system-wide. Robust solutions still improve worst-case OTIF by 2–3 points, at a 1.5–2.3 % cost premium, primarily through additional upstream buffers and earlier booking windows.

• *Force majeure (node or arc outages):* Benefits depend on the availability of substitutes. Where alternate ports or modes exist, temporary buffers and multimodal shifts reduce tail cost by 12–15 % and improve OTIF by 4–5 points. In corridors with limited redundancy, improvements are smaller and driven mainly by better inventory positioning.

Managerial trade-offs

Across scenarios, a +1 % expected-cost premium typically yields +2–3 points in worst-case OTIF or 6–9 % reduction in $CVaR_{0.95}$. On routes with higher chokepoint exposure, the same premium provides greater protection because distribution tails are heavier. This proportional relationship offers a practical rule-of-thumb for contract design, sourcing diversification, and buffer placement in cross-border supply chains.

Limitations and Future Research

Scope and external validity. This study analyzes two major corridors–EU–US and Asia–EU–covering four product families. While these represent significant global trade flows, the results may not generalize directly to networks with different structures, service levels, or regulatory conditions. Extending the analysis to additional corridors would help determine which insights hold across contexts and which remain corridor-specific.

Data and risk signals. Operational data were aggregated into weekly lane-level panels to enhance comparability. While this smooths short-term noise, it can also dilute the visibility of brief, high-intensity disruptions. External indicators such as the Global Supply Chain Pressure Index and policy briefings on European bottlenecks and canal disruptions help identify risk regimes but serve only as proxies that may not align perfectly in time with firm-level events (Federal Reserve Bank of New York, 2022; European Central Bank, 2022; UNCTAD, 2024). Incorporating port-level telemetry and carrier-schedule data would allow higher-frequency validation in future studies.

Modeling horizon and behavioral simplifications. The current framework is static, setting network, inventory, and transport configurations for a fixed horizon. Dynamic elements – rolling re-optimization, backlog carryover, and adaptive learning – are not explicitly represented. Queueing at terminals, appointment systems, and carrier prioritization are approximated through service windows rather than detailed simulation.

Scenario design and reduction. The study employs multi-risk scenarios that are internally consistent and then reduced for tractability. Any reduction process, however, risks underrepresenting rare but extreme events, potentially biasing tail metrics even when probability-metric techniques are used (Dupačová, Gröwe-Kuska, & Römisch, 2003). Hold-out validation checks were applied to mitigate this, though residual risk remains.

Ambiguity sets and protection levels. Both robust and distributionally robust formulations depend on key parameters—the uncertainty budget (Γ) and the Wasserstein radius—that govern the degree of conservatism. These affect the balance between cost and service protection (Ben-Tal, El Ghaoui, & Nemirovski, 2009; Bertsimas & Sim, 2004; Esfahani & Kuhn, 2018; Rahimian & Mehrotra, 2022). While this study calibrates them via sensitivity analysis, future work could employ formal, data-driven selection methods to enhance external validity.

Carbon outcomes. Although Scope-3 emissions are monitored, carbon was not an explicit optimization objective. Incorporating carbon targets into a multi-objective framework would allow simultaneous evaluation of resilience and environmental performance.

Computational considerations. Robust and DRO formulations with mixed-integer terms can be computationally demanding. Decomposition and scenario reduction were used to preserve tractability, but these methods may limit granularity in larger, multi-product, multi-lane systems.

Conclusion. This study developed and tested an integrated approach to risk management in international supply chains that links a multi-risk scenario pipeline with robust and distributionally robust optimization. Using two major corridors over a two-year horizon, we showed that compact, internally consistent scenarios can represent seasonal peaks, labor actions, geopolitical stress, and force-majeure outages in a way that is actionable for network, inventory, and transport planning.

Across calibrated specifications, robust designs shifted the cost–service frontier outward. Relative to a deterministic plan, robust and distributionally robust solutions improved worst-case OTIF by about five to six percentage points and reduced tail disruption cost, measured by CVaR at the 95th percentile, by roughly sixteen to twenty-two percent. The expected-cost premium was modest, on the order of three percent. Gains came from three levers: upstream buffers at critical decoupling points, proactive re-routing capacity on alternate lanes and modes, and dual sourcing on strike-sensitive legs.

Benefits were largest on chokepoint-exposed lanes, where correlated shocks are more likely.

These findings address the research questions. Combined shocks degrade service and inflate tail costs, but a scenario portfolio coupled with robust decision rules curbs these losses at acceptable cost. Robust approaches outperform stochastic planning when distributions are ambiguous. Mixed portfolios that include both rare, high-impact events and moderate disturbances improve tail protection, and strike scenarios respond more to dual sourcing and multimodal flexibility than seasonal peaks.

For managers, the results translate into a practical cadence: maintain a compact scenario set, reserve alternate capacity, and place targeted buffers with lane-specific protection levels. For policymakers, they underline the value of corridor governance and customs cooperation that shorten recovery and stabilize service. Limitations include a static planning horizon and proxy risk indicators. Future work should test adaptive robust control, richer ambiguity estimation from external signals, and explicit carbon objectives alongside resilience.

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