

Article

Maritime Corridor Readiness Under Chokepoint Disruption: A Distributionally Robust Decision Model for Eastern Mediterranean Supply Chains

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Highlights

Please indicate how your work links to systems science via your contributions to systems practice, theory, and/or methodology.

- Defines corridor readiness as a bounded maritime supply-chain system with shared infrastructure capacities and cross-actor interdependencies.
- Couples pre-disruption preparedness, post-disruption recourse, probability ambiguity, and tail risk in one auditable decision architecture.

What are the main findings and/or the implications of the main findings?

- The optimized readiness portfolio lowers the composite benchmark objective by USD 241.623 billion but concentrates regional preparation.
- The aggregate optimum becomes vulnerable in the Turkish Straits state; policy reweighting changes the portfolio and reverses that loss.

Abstract

Maritime chokepoint exposure can be quantified, but supply-chain risk management still requires an ex ante decision about which alternatives to keep ready. The objective is to identify and evaluate an ex ante corridor-readiness portfolio before the disruption state is known, while accounting for shared regional capacity, distributional ambiguity, and tail risk. This study models the Eastern Mediterranean as an interconnected maritime-logistics system comprising five countries, five sectors, five corridors, and six empirically calibrated disruption states. A two-stage distributionally robust decision model couples pre-disruption corridor readiness with post-disruption flow recourse under shared regional capacities, Wasserstein ambiguity, and CVaR tail-risk pricing. Relative to the inferred status quo, the optimized portfolio reduces the composite USD-equivalent objective by USD 241.623 billion, equivalent to 22.6% of the model's average annual trade-account base under the maintained normalization. This is a calibrated benchmark-distance-to-base ratio, not a realized saving. The optimized portfolio concentrates readiness and improves aggregate performance, yet it performs USD 14.465 billion worse in the Turkish Straits disruption state. Doubling and renormalizing that state's policy weight shifts the portfolio away from the Turkish Straits and reverses the state-specific loss. The contribution is a transparent decision-analytics framework that places system boundaries, infrastructure interdependencies, advance preparedness, recourse, and residual vulnerability in one auditable supply-chain risk model.



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Keywords: supply-chain risk management; maritime logistics; corridor readiness; chokepoint disruption; system interdependencies; decision analytics; distributionally robust optimization; recourse

1. Introduction

Maritime chokepoint disruption delays ships, lengthens voyages, and raises costs. The advance decision is whether an alternative corridor is operationally ready, not merely listed in a contingency plan. Maritime authorities, ports, carriers, and cargo owners must make that decision before the disruption's location and severity are known. This study asks which maritime and intermodal interfaces merit advance preparation.

Countries and sectors share canals, straits, rail chains, transshipment interfaces, and related capacity. One participant's choices affect others' options. System performance therefore depends on interacting actors, infrastructure, constraints, and the boundary within which decisions are counted [1]. This study makes that boundary explicit.

Chokepoint research establishes the scale and propagation of the exposure. Major passages operate as live constraints on maritime transport [2]; closure studies quantify route and shipping impacts [3]; network evidence identifies systemic consequences [4]; the Suez blockage demonstrates the economic cost of a realized interruption [5]; and agent-based work shows how a chokepoint shock can propagate through LNG trade [6]. UNCTAD reports that rerouting Asia–Europe shipping around the Cape of Good Hope can add roughly twelve days to a voyage, illustrating the operational cost of relying on nominal substitutes when a major maritime chokepoint is impaired [2]. These studies explain where the supply chain is vulnerable, but exposure measurement alone cannot identify which substitute interfaces should be prepared in advance.

Preparedness is distinct from recovery after a shock. Reviews of maritime disruption and port risk emphasize advance preparation, response capacity, and the connection between operational measures and resilience performance [7–9]. Evidence from container shipping during COVID-19 likewise shows that disruption and recovery cannot be understood within a single route leg [10,11]. The broader supply-chain literature treats resilience as a combination of preparation, response, and recovery options rather than a purely post-event property [12–14]. Modern resilience thinking broadens this further beyond engineering bounce-back toward persistence, adaptation, and transformation [15]. A systems-based conceptualization further links readiness, response, and recovery to the time, cost, and range of available actions [16]. Quantitative resilience approaches are organized around capacities to withstand, adapt, and recover [17]. This study's readiness variable represents advance preparedness, while recourse represents post-state adjustment. This temporal distinction motivates the separation between pre-disruption readiness and post-disruption recourse used here.

Route availability and route usability are also different. Canal and route-choice research shows that operational, timing, and cost consequences change sharply when normal passages are impaired [18]. Studies of direct shipping adaptability and the Northern Sea Route demonstrate that nominal alternatives remain bounded by network adjustment, physical capacity, and stakeholder risk [19–21]. Port and intermodal research reaches the same operational conclusion: resilience depends on critical-node exposure, recovery capacity, service quality, and workable intermodal substitutes [22–24]. Ports and corridors also operate within geopolitical and institutional constraints rather than as neutral infrastructure [25,26]. A line on a map becomes a contingency option only when access, capacity, and preparedness have been tested.

Decision analytics supplies the machinery for translating that operational problem into an ex ante portfolio choice. Trade-cost theory explains why time, distance, and uncertainty enter generalized transport costs [27,28], while open-data port-choice research shows that aggregate public information can support transparent inference when shipment-level routes are unavailable [29]. Robust optimization prices protection against parameter uncertainty [30], and distributionally robust methods permit advance decisions to be evaluated without treating estimated probability distributions as known [31,32]. Quantitative resilience modeling spans withstand, adapt, and recover capacities [17]. Two-stage robust and distributionally robust applications already separate advance commitments from recourse in disaster relief, supply-chain mitigation, maritime inventory routing, berth allocation, vessel deployment, and port-hinterland systems [33–39]. Related maritime models address fleet deployment and feeder networks [40,41]. For the problem studied here, the remaining practical decision is not another route ranking or generic reformulation, but which corridor interfaces should be operationally prepared before disruption.

Exposure maps identify vulnerability but cannot select the substitute interfaces to prepare. The decision gap is an auditable readiness choice under shared capacity, uncertainty, and residual state risk. Our objective is to identify and evaluate that choice. The research question is as follows: which corridor-readiness portfolio minimizes the risk-adjusted benchmark objective before a chokepoint disruption is known, and what state-specific vulnerabilities remain?

The system covers Türkiye, Egypt, Greece, Israel, and Lebanon; five sectors; and five strategic alternatives: Suez, the Cape detour, the Turkish Straits/Black Sea route, the Middle Corridor rail chain, and East Mediterranean transshipment. Six disruption states come from public daily chokepoint observations. Public trade, dependence, logistics, connectivity, and route data define an inferred status quo. A two-stage Wasserstein-CVaR mixed-integer model selects advance readiness and evaluates post-disruption recourse with fixed trade totals and shared capacities.

The optimized composite objective is USD 241.623 billion below the inferred status quo, but readiness concentrates and the Turkish Straits disruption loss is USD 14.465 billion worse. Doubling that state's raw policy weight and renormalizing the weights lowers the Turkish Straits planned share from 55.9% to 31.3% and changes the state-loss gap from −USD 14.5 billion to +USD 11.4 billion. The model thus reveals a risk trade-off that can be addressed through policy priorities.

The contribution is threefold, and each part differs from the streams above. First, building on exposure-mapping studies [2–4], this study translates chokepoint exposure into a pre-disruption readiness decision. Second, building on two-stage robust and distributionally robust applications [33–39], it embeds advance readiness and post-disruption recourse in a bounded regional system with shared infrastructure accounting. Third, it provides vulnerability-revealing decision analytics: the benchmark reports not only the portfolio it favors but also the disruption state in which that portfolio underperforms. The model-ready decision layer is auditable end to end, and its public-source provenance is documented so that coarser inputs can be challenged and replaced when higher-resolution operational data become available.

2. Materials and Methods

Section 2 defines the system boundaries and decision timing (Section 2.1); formalizes the decision variables and risk-adjusted objective (Section 2.2); imposes readiness and recourse feasibility (Section 2.3); constructs scenario loss with Wasserstein ambiguity and CVaR tail-risk pricing (Section 2.4); describes the public data and empirical disruption states (Section 2.5); infers the status-quo benchmark (Section 2.6); and summarizes calibration and

the corridor menu (Section 2.7). Figure 1 illustrates this workflow from empirical inputs to portfolio comparison.

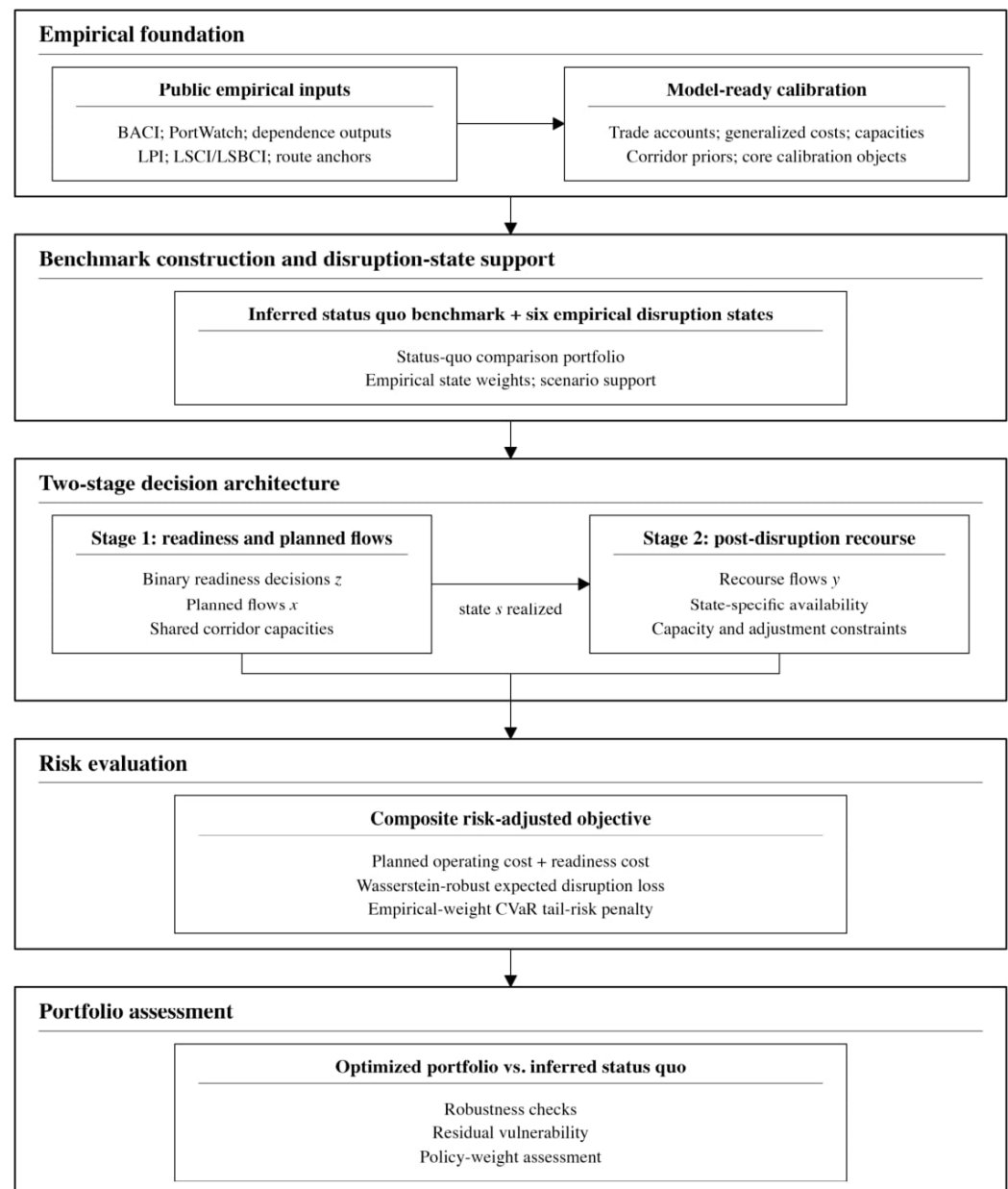


Figure 1. Research workflow from public empirical inputs to portfolio comparison with robustness, vulnerability, and policy-weight assessment.

2.1. System Definition and Decision Setting

The system has four boundaries. Spatially, it covers five Eastern Mediterranean countries and five corridor interfaces. Functionally, it includes fixed country-sector trade, generalized costs, readiness, shared capacity, and recourse. Temporally, it separates advance choices from post-disruption adaptation. Its actor boundary includes public and commercial parties, represented by a normative regional decision maker for common physical accounting. No supranational control of trade is assumed. The five countries allow consistent calibration across public trade, logistics, connectivity, and chokepoint data. The sparse corridor menu spans a main route, long maritime detour, regional maritime substitute, an intermodal rail contingency, and a regional transshipment option rather than attempting to enumerate every technically feasible route.

Canals, straits, rail chains, and transshipment interfaces have capacity shared across countries and sectors. Disruption changes their availability and cost; implementation requires actors to share information and coordinate risks and costs [42]. Shared constraints represent the physical links; institutional negotiation remains outside the model.

Fixed country-sector trade requirements, generalized corridor costs, readiness costs, shared capacities, scenario severities, availability multipliers, and empirical state weights are exogenous calibration objects. Planned flows, binary readiness choices, realized flows, and directional adjustments are endogenous. Table 1 maps those objects to the timing of the decision. These boundaries define what is counted inside the optimization; the next subsection formalizes the decisions and risk-adjusted objective within that boundary.

Table 1. System boundary and decision architecture.

Layer	Exogenous System Condition	Endogenous Decision or Evaluation	Operational Interpretation
Before disruption	Trade requirements, baseline costs, and capacity	Planned flows x and readiness z	Select interfaces that receive advance access and preparedness
Disruption environment	Six-state support, empirical weights, severities, and availability multipliers	State realization s	Reveal which chokepoint conditions and capacity losses apply
After disruption	Fixed trade requirements and state-specific capacity	Recourse flows y and adjustments p, n	Reallocate flows after the disruption state becomes known
Risk evaluation	Wasserstein radius, state distance, CVaR confidence, and weight	Robust expected loss and tail-loss variables	Price probability ambiguity and high-loss outcomes

2.2. Decision Variables and Objective

Let i denote countries, g sectors, c corridors, and s realized disruption states, while r denotes reference support points in the Wasserstein dual over the same six-state support.

The first-stage variable x_{igc} is planned volume before disruption, while z_{ic} equals one when country i maintains planned access to corridor c . After state s is realized, y_{igcs} reallocates the same country-sector trade requirement. Nonnegative p_{igcs} and n_{igcs} measure upward and downward movement from the first-stage plan.

Throughout the formulation, D_{ig} denotes the fixed country-sector trade requirement, b_{ic} the baseline generalized unit cost, F_{ic} the fixed readiness cost, Q_c the shared corridor capacity, and a_{cs} the state-specific availability multiplier; full notation, domains, and units are provided in File S1.

The objective combines planned operating cost, readiness cost, Wasserstein-robust expected disruption loss, and an empirical-weight CVaR tail-loss penalty:

$$\min [\text{baseline transport cost} + \text{readiness cost} + \text{robust expected disruption loss} + \text{weighted CVaR tail loss}]. \quad (1)$$

Its compact deterministic equivalent is

$$\min \sum_{i,g,c} b_{ic} x_{igc} + \sum_{i,c} F_{ic} z_{ic} + \sum_{r \in S} \hat{w}_r \rho_r + \epsilon \lambda_W + \omega_{\text{CVaR}} \left(\eta + \frac{1}{1 - \alpha} \sum_{s \in S} \hat{w}_s u_s \right). \quad (2)$$

The first two terms value the planned portfolio. The third and fourth terms implement the Wasserstein-robust expected loss through per-support dual variables ρ_r and ambiguity

multiplier λ_W . The quantities $\hat{w}_r$ and $\hat{w}_s$ denote the empirical weights of the corresponding support states. The final bracket is the raw conditional value-at-risk (CVaR) term, multiplied by ω_{CVaR} . The baseline uses $\epsilon = 0.30$, $\alpha = 0.95$, and $\omega_{\text{CVaR}} = 2.5$. These are maintained decision-analytic settings rather than statistically estimated structural coefficients: $\epsilon = 0.30$ is approximately 29% of the observed support diameter (descriptive context only), and $\omega_{\text{CVaR}} = 2.5$ is a baseline risk-preference choice. Their influence is quantified in File S1, Table S6; the underlying grids are retained in File S2.

2.3. Feasibility, Readiness, and Recourse

Feasibility connects fixed trade requirements, advance readiness, shared capacity, and state-contingent recourse. First-stage demand satisfaction requires

$$\sum_c x_{igc} = D_{ig} \quad \forall i, g. \quad (3)$$

Planned corridor use is linked to readiness through

$$\sum_g x_{igc} \leq (\sum_g D_{ig}) z_{ic} \quad \forall i, c \quad (4)$$

and baseline corridor capacity is shared across countries and sectors:

$$\sum_{i,g} x_{igc} \leq Q_c \quad \forall c. \quad (5)$$

After state s is realized, fixed trade requirements are reassigned:

$$\sum_c y_{igcs} = D_{ig} \quad \forall i, g, s. \quad (6)$$

State-dependent shared capacity imposes

$$\sum_{i,g} y_{igcs} \leq a_{cs} Q_c \quad \forall c, s, \quad (7)$$

and movement away from the plan is recorded directionally:

$$y_{igcs} - x_{igc} = p_{igcs} - n_{igcs} \quad \forall i, g, c, s. \quad (8)$$

Readiness is a reduced-form representation of pre-positioned access. Depending on the corridor, it can represent customs pre-clearance, terminal arrangements, rail slots, feeder capacity, contingency contracting, or an emergency communication channel. Equation (4) links readiness to planned use, but it does not make an unprepared corridor physically impossible after the shock. If $z_{ic} = 0$, emergency activation remains feasible through recourse; because planned flow is zero, such use is recorded as an upward adjustment and incurs the disruption and adjustment costs in Equation (9). The model therefore distinguishes costly emergency response from advance operational readiness. Because readiness is a country–corridor decision shared across sectors, $z_{ic} = 0$ excludes planned flow through corridor c for country i , while $z_{ic} = 1$ permits the country's sector flows to share that prepared interface subject to demand balance and shared corridor capacity.

2.4. Scenario Loss, Ambiguity, and Tail Risk

Scenario loss prices realized disruption use and movement away from the first-stage plan, after which Wasserstein ambiguity and CVaR evaluate expected and tail risk:

$$L_s(y, p, n) = \sum_{i,g,c} [\delta_g \theta_{ics} y_{igcs} + \kappa_{ic}^+ p_{igcs} + \kappa_{ic}^- n_{igcs}]. \quad (9)$$

Here, δ_g denotes the sector disruption-cost multiplier, θ_{ics} the state-specific disruption surcharge, and κ_{ic}^+ and κ_{ic}^- the directional adjustment costs. The first term is the sector-weighted disruption surcharge on realized corridor use; the other terms price upward and downward movement from the first-stage plan. Wasserstein support-pair constraints protect the expected-loss component against misspecification of the empirical state weights:

$$\rho_r + \lambda_W d_{rs} \geq L_s(y_s, p_s, n_s) \quad \forall r, s, \quad (10)$$

while the CVaR constraints retain sensitivity to high-loss states:

$$u_s \geq L_s(y_s, p_s, n_s) - \eta, \quad u_s \geq 0 \quad \forall s. \quad (11)$$

where d_{rs} denotes the distance between support states, while η and u_s are the CVaR threshold and scenario tail-excess variables, respectively.

Distributional robustness applies to expected disruption loss; CVaR uses empirical state weights. The objective is therefore robust expected loss plus an empirical-weight CVaR penalty, evaluated identically for the inferred status quo and optimized portfolio.

2.5. Data, Scenario Construction, and Regional Setting

The calibration combines public trade, shipping, connectivity, and logistics information. CEPII BACI data [43] in the HS 2022 classification (release 202601) provide bilateral trade flows for 2022–2024, aggregated into agriculture and food, chemicals and materials, energy and fuels, manufactured goods, and raw materials. IMF–World Bank PortWatch daily observations [44] from 1 January 2019 to 14 March 2026 provide the chokepoint transit series. Country chokepoint dependence and freight-surcharge proxies are taken from public outputs associated with Verschuur et al. [4]. The generalized-cost and capacity layers use the World Bank Logistics Performance Index (LPI) [45], UNCTAD liner-connectivity and seaborne-trade indicators [46], and corridor distances retrieved from the sea-distances.org calculator [47]. Route anchors are identified in the corridor menu (Section 2.7), while File S2 supplies the calibrated distance reference values and construction notes. BACI provides consistent bilateral country-sector trade accounts; PortWatch provides public daily chokepoint transit observations over the empirical window; Verschuur outputs calibrate country-level chokepoint dependence; LPI and LSCI form transparent logistics and maritime-connectivity quality factors; LSBCI adjusts the bilateral and partner-region route prior; and sea-distances.org anchors provide transparent route-distance and cost references.

Each country's sectoral export and import accounts define D_{ig} . Bilateral trade between two focal countries appears once in each country's account, comprising about 2.9% of the regional aggregate. Flow requirements and USD-equivalent capacity use this same accounting basis.

The two UNCTAD connectivity measures enter different calibration layers. The bilateral Liner Shipping Connectivity Index (LSBCI), aggregated to partner regions, adjusts the inferred route prior. The country-level Liner Shipping Connectivity Index (LSCI), combined with LPI, enters the generalized-cost quality factor. Keeping these measures

distinct preserves the difference between bilateral route connectivity and country-level maritime connectivity.

Daily chokepoint reductions are measured relative to a trailing 30-day mean and classified by fixed rules. A day is baseline when the largest of the Suez, Bab el-Mandeb, and Turkish Straits reductions is below 0.10. It is a combined Suez–Bab state when both reductions are at least 0.25. A single-chokepoint state requires its reduction to be at least 0.30 and at least 0.05 greater than each of the other two; all remaining nonbaseline days form the regional-compound state. The six empirical state weights are the normalized shares of classified days. File S1 reports the state severities, weights, and distance construction. These are reproducible scenario-classification rules, not estimated causal breakpoints or labels for the events behind transit reductions.

The calibration favors inspectable public inputs over finer commercial routing, freight, insurance, or contract data. Because shipment-level routes are unavailable, the status quo is inferred and tested through direct perturbations.

2.6. Construction of the Inferred Status Quo

The status quo is built in three stages. Connectivity-adjusted regional corridor priors and BACI partner-region trade weights form a country-sector prior (Equations (12) and (13)). Dependence matching yields an intermediate share, then fixed blending and normalization produce the final comparison share (Equations (14) and (15)).

$$\pi_{irc} = N(M_{rc}(\lambda_{ir})b_{rc}) \quad (12)$$

$$\underline{\pi}_{igc} = \sum_r \omega_{igr} \pi_{irc} \quad (13)$$

where π_{irc} is the connectivity-adjusted corridor prior for partner region r (b_{rc} the fixed region prior vector, λ_{ir} the clamped country–region liner-connectivity measure, M_{rc} the direct, remaining, and alternative-interface scaling), ω_{igr} is the BACI partner-region trade weight for country i and sector g , and $\underline{\pi}_{igc}$ is the resulting country-sector prior. Sector differentiation in the prior arises through partner composition, and the full numerical vectors, clamps, and scaling rules are documented in File S1. $N(\cdot)$ denotes nonnegative normalization: negative entries, if any, are clipped at zero, and the vector is rescaled to unit sum, with the documented fallback for a zero-sum vector.

Second, the sector prior is matched to the country's public chokepoint-dependence profile [4], giving an intermediate share s_{ig}^* (Equation (14)). Fixed rescaling, re-capping, blending, and renormalization then convert the intermediate share into the final delivered benchmark share q_{igc}^{SQ} (Equation (15)). Here $\hat{s}_{igr}$ denotes the recapped region-specific rescaling blended 0.82/0.18 with the region prior (normalized).

$$s_{ig}^* \in \arg \min_{s \in \Delta^5, s_4 \leq m_g} [3.5 \sum_k |\sum_c e_{ck} s_c - H_{ik}| + 1.5 \sum_c |s_c - \underline{\pi}_{igc}|] \quad (14)$$

$$q_{igc}^{SQ} = N(0.78 \sum_r \omega_{igr} \hat{s}_{igr} + 0.22 \underline{\pi}_{igc}) \quad (15)$$

where k indexes chokepoints, H_{ik} is the public dependence target, e_{ck} the corridor–chokepoint exposure, s_c a candidate share, and m_g the nominal sector-specific Middle Corridor limit (0.05 for energy and fuels, 0.10 for agriculture and food, 0.15 for chemicals and materials, and 0.25 for manufactured goods and raw materials), which reflects the limits of rail substitution for bulky cargo. The limit binds the intermediate construction step; later fixed blends and normalization can make the final q_{igc}^{SQ} share differ slightly from the nominal pre-blend limit. Each country-sector share vector sums to one. The shares are an auditable comparison portfolio, not observed firm routing. Maintained weighting and

blending choices balance public dependence targets against the route prior; their influence is tested by perturbation and component-exclusion checks. File S1 documents scaling, caps, missing values, and those checks.

2.7. Core Calibration and Corridor Menu

The calibration fixes the scale of trade requirements, shared capacity, risk settings, and the intentionally sparse five-corridor choice set. Table 2 summarizes the controlled system dimensions and calibration. The first-stage aggregate capacity ratio is 3.877. The minimum state-level aggregate ratio, defined as $\min_s \sum_c a_{cs} Q_c / \sum_{i,g} D_{igt}$, is 3.012. These are aggregate capacity ratios. Route and connectivity priors construct the inferred status quo; trade requirements, costs, readiness, availability, capacities, and risk settings determine optimized allocations.

The baseline fixed-readiness coefficient is 1% of modeled country trade, scaled by corridor base cost relative to the country's corridor mean. It is a decision scale, not an observed cost. File S1 tests 0–2%; File S2 provides the inputs and code that construct each readiness-cost matrix.

Table 2. Core calibration objects.

Object	Baseline Value or Construction	Interpretation
Countries	5	Türkiye, Egypt, Greece, Israel, and Lebanon
Sectors	5	Public BACI aggregation
Corridors	5	Suez, Cape, Turkish Straits, Middle Corridor, and East Mediterranean
Scenarios	6	PortWatch-derived disruption states
Country-account trade base	USD 1068.349 bn	Sum of focal country-sector accounts; 2022–2024 annual average.
First-stage capacity ratio	3.877	Aggregate baseline capacity relative to the country-account trade base
Minimum scenario capacity ratio	3.012	Lowest aggregate shared-capacity ratio across states
Ambiguity radius	0.30	Baseline Wasserstein radius
CVaR confidence	0.95	Upper-tail confidence level
CVaR weight	2.5	Multiplier on the raw CVaR term

The five-corridor menu is deliberately sparse so that readiness choices remain interpretable (Table 3). Route references are cost anchors, not claims that every country-sector flow follows the named port pair. Route-geography priors, partner-region connectivity, and country-specific generalized-cost adjustments determine how each anchor enters the benchmark. Selection favors strategic substitution, modal diversity, geographic plausibility, public-data calibration, and interpretability. The menu includes a main route, long detour, regional maritime substitute, rail contingency, and transshipment interface.

The bounded corridor system is shown in Figure 2.

Table 3. Corridor menu used in the benchmark.

Corridor	Route Reference	Modeled Role
Suez mainline	Shanghai–Mersin via Suez	Main Asia–Mediterranean maritime route
Cape detour	Shanghai–Mersin via Cape of Good Hope	Long maritime fallback
Turkish Straits/Black Sea	Novorossiysk–Mersin or Constanța–Alexandria benchmark	Short regional maritime substitute
Middle Corridor rail	China–Kazakhstan–Caspian–Türkiye chain	Intermodal contingency channel
East Mediterranean transshipment	Mersin–Genoa distance anchor	Regional transshipment substitute

**Figure 2.** Eastern Mediterranean corridor system. The schematic was produced by the author from public route references and does not imply a position on boundaries, sovereignty, or legal status.

3. Results

3.1. Portfolio Shift and Objective Gap

The optimized composite USD-equivalent objective is 997.702 billion versus 1239.325 billion for the inferred status quo: a 241.623 billion gap, equal to 22.6% of the USD 1068.349 billion annual focal-country trade-account base. The optimized objective comprises 723.224 billion in baseline generalized cost, 11.353 billion in readiness cost, 62.958 billion in Wasserstein-robust loss, and 200.166 billion in weighted tail loss ($2.5 \times$ raw CVaR of 80.067 billion). Relative to the status quo, baseline cost falls by 204.709 billion, readiness cost by 42.064 billion, and robust expected loss by 2.078 billion, while weighted CVaR rises by 7.227 billion. This is a composite benchmark difference, not realized cash savings or tail-risk dominance.

The gap remains large across the principal formulation checks (Table 4). A positive gap follows mechanically for a feasible benchmark, so its magnitude, decomposition, portfolio, and state losses matter more than its sign. The independent-country LP removes shared-capacity coupling and binary readiness; its USD 186.818 billion gap therefore cannot isolate the effect of shared capacity. Setting readiness costs to zero gives a 202.633 billion gap. An empirical-support model with CVaR but no Wasserstein radius remains close to the baseline at 238.581 billion, showing that the ambiguity premium does not create the central result. Pre- and post-1 December 2023 state weights produce gaps of 231.012 billion and 261.317 billion, respectively. The joint LP relaxation is a nonimplementable lower bound with fractional readiness; its 6.721 billion distance from the mixed-integer optimum measures the objective cost of discrete readiness choices in the calibrated system. The 6.721 billion integrality premium applies to the implemented aggregate-linkage formulation, not every possible linkage.

Table 4. Objective gap and selected robustness checks.

Case	Status Objective	Optimized Objective	Gap
Full Wasserstein-CVaR baseline	1239.325	997.702	241.623
Independent-country LP	1209.671	1022.854	186.818 *
Joint LP relaxation	1239.325	990.981	248.344
Joint model, zero readiness cost	1185.908	983.275	202.633
SAA + CVaR, no Wasserstein	1196.898	958.317	238.581
Pre-2023-12-01 state weights	1214.598	983.586	231.012
Post-2023-12-01 state weights	1265.979	1004.662	261.317

Note: Values are USD-equivalent billions. The LP relaxation of the implemented aggregate-linkage formulation permits fractional readiness and is not implementable. * The independent-country gap is calculated from unrounded output; displayed components differ by one final digit because of rounding.

The saved parameter grids show a persistent gap but some portfolio changes. Across $\varepsilon = 0\text{--}0.50$, the paired objective gap is USD 238.581–247.414 billion; across CVaR weights 1.0–4.0, it is USD 241.623–276.643 billion. At $\alpha = 0.975$ and 0.990, East Mediterranean transshipment enters the active mix, while six country–corridor pairs remain prepared. File S1, Table S6 reports the settings; none establishes a uniquely correct risk parameter or invariant portfolio.

Figure 3 places the main formulations on a common objective scale. The inferred status quo is also tested directly rather than defended only through alternative model layers. Blending it halfway toward a cost-favored routing leaves a 219.611 billion gap. Across 3000 multiplicative perturbations at $\pm 5\%$, $\pm 10\%$, and $\pm 20\%$, the status-minus-optimized gap remains positive in every draw; the minimum observed gap is 220.399 billion.

Two further tests target the system architecture directly. If every second-stage corridor use is restricted to a country–corridor interface activated before disruption, the gap is 236.543 billion, and the optimized solution retains six active country–corridor pairs. In the baseline, the highest corridor-state capacity utilization is 92.5%, leaving 27.314 billion of calibrated slack; a 15% contraction in all corridor capacities leaves a 234.029 billion gap. No corridor-state capacity constraint binds in the baseline; shared capacity is a feasibility rule, not an isolated explanation of the objective gap. The contraction test probes its relevance. Direct status-quo perturbations and removal of the Wasserstein radius also leave a large calibrated benchmark gap.

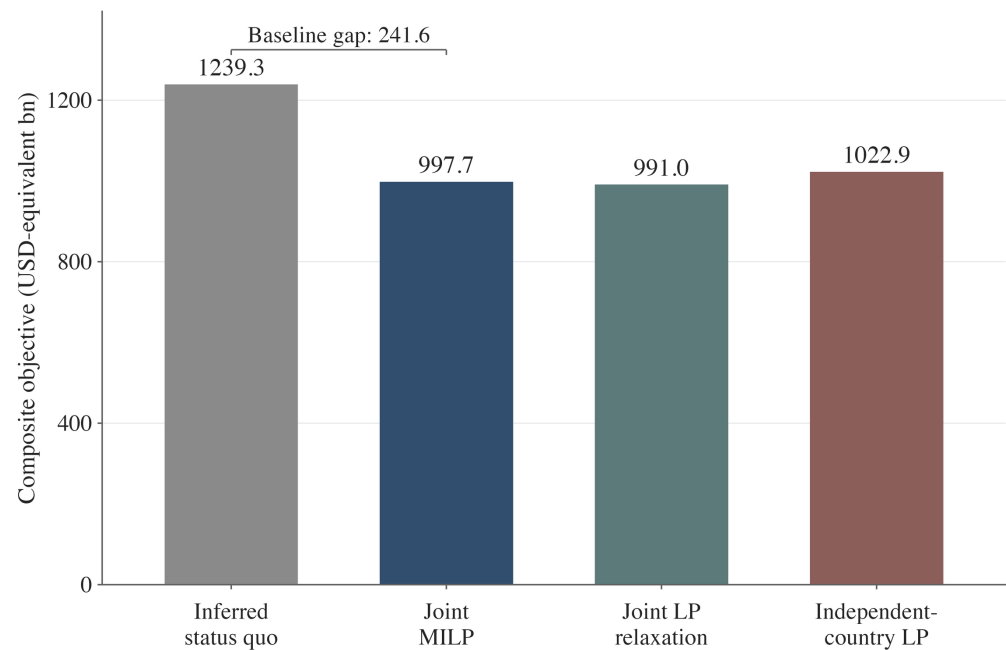


Figure 3. Composite objective comparison across benchmark formulations. Values are USD-equivalent billions; lower values are preferred.

3.2. Readiness Concentration and State-Specific Vulnerability

The optimized plan assigns 44.1% of volume to Suez and 55.9% to the Turkish Straits/Black Sea corridor, versus five active alternatives in the inferred status quo. Regional concentration (HHI) rises from 0.252 to 0.507 under the maintained costs and risk settings. The readiness-cost grid changes the number of prepared country–corridor pairs. Neither first-stage nor corridor–state capacity binds in the baseline, so binding capacity does not explain this concentration. Readiness selects prepared interfaces, not preparation intensity.

Readiness is chosen by country and corridor and shared across sectors. Planned flow x_{igc} varies by country, sector, and corridor; recourse y_{igcs} also varies by disruption state. D_{ig} , disruption-cost multipliers, and BACI partner composition preserve sector differences. Table 5 aggregates country-level flow decisions; it does not imply identical corridor shares for every sector within a country.

Türkiye’s Suez/Turkish Straits shares move from 0.337/0.286 in the inferred status quo to 0.552/0.448 in the optimum. Greece’s Suez share rises from 0.192 to 1.000; Egypt, Israel, and Lebanon’s Turkish Straits shares rise from 0.065, 0.030, and 0.065 to 1.000. These are generalized-cost corridor proxies, not verified shipment routes or national investment mandates.

In the reconstructed 125-cell solution, Turkish agriculture/food, chemicals/materials, energy/fuels, and raw materials use Suez; manufactured goods split 29.7% Suez and 70.3% Turkish Straits. All five sectors use the Turkish Straits proxy in Egypt, Israel, and Lebanon, and Suez in Greece. File S1, Table S8 gives all country–sector comparisons; File S2 supplies the CSV and checks. The rerun matches the archived objective and 25 country–corridor totals; the original unsaved sector cells cannot be compared individually.

A 70% maximum country–corridor share activates East Mediterranean transshipment, lowers regional HHI to 0.395, and retains a USD 209.948 billion gap. This reduces concentration relative to the unconstrained baseline. Diversification raises the modeled objective cost.

The composite-objective improvement carries a specific residual risk. Figure 4 reports the status-minus-optimized scenario-loss gap, so positive values favor the optimized portfolio. The optimized portfolio performs better in the Suez, Bab el-Mandeb, regional-

compound, and combined Suez–Bab states and is nearly tied in the baseline state. In the Turkish Straits disruption state, however, it performs 14.465 billion worse because the pre-disruption portfolio relies heavily on that regional substitute. An aggregate objective alone would conceal this exposure. The policy-weight test addresses this residual risk without claiming an empirically optimal weight.

Table 5. Country-level planned corridor shares in the inferred status quo and optimized baseline.

Country	Suez	Cape	Turkish Straits/Black Sea	Middle Corridor	East Med.
Panel A. Inferred status quo					
Türkiye	0.337	0.048	0.286	0.032	0.297
Egypt	0.391	0.128	0.065	0.122	0.295
Greece	0.192	0.135	0.197	0.122	0.353
Israel	0.291	0.195	0.030	0.146	0.338
Lebanon	0.308	0.180	0.065	0.128	0.319
Panel B. Optimized baseline					
Türkiye	0.552	0.000	0.448	0.000	0.000
Egypt	0.000	0.000	1.000	0.000	0.000
Greece	1.000	0.000	0.000	0.000	0.000
Israel	0.000	0.000	1.000	0.000	0.000
Lebanon	0.000	0.000	1.000	0.000	0.000

Note: Values are country-level planned-flow shares; each row sums to one. East Med. means East Mediterranean transshipment. Panel A is the inferred status quo, and Panel B is the joint MILP optimum (File S2). Readiness is shared across sectors within each country–corridor pair. Table 5 alone does not identify sector routing; File S1, Table S8 reports the country–sector comparison. These modeled allocations do not prescribe national policy.

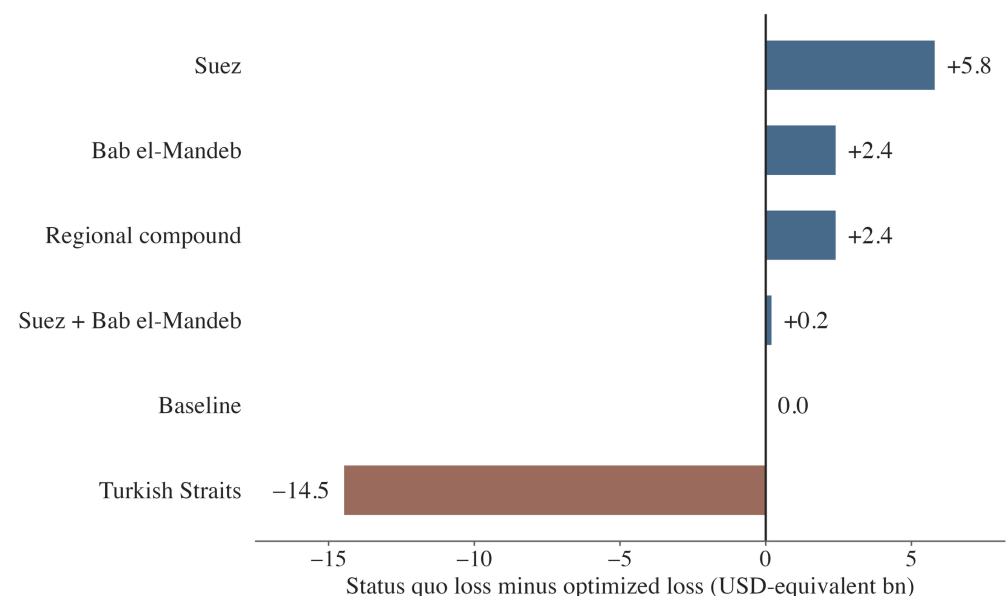


Figure 4. Scenario-specific loss advantage of the optimized portfolio over the inferred status quo. Positive values favor the optimized portfolio; negative values favor the status quo.

The exposure can be priced explicitly. The baseline empirical weight of the Turkish state is 0.1174. Multiplying that raw weight by two and renormalizing all six weights raises its normalized weight to 0.2102. The optimized Turkish Straits share then falls from 55.9%

to 31.3%, East Mediterranean transshipment enters the active regional mix, and the Turkish-state loss gap changes from –USD 14.5 billion to +USD 11.4 billion. The model therefore traces a risk-management frontier: greater protection against a policy-critical disruption state can be purchased through a different readiness portfolio rather than appended as an after-the-fact caveat.

4. Discussion

4.1. Systems Contribution to Supply-Chain Risk Management

The central result is the move from an exposure dashboard to a preparedness decision. Exposure indicators can identify dependence on Suez, Bab el-Mandeb, or the Turkish Straits [2–4]. They do not identify which substitute corridors to prepare. This model selects country–corridor readiness and evaluates recourse; terminal, feeder, rail, customs, and contract arrangements would implement that choice.

The model joins country-sector decisions through shared corridor capacities, connects advance readiness to recourse through fixed costs, and locates residual risk through state losses. This prevents nominal route availability from being treated as preparedness or an aggregate optimum as complete evidence of protection. The contribution is their joint representation in a bounded decision system.

The inferred status quo is not an observed routing matrix, but its trade, prior, dependence, cost, capacity, severity, and weight inputs are auditable. Direct perturbations leave a positive benchmark gap. Users with proprietary route and contract data can recalibrate the inputs while retaining the readiness–recourse structure.

The findings relate to these literature streams in four specific ways. Exposure studies identify dependence [2–4]; this paper moves from measurement to ex ante interface preparation. That move is consistent with distinguishing preparation from response and recovery [15,17]: the model operationalizes advance preparedness plus recourse without measuring transformation or viability. The concentration result reinforces the usability literature’s warning that nominal alternatives are not prepared alternatives [18–26], and relative to two-stage robust and distributionally robust applications [30–39], the contribution is not the method family itself but its use for a bounded shared-capacity readiness system that reports its residual state vulnerability.

Verschuur et al. [4] estimate chokepoint exposure; this model selects advance country–corridor access and evaluates recourse. Wang et al. [33] and Cao et al. [34] already use two-stage distributionally robust mitigation, so that method alone is not our novelty. Our application combines interface readiness, shared corridor accounting, and state-loss reporting. Goldschmidt et al. [48] study severe-disruption sourcing under-diversification; concentration here is a conditional model optimum, not observed decision-maker bias.

4.2. Readiness Concentration and Residual Risk

Prepared access can require documentation, terminals, rail slots, feeders, and contracts. Fixed charges can favor a smaller prepared set under the calibrated costs and risks. The choice concerns which interfaces are ready, not readiness intensity; it does not imply that fewer routes are generally more resilient.

At the same time, concentration creates residual exposure. Severe-disruption sourcing research warns that under-diversification can persist even when decision makers recognize disruption risk [48]. The Turkish-state loss makes that danger visible. Reporting state losses and allowing reweighting or concentration limits keeps the trade-off open to decision makers. Maximum-share constraints change feasibility; Turkish-state reweighting changes objective priorities.

4.3. Governance, Decision Ownership, and Benchmark Scope

Shared capacity is a physical accounting rule, not a political coalition. Countries cannot independently consume the same canal, strait, rail, or transshipment capacity. The regional objective can inform coordination among public and commercial actors but assigns neither legal authority nor implementation costs.

The independent-country LP removes joint accounting and binary readiness, so its gap is not a pure coordination surplus. Users should examine country consequences and state losses alongside the regional objective. Uneven gains may require negotiated access, compensation, reserve capacity, or political-feasibility rules. The model identifies these questions without resolving governance. Table 5 shows within-region heterogeneity, not five independent national mandates.

This governance reading is bounded by the scope of the benchmark itself. The annualized model fixes country-sector trade and omits demand destruction, freight rates, carrier power, insurance contracts, congestion equilibrium, and multi-period investment. Its five-country, five-proxy menu includes planning anchors rather than service forecasts. It compares readiness portfolios; it does not predict commercially executable volumes.

5. Conclusions

The objective was to evaluate advance corridor readiness under shared capacity, ambiguity, and tail risk. The model links readiness to post-disruption recourse and reports both aggregate and state-specific outcomes.

First, aggregate improvement can coexist with concentration and residual vulnerability. The optimized portfolio lowers the composite benchmark objective by USD 241.623 billion against the inferred status quo—a modeled difference, not realized savings—yet performs USD 14.465 billion worse in the Turkish Straits disruption state. Fixed readiness charges favor fewer prepared interfaces; reliance on that regional substitute raises loss when it is disrupted.

Second, that vulnerability responds to explicit choices. A 70% maximum-share constraint lowers concentration to HHI 0.395 while retaining a USD 209.948 billion gap. Separately, doubling the Turkish-state raw weight (normalized to 0.2102) lowers the Turkish Straits planned share from 55.9% to 31.3%, activates East Mediterranean transshipment, and changes the state-loss gap from about −USD 14.5 billion to +USD 11.4 billion. These are distinct diversification and state-priority levers.

Maritime authorities and operators can check customs, terminal, feeder, rail, and contingency access at selected interfaces, set unacceptable disruption losses, and compare maximum-share or state-priority alternatives. They should report aggregate and state-specific outcomes. Implementation requires service-capacity evidence, access contracts, country-sector incidence, and agreed readiness-cost responsibility; the benchmark assigns no legal authority or national budgets.

The benchmark is static and annualized, with fixed country-sector trade and five public-data corridor proxies. It excludes demand destruction, freight-rate formation, carrier market power, insurance contracts, congestion equilibrium, and multi-period investment. The inferred status quo is not based on shipment-level routing; these bounds qualify interpretation.

Future work should recalibrate with shipment-level routes, terminal, and contract data; model dynamic investment, capacity, and repeated disruptions; incorporate demand, freight, carrier behavior, and congestion; extend geographic coverage; and study coordination, cost sharing, and decision ownership. These extensions would test the readiness–recourse architecture beyond its fixed calibration boundaries.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/systems14111337/s1>: File S1, Supplementary Methods and Robustness Details; File S2, Reproducibility Package containing model-ready inputs, optimization code, environment files, run instructions, a data dictionary, provenance documentation, reference outputs, and SHA-256 checksums.

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