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Rail Corridor Diversification for Resilient Supply Chains: A Simulation-Based Study of the Emerging Saudi–Türkiye Logistics Corridor

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Abstract

Global supply chains are increasingly exposed to maritime chokepoints, geopolitical disruption, border friction and sustainability pressure. This paper reframes the emerging Saudi–Türkiye rail and logistics corridor as a supply chain resilience capability rather than a conventional transport infrastructure project. The study addresses a gap in the literature: supply chain resilience research has largely emphasized firm-level practices such as inventory buffers, supplier diversification and operational recovery, while the resilience role of logistics corridors remains underexplored. A Monte Carlo simulation and scenario-analysis framework is developed to compare four route-inventory alternatives between Saudi Arabia and Türkiye: the Jeddah–Suez–Mersin maritime route, the Dammam–Hormuz–Suez–Mersin maritime sensitivity route, the Saudi–Jordan–Syria–Türkiye rail corridor and the Iraq–Türkiye multimodal corridor. The model evaluates total logistics cost, lead time, reliability, disruption exposure, carbon emissions and a composite Corridor Resilience Index. Open-source route data and freight benchmarks are used to calibrate the maritime inputs, while non-operational rail and multimodal corridor segments are treated as scenario assumptions. The paper contributes by conceptualizing corridor diversification as a supply chain resilience capability, developing a multi-criteria simulation framework and translating route performance into managerial decision rules for resilient logistics planning.

Keywords
Supply Chain Resilience, Corridor Diversification, Monte Carlo Simulation, Rail Logistics and Saudi–Türkiye Corridor.

1. Introduction
Supply chain resilience has become a central concern for firms and governments because logistics networks are increasingly disrupted by maritime chokepoints, geopolitical shocks, port congestion, climate events and border uncertainty. The Gulf–Türkiye–Europe trade space is especially sensitive to route concentration because many flows depend on sea lanes that may be affected by Red Sea, Suez Canal, Bab al-Mandab or Strait of Hormuz disruptions. In this context, resilience is not only a firm-level capability; it is also shaped by the availability, reliability and interoperability of regional logistics corridors.

Rail corridor diversification is strategically relevant because it can add route redundancy, stabilize lead times, reduce exposure to maritime disruption and support lower-carbon logistics. Rail is not assumed to be universally superior to maritime transport. Instead, the supply chain question is conditional: under which uncertainty conditions does an alternative rail-enabled corridor improve service continuity, reliability and risk-adjusted logistics performance?
The emerging Saudi–Türkiye connectivity initiative provides a timely case for examining this question. Recent official and media reports indicate that Saudi Arabia and Türkiye have announced railway and logistics cooperation and discussed a corridor through Jordan and Syria, while the Iraq–Türkiye Development Road offers an additional multimodal alternative. However, the proposed Saudi–Türkiye corridor should be treated as an emerging and not yet fully operational end-to-end freight system. Therefore, an ex-ante simulation approach is appropriate for evaluating potential supply chain value before complete commercial operation.

This paper therefore studies the corridor from a supply chain perspective. It does not ask only whether a rail line can be constructed. It asks how rail corridor diversification could improve supply chain resilience performance by reducing maritime dependency, improving route redundancy and supporting logistics continuity under uncertainty (Figure 1) (Table 1).

Table 1: Research gaps and scientific contributions

Research gap	**Why the gap matters**	**Contribution of this study**
Firm-level focus in resilience studies	Most resilience studies emphasize suppliers, inventories and recovery within firms.	Moves the analysis to logistics corridors as resilience-enabling assets.
Limited corridor-level quantification	Existing corridor discussions are often descriptive or policy-oriented.	Builds a simulation framework that links corridor choice to supply chain resilience performance.
Weak integration of maritime disruption and inland alternatives	Maritime disruption is often studied separately from inland corridor design.	Compares maritime, rail-enabled and multimodal routes under common disruption scenarios.
Limited evidence on the Saudi–Türkiye corridor	The corridor is emerging and lacks full operating data.	Provides an ex-ante model that can be updated as operational data become available.
Single-criterion route comparison	Many route comparisons emphasize cost or distance only.	Integrates cost, lead time, reliability, disruption exposure and emissions.

Figure 1: Conceptual schematic map of the proposed modern Hejaz Railway and Saudi–Türkiye logistics corridor

Note: Author-generated schematic map for academic illustration only. It is not an official engineering alignment, does not represent final construction decisions and is used only to clarify the conceptual corridor logic.

1.1 Objectives

The objectives of this study are: (1) to position rail corridor diversification as a supply chain resilience capability; (2) to develop a corridor-level model linking route redundancy, maritime dependency, lead-time stability and disruption exposure to supply chain resilience performance; (3) to compare four routing alternatives using Monte Carlo simulation; (4) to translate simulation results into managerial and policy decision rules; and (5) to identify the operational risks that must be reduced for the corridor to create supply chain value.

1.2 Research Hypotheses

H1: Rail corridor diversification positively improves supply chain resilience performance under maritime disruption.
H2: Rail-enabled corridors reduce lead-time variability relative to maritime alternatives when Red Sea/Suez disruption increases.

H3: Reduced maritime dependency mediates the relationship between corridor diversification and service continuity.
H4: Border delay negatively moderates the resilience value of rail-enabled corridors.
H5: The resilience value of rail corridor diversification is higher for time-sensitive and medium-to-high value goods than for low-value non-urgent cargo.

2. Literature Review

Supply chain resilience refers to the capability of a supply chain to prepare for, respond to, recover from and adapt to disruptions. Christopher and Peck (2004) emphasized the need to design supply chains that can withstand shocks rather than only optimize efficiency. Ponomarov and Holcomb (2009) conceptualized resilience as adaptive capability, while Hohenstein et al. (2015) and Tukamuhabwa et al. (2015) reviewed resilience antecedents such as flexibility, collaboration, visibility and redundancy. More recent work has extended resilience toward viability, survivability and ripple-effect control in complex supply networks (Ivanov 2020; Ivanov and Dolgui 2020).

Dynamic Capabilities Theory supports the view that resilient supply chains must sense disruption, seize alternative options and reconfigure logistics resources (Teece et al. 1997; Chowdhury and Quaddus 2017). Contingency logic further suggests that no single route is optimal across all conditions; the best logistics configuration depends on product value, urgency, disruption intensity, border efficiency and sustainability priorities (Brandon-Jones et al.

2014). This theoretical combination is appropriate because corridor choice is not only a transport decision but also a dynamic reconfiguration capability.

Transport corridor and maritime logistics research demonstrates that physical connectivity alone does not guarantee supply chain performance. Corridor performance depends on terminals, customs processes, information integration, hinterland access, reliability and institutional coordination (Notteboom and Rodrigue 2005; Rodrigue 2020). Recent maritime disruptions have shown that chokepoint dependency can amplify lead-time uncertainty, insurance cost, rerouting and inventory pressure (UNCTAD 2024; Sheffi 2005). Therefore, route diversification can be interpreted as a resilience mechanism when it creates feasible options before disruptions occur.

Simulation is widely used in supply chain risk analysis because disruptions and logistics delays are uncertain rather than deterministic. Monte Carlo simulation allows key variables to be represented as probability distributions and produces route-performance distributions instead of single-point estimates (Sawik 2019; Tang 2006). This is especially suitable for emerging corridors where full operational data are not yet available, but reasonable minimum, most-likely and maximum values can be tested.

3. Methods

This research is designed as an exploratory, simulation-based supply chain resilience study. The unit of analysis is a representative 40-foot container moving between Saudi Arabian logistics nodes and Turkish gateway markets. The route inventory distinguishes observed maritime services from emerging rail and multimodal alternatives. R1 uses Jeddah Islamic Port as the base maritime gateway to Mersin/Türkiye, R2 uses Dammam/King Abdulaziz Port as a Gulf-origin maritime sensitivity case, R3 represents the proposed Saudi–Jordan–Syria–Türkiye rail corridor, and R4 represents the Iraq–Türkiye multimodal alternative linked to the Development Road concept. This structure allows the study to compare route diversification as a supply chain capability rather than treating the corridor only as a transport engineering project (Figure 2) (Table 2-3).

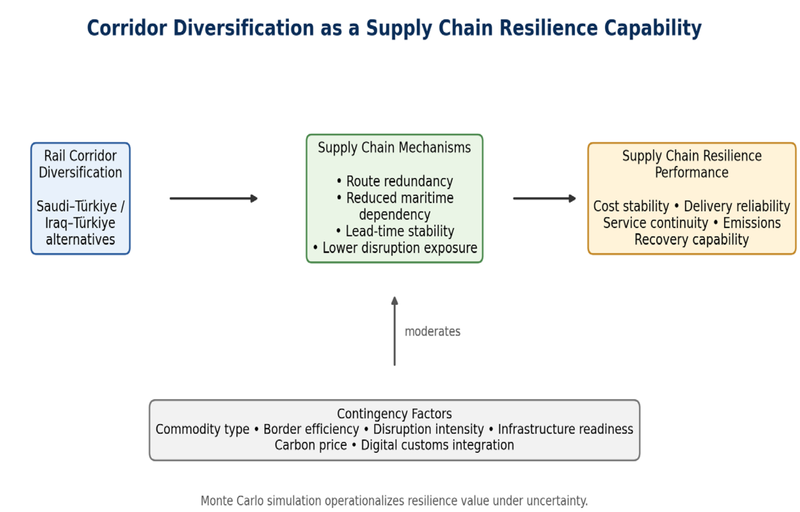

Figure 2: Supply chain resilience framework for rail corridor diversification

Table 2: Supply chain constructs and operationalization

Construct type	Variable	Operational meaning
Independent variable	Rail corridor diversification	Availability of rail-enabled alternatives beyond conventional maritime routing
Mediating mechanisms	Route redundancy; reduced maritime dependency; lead-time stability	Ability to shift flows and reduce exposure to chokepoints

Construct type	Variable	Operational meaning
Dependent variable	Supply chain resilience performance	Service continuity, reliability, recovery capability, cost stability and emissions performance
Moderators	Border efficiency; commodity type; disruption intensity; carbon price	Conditions that strengthen or weaken the corridor's value
Decision output	Corridor Resilience Index (CRI)	Composite route score integrating cost, time, reliability, risk and emissions

Table 3: Route alternatives and supply chain role

Route	Description	Dominant mode	Supply chain role
R1	Riyadh/Jeddah–Suez–Mersin maritime base route	Sea + port + inland leg	Observed maritime baseline calibrated with public route data
R2	Dammam–Hormuz–Suez–Mersin maritime sensitivity route	Sea + Gulf port + inland leg	Sensitivity case for Gulf-origin flows; timing is scenario-calibrated because direct public timing is limited
R3	Saudi Arabia–Jordan–Syria–Türkiye rail corridor	Rail-dominant	Emerging direct corridor and modern Hejaz concept
R4	Saudi/Gulf–Iraq–Türkiye multimodal corridor	Rail/road multimodal	Alternative overland corridor linked to the Development Road concept

The simulation uses triangular distributions because they are transparent and suitable when historical observations are limited but plausible minimum, most-likely and maximum values can be estimated. For route r, the model calculates total logistics cost, lead time, emissions, delivery reliability and a composite corridor resilience index as follows:

$$TLC\_r = FC\_r + HC\_r + BC\_r + IC\_r + CC\_r + RP\_r \quad (1)$$

$$LT\_r = TT\_r + TD\_r + BD\_r + DD\_r \quad (2)$$

$$CO2\_r = Load \times \Sigma\_m\ (Distance\_\{r,m\} \times EF\_m) \quad (3)$$

$$REL\_r = P(LT\_r \leq SLA\_r) \quad (4)$$

$$CRI\_r = 100 \times [0.25(1-NC\_r) + 0.25(1-NLT\_r) + 0.20REL\_r + 0.15(1-NDR\_r) + 0.15(1-NCO2\_r)] \quad (5)$$

where TLC_r represents the total logistics cost of route r. FC_r is freight cost, HC_r is handling and terminal cost, BC_r is border and customs cost, IC_r is inventory carrying cost during transit, CC_r is carbon cost and RP_r is disruption risk premium. LT_r is total lead time, TT_r is physical transport time, TD_r is terminal or port dwell time, BD_r is border delay and DD_r is disruption delay. CO2_r measures route-level emissions; Load is shipment weight, Distance_{r,m} is the distance travelled on route r by mode m and EF_m is the emission factor for mode m. REL_r is delivery reliability, defined as the probability that total lead time is less than or equal to the service-level threshold SLA_r. CRI_r is the Corridor Resilience Index. NC_r, NLT_r, NDR_r and NCO2_r are normalized cost, lead time, disruption risk and carbon emissions, respectively. A higher CRI_r indicates a more resilient logistics corridor.

4. Data Collection

Data collection follows a route-inventory and open-source calibration strategy. Observed or benchmark values are used when public data are available: Jeddah–Mersin maritime time and distance, public container freight benchmarks, emissions conversion factors and proxy freight quotations. For emerging segments that do not yet operate as end-to-end commercial services, especially the Saudi–Jordan–Syria–Türkiye rail corridor and the Iraq–Türkiye multimodal alternative, inputs are explicitly classified as scenario assumptions rather than observed data. This distinction improves methodological transparency and prevents the ex-ante model from being interpreted as a claim of current operating performance (Table 4 and 5).

Table 4: Data sources for future model calibration

Source	Classification	Useful variables	Access and limitation
Fluent Cargo	Open logistics route platform	Route distance, transit time, sailing frequency	Open route estimate; not a carrier contract
Freightos FBX and Drewry WCI	Commercial/open benchmark	40ft freight-cost benchmarks and stress ranges	Benchmarks; not lane-specific contracts
Agora Freight and Cogoport	Open freight quote/proxy platforms	Open route/proxy quotes for Saudi–Türkiye lanes	Indicative quotations; verify with carriers
GOV.UK GHG factors and Climatiq/BEIS factors	Governmental/open emissions factors	Emission factors by transport mode	Open factors; depends on load factor and fuel
UNCTAD and Reuters	International/news sources	Suez/Red Sea disruption evidence	Aggregate disruption evidence
SAR, TCDD, UIC and World Bank	Operator/international sources	Rail network and freight indicators	Operator-level details may be restricted
Expert review and future carrier quotations	Validation source	Corridor status and development evidence	Emerging project; no full operational data

Table 5: Open-source calibrated Monte Carlo input assumptions for ex-ante corridor assessment

Route	Base cost USD/FEU	Transit time days	Port/border delay days	Disruption probability	Disruption delay days	Data status / basis
R1 Jeddah–Suez–Mersin	2,182 / 3,549 / 5,139	16.96 / 19 / 26	0.5 / 1 / 2	5% / 12% / 25%	2 / 8 / 25	Observed time/distance + open cost benchmarks
R2 Dammam–Hormuz–Suez–Mersin	4,501 / 5,500 / 9,134	20 / 25 / 34	0.5 / 1.5 / 3	6% / 15% / 30%	2 / 8 / 25	Proxy quote + scenario-calibrated timing; longer than R1 due to Gulf/Hormuz leg
R3 Saudi–Jordan–Syria–Türkiye rail	2,300 / 3,800 / 6,500	4 / 7 / 12	1 / 3.5 / 9	8% / 20% / 40%	2 / 7 / 22	Emerging corridor; scenario-based
R4 Iraq–Türkiye multimodal	2,400 / 4,200 / 7,200	5 / 8 / 15	2 / 5.5 / 13	10% / 22% / 45%	2 / 8 / 26	Planned corridor; scenario-based

Note: R1 is calibrated from open route data and cost benchmarks. R2 uses a public cost proxy and scenario-calibrated timing because direct Dammam–Mersin timing is limited. R3 and R4 are scenario-based emerging corridors. All ranges require validation with carrier quotations, rail operator data, border records and expert review before policy use.

5. Results and Discussion

5.1 Numerical Results

The numerical outputs are illustrative and should be read as a decision-support demonstration rather than observed corridor performance. Table 6 uses corrected calibrated inputs for the maritime routes and scenario-based values for non-operational rail and multimodal corridors. R2 was revised so that its modeled lead time reflects the additional Gulf and Hormuz leg and is not shorter than the Jeddah–Suez baseline. R3 ranks highest in the future-state baseline because it has shorter modeled lead time and lower emissions, but this depends on infrastructure completion and effective border governance.

Table 6: Baseline illustrative simulation results based on corrected calibrated inputs

Route	Mean base freight cost USD/FEU	Mean lead time days	Reliability	Emissions kgCO2e	CRI
R3 Saudi–Jordan–Syria–Türkiye rail	4,201	14.5	98.2%	2,461	83.3
R1 Jeddah–Suez–Mersin	3,627	23.5	89.8%	4,072	74.7
R4 Iraq–Türkiye multimodal	4,598	19.3	90.8%	3,766	59.5
R2 Dammam–Hormuz–Suez–Mersin	6,373	30.0	62.0%	5,200	23.6

Note: Cost is mean base freight cost from Table 5, not full TLC in Equation (1). Reliability = $P(LT_r \leq 30$ days$)$. Emissions assume a 20-ton FEU. CRI uses baseline min-max normalization. Results are illustrative, not observed performance (Table 7).

Table 7: Scenario winners and supply chain interpretation

Scenario	Best route	CRI	Supply chain interpretation
S0 Base	R3 Rail	83.3	Future-state rail potential is strongest if infrastructure and border assumptions are achieved.
S1 Red Sea/Suez shock	R3 Rail	83.3	Rail-enabled redundancy protects service continuity because maritime route scores deteriorate sharply.
S2 Border friction	R1 Jeddah–Suez	74.7	Severe border delay can eliminate overland resilience benefits and restore the observed maritime route as the preferred option.
S3 Carbon pricing	R3 Rail	84.4	Lower-emission corridors gain value when carbon performance receives greater decision weight.
S4 Combined shock	R3 Rail	73.0	Rail remains valuable under combined maritime shock and moderate border friction, but its margin depends on border governance.

5.2 Graphical Results

Figure 3 shows the corrected scenario rankings using baseline normalization. The R3 rail-enabled corridor remains the strongest future-state option in the base, maritime shock, carbon-pricing and combined-shock scenarios. However, when border friction increases sharply, the observed R1 maritime route becomes the preferred option. This confirms the contingency argument that corridor diversification creates strategic options rather than a universally superior route (Figure 3).

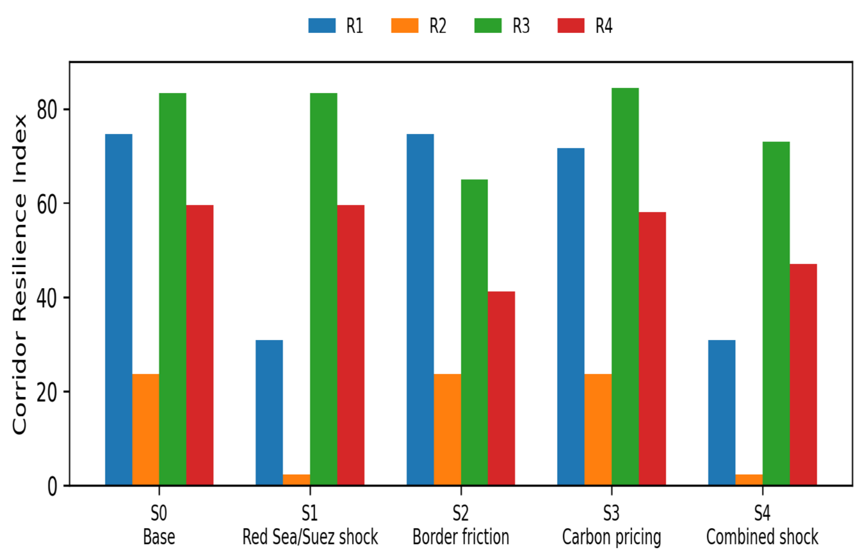

Figure 3: Corridor Resilience Index across disruption scenarios

Figure 4 summarizes the corrected baseline trade-off among base freight cost, lead time and emissions. R1 remains the lowest-cost observed maritime baseline. R2 is no longer treated as faster than R1; it is modeled as a longer and more expensive Gulf-origin sensitivity route because it includes the additional Hormuz and Suez exposure. The R3 corridor has the strongest modeled time and emissions profile, but its operational validity depends on future infrastructure and border performance.

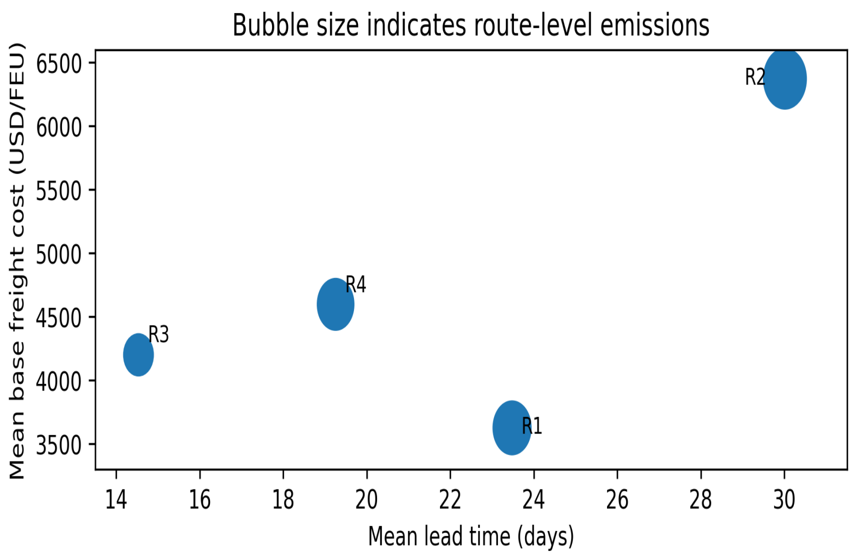

Figure 4: Baseline cost, lead-time and emissions trade-off

Figure 5 shows that the R3 corridor is sensitive to rail cost escalation, border delay and disruption probability. This means the corridor's supply chain value depends not only on track availability but also on competitive pricing, customs integration, security coordination and reliable cross-border operations.

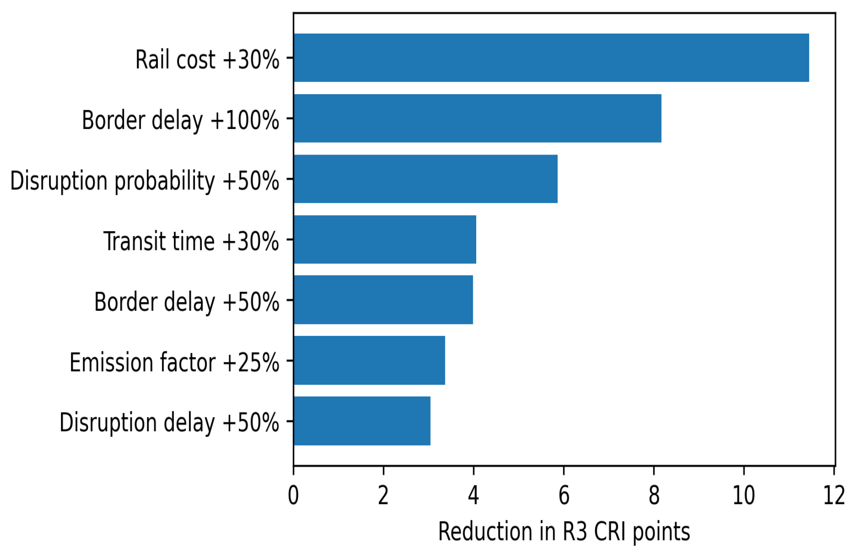

Figure 5: Sensitivity of R3 resilience score to adverse parameter shifts

5.3 Supply Chain Value Added and Proposed Improvements

Table 8, 9 and 10 presented improvements.

Table 8: Supply chain value added of the proposed corridor

Value mechanism	How it works	Supply chain benefit
Route redundancy	Provides an alternative when maritime routes become unreliable.	Improves continuity and recovery options.
Lead-time stability	Reduces exposure to long maritime detours in disruption scenarios.	Supports planning, production scheduling and service reliability.
Risk reduction	Spreads freight exposure across more than one corridor.	Lowers dependence on a single chokepoint.
Carbon performance	Rail-enabled options may reduce emissions compared with long diversions or road-heavy alternatives.	Supports green supply chain and ESG objectives.
Decision support	Converts route uncertainty into comparable resilience indicators.	Helps managers select routes by scenario rather than by cost alone.

Table 9: Managerial decision rules for supply chain route selection

Condition	Recommended decision	Rationale
Normal operations with low disruption	Use R1 as observed maritime baseline; monitor R3 readiness	R1 has observable service data, while R3 remains future-state.
Red Sea/Suez disruption exceeds tolerance	Shift time-sensitive flows to R3/R4 when available	Rail-enabled redundancy protects service continuity.
High border delay on overland corridors	Use R1 or redesign customs process	Border friction can destroy rail resilience value.
Gulf-origin industrial flows	Test R2 as sensitivity route	Dammam-based flows face Hormuz and Suez exposure.
High carbon pressure	Prioritize rail-enabled corridors when operational	Lower emissions improve resilience under sustainability constraints.
Low-value, non-urgent cargo	Use lowest total landed cost option	Resilience premium may not be justified for all commodities.

Table 10: Risk register for corridor implementation

Risk	Likelihood	Impact	Mitigation
Border delay	High	High	Digital customs, green lanes and pre-clearance
Incomplete infrastructure	High	High	Phased implementation and service pilots
Geopolitical disruption	Medium/high	High	Multilateral transit agreements and security protocols
Technical interoperability	Medium	Medium	Harmonized standards and terminal interfaces
Demand uncertainty	Medium	Medium	Anchor shippers and long-term logistics contracts
Data availability	Medium	Medium	Operator data sharing and commercial benchmark calibration

5.4 Validation

Validation is treated as a staged process because the corridor is emerging. Conceptual validation confirms that the model variables match supply chain resilience theory. Face validation evaluates whether the direction of results is plausible for logistics experts. Scenario validation tests whether route rankings change logically when maritime disruption, border friction or carbon price increases. Future empirical validation should calibrate the assumptions using freight-rate indices, operator data and expert elicitation from shippers, railway operators, customs authorities and logistics service providers. Before journal or policy use, the input ranges should be reviewed by an expert panel including at least one freight forwarder, one rail/logistics operator, one customs or border-process specialist and one supply chain academic (Table 11).

Table 11: Validation plan

Validation layer	Method	Purpose
Conceptual validation	Map variables to resilience theory and dynamic capability logic	Confirms model-theory alignment
Face validation	Review assumptions with logistics and rail experts	Improves practical realism
Sensitivity validation	Vary border delay, disruption probability and freight cost	Identifies dominant uncertainty drivers
Benchmark validation	Compare maritime assumptions with FBX/Drewry and route data	Improves external plausibility
Future operational validation	Use actual shipment data when corridor pilots operate	Converts illustrative model into empirical model

6. Conclusion

This paper reframes the emerging Saudi–Türkiye rail corridor as a supply chain resilience issue rather than a conventional infrastructure topic. Using a route-inventory and open-source calibration approach, the study demonstrates how rail corridor diversification can be evaluated as a strategic capability that may reduce maritime dependency, improve route redundancy and support logistics continuity under disruption. The analysis also shows that the corridor's value is conditional: it increases when maritime disruption or carbon pressure rises, but it can be weakened by border delay, incomplete infrastructure and institutional coordination failures.

The scientific contribution is threefold. First, the paper extends supply chain resilience analysis from the firm level to the corridor level. Second, it develops a simulation-based decision-support framework that integrates cost, lead time, reliability, disruption exposure and emissions into a Corridor Resilience Index. Third, it applies the framework to an emerging Gulf–Türkiye–Europe logistics corridor and translates the results into decision rules, risk priorities and validation requirements.

The results should be interpreted as illustrative because the rail and Iraq-linked alternatives are not yet fully operational and several values remain scenario assumptions. Future research should calibrate the model with real shipment data, direct freight quotations, rail operator data, customs processing times, expert elicitation and commodity-specific demand flows. For doctoral-level supply chain research, the key contribution is not the route map itself but the conceptualization and measurement of corridor diversification as a supply chain resilience capability.

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