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Risk and Cost Assessment of Suez Canal Transit Compared with Alternative Multimodal Corridors for Container Shipping between Abu Dhabi and Constanța

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Abstract. This paper quantifies the operational risk and the transport cost of a 10,000 TEU shipment between Abu Dhabi and Constanța South and compares the Suez Canal route with the Cape of Good Hope detour and with two multimodal corridors through Iran. One framework is applied to all four routes: a documented risk register, an expected-delay model, a Markov chain and an exposure-time model for the Suez Canal segment, a Monte Carlo simulation with 10,000 runs, reliability importance measures, and a Benchmark Index combining cost, time, capacity, energy and risk cost. Under baseline conditions the Suez Canal route costs USD 1.93 million and takes 9.0 days, against USD 3.93 million and 25.2 days around the Cape and USD 19.4–28.7 million and 25–33 days on the land corridors. The Benchmark Index ranks the routes Suez Canal (0.76), Cape of Good Hope (0.31), Iran–Caucasus (0.090) and Iran–Turkey (0.083), an order that is stable under all tested weights. Even with a 2024 war-risk premium the Suez Canal remains the most efficient option (0.63), so the 2024 diversions reflect insurability and safety rather than expected cost; the modelled cost difference between the maritime routes is consistent with the diversion costs reported for 2024.
Keywords: Suez Canal; Red Sea crisis; operational risk; Markov chain; Benchmark Index.

1. Introduction

The Suez Canal handled a record 26,434 transits in 2023, of which container ships accounted for 43 per cent of the number of transits (UNCTAD, 2024). In 2024, after the start of the attacks on merchant shipping in the southern Red Sea in November 2023, the number of transits fell to 13,213 and canal revenue fell from USD 10.2 billion to USD 3.9 billion (Business Today Egypt, 2025). By June 2024 the tonnage arriving at the Gulf of Aden was 76 per cent below the level of mid-December 2023, and in May 2025 Suez transits were still about 70 per cent below the 2023 average (UNCTAD, 2024, 2025). Between mid-December 2023 and early January 2024 alone, 354 container ships with a capacity of 4.65 million TEU, or 16.4 per cent of the world container fleet, were diverted around the Cape of Good Hope (Notteboom et al., 2024). Diversion added about 4,575 nautical miles and 12 days to a Shanghai–Rotterdam voyage, tripled bunker consumption for some services because of longer distances and higher speeds, and raised the Shanghai Containerized Freight Index for North Europe from 707 to 3,103 USD/TEU between mid-November 2023 and late January 2024 (Notteboom et al., 2024; UNCTAD, 2024). War-risk premiums for Red Sea transits rose from 0.3 per cent of hull value to about 1 per cent in January 2024 and again to 0.7–1 per cent after the sinking of two vessels in July 2025 (ITF, 2024; gCaptain, 2025).

The motivation of this research is, first, operational. The crisis showed that a chokepoint failure is not a rare theoretical event and that the decision to divert has to be taken quickly and under uncertainty. The information normally available to an operator is qualitative, in the form of security advisories and press reporting, whereas the decision requires a quantified comparison of delay probability, cost and residual risk for each alternative. A transparent and reproducible calculation framework is therefore of direct practical value for route selection and contingency planning.

The second motivation is regional. The port of Constanța South–Agigea is the largest container facility on the Black Sea, with a design capacity of about 1.5 million TEU at its main terminal (Netherlands Enterprise Agency, 2025), and it is the main maritime gateway of Romania and of a wide hinterland in Central and South-Eastern Europe. The reliability and the cost of its connection with the Persian Gulf therefore concern many shippers, and the Abu Dhabi–Constanța South relation has not, to the authors' knowledge, been treated quantitatively in the published literature. This is the research gap addressed by the paper.

The literature on the Red Sea crisis has grown rapidly. Notteboom et al. (2024) analyzed the ramifications of the crisis for vessel operations, shipping networks and supply chains; the International Transport Forum (ITF, 2024) documented the cost, freight rate and insurance effects and the case for international co-operation; UNCTAD (2024, 2025) placed the crisis in the wider context of maritime chokepoints, longer average hauls and higher emissions; Sun et al. (2026) estimated the environmental and economic cost of rerouting at not less than 46 per cent additional greenhouse gas emissions and 20–34 additional days per round trip; Liu et al. (2026) measured the heterogeneous resilience of ports under the crisis; and Karakaş (2026) compared the Suez Canal and the Cape of Good Hope routes from the point of view of fleet resilience. Safety statistics for 2024 are provided by the Allianz Commercial (2025) review, which reports 3,310 shipping incidents, 56 per cent of them caused by machinery damage or failure, and a Bab el-Mandeb traffic in February 2025 still 50 per cent below pre-crisis levels; piracy statistics are provided by the ICC International Maritime Bureau (ICC IMB, 2025), which recorded 116 incidents in 2024 and a resurgence of Somali activity in the western Indian Ocean.

Markov-chain modelling of stochastic delay is well established in operations research (Norris, 1997; Ross, 2014; Hillier & Lieberman, 2010), and Monte Carlo simulation is the standard method for propagating uncertain delays through supply chains (Chopra, 2019). Probabilistic importance measures, namely the Birnbaum, Fussell-Vesely, risk reduction worth and risk achievement worth measures, originate in reliability engineering and rank the contribution of individual events to system risk (Kuo & Zhu, 2012; Modarres et al., 2017). Multimodal route benchmarking on combined cost, time and energy criteria follows the comparative methodology of Paulauskas and Paulauskas (2024) for the major sea routes between Asia and Europe, and the unit-cost treatment of multimodal chains follows Vilko and Hallikas (2012). The Trans-Caspian and the Iranian corridors have been assessed as strategic alternatives to the maritime trunk route by the World Bank (2023), the Asian Development Bank (ADB, 2022), Kenderdine and Bucsky (2021) and Palu and Hilmola (2023), who identify the break of gauge, port waiting times, border crossings and the small Caspian and Black Sea feeder capacity as the main constraints; the missing Rasht–Astara rail link of the International North–South Transport Corridor was still awaiting construction in 2025 (van der Laan, 2025).

These contributions remain largely separate. Stochastic delay modelling, reliability importance measures and multi-criteria route benchmarking are seldom applied to the same case, and the route studies address either the global Asia–Europe trunk route or individual land corridors rather than a specific port-to-port relation. The present paper combines the three instruments within one framework, applies the same framework to all four alternatives, and documents every parameter from recent sources.

The objectives of the paper are to: (i) identify and classify the operational risks of each of the four routes by probability and consequence; (ii) model the delay of the Suez Canal segment with a Markov chain and with an exposure-time exponential model, and the delay of all four routes with an analytical expectation and a Monte Carlo simulation, so that transit times are directly comparable; (iii) rank the risk scenarios of every route by their contribution to total risk with the Birnbaum, Fussell-Vesely, risk reduction worth and risk achievement worth measures; and (iv) benchmark the four routes on a combined cost, time, capacity, energy and risk index, test the stability of the ranking against the weights, and validate the maritime cost differential against the diversion costs reported for 2024.

The paper is organized as follows. Section 2 presents the study area, the data sets, the modelling assumptions and the calculation methodology. Section 3 presents and discusses the results, the sensitivity analysis, the validation against the 2024 diversion data and the limitations of the study, and Section 4 states the conclusions.

2. Materials and methods

2.1. Study area and alternative routes

The study area covers the maritime and multimodal transport space between the Persian Gulf and the western Black Sea. The origin is the container terminal of Abu Dhabi (United Arab Emirates) and the destination is the port of Constanța South–Agigea (Romania). Four alternatives connect the two terminals (Table 1): two purely maritime routes, through the Suez Canal and around the Cape of Good Hope, and two multimodal corridors through the Iranian port of Bandar Abbas, one continuing by rail through Azerbaijan and Georgia to the port of Poti and by sea to Constanța (referred to below as the Iran–Caucasus corridor), the other continuing by rail through Tabriz to Istanbul and by sea to Constanța (the Iran–Turkey corridor). Maritime distances are given in nautical miles and, for comparability, also in kilometers; rail distances are given in kilometers.

The Suez Canal route leaves the Persian Gulf through the Strait of Hormuz and continues across the Gulf of Oman, the Arabian Sea, the Gulf of Aden and Bab el-Mandeb, the Red Sea, the Suez Canal, the eastern Mediterranean and the Turkish Straits into the Black Sea. It crosses four chokepoints and two areas with a documented security record, the Gulf of Aden and the southern Red Sea.

The Cape of Good Hope route follows the same track as far as the Arabian Sea, rounds southern Africa and re-enters the Mediterranean through the Strait of Gibraltar; it avoids Bab el-Mandeb and the canal but almost triples the sailing distance and exposes the vessel to South Atlantic and Agulhas Current weather.

The two corridors share the short maritime leg from Abu Dhabi to Bandar Abbas and then diverge. The Iran–Caucasus corridor requires a break of gauge at Astara (1,435 mm in Iran, 1,520 mm in Azerbaijan and Georgia) and, in its present state, road bridging of the 162 km Rasht–Astara section whose rail construction was agreed for 2025 (van der Laan, 2025; Palu & Hilmola, 2023). The Iran–Turkey corridor is continuous in gauge but crosses Lake Van by train ferry between Van and Tatvan.

Table 1. Alternative routes between Abu Dhabi and Constanța South.

Route	Itinerary	Length	Modes and interfaces	Critical points
A. Suez Canal	Abu Dhabi – Hormuz – Gulf of Aden – Bab el-Mandeb – Red Sea – Suez Canal – E. Mediterranean – Turkish Straits – Constanța South	4,047 nm (7,495 km)	Sea only; no transshipment	Four chokepoints; Gulf of Aden and southern Red Sea security
B. Cape of Good Hope	Abu Dhabi – Hormuz – Arabian Sea – Cape of Good Hope – Gibraltar – Turkish Straits – Constanța South	11,980 nm (22,187 km)	Sea only; no transshipment	Distance; Agulhas and South Atlantic weather; bunkering
C. Iran–Caucasus corridor	Abu Dhabi – Bandar Abbas (sea) – Astara – Poti (rail) – Constanța South (sea)	4,657 km (2,515 nm equiv.)	Sea–rail–rail–sea; three interfaces; break of gauge at Astara	Bandar Abbas congestion; Rasht–Astara missing link; two borders; sanctions exposure
D. Iran–Turkey corridor	Abu Dhabi – Bandar Abbas (sea) – Tabriz – Istanbul (rail) – Constanța South (sea)	6,389 km (3,450 nm equiv.)	Sea–rail–rail–sea; two interfaces; Lake Van train ferry	Bandar Abbas congestion; rail capacity; Lake Van ferry; sanctions exposure

2.2. Data sets

The analysis is based exclusively on secondary data; no primary measurements were carried out. Six data sets were assembled (Table 2). Where a source reports a range, the mid-point of the range is used in the analytical calculations and the full range is used in the Monte Carlo simulation. Where sources disagree, the more recent value is retained.

Monetary values are expressed in United States dollars at 2024 price levels, without discounting; maritime distances in nautical miles; land distances in kilometers; times in hours; and energy in kilowatt-hours of fuel energy, obtained from fuel mass with the lower heating value of marine fuel (IMO, 2020).

Table 2. Data sets used in the analysis.

Data set	Content	Source	Used in
Canal traffic and tariffs	Annual transits, revenue, transit dues schedule for laden container ships	Suez Canal Authority (2024); Business Today Egypt (2025); UNCTAD (2024)	Section 2.5; Tables 3, 5
Crisis statistics	Diverted capacity, added distance and days, freight-rate and insurance effects	Notteboom et al. (2024); ITF (2024); UNCTAD (2024, 2025); gCaptain (2025)	Sections 1, 2.4, 3.7
Incidents and risk	Casualty statistics, machinery failure share, piracy incidents	Allianz Commercial (2025); ICC IMB (2025)	Table 4
Distances	Maritime distances; rail segment lengths	Route distance calculators; national rail network data	Tables 1, 10
Cost and energy	Bunker price, fuel consumption, charter rates, rail tariffs, energy intensities	Ship & Bunker (2025); Rodrigue (2024); ING Research (2025); ADB (2022); U.S. BTS (2024); IMO (2020)	Tables 3, 6, 10, 11
Corridor operations	Transit times, border delays, Caspian and Black Sea feeder capacity, crane productivity	World Bank (2023); ADB (2022); Palu & Hilmola (2023); Steenken et al. (2004)	Section 2.9; Tables 3, 4

2.3. Research design and modelling assumptions

A hypothetical shipment of 10,000 TEU is routed from Abu Dhabi to Constanța South over the four alternatives. For the maritime routes the shipment is carried by one container vessel of the 10,000 TEU class; for the corridors it is carried by feeder vessels on the sea legs and by block trains on the rail legs. Loading at the origin terminal and discharge at the destination terminal are common to all alternatives and are excluded; port congestion at the origin and the destination is assumed identical for all four options. Risk parameters are treated as time-invariant over a single transit. Two conditions are considered for the Suez Canal route: baseline conditions, representing the security environment before November 2023, and 2024 crisis conditions, with an additional war-risk premium and an elevated probability of security-related delay.

The cost of the two maritime routes and the cost of the two corridors are computed on different bases, and this choice needs to be explained. On a maritime route the shipper, or the carrier acting for the shipper, controls a complete vessel, and the relevant cost is the voyage cost of that vessel: time-charter hire, bunker fuel, canal dues and, where applicable, the additional war-risk premium. On a multimodal corridor no single operator controls the whole chain; capacity is bought from rail operators and feeder lines per container, and the relevant cost is the sum of the tariffs per TEU-kilometer, the terminal handling charges per TEU and the fixed documentation costs of each segment. The two bases are therefore the ones actually faced by the decision-maker on each route. Both are reduced to the same quantities, the total cost of the 10,000 TEU shipment in USD and the cost per TEU, and it is these that enter the comparison. The same holds for time: the voyage time of the vessel and the door-to-door time of the corridor are both expressed in hours for the complete shipment, including transshipment and border time on the corridors.

Table 3 lists every parameter used in the models, its value, its source and the routes to which it applies. The bunker price is the 2024 annual average of the Ship & Bunker Global 20 Ports index for very low Sulphur fuel oil, 626 USD/t (Ship & Bunker, 2025). The fuel consumption of 140 t/day at 20 knots is derived from the 150 t/day reported for an 8,000 TEU vessel at 21 knots (Rodrigue, 2024) with the cubic speed law and a small size correction; the consumption during the canal passage at 8 knots is taken as 40 t/day. The time-charter equivalent of 70,000 USD/day is within the 41,000–74,000 USD/day range reported for 3,500–8,500 TEU vessels on 24-month charters in early 2025 (ING Research, 2025) and is applied to the slightly larger vessel used here.

The Suez Canal dues are computed from the laden container-ship tariff in force since 15 January 2024 (Suez Canal Authority, 2024) for a Suez Canal net tonnage of 100,000, which is representative of the 10,000 TEU class, at 1.33 USD per special drawing right. The war-risk additional premium of 0.7 per cent of an insured hull value of USD 100 million corresponds to the levels quoted in January 2024 and July 2025 (ITF, 2024; gCaptain, 2025). Rail tariffs are derived from the Middle Corridor rate of

about USD 5,400 per TEU for roughly 11,000 km between China and Germany (ADB, 2022), which corresponds to about 0.49 USD/TEU-km including handling; after separating the terminal handling charge of 80 USD/TEU per lift, a line-haul rate of 0.45 USD/TEU-km is retained. Feeder rates of 0.15 USD/TEU-km with the same handling charge reproduce the 160–250 USD/TEU level of short-sea services in the Gulf and the Black Sea in 2024. Crane productivity of 20 moves per hour and six cranes per interface are typical values for container terminal operations (Steenken et al., 2004), and the border dwell time of 24 h per rail border and the road bridging of 48 h at Rasht–Astara follow the corridor assessments of the World Bank (2023) and the ADB (2022).

Energy intensities are 0.21 MJ per tone-km for rail freight (U.S. Bureau of Transportation Statistics, 2024) and 0.10 MJ per tone-km for feeder vessels, consistent with the fleet averages of the Fourth IMO GHG Study (IMO, 2020); the energy of the main vessel is computed directly from its fuel consumption. The gross mass of the shipment is 140,000 t, that is 14 t per TEU. The inventory holding cost of the cargo is based on a value of 30,000 USD/TEU and an annual holding rate of 10 per cent (Chopra, 2019), and the detention cost of wagons and containers on the land corridors on 0.5 USD per TEU-hour.

Table 3. Model parameters, values, sources and applicability.

Parameter	Symbol	Value	Source	Applies to
Shipment size	Q	10,000 TEU	Design assumption	All routes
Service speed at sea	v	20 knots	UNCTAD (2024); Rodrigue (2024)	A, B
Speed in the canal / canal length	v_c, d_c	8 knots; 104 nm	Suez Canal Authority (2024)	A
Fuel consumption at 20 knots / in canal	f_s, f_c	140 t/day; 40 t/day	Rodrigue (2024), scaled	A, B
Bunker price (VLSFO, 2024 average)	p_b	626 USD/t	Ship & Bunker (2025)	A, B
Time-charter equivalent	h	70,000 USD/day	ING Research (2025)	A, B
Suez Canal net tonnage / exchange rate	SCNT, e	100,000; 1.33 USD/SDR	Suez Canal Authority (2024)	A
War-risk additional premium (crisis)	w	0.7 % of USD 100 million	ITF (2024); gCaptain (2025)	A (crisis)
Lower heating value of fuel	LHV	41,000 MJ/t	IMO (2020)	A, B
Rail line-haul tariff	α_{rail}	0.45 USD/TEU-km	ADB (2022), derived	C, D
Feeder tariff	α_{sea}	0.15 USD/TEU-km	Short-sea market 2024, derived	C, D
Terminal handling charge	β	80 USD/TEU per segment	ADB (2022); UNCTAD (2024)	C, D
Fixed documentation cost per segment	σ	20,000 USD	Authors' assumption	C, D
Feeder speed / rail commercial speed	v_f, v_r	16 knots; 35 km/h	World Bank (2023); ADB (2022)	C, D
Cranes per interface / productivity	n_c, r	6; 20 moves/h	Steenken et al. (2004)	C, D
Border dwell time / road bridging	t_b, t_{road}	24 h per border; 48 h	World Bank (2023); ADB (2022); van der Laan (2025)	C, D
Energy intensity, rail / feeder	e_{rail}, e_{sea}	0.21; 0.10 MJ/t-km	U.S. BTS (2024); IMO (2020)	C, D
Gross mass per TEU	m	14 t/TEU	Design assumption	C, D
Cargo value / holding rate	V, i	30,000 USD/TEU; 10 %/year	Chopra (2019)	All routes
Detention cost, land corridors	c_d	0.5 USD/TEU-h	Authors' assumption	C, D

2.4. Risk scenarios of the four routes

The first objective requires a risk register for every route, not only for the Suez Canal. Table 4 lists, for each route, the scenarios that can delay the shipment, the probability that the scenario occurs during one transit, the range of the resulting delay, and the source or reasoning behind each value. The Suez Canal scenarios are derived from the canal's convoy system and traffic statistics, from the 2024 casualty statistics in which machinery failure accounts for 56 per cent of incidents (Allianz Commercial, 2025), from the grounding record of the canal (UNCTAD, 2021), from the attack and diversion statistics of 2024 (ITF, 2024; UNCTAD, 2024) and from the 2024 piracy report (ICC IMB, 2025). Under baseline conditions the probability of a security-related delay in the southern Red Sea is 0.02; under 2024 crisis conditions it is raised to 0.125, and a seventh scenario, a missile or drone attack on the vessel with a probability of 0.01 per transit and a consequence of 10–30 days, is added; this probability is of the order of the ratio between the attacks reported in 2024 and the transits that continued through the strait (ITF, 2024).

The Cape of Good Hope scenarios reflect weather in the Agulhas Current and the South Atlantic, the need for a bunkering call on a voyage of 25 days, technical failure over a longer exposure time, and the security and congestion points that the route shares with the Suez route outside the Red Sea. The corridor scenarios reflect the constraints identified by the World Bank (2023), the ADB (2022) and Palu and Hilmola (2023): port waiting at Bandar Abbas, shortage of wagons and rail capacity, border and customs delays, Black Sea and Turkish Straits weather and congestion, the Lake Van ferry, and compliance holds related to sanctions on Iranian entities. Probabilities are per shipment and consequences are additional hours over the undisturbed time.

Table 4. Risk scenarios, probabilities per shipment and delay consequences for the four routes.

Route	Scenario	P_i	Delay range (h)	C_i (h)	Source / basis
A. Suez Canal	Heavy traffic / convoy waiting	0.12	12–24	18	SCA convoy statistics; UNCTAD (2024)
	Adverse weather (fog, sandstorm)	0.06	4–6	5	Allianz Commercial (2025)
	Technical failure of the vessel	0.025	8–12	10	Allianz Commercial (2025)
	Grounding or collision in the canal	0.015	12–48	30	UNCTAD (2021); Allianz Commercial (2025)
	Security incident, southern Red Sea	0.02	24–72	48	ITF (2024); UNCTAD (2024); baseline 0.02
	Piracy, Gulf of Aden – Somali basin	0.04	12–36	24	ICC IMB (2025)
B. Cape of Good Hope	Agulhas / South Atlantic weather	0.15	6–18	12	Rodrigue (2024); Allianz Commercial (2025)
	Bunkering call deviation	0.1	12–36	24	Notteboom et al. (2024)
	Technical failure on the long voyage	0.04	8–16	12	Allianz Commercial (2025)
	Security, Strait of Hormuz – Arabian Sea	0.05	12–36	24	ITF (2024)
	Congestion, Gibraltar – Turkish Straits	0.05	4–8	6	UNCTAD (2024)
	Piracy, Gulf of Guinea offshore	0.02	12–36	24	ICC IMB (2025)
C. Iran–Caucasus	Security, Strait of Hormuz	0.05	12–36	24	ITF (2024)
	Port congestion, Bandar Abbas	0.2	24–72	48	World Bank (2023); ADB (2022)
	Rail capacity / wagon shortage	0.25	48–96	72	World Bank (2023); Palu & Hilmola (2023)
	Border and customs delay (Astara, Georgia)	0.3	24–72	48	ADB (2022); World Bank (2023)
	Weather / berth delay, Poti – Black Sea	0.15	12–36	24	Netherlands Enterprise Agency (2025)
	Sanctions compliance hold	0.1	72–168	120	Palu & Hilmola (2023)
Route	**Scenario**	P_i	**Delay range (h)**	C_i (h)	**Source / basis**
D. Iran–Turkey	Security, Strait of Hormuz	0.05	12–36	24	ITF (2024)
	Port congestion, Bandar Abbas	0.2	24–72	48	World Bank (2023); ADB (2022)
	Rail capacity / wagon shortage	0.25	48–96	72	World Bank (2023); Palu & Hilmola (2023)
	Lake Van ferry and Kapıköy border delay	0.3	24–72	48	ADB (2022)
	Congestion, Istanbul – Turkish Straits	0.1	12–36	24	UNCTAD (2024)
	Sanctions compliance hold	0.1	72–168	120	Palu & Hilmola (2023)
A (crisis)	Security incident, southern Red Sea	0.125	24–72	48	ITF (2024); UNCTAD (2024)
	Attack on the vessel (missile / drone)	0.01	240–720	480	ITF (2024); gCaptain (2025)

2.5. Transport cost, time and energy of the maritime routes

The undisturbed voyage time of a maritime route with total distance d, of which d_c is sailed inside the canal at speed v_c and the remainder at sea speed v, is

$$T_0 = \frac{d - d_c}{v} + \frac{d_c}{v_c} \quad (1)$$

For the Cape of Good Hope route $d_c = 0$. The fuel consumed on the voyage is

$$F = \frac{f_s(d - d_c)}{24v} + \frac{f_c d_c}{24 v_c} \quad (2)$$

where f_s and f_c are the daily consumptions at sea and in the canal. The voyage cost of the vessel is the sum of bunker cost, hire, canal dues and, under crisis conditions, the war-risk additional premium:

$$C_{sea} = F p_b + \frac{h T_0}{24} + C_{dues} + w V_h \quad (3)$$

The canal dues follow the tiered tariff of the Suez Canal Authority, in which the net tonnage of the vessel is split into successive bands s_k charged at decreasing rates r_k in special drawing rights:

$$C_{dues} = e \sum_{k=1}^{K} r_k s_k \quad (4)$$

For a Suez Canal net tonnage of 100,000 the tariff bands give 439,500 SDR (Table 5), that is USD 584,535 at the 2024 exchange rate. Pilotage, mooring and agency charges are excluded because they are small relative to the dues and apply equally to both maritime routes. The energy of the voyage, in kWh, is obtained from the fuel mass and the lower heating value:

$$E = \frac{F \cdot \mathrm{LHV}}{3.6} \quad (5)$$

Table 5. Computation of the Suez Canal transit dues for a laden container vessel of 100,000 SCNT (tariff in force since 15 January 2024).

Band	Tonnage in band (SCNT)	Rate (SDR/SCNT)	Dues (SDR)
1	5,000	11.04	55,200
2	5,000	7.58	37,900
3	10,000	5.89	58,900
4	20,000	4.13	82,600
5	30,000	3.82	114,600
6	30,000	3.01	90,300
Total	**100,000**		**439,500**

2.6. Analytical expected delay and total transit time

For every route the expected delay of one shipment is the sum over the scenarios of Table 4 of the probability of each scenario multiplied by the mid-point of its consequence:

$$R = \sum_{i=1}^{n} P_i C_i \quad (6)$$

R is at the same time the expected delay in hours and the measure of total system risk used by the importance analysis of Section 2.8, which makes the link between the risk register and the importance measures explicit. The total transit time of the shipment on a route is

$$T = T_0 + R \quad (7)$$

Equation (7) is applied identically to the four routes, so that the resulting transit times are directly comparable. The Markov chain and the exposure-time model of Section 2.7 are applied to the Suez Canal segment only, because the canal is the one segment of the four routes in which the delay is generated by a queueing and convoy system with persistent congestion states; they provide two independent checks on the value of R for that route. The Monte Carlo simulation of Section 2.9 is applied to all four routes and provides the distribution around the expected value.

2.7. Markov chain and exposure-time models of the Suez Canal segment

The condition of the canal segment at the arrival of a vessel is described by three states: S_1 normal, S_2 moderate delay and S_3 severe delay. One step of the chain corresponds to one transit. The transition probabilities from the normal state are derived from the risk register, so that the chain and the register share the same data. A moderate delay arises if at least one of the moderate scenarios (heavy traffic, adverse weather, technical failure) occurs, and a severe delay if at least one of the severe scenarios (grounding or collision, security incident, piracy) occurs. Treating the scenarios as independent,

$$p_{12} = 1 - \prod_{i \in M}(1 - P_i) = 1 - 0.88 \cdot 0.94 \cdot 0.975 = 0.193 \quad (8)$$

$$p_{13} = 1 - \prod_{i \in S}(1 - P_i) = 1 - 0.985 \cdot 0.98 \cdot 0.96 = 0.073 \quad (9)$$

where M and S are the sets of moderate and severe scenarios. The probability of remaining in the normal state is $p_{11} = 1 - p_{12} - p_{13} = 0.733$. The transitions out of the delayed states describe the persistence of

congestion once it has formed; they are calibrated on the recovery of the canal after the 2021 grounding, when the backlog of more than 400 vessels was cleared in about four days after a six-day closure (UNCTAD, 2021), which corresponds to a probability of about 0.3 of returning to normal conditions from a moderate delay and about 0.2 from a severe delay within one transit interval. With rows and columns in the order S_1, S_2, S_3 the transition matrix is

$$P = \begin{bmatrix} 0.733 & 0.193 & 0.073 \\ 0.300 & 0.600 & 0.100 \\ 0.200 & 0.400 & 0.400 \end{bmatrix} \tag{10}$$

The delay attached to the two delayed states is the mid-point of the moderate and severe ranges of Table 4: T_2 = 18 h and T_3 = 48 h. Two quantities are computed from the chain, and they answer different questions. The one-step expected delay is the delay expected by a vessel that arrives while the canal is in the normal state:

$$E_1 = p_{12}T_2 + p_{13}T_3 = 0.193 \cdot 18 + 0.073 \cdot 48 = 7.00\ \text{h} \tag{11}$$

The long-run expected delay is the delay expected by a vessel that arrives at an arbitrary moment, when the canal may already be congested; it uses the stationary distribution of the chain, which is the solution of

$$\pi = \pi P,\ \ \sum_{j=1}^{3} \pi_j = 1 \tag{12}$$

$$\pi = [0.508 \quad 0.369 \quad 0.124],\ E_{st} = \pi_2 T_2 + \pi_3 T_3 = 12.57\ \text{h} \tag{13}$$

The one-step value is the appropriate one for a shipment planned under normal conditions, and it is the value compared with the other models; the stationary value (12.6 h) is an upper bound that accounts for the persistence of congestion and is reported for completeness. The two-step transition matrix $\mathbf{P}^2$ gives an intermediate value of 10.1 h. Under crisis conditions the severe transition probability becomes p_{13} = 1 − 0.985 · 0.875 · 0.96 · 0.99 = 0.181 and the one-step expected delay 12.16 h.

The discrete chain describes the state at arrival but not the dependence of the delay probability on the time the vessel spends in the exposed zone. This dependence is captured by the exposure-time exponential model (MPETS), in which each transition from the normal state is a Poisson process with a constant rate λ_{ij}. The rate is calibrated so that, over the reference exposure time τ_{ref} of the zone in which the scenarios of Table 4 are defined, the model reproduces the per-transit probabilities of the chain:

$$\lambda_{ij} = -\frac{\ln(1 - p_{ij})}{\tau_{ref}} \tag{14}$$

$$p_{ij}(t) = 1 - e^{-\lambda_{ij} t} \tag{15}$$

$$E(t) = p_{12}(t)T_2 + p_{13}(t)T_3 \tag{16}$$

The reference exposure is the passage from Bab el-Mandeb to Port Said, about 1,400 nm at 20 knots plus the canal passage, that is τ_{ref} = 83 h, which gives $\lambda_{12} = 2.59 \times 10^{-3}$ h^{-1} and $\lambda_{13} = 0.92 \times 10^{-3}$ h^{-1}. At $t = \tau_{ref}$ the model returns p_{12} = 0.193, p_{13} = 0.073 and E = 7.00 h, identical to the one-step Markov result; the two models therefore use the same probabilities and the same delay durations, and they differ only in what they add. The value of the exposure-time model lies in the sensitivity of the delay to a longer stay in the zone, for example because of convoy waiting or slow steaming: at t = 120 h the expected delay rises to 9.81 h and at t = 168 h to 13.21 h.

2.8. Importance measures of the risk scenarios

The contribution of each scenario to the total risk of a route is ranked with the importance measures of reliability engineering (Kuo & Zhu, 2012; Modarres et al., 2017). Because R in Equation (6) is linear in the probability P of any one scenario, it can be written for scenario i as

$$R = aP_i + b,\ \ a = C_i,\ \ b = \sum_{j \neq i} P_j C_j \tag{17}$$

where a is the contribution of scenario i per unit of probability and b is the contribution of all other scenarios. The Birnbaum measure is the sensitivity of total risk to the probability of the scenario, the Fussell-Vesely measure is the fraction of total risk attributable to the scenario, the risk reduction worth is the factor by which total risk would fall if the scenario were eliminated, and the risk achievement worth is the factor by which total risk would rise if the scenario became certain:

$$I_B = \frac{\partial R}{\partial P_i} = a = C_i \tag{18}$$

$$I_{FV} = \frac{aP_i}{R} = \frac{P_i C_i}{aP_i + b} \quad (19)$$

$$I_{RRW} = \frac{R}{R(P_i = 0)} = \frac{aP_i + b}{b} \quad (20)$$

$$I_{RAW} = \frac{R(P_i = 1)}{R} = \frac{a + b}{aP_i + b} \quad (21)$$

The Birnbaum measure has the dimension of hours; the other three are dimensionless. All four are computed directly from the probabilities and consequences of Table 4, so that every value in the importance tables of Section 3 can be traced to the risk register.

2.9. Monte Carlo simulation of delay

The analytical expectation of Equation (6) does not describe the dispersion of the delay, which matters for contingency planning. For each route the delay of one shipment is therefore simulated as

$$D = \sum_{i=1}^{n} X_i Y_i, \quad X_i \sim \text{Bernoulli}(P_i), \quad Y_i \sim \text{Triangular}\left(C_{i,min}, C_i, C_{i,max}\right) \quad (22)$$

where X_i indicates whether scenario i occurs and Y_i is its duration, drawn from a triangular distribution over the delay range of Table 4 with the mode at the mid-point. The triangular distribution is chosen because the sources give the range and the typical value of each delay but not its full distribution. N = 10,000 independent shipments are simulated for each route with a fixed random seed, and the mean, the standard deviation, the 95 per cent confidence interval of the mean, the median, the 95th percentile and the probability of a delay-free transit are reported. The confidence interval of the mean is

$$\overline{D} \pm 1.96 \frac{s}{\sqrt{N}} \quad (23)$$

The same procedure with the same distributions is applied to the four routes, which makes the simulated transit times directly comparable; the Suez Canal route is simulated under both baseline and crisis conditions.

2.10. Cost, time and energy of the multimodal corridors

Each corridor consists of n = 4 segments. Following the unit-cost formulation of Vilko and Hallikas (2012), the cost of segment i of length d_i comprises a line-haul component proportional to the distance and the number of containers, a handling component proportional to the number of containers, and a fixed component per segment:

$$C_{corr} = \sum_{i=1}^{n} (\alpha_i d_i Q + \beta_i Q + \sigma_i) \quad (24)$$

where α_i is the tariff in USD per TEU-km (α_{rail} or α_{sea} according to the mode), β_i the terminal handling charge in USD/TEU and σ_i the fixed documentation and customs cost of the segment in USD. The corresponding unit cost per TEU-km, which allows a comparison with the maritime routes on a distance basis, is

$$c_{unit,i} = \alpha_i + \frac{\beta_i}{d_i} + \frac{\sigma_i}{d_i Q} \quad (25)$$

The door-to-door time of the corridor is the sum of the movement times of the segments, the transshipment time at the n_{int} interfaces between modes, the dwell time at the n_b rail border crossings and, on the Iran–Caucasus corridor, the road bridging time of the missing rail link:

$$T_{0,corr} = \sum_{i=1}^{n} \frac{d_i}{v_i} + n_{int} \frac{2Q}{n_c r} + n_b t_b + t_{road} \quad (26)$$

In the transshipment term, Q is in TEU, n_c is the number of cranes working simultaneously and r their productivity in moves per crane-hour, so the term is in hours; the factor 2 accounts for the discharge from the incoming mode and the loading of the outgoing mode. With Q = 10,000 TEU, n_c = 6 and r = 20 moves/h each interface takes 166.7 h. The energy of the corridor is computed from the gross mass of the shipment m per TEU, the segment distances and the energy intensity e_i of each mode:

$$E_{corr} = \frac{mQ}{3.6} \sum_{i=1}^{n} d_i e_i \quad (27)$$

with m in t/TEU, d_i in km and e_i in MJ per tonne-km, which gives E_{corr} in kWh.

2.11. Risk cost and Benchmark Index

The residual risk of each route is expressed as a cost so that it can enter the Benchmark Index. The risk cost is the expected delay multiplied by the hourly cost of holding the shipment:

$$A = R \cdot c_h, \quad c_h = \frac{h}{24} + \frac{QVi}{8760} \text{ (sea)}, \quad c_h = c_d Q + \frac{QVi}{8760} \text{ (land)} \quad (28)$$

On the maritime routes the hourly cost is the vessel hire plus the inventory holding cost of the cargo, 6,341 USD/h; on the corridors it is the detention cost of wagons and containers plus the same inventory cost, 8,425 USD/h. The Benchmark Index adapts the comparative methodology of Paulauskas and Paulauskas (2024) to the five criteria of this study. Each criterion is normalized by a reference value and weighted, and the index is the reciprocal of the weighted sum, so that a higher index denotes a more efficient route:

$$I_B = \frac{1}{\eta_T\left(k_P\frac{P_T}{P_0} + k_T\frac{T_T}{T_0} + k_D\frac{D_T}{D_0} + k_E\frac{E_T}{E_0} + k_A\frac{A_T}{A_0}\right)} \quad (29)$$

where P_T is the total cost of the shipment in USD, T_T the total transit time in hours including the expected delay, D_T the capacity requirement of the route expressed as the number of transport units needed to move the shipment (one vessel on a maritime route; on a corridor the number of feeder vessels of 1,500 TEU and of block trains of 100 TEU, counted separately on each side of a break of gauge), E_T the energy in kWh and A_T the risk cost in USD.

The reference values are P_0 = 1,000,000 USD, T_0 = 100 h, D_0 = 10 units, E_0 = 10,000,000 kWh and A_0 = 100,000 USD; they are of the order of magnitude of the maritime routes, so that each normalized term is of order one for those routes and the index is not dominated by a single criterion. The weights k_P = 0.25, k_T = 0.20, k_D = 0.15, k_E = 0.25 and k_A = 0.15 sum to one and give cost and energy the largest weight, in line with the criteria weighting of Paulauskas and Paulauskas (2024); η_T = 1 represents a transport system operating at its nominal efficiency. Because the weights are a judgement, Section 3.6 recomputes the index for each weight increased and decreased by 0.10, with the other weights rescaled to sum to one, and for equal weights, and checks whether the ranking of the routes changes.

3. Results and discussions

3.1. Cost, time and energy of the maritime routes

Table 6 gives the results of Equations (1)–(5) for the two maritime routes. On the Suez Canal route the vessel sails 3,943 nm at 20 knots in 197.15 h and the 104 nm of the canal at 8 knots in 13.0 h, an undisturbed time of 210.15 h (8.76 days); around the Cape the undisturbed time is 599 h (24.96 days). Fuel consumption is 1,171.7 t through the canal and 3,494.2 t around the Cape, a ratio of 2.98, which is consistent with the tripling of bunker consumption reported for diverted services (UNCTAD, 2024). Under baseline conditions the Suez Canal route costs USD 1,930,962 (193.1 USD/TEU), of which 38 per cent is bunker fuel, 32 per cent hire and 30 per cent canal dues. The Cape of Good Hope route costs USD 3,934,432 (393.4 USD/TEU), 2.04 times the baseline Suez cost; the saving of the canal dues is far outweighed by 16.2 additional days of hire and by the additional fuel. Under 2024 crisis conditions the war-risk premium raises the Suez cost to USD 2,630,962 (263.1 USD/TEU), and the Cape route remains 50 per cent more expensive. The cost structure of all routes is shown in Figure 1.

Table 6. Cost, time and energy of the maritime routes (10,000 TEU).

Item	Suez Canal, baseline	Suez Canal, 2024 crisis	Cape of Good Hope
Distance	4,047 nm	4,047 nm	11,980 nm
Undisturbed time T_0 (h / days)	210.15 / 8.76	210.15 / 8.76	599.00 / 24.96
Fuel consumption F (t)	1,171.7	1,171.7	3,494.2
Bunker cost (USD)	733,489	733,489	2,187,348
Vessel hire (USD)	612,938	612,938	1,747,083
Canal dues (USD)	584,535	584,535	0
War-risk additional premium (USD)	0	700,000	0
Total cost (USD)	**1,930,962**	**2,630,962**	**3,934,432**
Cost per TEU (USD/TEU)	193.1	263.1	393.4
Unit cost (USD/TEU-km)	0.0258	0.0351	0.0177
Energy E (kWh)	13,344,456	13,344,456	39,794,676

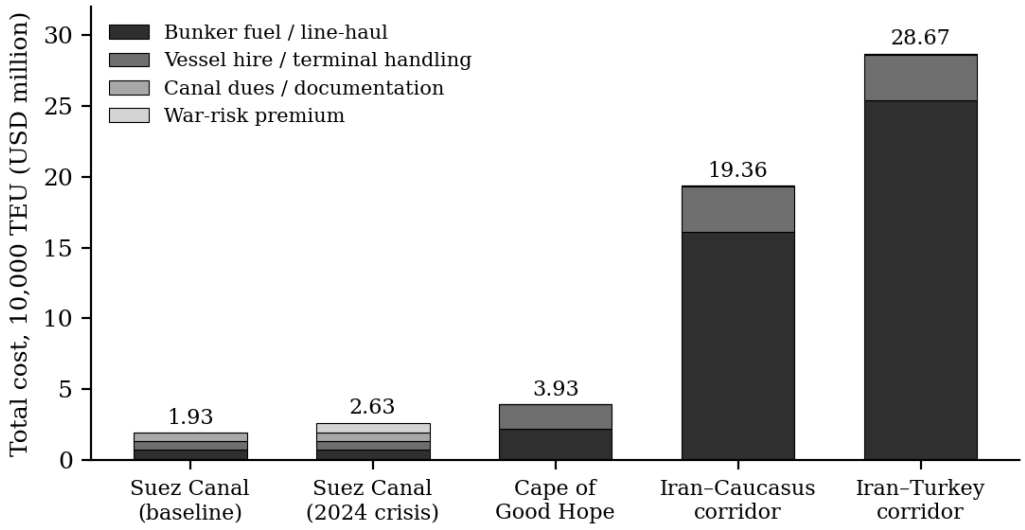


Figure 1. Cost structure of the five route cases for a 10,000 TEU shipment.

3.2. Delay of the Suez Canal segment: analytical, Markov chain, exposure-time and Monte Carlo estimates

Table 7 brings together the four estimates of the delay on the Suez Canal route. Under baseline conditions the analytical expectation of Equation (6) is 5.08 h, the one-step Markov chain gives 7.00 h, the exposure-time model gives the same value at the reference exposure and 9.81 h if the exposure is extended to 120 h, and the Monte Carlo mean is 4.93 h with a 95 per cent confidence interval of 4.72–5.14 h. The analytical and the simulated values agree within the confidence interval, as they must, since the simulation samples the same distributions. The Markov one-step value is about 2 h higher because it assigns the class delay of 18 h and 48 h to every moderate and severe event, whereas the register assigns a shorter delay to weather and technical events; the difference is a measure of the aggregation error of the three-state description and is small relative to the transit time. The stationary value of 12.6 h is an upper bound for arrivals during an existing congestion. The total transit time under baseline conditions is therefore 215.2 h (8.97 days) with the analytical delay and 217.2 h with the Markov delay. Under crisis conditions the expected delay rises to 14.92 h analytically and 12.16 h in the chain, and the Monte Carlo mean is 13.6 h with a standard deviation of 46.0 h, dominated by the low-probability attack scenario.

Table 7. Delay estimates for the Suez Canal route (hours).

Estimate	Baseline conditions	2024 crisis conditions	Basis
Analytical expectation R, Eq. (6)	5.08	14.92	Table 4
Markov chain, one step from S_1, Eq. (11)	7.00	12.16	Eqs. (8)–(10)
Markov chain, two steps	10.09	–	$\mathbf{P}^2$
Markov chain, stationary, Eq. (13)	12.57	–	Eq. (12)
Exposure-time model, t = 83 h, Eq. (16)	7.00	–	Eqs. (14)–(15)
Exposure-time model, t = 120 h	9.81	–	Eqs. (14)–(15)
Exposure-time model, t = 168 h	13.21	–	Eqs. (14)–(15)
Monte Carlo mean (95 % CI), Eq. (22)	4.93 (4.72–5.14)	13.60 (12.70–14.51)	N = 10,000
Total transit time T with analytical delay (h / days)	215.2 / 8.97	225.1 / 9.38	Eq. (7)

3.3. Monte Carlo delay and comparable transit times of the four routes

Table 8 and Figure 2 give the simulation results for the four routes and the resulting transit times. The two maritime routes have small expected delays, 4.9 h and 6.6 h, and a delay-free transit in 75 and 65 per cent of the simulated shipments; their 95th percentiles, 26 h and 30 h, are of the order of one day. The corridors have expected delays of 60 h and 57 h, a delay-free transit in only about 30 per cent of the shipments, and 95th percentiles of about one week. The confidence intervals of the means are narrow,

about ± 0.2 h for the maritime routes and ± 1.1 h for the corridors, which shows that 10,000 runs are sufficient. With the expected delay added to the undisturbed time, the shipment takes 9.0 days through the Suez Canal, 25.2 days around the Cape, 33.2 days on the Iran–Caucasus corridor and 25.1 days on the Iran–Turkey corridor. These four values are obtained with the same equation and the same simulation procedure and are therefore directly comparable.

Table 8. Monte Carlo delay statistics (N = 10,000) and comparable transit times of the four routes.

Route	R (h)	Mean (h)	SD (h)	95 % CI of mean (h)	Median (h)	95th pct. (h)	No delay (%)	T_0 (h)	T (h / days)
A. Suez Canal, baseline	5.08	4.93	10.89	4.72–5.14	0.0	25.7	75	210.2	215.2 / 9.0
A. Suez Canal, 2024 crisis	14.92	13.60	45.96	12.70–14.51	0.0	56.4	66	210.2	225.1 / 9.4
B. Cape of Good Hope	6.66	6.59	10.97	6.37–6.80	0.0	29.9	65	599.0	605.7 / 25.2
C. Iran–Caucasus	58.80	60.10	58.31	58.96–61.24	51.3	174.4	30	737.5	796.3 / 33.2
D. Iran–Turkey	57.60	57.14	57.21	56.02–58.26	49.4	168.6	33	545.7	603.3 / 25.1

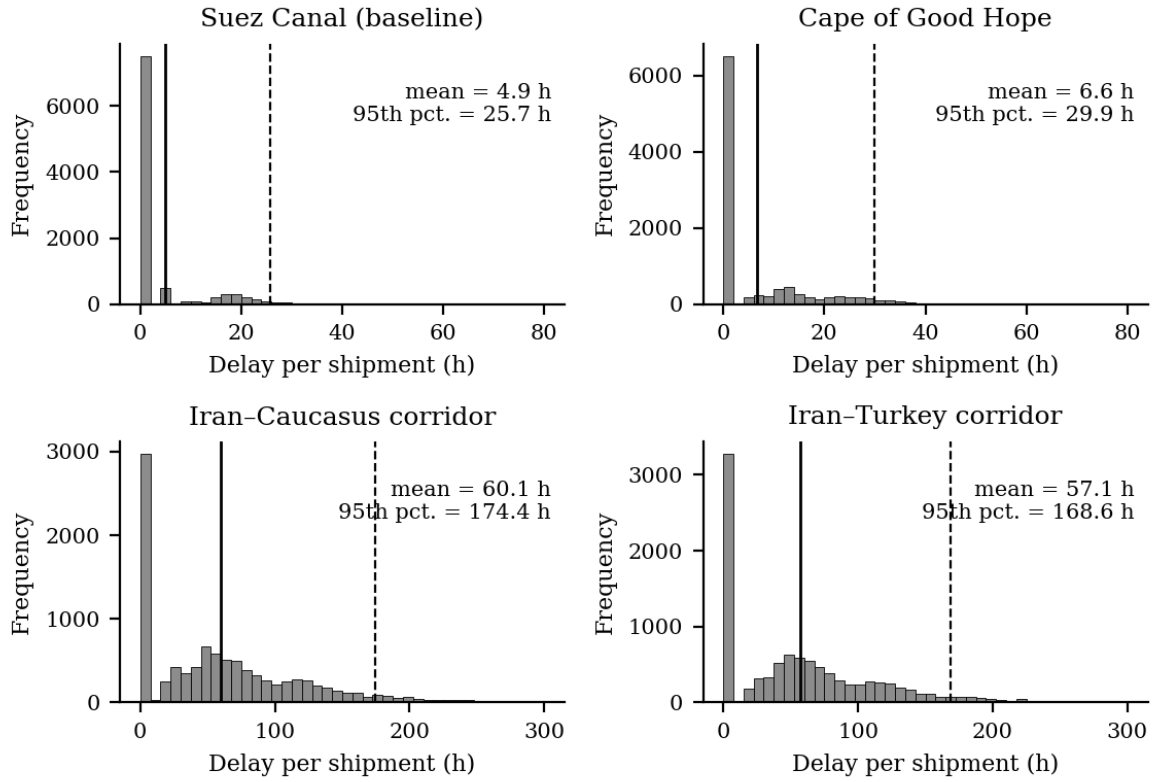


Figure 2. Simulated distribution of the delay per shipment on the four routes (N = 10,000); the solid line marks the mean and the dashed line the 95th percentile.

3.4. Importance measures of the risk scenarios

Tables 9 and 10 give the importance measures of Equations (18)–(21) for the Suez Canal route under both conditions and for the other three routes; Figure 3 compares the Fussell-Vesely measures of the Suez scenarios. Under baseline conditions heavy traffic and convoy waiting is the dominant scenario, with 43 per cent of the total risk of 5.08 h and a risk reduction worth of 1.74, followed by the security and piracy scenarios with 19 per cent each. The Birnbaum measure, equal to the consequence of the scenario, and the risk achievement worth rank the scenarios differently: the security incident (10.3) and the grounding or collision (6.8) would multiply total risk the most if they became certain, which identifies them as the scenarios to insure against even though their present contribution is modest.

Under crisis conditions the picture changes: the security incident contributes 40 per cent and the attack scenario 32 per cent of a total risk of 14.9 h, and the risk achievement worth of the attack scenario, 32.8, is an order of magnitude above any other value in the tables.

On the Cape route the bunkering call and the weather in the Agulhas Current dominate. On both corridors the shortage of rail capacity (31 per cent), the border or ferry delays (24 per cent) and the sanctions compliance hold (20 per cent) account for three quarters of the total risk, and the compliance hold has the highest risk achievement worth because of its long consequence.

Table 9. Risk importance measures of the Suez Canal scenarios under baseline and 2024 crisis conditions.

Condition	Scenario	P_i	C_i (h)	P_iC_i (h)	I_B (h)	I_{FV}	I_{RRW}	I_{RAW}
Baseline	Heavy traffic / convoy waiting	0.12	18	2.16	18	0.425	1.740	4.12
	Adverse weather (fog, sandstorm)	0.06	5	0.30	5	0.059	1.063	1.93
	Technical failure of the vessel	0.025	10	0.25	10	0.049	1.052	2.92
	Grounding or collision in the canal	0.015	30	0.45	30	0.089	1.097	6.82
	Security incident, southern Red Sea	0.02	48	0.96	48	0.189	1.233	10.26
	Piracy, Gulf of Aden – Somali basin	0.04	24	0.96	24	0.189	1.233	5.54
	Total risk R = *5.08 h*			**5.08**		**1.000**		
2024 crisis	Heavy traffic / convoy waiting	0.12	18	2.16	18	0.145	1.169	2.06
	Adverse weather (fog, sandstorm)	0.06	5	0.30	5	0.020	1.021	1.32
	Technical failure of the vessel	0.025	10	0.25	10	0.017	1.017	1.65
	Grounding or collision in the canal	0.015	30	0.45	30	0.030	1.031	2.98
	Security incident, southern Red Sea	0.125	48	6.00	48	0.402	1.673	3.82
	Piracy, Gulf of Aden – Somali basin	0.04	24	0.96	24	0.064	1.069	2.54
	Attack on the vessel (missile / drone)	0.01	480	4.80	480	0.322	1.474	32.85
	Total risk R = *14.92 h*			**14.92**		**1.000**		

Table 10. Risk importance measures of the Cape of Good Hope route and of the two multimodal corridors.

Route	Scenario	P_i	C_i (h)	P_iC_i (h)	I_B (h)	I_{FV}	I_{RRW}	I_{RAW}
B. Cape	Agulhas / South Atlantic weather	0.15	12	1.80	12	0.270	1.370	2.53
	Bunkering call deviation	0.1	24	2.40	24	0.360	1.563	4.24
	Technical failure on the long voyage	0.04	12	0.48	12	0.072	1.078	2.73
	Security, Strait of Hormuz – Arabian Sea	0.05	24	1.20	24	0.180	1.220	4.42
	Congestion, Gibraltar – Turkish Straits	0.05	6	0.30	6	0.045	1.047	1.86
	Piracy, Gulf of Guinea offshore	0.02	24	0.48	24	0.072	1.078	4.53
	Total risk R = *6.66 h*			**6.66**		**1.000**		
C. Iran–Caucasus	Security, Strait of Hormuz	0.05	24	1.20	24	0.020	1.021	1.39
	Port congestion, Bandar Abbas	0.2	48	9.60	48	0.163	1.195	1.65
	Rail capacity / wagon shortage	0.25	72	18.00	72	0.306	1.441	1.92
	Border and customs delay (Astara, Georgia)	0.3	48	14.40	48	0.245	1.324	1.57
	Weather / berth delay, Poti – Black Sea	0.15	24	3.60	24	0.061	1.065	1.35
	Sanctions compliance hold	0.1	120	12.00	120	0.204	1.256	2.84
	Total risk R = *58.80 h*			**58.80**		**1.000**		
D. Iran–Turkey	Security, Strait of Hormuz	0.05	24	1.20	24	0.021	1.021	1.40
	Port congestion, Bandar Abbas	0.2	48	9.60	48	0.167	1.200	1.67
	Rail capacity / wagon shortage	0.25	72	18.00	72	0.312	1.455	1.94
	Lake Van ferry and Kapıköy border delay	0.3	48	14.40	48	0.250	1.333	1.58
	Congestion, Istanbul – Turkish Straits	0.1	24	2.40	24	0.042	1.043	1.38
	Sanctions compliance hold	0.1	120	12.00	120	0.208	1.263	2.88
	Total risk R = *57.60 h*			**57.60**		**1.000**		

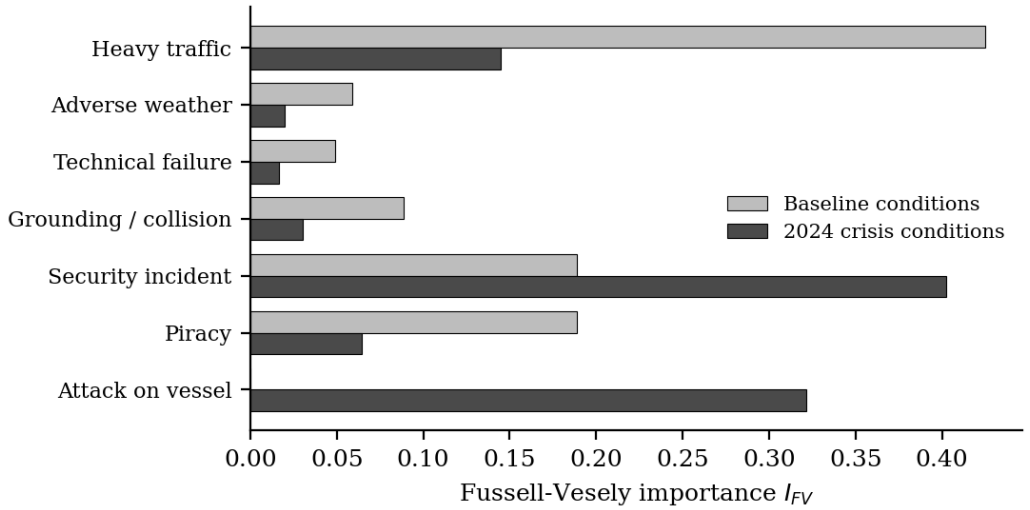


Figure 3. Fussell-Vesely importance of the Suez Canal risk scenarios under baseline and 2024 crisis conditions.

3.5. Cost, time and energy of the multimodal corridors

Table 11 gives the segment results of Equations (24)–(27). The Iran–Caucasus corridor costs USD 19,364,500 (1,936 USD/TEU) and the Iran–Turkey corridor USD 28,667,500 (2,867 USD/TEU), that is 10 and 15 times the baseline Suez cost. The rail legs account for 79 and 88 per cent of the corridor cost respectively.

The unit cost per TEU-km of the corridors, about 0.42–0.45 USD, is an order of magnitude above the 0.026 USD/TEU-km of the main-line vessel, which is the economic reason for the dominance of the maritime route. In time, the movement of the shipment takes only 141 and 188 h, but the three or two transshipments take 500 and 333 h, to which the border dwell and the road bridging add 96 and 24 h; the undisturbed times are 737.5 h (30.7 days) and 545.7 h (22.7 days). It is therefore the interfaces, not the line-haul distance, that generate the greater part of the corridor time, in agreement with the World Bank (2023) diagnosis of the Middle Corridor. The energy of the corridors, 31.1 and 47.4 GWh, lies between the Suez route (13.3 GWh) and the Cape route (39.8 GWh) because rail is energy-efficient per tonne-km but the shipment is heavy and the Iran–Turkey rail leg long.

Table 11. Cost, time and energy of the multimodal corridors by segment (10,000 TEU).

Corridor	Segment	Mode	Distance (km)	Cost (USD)	Unit cost (USD/TEU-km)	Time (h)	Energy (kWh)
C. Iran–Caucasus	Abu Dhabi – Bandar Abbas	sea	531	1,616,500	0.304	17.9	2,065,000
	Bandar Abbas – Astara	rail	2,133	10,418,500	0.488	60.9	17,419,500
	Astara – Poti	rail	900	4,870,000	0.541	25.7	7,350,000
	Poti – Constanța South	sea	1,093	2,459,500	0.225	36.9	4,250,556
	Transshipment (3 interfaces), borders (2), road bridging	–	–	–	–	500.0 + 48 + 48	–
	Corridor total		**4,657**	**19,364,500**	**0.416**	**737.5**	**31,085,056**
D. Iran–Turkey	Abu Dhabi – Bandar Abbas	sea	531	1,616,500	0.304	17.9	2,065,000
	Bandar Abbas – Tabriz	rail	3,633	17,168,500	0.473	103.8	29,669,500
	Tabriz – Istanbul	rail	1,635	8,177,500	0.500	46.7	13,352,500
	Istanbul – Constanța South	sea	590	1,705,000	0.289	19.9	2,294,444
	Transshipment (2 interfaces), borders (1), road bridging	–	–	–	–	333.3 + 24 + 0	–
	Corridor total		**6,389**	**28,667,500**	**0.449**	**545.7**	**47,381,444**

3.6. Benchmark Index and sensitivity to the weights

Table 12 gives the five criteria of every route, the normalized and weighted terms of Equation (29) and the resulting Benchmark Index. For the Suez Canal route under baseline conditions the weighted sum is

1.310, of which cost contributes 0.483, time 0.430, capacity 0.015, energy 0.334 and risk cost 0.048, and the index is

$$I_{B,Suez} = \frac{1}{1 \cdot \left(0.25 \cdot \frac{1{,}930{,}962}{1{,}000{,}000} + 0.20 \cdot \frac{215.2}{100} + 0.15 \cdot \frac{1}{10} + 0.25 \cdot \frac{13{,}344{,}456}{10{,}000{,}000} + 0.15 \cdot \frac{32{,}214}{100{,}000}\right)} = 0.763 \qquad (30)$$

The routes rank Suez Canal (0.763), Cape of Good Hope (0.306), Iran–Caucasus corridor (0.090) and Iran–Turkey corridor (0.083). Under 2024 crisis conditions the Suez index falls to 0.626, still twice the Cape value. The gap between the two maritime routes is a factor of 2.5; the gap between the maritime routes and the corridors is a factor of 3.4 to 9. On the corridors the cost term alone (4.84 and 7.17) exceeds the complete weighted sum of the Cape route, and the capacity and risk-cost terms add a further 3.95 and 2.44.

Table 12. Criteria, weighted normalised terms and Benchmark Index of the four routes.

Route	P_T (USD)	T_T (h)	D_T	E_T (kWh)	A_T (USD)	$k_P P_T / P_0$	$k_T T_T / T_0$	$k_D D_T / D_0$	$k_E E_T / E_0$	$k_A A_T / A_0$	Sum	I_B
A. Suez Canal, baseline	1,930,962	215.2	1	13,344,456	32,214	0.483	0.430	0.015	0.334	0.048	1.310	**0.763**
A. Suez Canal, 2024 crisis	2,630,962	225.1	1	13,344,456	94,613	0.658	0.450	0.015	0.334	0.142	1.598	**0.626**
B. Cape of Good Hope	3,934,432	605.7	1	39,794,676	42,233	0.984	1.211	0.015	0.995	0.063	3.268	**0.306**
C. Iran–Caucasus	19,364,500	796.3	214	31,085,056	495,370	4.841	1.593	3.210	0.777	0.743	11.164	**0.090**
D. Iran–Turkey	28,667,500	603.3	114	47,381,444	485,260	7.167	1.207	1.710	1.185	0.728	11.996	**0.083**

Table 13 and Figure 4 give the index of the four routes for twelve weighting schemes: the base case, equal weights, and each weight increased and decreased by 0.10 with the others rescaled. The Suez Canal route ranks first and the Cape of Good Hope route second in all twelve cases, and the ratio between them never falls below 2.3. The two corridors always rank third and fourth, but their order changes in three of the twelve cases (equal weights, lower cost weight, higher capacity weight), because the Iran–Caucasus corridor is cheaper while the Iran–Turkey corridor is faster and needs fewer transport units. The conclusion on the ranking of the maritime routes is therefore independent of the weights; the conclusion on the order of the two corridors is not, and only their common position below the maritime routes is retained.

Table 13. Benchmark Index under alternative weighting schemes.

Weighting scheme	k_P / k_T / k_D / k_E / k_A	A. Suez	B. Cape	C. Iran–Caucasus	D. Iran–Turkey	Ranking
Base weights	0.25 / 0.20 / 0.15 / 0.25 / 0.15	0.763	0.306	0.090	0.083	A > B > C > D
Equal weights (0.20 each)	0.20 / 0.20 / 0.20 / 0.20 / 0.20	0.856	0.345	0.088	0.090	A > B > D > C
k_P + 0.10	0.32 / 0.18 / 0.14 / 0.23 / 0.14	0.732	0.300	0.084	0.074	A > B > C > D
k_P − 0.10	0.17 / 0.22 / 0.17 / 0.28 / 0.17	0.806	0.313	0.098	0.099	A > B > D > C
k_T + 0.10	0.23 / 0.27 / 0.14 / 0.23 / 0.14	0.721	0.284	0.092	0.087	A > B > C > D
k_T − 0.10	0.28 / 0.11 / 0.17 / 0.28 / 0.17	0.822	0.338	0.087	0.079	A > B > C > D
k_D + 0.10	0.23 / 0.18 / 0.23 / 0.23 / 0.14	0.833	0.336	0.083	0.084	A > B > D > C
k_D − 0.10	0.28 / 0.22 / 0.06 / 0.28 / 0.17	0.692	0.276	0.100	0.083	A > B > C > D
k_E + 0.10	0.23 / 0.18 / 0.14 / 0.32 / 0.14	0.762	0.300	0.096	0.088	A > B > C > D
k_E − 0.10	0.28 / 0.22 / 0.17 / 0.17 / 0.17	0.765	0.314	0.083	0.078	A > B > C > D
k_A + 0.10	0.23 / 0.18 / 0.14 / 0.23 / 0.23	0.819	0.332	0.094	0.088	A > B > C > D
k_A − 0.10	0.28 / 0.22 / 0.17 / 0.28 / 0.06	0.704	0.279	0.084	0.078	A > B > C > D

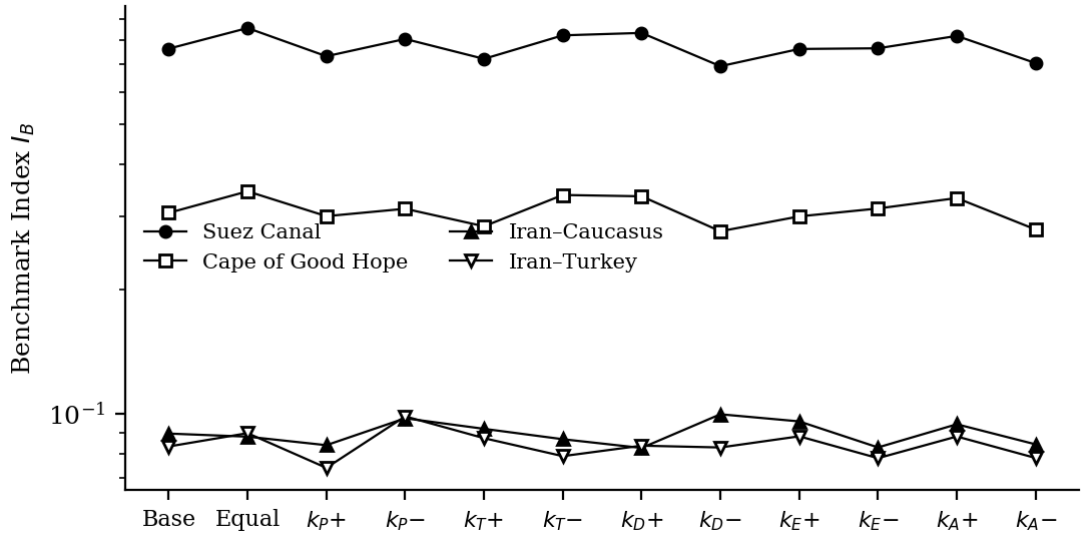


Figure 4. Benchmark Index of the four routes under the twelve weighting schemes of Table 13 (logarithmic scale).

3.7. Validation against the diversion costs reported for 2024

The maritime cost model can be checked against the costs of the 2024 diversions reported in the literature (Table 14). The model gives a distance ratio of 2.96 and 16.2 additional days for the Abu Dhabi–Constanța relation, against a ratio of 1.29 and 12 additional days for Shanghai–Rotterdam (Notteboom et al., 2024) and 1.30 and 10 days for Shenzhen–Rotterdam (UNCTAD, 2024); the relative detour is larger here because the Persian Gulf lies much closer to the canal than to the Cape.

All model values refer to a single one-way voyage from Abu Dhabi to Constanța South, whereas UNCTAD (2024) and ITF (2024) report costs per round trip of an Asia–Europe service; Table 14 therefore gives the model values both per one-way voyage and, doubled, per round trip (Abu Dhabi–Constanța–Abu Dhabi), under the assumption of a symmetrical return leg.

The additional cost of the detour in the model is USD 2,003,470 per one-way voyage, or about USD 4.0 million per round trip; UNCTAD (2024) and ITF (2024) report USD 0.7 million of additional cost per round trip of a median-sized container ship. Expressed per container carried on one leg, the model gives 200 USD/TEU, that is about 401 USD per forty-foot unit, against the 272 USD per forty-foot unit arriving in Europe around the Cape and 160 USD through the canal with its surcharges reported by UNCTAD (2024).

The model figures are higher in proportion to the larger relative detour of this relation and to the larger and faster vessel used here, and they are of the same order as the reported values. The tripling of fuel consumption reported for diverted services (UNCTAD, 2024) is reproduced by the ratio of 2.98 between the two routes.

Finally, the model reproduces the observed market behavior: with the war-risk premium and the elevated security risk of 2024 the Suez route remains 33 per cent cheaper than the Cape route, so the near-complete diversion of container services in 2024 cannot be explained by expected cost alone; it is explained by the attack scenario, whose risk achievement worth of 33 in Table 9 shows that the risk to the vessel and the crew, rather than the expected delay, was the binding constraint.

This is consistent with the observation that insurers and charterers, not freight economics, set the limits of Red Sea transit in 2024 (ITF, 2024; Notteboom et al., 2024).

Table 14. Comparison of the model (one-way voyage Abu Dhabi – Constanța South, and its round-trip equivalent) with the diversion effects reported for 2024.

Quantity	This model, Abu Dhabi – Constanța	Reported for Asia – Europe, 2024	Source
Distance ratio, Cape / Suez	2.96	1.29 (Shanghai – Rotterdam); 1.30 (Shenzhen – Rotterdam)	Notteboom et al. (2024); UNCTAD (2024)
Additional sailing days	16.2	12 (Shanghai – Rotterdam); 10 (Shenzhen – Rotterdam)	Notteboom et al. (2024); UNCTAD (2024)
Fuel consumption ratio	2.98	up to 3 (distance and speed)	UNCTAD (2024)
Additional cost of the detour per ship	USD 2.00 million per one-way voyage; USD 4.01 million per round trip (Abu Dhabi – Constanța – Abu Dhabi)	USD 0.7 million per round trip, median-sized Asia – Europe container ship	UNCTAD (2024); ITF (2024)
Additional cost per container carried	200 USD/TEU; 401 USD/FEU (one leg)	272 USD/FEU around the Cape vs 160 USD/FEU via Suez, per unit arriving in Europe	UNCTAD (2024); ITF (2024)
War-risk premium	0.7 % of hull value (crisis case)	0.3 % to about 1 % of hull value	ITF (2024); gCaptain (2025)
Suez transits	Not modelled	−50 % in 2024; −70 % in May 2025 vs 2023	Business Today Egypt (2025); UNCTAD (2025)

3.8. Discussion

Under baseline conditions the Suez Canal route is superior on every one of the five criteria of Table 12, including the risk cost, where its margin is the smallest: the Cape route avoids the Red Sea but accumulates weather, bunkering and technical exposure over a voyage three times longer, so its expected delay (6.66 h) and its risk cost exceed those of the canal route (5.08 h). The Suez Canal route also remains superior on the combined index under all weighting schemes tested. The result rests on three quantitative facts established in Section 3: the detour multiplies the sailing distance by 3.0 and the fuel by 3.0, which the saving of the canal dues cannot offset; the expected delay of the canal segment is of the order of 5–7 h according to four different methods, that is less than 4 per cent of the transit time; and the corridors cost 10–15 times more and take at least three times longer, mainly because of their interfaces. The first conclusion of the paper, that the Suez Canal route should remain the default choice for the Abu Dhabi–Constanța South relation, follows directly from these results.

The 2024 crisis case qualifies this conclusion in an instructive way. Even with a war-risk premium of USD 700,000 and a security-delay probability raised from 0.02 to 0.125, the Suez route keeps a cost advantage of about a third and a Benchmark Index twice that of the Cape route. The near-total diversion observed in 2024 is therefore not a cost decision but a safety decision, and the importance analysis locates it: the attack scenario has a modest expected delay but a risk achievement worth of 33, an order of magnitude above every other scenario. For an operator this means that the two questions, whether the route is economical and whether it is insurable and acceptable to the crew and the charterer, must be answered separately, and that the second one governs during a crisis. The Cape route is the necessary contingency for that situation, and its cost and time penalties are now quantified for this relation at USD 2.0 million and 16 days per shipment.

The two land corridors are unlikely to compete on cost or time under present infrastructure, and the model shows why: rail line-haul at 0.45 USD/TEU-km is an order of magnitude above the main-line vessel, each interface of a 10,000 TEU shipment takes about a week of crane time, and the border, ferry and compliance scenarios give them an expected delay ten times that of the maritime routes. The result agrees with the finding of Palu and Hilmola (2023) that the Trans-Caspian route is about 1.7 times more expensive and twice as slow as the maritime alternative for Northern Europe, and with the World Bank (2023) conclusion that the Middle Corridor will remain largely a regional corridor. Their value is strategic. They bypass both Bab el-Mandeb and the Suez Canal, and their index is only weakly sensitive to the maritime crisis parameters; for high-value or time-critical cargo of a few hundred TEU rather than a full vessel load, for which the transshipment term of Equation (26) becomes small, the Iran–Turkey corridor in particular would deserve a separate assessment.

The results also show which risk-management measures matter. Under baseline conditions the largest expected contribution comes from heavy traffic and convoy waiting, which can be reduced by slot booking and arrival-time management with the canal authority; the highest risk achievement worth belongs to the security and grounding scenarios, which call for insurance and for the retention of the Cape option rather than for operational measures. On the corridors the rail capacity and compliance scenarios dominate, which points to capacity agreements with the rail operators and to legal due diligence before any use of the Iranian corridors.

The study has limitations. The parameters are 2024 averages and the results are static; a fleet-level or a time-series treatment of freight and charter rates would change the absolute values though not, given the size of the gaps, the ranking. The risk probabilities are derived from aggregated industry statistics and describe the average exposure of a vessel, not that of a specific service. The transitions out of the delayed states of the Markov chain are calibrated on one event, the 2021 grounding, and the Poisson assumption of the exposure-time model excludes clustering of security incidents. The feeder tariffs, the documentation costs and the detention costs on the corridors are assumptions, identified as such in Table 3, and the corridor distances are taken from route planners rather than from operator tariffs. Finally, the capacity term of the index counts transport units and does not describe the actual capacity available on the Caspian and Black Sea feeder services, which the ADB (2022) puts at about 3,000 TEU per week on the Caspian, so that a 10,000 TEU shipment could not in fact be moved on the corridors in the time computed here without additional feeder capacity. This last point strengthens rather than weakens the ranking.

4. Conclusions

The paper set out four objectives, and each has been met for all four routes. (i) A risk register with six scenarios per route, and seven for the Suez Canal under crisis conditions, was built from 2024–2025 sources with documented probabilities and consequences. (ii) The delay of the Suez Canal segment was estimated with an analytical expectation, a Markov chain calibrated on the same register, an exposure-time exponential model consistent with the chain, and a Monte Carlo simulation, which agree within 2 h; the delay of all four routes was estimated with the same expectation and the same simulation, so that the transit times of 9.0, 25.2, 33.2 and 25.1 days are directly comparable. (iii) The Birnbaum, Fussell-Vesely, risk reduction worth and risk achievement worth measures were computed for every scenario of every route from the register itself; heavy traffic dominates the expected risk of the canal under baseline conditions, the attack scenario dominates its achievement worth under crisis conditions, and rail capacity, border and compliance scenarios dominate the corridors. (iv) The Benchmark Index, with every term defined and traceable, ranks the routes Suez Canal (0.76), Cape of Good Hope (0.31), Iran–Caucasus corridor (0.090) and Iran–Turkey corridor (0.083); the order of the two maritime routes is stable under all twelve weighting schemes, and the cost differential between them is consistent with the diversion costs reported for 2024.

For shipping companies and shippers serving the Persian Gulf–Black Sea relation the recommendation is therefore to keep the Suez Canal route as the default, at USD 193 per TEU and 9 days under baseline conditions, supported by slot management against the traffic scenario and by insurance against the security and grounding scenarios; to maintain the Cape of Good Hope route as the operational contingency, at a documented penalty of about USD 200 per TEU and 16 days, to be activated when the attack scenario makes the canal route uninsurable or unacceptable rather than when it becomes more expensive; and to monitor the Iranian corridors as diversification options for partial loads, pending the completion of the Rasht–Astara link, the expansion of feeder capacity and a change in the sanctions environment. Further research should extend the framework to fleet and service level, replace the static parameters by time series of freight, charter and insurance rates, and calibrate the Markov transitions on vessel-level tracking data.

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