

Transportation Research Part A

Assessing Strategies for Mitigating Maritime Chokepoint Disruptions

--Manuscript Draft--

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Article Type:	VSI: Resilience & Regional Econ Dev
Keywords:	Transportation resilience; Chokepoint disruptions; Recovery; Discrete Event Simulation; Societal Costs; Disruption management.
Abstract:	<p>Vulnerabilities in global cargo trade arising from disruptions at maritime chokepoints, such as the Suez Canal, have heightened awareness of the need for strategies to reduce these risks. One potential mitigation measure is rerouting via alternative pathways.</p> <p>This study develops a model for evaluating mitigation strategies, such as waiting the end of blockage, rerouting with increased and normal speeds, in the event of canal blockages. The model is flexible and can be applied whether the decision-makers' objective is to minimize time, operational costs, emissions costs, or total cost to society. It integrates the A-star algorithm with Discrete Event Simulation and is applied to a case study of Suez Canal blockages of varying durations.</p> <p>The case study results show that rerouting strategies can reduce time-related costs by approximately USD 1.5–4 million to USD 1–3.1 million. However, additional fuel consumption leads to higher costs of approximately USD 5 million, 1.2–2 million, 1.7–1.8 million, and 0.75 million (for increased-speed and normal-speed rerouting, respectively). Rerouting strategies result in higher societal costs for blockages shorter than 25 days, whereas rerouting at normal speed results in lower societal costs for longer blockages.</p> <p>Sensitivity analysis indicates that the preferred mitigation strategy depends on fleet characteristics. For instance, highly energy-efficient vessels favor increased-speed rerouting in all blockage scenarios, whereas moderately efficient vessels lead to different strategies depending on market conditions, favoring either normal-speed or increased-speed rerouting.</p> <p>Finally, random forest analysis highlights the relative impact of each factor on societal cost across scenarios and strategies.</p>

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Dear editors,

I would like to submit the manuscript for consideration in the Journal of Transportation Research Part A: Policy and Practice for the special issue “Transportation resilience and its role in regional economic development”. My article is entitled:

“Assessing Strategies for Mitigating Maritime Chokepoint Disruptions”.

A study addresses a key gap in disruption management, specifically the need to evaluate blockage mitigation strategies, such as rerouting and waiting strategies, for primary chokepoints in the maritime business, within the context of considering the full cost of shipping, and the factors that impact the choice of those strategies.

A central novelty of the work is the use of Discrete Event Simulation (DES) to model and assess mitigation strategies, and the A-star algorithm for finding optimal rerouting pathways. The considered case in this research is the container flow between Europe and Asia via the Suez Canal, with various durations of blockage. The aforementioned approaches enable the assessment of various costs from different perspectives (e.g., time, operational, CO₂ emission, and Societal costs) of complex operational variables, e.g., the variety of possible transit demand via the Suez Canal (the unpredictability of accumulating queues for passage), the demand for cargo transportation between Europe and Asia, and the vessels affected by blockages. Furthermore, sensitivity analysis, combined with Random Forest, highlights the most critical factors that stakeholders should consider when making a decision.

Findings reveal the dominance of rerouting strategies in terms of speed for all considered blockage duration scenarios from a time cost perspective. However, from three other perspectives (operational, emission, and societal costs), the increased speed results in additional costs that outweigh the benefits of rerouting from a time perspective. For long considered blockages, rerouting can be a solution, but only with the normal (not increased) speed.

Moreover, sensitivity analyses reveal the impact of freight rates for all considered mitigation pathways. In contrast, inventory cost is the second most crucial factor for strategies involving

waiting at the end of the blockage and rerouting at normal speed. The Energy Efficiency Design Index sufficiently impacts the recruiting strategies along with the fuel cost.

This manuscript is original, has not been published, and is not currently under consideration elsewhere. The first version of this research was presented at two conferences. First, at the "The Transportation Research Symposium" in Rotterdam, May 25-28, 2025. Second, at the "IAME" in Bergen, June 25-27, 2025.

I believe my manuscript aligns with the journal's aim, given its emphasis on the maritime, environmental, cost, and time implications of blockage mitigation strategy selection, factors affecting this choice, methodological innovation, and policy-relevant insights into sustainable shipping. Based on my interpretation of the special issue, the themes raised in the manuscript consider transportation resilience, economic impacts of transportation resilience (understanding transportation resilience and economic impacts of transportation resilience, respectively), and partially in emerging challenges (emerging challenges in transportation resilience), since the model can be implemented in such cases.

In my opinion, this research contributes to the literature on disruption management by considering rerouting strategies (recovery pathways) and the factors influencing them, as well as resilience at the regional level by evaluating the different types of costs, time, and environmental footprint associated with decisions.

Thank you for considering my submission. I look forward to your response.

Best wishes,
Mikhail Strukov.

Highlights

Evaluates strategies for mitigating maritime chokepoints blockages;
Assesses strategies from time, operational, CO2, and societal cost;
Provides policy guidance for resilient planning of chokepoint
disruptions;
Applies A-star and Discrete Event Simulation for assessment;
Considers Suez Canal disruption as a case study.

Assessing Strategies for Mitigating Maritime Chokepoint Disruptions

1 **Abstract**

2 Vulnerabilities in global cargo trade arising from disruptions at maritime chokepoints, such
3 as the Suez Canal, have heightened awareness of the need for strategies to reduce these risks.
4 One potential mitigation measure is rerouting via alternative pathways.

5 This study develops a model for evaluating mitigation strategies, such as waiting the end
6 of blockage, rerouting with increased and normal speeds, in the event of canal blockages. The
7 model is flexible and can be applied whether the decision-makers' objective is to minimize time,
8 operational costs, emissions costs, or total cost to society. It integrates the A-star algorithm
9 with Discrete Event Simulation and is applied to a case study of Suez Canal blockages of varying
10 durations.

11 The case study results show that rerouting strategies can reduce time-related costs by ap-
12 proximately USD 1.54 million to USD 13.1 million. However, additional fuel consumption leads
13 to higher costs of approximately USD 5 million, 1.22 million, 1.71.8 million, and 0.75 million (for
14 increased-speed and normal-speed rerouting, respectively). Rerouting strategies result in higher
15 societal costs for blockages shorter than 25 days, whereas rerouting at normal speed results in
16 lower societal costs for longer blockages.

17 Sensitivity analysis indicates that the preferred mitigation strategy depends on fleet char-
18 acteristics. For instance, highly energy-efficient vessels favor increased-speed rerouting in all
19 blockage scenarios, whereas moderately efficient vessels lead to different strategies depending on
20 market conditions, favoring either normal-speed or increased-speed rerouting.

21 Finally, random forest analysis highlights the relative impact of each factor on societal cost
22 across scenarios and strategies.

23 **Keywords**

24 Transportation resilience, Chokepoint disruptions, Recovery, Discrete Event Simulation, So-
25 cietal Costs, Disruption management.

1 Introduction

The Suez Canal Route (SCR) is a vital maritime artery in cargo trade, which handled approximately 73 vessels per day in 2023 (United Nations Global Platform & IMF PortWatch Team, 2024). Compared to alternative sailing routes, the SCR significantly reduces sailing distance between Asia and Europe, thereby also reducing sailing time, fuel consumption, and emissions. The importance of the SCR is reflected in its handling of approximately 12% of global cargo trade and 30% of container trade (Guo *et al.*, 2022). However, the SCR has proven vulnerable to disruptions. One such vulnerability was exposed in 2021, when the 400-meter-long container vessel *Ever Given* blocked the Suez Canal for six days (Mechai & Wicaksono, 2024). That incident resulted in a trade hold of approximately 400 million USD and a daily revenue loss of approximately 15 million USD for the canal (Russon, 2021). Another vulnerability that materialized at the end of 2023 was attacks by Houthi rebels on merchant ships off the western coast of Yemen. These attacks forced a substantial number of vessels to refrain from sailing through the SCR (Jolly, 2023).

Due to the vulnerabilities of the SCR, shipping companies investigate alternative routes between Asia and Europe. One such alternative is the Cape of Good Hope Route (CGHR), which passes the southern tip of Africa. However, compared to the SCR, the CGHR adds nearly 3,500 nautical miles (approximately 6,482 km) of sailing distance for ships traveling between Asia and Europe. Consequently, using the CGHR results in longer sailing times, higher fuel consumption, and greater CO₂ emissions (Li *et al.*, 2022). Nevertheless, the CGHR is considered a viable alternative in the event of a blockage of the SCR (Wan *et al.*, 2023).

Soltani & Mirzapour Al-e Hashem (2023) summarized delays into two groups: port delays caused by traffic and unpredictable disruptions. Both types of delays affect the global supply chain, market structure, and final delivery (Mavrothalassitis *et al.*, 2023). Wu *et al.* (2019) analyzed the impact of main channel disruptions on container shipping. Their results indicate that disruption of the Suez Canal increases transportation time by 25% and reduces worldwide port connectivity by 6.87%. Moreover, the findings show a high degree of shipping dependence on the Suez Canal, particularly in European and East Asian regions (62.54% and 31.04%, respectively). According to Wan *et al.* (2023), container vessels are the most affected ship type. Similarly, Tran *et al.* (2025) introduced a model to analyze ship costs, environmental costs, and inventory-carrying costs of Suez Canal disruptions for Maersk Line’s EastWest container network. Their results indicate additional costs of 88.79 million USD in total, comprising 8.04 million USD in ship-related costs, 4.46 million USD in environmental costs (from additional CO₂ emissions of 44,574 tonnes), and, most notably, 76.29 million USD in inventory-carrying costs. Meanwhile, Qu *et al.* (2024) estimated worldwide losses from a Suez Canal blockage at 136.9 million USD.

Generally, shipping companies adopt one of two approaches when traffic through the SCR is disrupted. The first is to wait outside the Suez Canal until the disruption ends. This approach (Harun-Al-Rashid *et al.*, 2022) implies waiting in a queue of ships that grows each day the route is blocked. Since the duration of the disruption is usually uncertain, this strategy adds uncertainty regarding the ship’s arrival time at its destination. The second approach is to reroute

67 the vessel, with the most relevant alternative being the CGHR (Wu & Xu, 2021). However, as
68 previously mentioned, this route increases costs for shipping companies due to longer sailing
69 distances, which result in higher fuel consumption, higher costs to cargo owners due to longer
70 delivery times, and higher societal costs due to increased emissions.

71 A speed-up strategy can reduce the sailing time along the CGHR. However, this strategy
72 increases costs due to higher fuel consumption (Wang & Meng, 2014) and, consequently, higher
73 emissions (Chang & Wang, 2014). On the other hand, delays cause customer dissatisfaction,
74 and potential loss of goodwill (Xing & Zhong, 2017). Consequently, several factors must be
75 considered by decision-makers when selecting a strategy during SCR blockages.

76 The primary objective of this paper is to develop a method for evaluating strategies to
77 mitigate the consequences of disruptions to key elements of shipping infrastructure, such as a
78 Suez Canal blockage. The developed model is further applied to identify the optimal strategy
79 for various stakeholders in such cases. More specifically, the following research questions are
80 addressed:

- 81 • RQ1: Which strategy minimizes maritime transport time and time cost?
- 82 • RQ2: Which strategy minimizes operational cost?
- 83 • RQ3: What is the impact of rerouting strategies on CO₂ emissions cost?
- 84 • RQ4: What is the optimal strategy for minimizing societal costs associated with a Suez
85 Canal blockage?

86 The first research question (RQ1) is of particular interest to cargo owners, as any delay
87 in arrival time can significantly affect the value of their goods. The second research question
88 (RQ2) is particularly relevant to shipping companies because it directly affects shipping costs.
89 The third research question (RQ3) is of particular importance to those concerned about global
90 warming, which the UN Secretary-General has described as an existential threat to humanity
91 (Guterres, 2018) and which is partly driven by CO₂ emissions. The final research question
92 (RQ4) focuses on economic losses for society as a whole, defined here as the sum of time costs,
93 operational costs, and emission costs.

94 The research objective is achieved through a two-step procedure. First, the A-star algorithm
95 is applied to identify the shortest routes for vessels sailing between Asia and Europe, along with
96 rerouting paths. Second, Discrete Event Simulation (DES) is employed to assess the efficiency
97 of shipping operations and the effectiveness of the implemented strategies.

98 The remainder of this paper is structured as follows. Section 2 reviews the relevant literature.
99 Section 3 describes the methodology for path-finding disruption strategies and the evaluation
100 criteria for each research question. Section 4 presents the results of the Suez Canal blockage
101 scenario for various blockage durations. Sensitivity analyses, considering the technical charac-
102 teristics of vessels, market components related to shipping, and the importance of individual
103 factors for each strategy and blockage scenario, are provided in Section 5. Finally, Section 6
104 concludes the paper and suggests directions for future research.

2 Literature review

The literature review focuses on the generalized freight cost (GFC) with Societal costs and their components, the impact of disruptions on maritime internal and external costs, and strategies for mitigating disruptions.

2.1 Generalized freight cost

The concept of GFC was first introduced approximately 50 years ago by several authors (Wilson, 1969, Mcintosh & Quarmby, 1970, Nichols, 1975) as a function of distance and time for evaluating the profitability of travel alternatives (Wardman & Toner, 2020). Zondag *et al.* (2010) defines GFC as the key component in the utility function for the logistical chain. The concept has been applied in various areas of transportation, including roads (e.g., Levinson & Gillen (1998), Zofío *et al.* (2014)), aviation (e.g., Sobieralski (2013), Mueller & Aravazhi (2020)), rail (e.g., Wardman & Toner (2020), Qin *et al.* (2024)), shipping (e.g., Zondag *et al.* (2010), Van Hassel *et al.* (2016), Kovalenko *et al.* (2024)), and multimodal transportation (e.g., Hanssen *et al.* (2012), Cui & Levinson (2018), Jensen *et al.* (2019)).

The definitions provided by Levinson & Gillen (1998), Zofío *et al.* (2014) emphasize an in-depth understanding of transportation expenses. Zofío *et al.* (2014) further elaborates on this by identifying both distance and time as key cost components, detailing various expenses such as fuel, tolls, and maintenance under distance costs, alongside salaries and financing under time costs. This dual perspective enables a more comprehensive assessment of transport costs, which is essential for effective decision-making in logistics and planning.

Nevertheless, container vessels in the industry adhere to predefined pathways and schedules to maintain consistency and reliability in cargo delivery (Wang & Wang, 2021). Shipping time is one of the most essential concepts in maritime shipping. According to Zhou *et al.* (2024), time ranks third in customers' preferences for cargo delivery to Europe after transportation cost and reliability, followed by safety, convenience, and sustainability. At the same time, while some studies concentrate on individual attributes (e.g., cost, emissions, time, safety), others consider a combined assessment of different components (e.g., emissions cost assessment, cost equivalent of time, and risk cost assessment related to delivery time) (Tran & Lam, 2022, Jeong *et al.*, 2023, Hu *et al.*, 2024, Flodén *et al.*, 2024).

This results in the formulation of the GFC, relevant to shippers, presented in equation 1, where P is the operational cost (cost associated with transport service), k is the time cost of shipping per unit of time, and T is the transport time (Hanssen *et al.*, 2012).

$$G(D) = P(D) + kT(D) \quad \text{where} \quad \frac{\partial P}{\partial D}, \frac{\partial T}{\partial D} > 0 \Rightarrow \frac{\partial G}{\partial D} > 0 \quad (1)$$

In the classic GFC definition (1), as distance increases, both operational and time costs increase. Hence, longer sailing distances imply greater resource use (e.g., fuel consumption, emissions costs) and time-related costs (e.g., time charter cost, depreciation cost).

2.2 Societal costs

In recent decades, regulations tightening CO₂ emissions (Brouer *et al.*, 2013) have led to higher delays (costs) but lower emissions. The trend toward lowering the environmental footprint of shipping, combined with recent crises such as SCR blockages, has highlighted vulnerabilities in the shipping industry and potential delays in delivery times. Furthermore, external costs are typically not considered by shippers when deciding on actions. Consequently, shipping companies generally choose the strategy that minimizes GFC. However, for society as a whole, the best strategy is the one that minimizes the sum of GFC and external costs (e.g., cost of CO₂ emissions) (Hanssen *et al.*, 2012). This means that what is best for the shipping company in isolation is not necessarily best for society. A key feature of shipping, absent in 1, is that sailing speed is a crucial factor influencing both time cost and fuel consumption, which directly affect operational and environmental costs (Christiansen *et al.*, 2013).

Accordingly, equation 2 is an elaboration of equation 1, adding the time cost component and presenting societal cost as the sum of GFC, external, and time costs. In equation 2, D and V represent sailing distance and speed, l is the societal cost per unit of emission, $E(V)$ is the emission quantity per unit distance as a function of speed (the relationship between sailing speed and emissions is described in Appendix B), and $P(D, V)$ is the operational cost depending on sailing speed.

$$\begin{aligned}
 SC(D, V) &= P(D, V) + k \cdot \frac{D}{V} + l \cdot D \cdot E(V), \quad \text{where:} \\
 T &= \frac{D}{V}, \quad E'(V) > 0, \quad D \geq 0, \quad V > 0, \quad k, l > 0, \\
 \frac{\partial P}{\partial V} &> 0, \quad \frac{\partial P}{\partial D} \geq 0, \\
 \frac{\partial SC}{\partial D} &= \frac{\partial P}{\partial D} + \frac{k}{V} + l E(V) > 0, \\
 \frac{\partial SC}{\partial V} &= \frac{\partial P}{\partial V} - k \cdot \frac{D}{V^2} + l \cdot D \cdot E'(V)
 \end{aligned} \tag{2}$$

Thus, an increase in distance always increases both time and emissions costs, whereas increasing speed reduces time cost but raises operational and emissions costs. The net effect depends on their relative magnitudes $\{\partial P/\partial V, l D E'(V), k D/V^2\}$.

Figure 1 illustrates how the societal cost (SC), GFC, and external cost vary with speed for a fixed distance. In line with the discussion above, GFC combines a decreasing time component and an increasing operational component, while the external cost increases with speed.

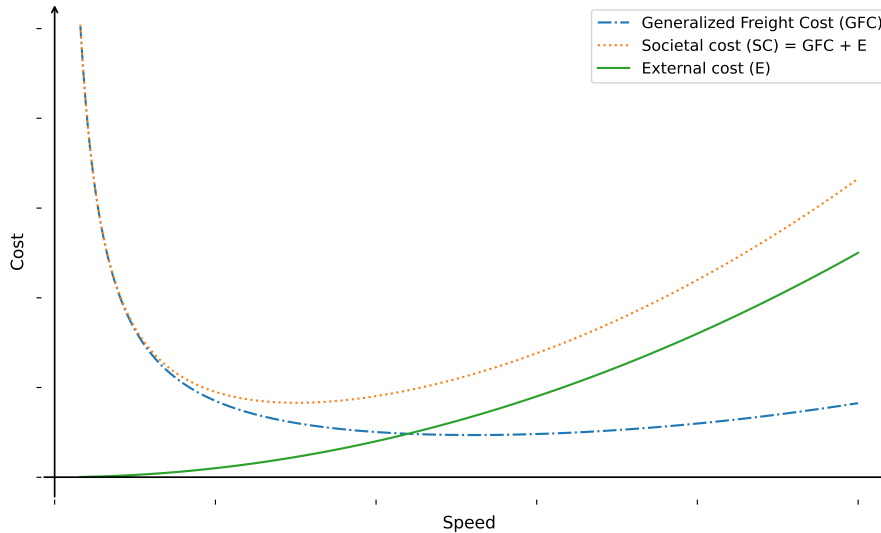


Figure 1 – Societal cost (SC), generalized freight cost (GFC), and external cost as functions of speed V .

Source: Author

2.3 Blockage mitigation strategies

Transportation disruptions and consequent delays may arise from various events, including natural disasters, adverse weather conditions, connectivity failures at transportation nodes, and piracy (Yap & Yang, 2024). Additionally, human activities such as port failures and vessel groundings can also lead to disruptions (Ronza *et al.*, 2009, Zhang *et al.*, 2020).

Strategies to mitigate the consequences of such disruptions have been suggested by several authors. The speed-up strategy is considered in the paper of Wang & Meng (2012a). Following that study, Brouer *et al.* (2013) examined three additional strategies: port-skipping, port order change, and combining all strategies. Results indicate improved delivery speed for all strategies, but with some disadvantages. For example, the port-skipping strategy risks misconnecting containers, the speed-up strategy enlarges costs due to higher fuel consumption, the port order change strategy may cause delays due to a disrupted delivery chain, and the combined strategy produces the best outcome overall. While the speed-up strategy enhances shipping efficiency, it cannot be entirely reliable in some cases. In summary, mitigation strategies for previous disruptions present trade-offs: the port-skipping strategy may decrease customer satisfaction and reduce overall supply chain efficiency due to increased transshipment costs and logistics complexity; the speed-up strategy may increase fuel consumption, which accounts for 3070% of all expenses for container vessel operations (Notteboom & Vernimmen, 2009, Golias *et al.*, 2009, Ronen, 2011), along with potential penalties; and the order change strategy may lead to delays in other legs of cargo delivery (Brouer *et al.*, 2013, Soltani & Mirzapour Al-e Hashem, 2023, Guo *et al.*, 2024, Fan *et al.*, 2025), resulting in substantial economic losses in terms of opportunity cost (lost profit from utilization of container vessels) (Koacz *et al.*, 2024).

Another notable strategy is rerouting. In recent years, there has been a rapid shift of focus from the most optimal transportation option SCR, which is accessible year-round and efficient in

188 terms of time and cost for European and Asian cargo flowsto the alternative pathway, CGHR.
189 For example, there was a complete stop of transit via the canal on March 2329, 2021, and cargo
190 flow through the Suez Canal fell by 82% in the second half of 2024 (IMF PortWatch, 2024,
191 United Nations Conference on Trade and Development, 2024). Previously, Arctic shipping
192 (benefiting from climate change, particularly for periodic shipping) (e.g., Furuichi & Otsuka
193 (2015), Bennett *et al.* (2020), Xu & Yin (2021)), CGHR (especially with lower fuel prices,
194 charter rates, and higher transit tolls on SCR) (e.g., Vuki & Cerbán (2022), Wiesener (2022)),
195 and alternative modes of transportation (e.g., Zeng *et al.* (2020), Zhou *et al.* (2024)) were
196 discussed as potential solutions for cargo delivery between Asia and Europe. Most studies
197 concluded that SCR remained optimal, with alternative passages viable depending on external
198 factors. However, two recent blockages demonstrated the readiness to reroute via the CGHR
199 when such blockages occur (Wu & Xu, 2021, Tran & Lam, 2024).

200 As shipping pathway interruptions occur, several strategies have been developed to mitigate
201 their negative impacts. However, recent global vulnerabilities underscore the need to consider
202 and prepare for emergency accidents and the possibility of rerouting. This research has a twofold
203 aim. First, it fills the literature gap by providing an algorithm for assessing blockages and
204 identifying the best possible mitigation strategies using waiting the end of the blockage, rerouting
205 and speed-up approaches to minimize costs, emissions, time, and societal costs. Second, to the
206 best of the author’s knowledge, this study is the first to analyze shipping disruptions while
207 simultaneously considering uncertainties in demand and shipping time, canal passage, rerouting
208 decisions, and the speed-up strategy from the perspectives of time, costs, and environmental
209 impact.

210 **3 Methodology**

211 This section presents the A-star algorithm used to identify the shortest shipping routes and
212 DES, which is employed to assess the implemented strategies for various scenarios.

213 **3.1 A-star algorithm**

214 In this study, the A-star path-finding algorithm is used to determine the shortest paths
215 between each considered European and Asian country under various statuses of the Suez Canal
216 (i.e., blockage and no blockage). This approach calculates the sailing time and distance for each
217 vessel, regardless of its current position within the system. A-star is an extension of Dijkstra’s
218 path-finding algorithm, introduced by Hart *et al.* (1972). This algorithm improves efficiency by
219 incorporating heuristics. The conventional A-star has been proven to outperform modifications
220 of the algorithm in maritime shipping (Kim *et al.*, 2014). Previously, Sibul *et al.* (2023) used
221 the A-star path-finding component of the framework for assessing navigation via the Northeast
222 Passage. The pseudo-code for the A-star algorithm is described in Algorithm 1 and 2.

Algorithm 1: A* Pathfinding Algorithm

Data: Graph G , Start Node $start$, Goal Node $goal$

Result: Shortest Path from $start$ to $goal$ and its total cost

Initialize priority queue $frontier$;

Insert $start$ into $frontier$ with priority 0;

Set $came_from[start] \leftarrow \text{None}$;

Set $cost_so_far[start] \leftarrow 0$;

while $frontier$ is not empty **do**

 Dequeue node with the lowest priority ($current$) from $frontier$;

if $current == goal$ **then**

break;

end

foreach neighbor $next$ of $current$ in G **do**

 Calculate $new_cost \leftarrow cost_so_far[current] + G[current][next][weight]$;

if $next$ is not in $cost_so_far$ **or** $new_cost < cost_so_far[next]$ **then**

 Update $cost_so_far[next] \leftarrow new_cost$;

 Calculate $priority \leftarrow new_cost + heuristic(next, goal)$;

 Enqueue $next$ into $frontier$ with $priority$;

 Set $came_from[next] \leftarrow current$;

end

end

end

Algorithm 2: Reconstruct Path from Node Connections

Data: $came_from$, Start Node $start$, Goal Node $goal$

Result: Shortest Path as a list of nodes

Initialize empty list $path$;

Set $current \leftarrow goal$;

while $current \neq start$ **do**

 Append $current$ to $path$;

 Set $current \leftarrow came_from[current]$;

if $current$ is *None* **then**

return empty list $[]$;

end

end

Append $start$ to $path$;

Reverse $path$;

return $path$;

More details on A-star development can be found in the supplementary material file.

3.2 Discrete Event Simulation

Furthermore, DES is frequently employed to understand a system's behavior under various strategies (Shannon, 1975). It has proven to be particularly well-suited for modeling complex systems with ordered events, enabling the analysis of dynamic and stochastic processes (Kiran, 2019). This method is widely used in the transportation industry (Kelton *et al.*, 2002). Previously, Musso & Sciomachen (2020) employed DES to analyze operations, focusing on mega container vessels, to evaluate performance indices under various strategies. Simulation results showed the potential efficiency of the container terminal in handling near-expected TEU throughput. Graf Von Westarp & Brabänder (2021) implemented DES to evaluate speed profiles in order to identify the best possible trade-off between minimizing fuel consumption and maintaining schedule reliability in liner shipping.

In terms of simulating pathways with key components (such as the SC) blocked, Gast *et al.* (2021) developed a novel queuing model for the Suez Canal with varying blockage durations and determined the canal's reopening time under 'business-as-usual' conditions. Rahimikelarijani *et al.* (2018) focused on the mitigation consequences (from a time perspective) of the closure of the Houston Ship Channel, using DES as the primary research method. Results indicated a substantial decrease of up to 70% in waiting time for the best closure scenario. These studies demonstrate the efficiency of DES for evaluating canal blockages and assessing the effectiveness of mitigation strategies.

For the case study, the primary components of each developed model (e.g., three blockage mitigation strategies) involve two groups of vessels. The first group is simulated with the Monte Carlo approach, with daily calls for Suez Canal passage based on historical data from 2019 to mid-2024 (United Nations Global Platform & IMF PortWatch Team, 2024). The second group consists of container carrier vessels (container flows between selected European and East Asian countries heavily engaged in trade) (Eurostat, 2024). The events of the system are as follows: arrival of vessels, routing decisions for some of the strategies, passage or waiting until the end of the canal blockage, and the blockage itself. Selected European and Asian countries are listed in Appendix A. More detailed information on vessel selection, characteristics, vessel flows between selected European and Asian countries, and SC statistics can be found in the supplementary material file.

First, a DES model is applied to analyze direct transportation via the SCR and the CGHR, assuming there is no Suez Canal blockage. Second, the DES model is adjusted to analyze the consequences of applying the following strategies to mitigate the effects of a Suez Canal blockage (Strategies 1, 2, and 3):

1. Wait ("W"): Vessels wait anchored until the end of the blockage;
2. Reroute ("RN") normal speed: Vessels sail at normal speed around the CGHR in case of a Suez Canal blockage;
3. Reroute ("RT") increased speed: Vessels sail at increased speed around the CGHR in case of a Suez Canal blockage.

265 Typically, shipping companies approve sailing routes before vessels depart on their voyages.
 266 However, in case of disruptions, companies may reconsider their strategy and adjust routes
 267 (Soltani & Mirzapour Al-e Hashem, 2023). In the developed DES models, reconsideration of
 268 the route occurs on the day of the blockage. The primary component considered for rerouting
 269 is the remaining sailing time. As mentioned earlier, the reason for choosing time as the decision
 270 variable is that time plays one of the most crucial roles in maritime cargo delivery (Zhou *et al.*,
 271 2024). The simplified algorithms for the simulation models are shown in Figure 2.

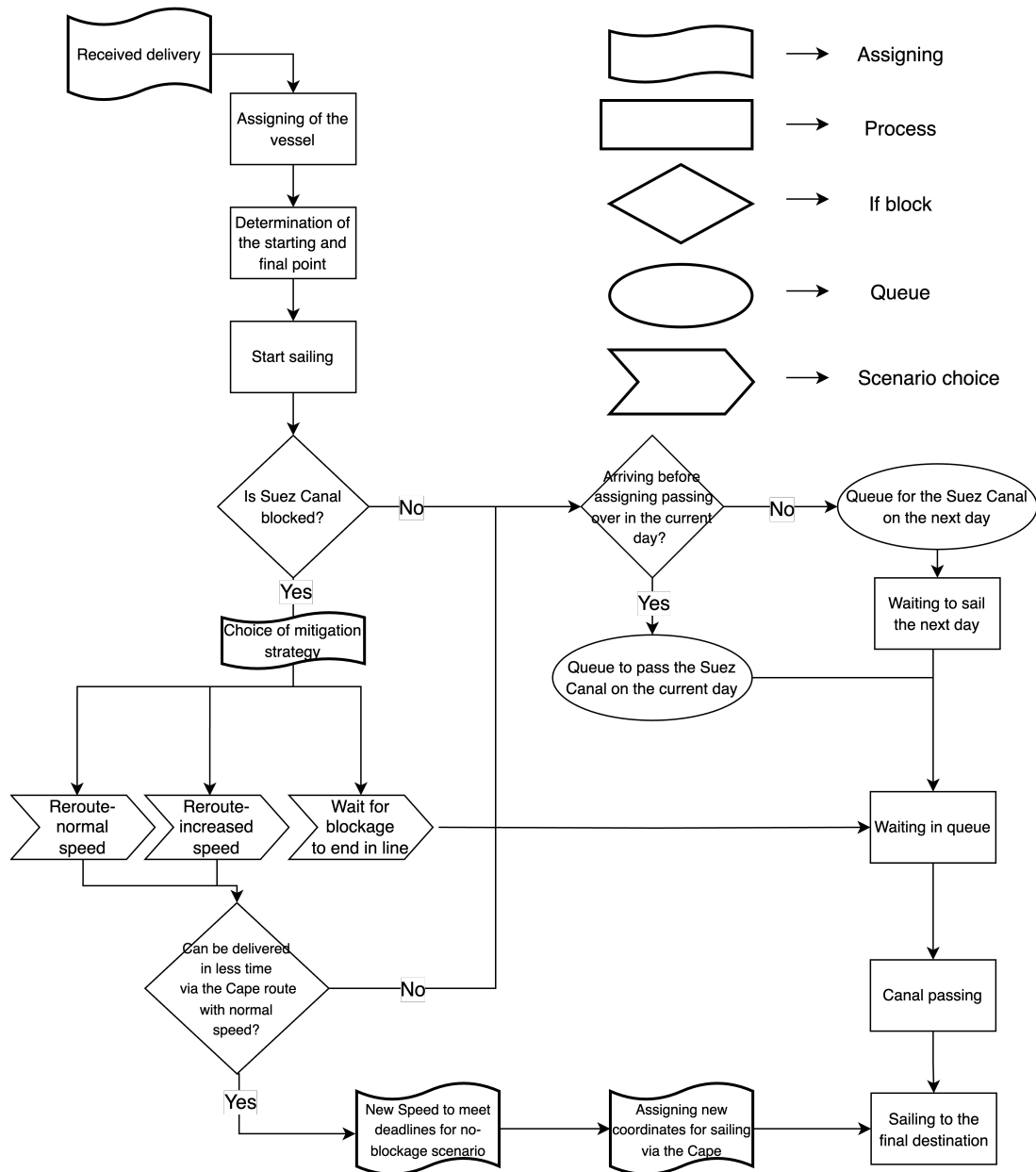


Figure 2 – Simplified algorithm of the DES models

Source: Author

3.3 Evaluation criteria

The current study aims to identify the optimal mitigation strategy given varying objectives. Each objective has its own evaluation criteria. A more detailed description of each evaluation criterion output can be found in Table 1.

Most of the components used in the evaluation criteria are obtained from the models' outputs. Time is used to assess time cost, including all primary and rerouting strategies (RQ1). Output files also contain information about sailing time (e.g., sailing before and after SC, waiting time in queue, passing time of SC) and vessel parameters (e.g., speed, fuel consumption). Based on this data, fuel consumption and all other relevant costs are calculated (RQ2, RQ3, and RQ4). More detailed explanations of calculation methods can be found in Appendices B and C.

Table 1 – *Evaluation criteria with description for each research question*

Research question	Evaluation criteria	Description	Calculation methods
RQ 1	Transport time and time cost	Transport time and time cost	Transport time Simulation models' outputs; Time cost Daily Maritime earnings, depreciation, time charter, and inventory costs ^{a,f}
RQ 2	Operational cost	1. Crew cost ^b 2. Fuel (main and auxiliary) and lubricant costs ^c 3. Canal fees ^d	Based on sailing time, fuel type and usage, tariff and fees calculation methods
RQ 3	CO ₂ emissions	Cost of produced CO ₂ emissions for considered vessels ^e	CO ₂ emissions production; EEDI for CO ₂ ; Cost of CO ₂ emissions
RQ 4	Societal cost	Societal cost	Sum of time, operational, and CO ₂ emissions costs

^a Koacz *et al.* (2024)

^b Ghaderi (2019); Kooij & Hekkenberg (2022); Liu *et al.* (2024)

^c Liu *et al.* (2024)

^d Suez Canal Authority (2025)

^e International Maritime Organization (IMO) (2018b)

^f Lindstad *et al.* (2011)

Source: Author

4 Results

To evaluate the applicability of the approach involving an A-star path-finding algorithm and a simulation model with 15 iterations, the real-life case of Suez Canal transit calls and 7 blockage durations (5, 10, 15, 20, 25, 30, and 35 days) is considered. The selection of container carriers in the model is random and sourced from (Clarksos Research Services Ltd., 2024). Each vessel possesses unique characteristics, such as sailing speed, types of primary and auxiliary

288 engines, and fuel consumption. The initial and final ports are determined based on a Monte
289 Carlo simulation of real-life data on container cargo flow between Europe and Asia, which passes
290 entirely through the Suez Canal.

291 According to the paths obtained with the A-star algorithm, the navigation distance via the
292 SCR is generally 30% shorter than that of the CGHR (an average difference of 3288 nm or 6100
293 km). These results deviate by 2.6% from the distances reported in [Li et al. \(2022\)](#).

294 Results for different types of costs are presented only for vessels affected by the blockage in
295 the following sections.

296 4.1 Transportation time and time costs

297 The considered blockage durations indicate a significant impact of the 'RT' strategy on short
298 blockage durations, even for as little as 5 days (see [Figure 3](#)). As the queue increases with each
299 subsequent day of blockage, mitigating most vessels at the beginning of the blockage involves
300 rerouting them via the CGHR to meet the initial shipping time.

301 Additionally, the 'RN' strategy results in zero vessels choosing to reroute for all blockage
302 scenarios shorter than 20 days. The reason is insufficient shipping time due to speed limitations.
303 Moreover, the longer the blockage lasts, the closer the results of the two rerouting strategies are
304 to each other.

305 A more detailed look at the sailing time results ([Figure 3](#)) shows that for all blockages shorter
306 than 20 days, no vessels chose to reroute under the 'RN' strategy. The blockage duration is
307 insufficient for vessels to reroute at the initial speed. However, as the blockage continues, more
308 vessels reroute and save on shipping time. The lowest sailing times are observed for 'RT' across
309 all scenarios, ranging from a few hours saved for a 5-day blockage to more than 20 days saved
310 for a 35-day blockage.

311 For longer blockage durations, the difference in sailing time between the two rerouting strate-
312 gies varies between 1 and 5 days.

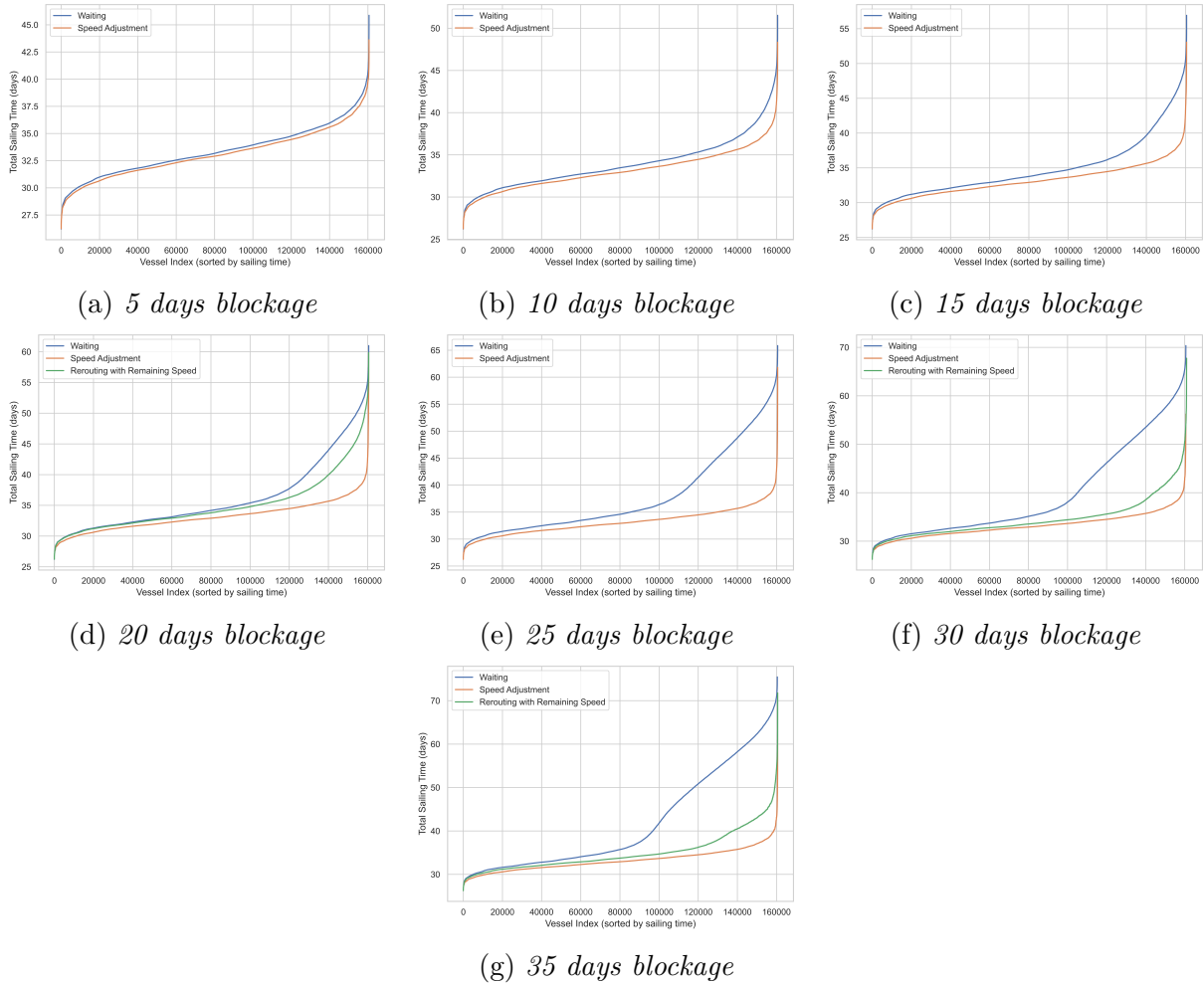


Figure 3 – *Sailing time results for different blockage durations*

Source: Author

313 Time cost delays in this research represent a monetary loss for ships that fail to fulfill
 314 subsequent orders due to delays, as well as the costs of shipping expressed as time charter cost
 315 and inventory carrying cost. As shown in Figure 4, where each line represents the mean value of
 316 time cost (for calculation methods, see Appendix C), the waiting strategy results in the highest
 317 values starting from 5 days.

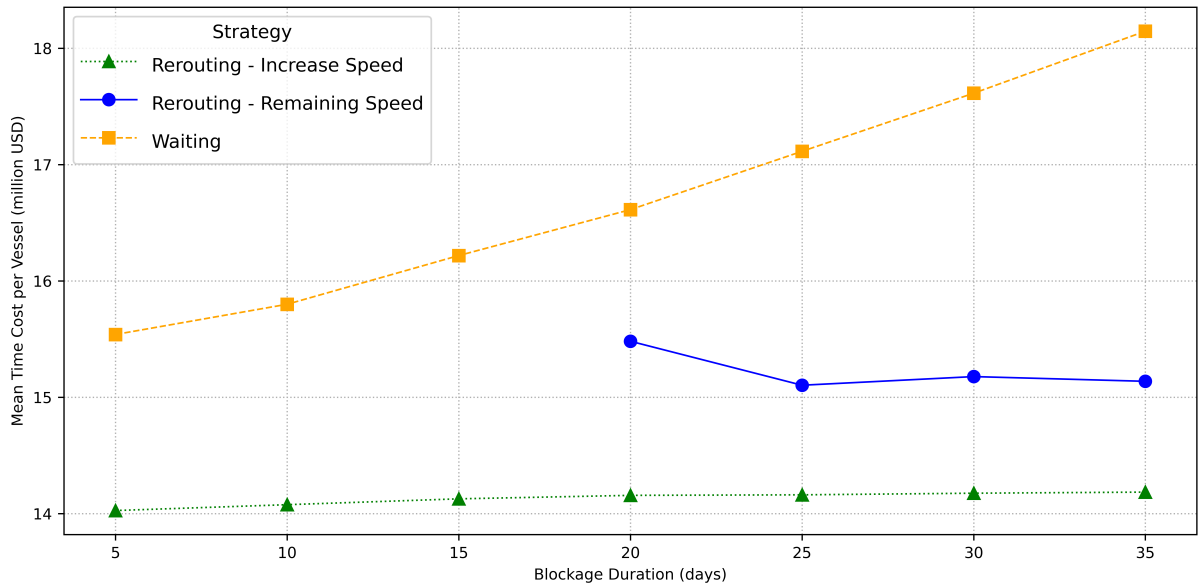


Figure 4 – Mean values of time cost of shipping for each blockage duration scenario

Source: Author

318 This results in the dominance of the 'RT' strategy for all blockage durations from the per-
 319 spective of time cost. The 'RN' strategy serves as a "trade-off" strategy, whereas 'W' is the
 320 least preferable strategy if stakeholders prioritize the time component of shipping. Decreased
 321 transportation time with rerouting strategies results in a reduction of 1.54 million USD for the
 322 'RT' strategy and 13.1 million USD for the 'RN' strategy. Comparing the rerouting strategies,
 323 cost differences vary in the range of 0.91.2 million USD per vessel.

324 4.2 Operational cost

325 Results for operational costs (including fuel, crew, and transit tolls) indicate the lowest
 326 values for the 'W' strategy due to reduced fuel consumption (shorter sailing distance results in
 327 less fuel consumption), which contributes up to 85% of operational cost for all strategies and
 328 results in lower costs for both fuel and emissions. However, transit tolls and crew costs are
 329 higher due to the canal passage time and fuel consumption during anchorage compared with
 330 rerouting strategies (see Appendix B).

331 Furthermore, based on the results, fuel and emissions costs gradually decrease for all blockage
 332 duration scenarios in rerouting strategies due to the reduction in the number of extreme voyages
 333 and the normalization of rerouting as a means of blockage mitigation (see Appendix B). The
 334 same reason explains the decrease in operational costs for the 'RN' strategy as for the 'RT'
 335 strategy.

336 Cost calculation methods are outlined in Appendix C.

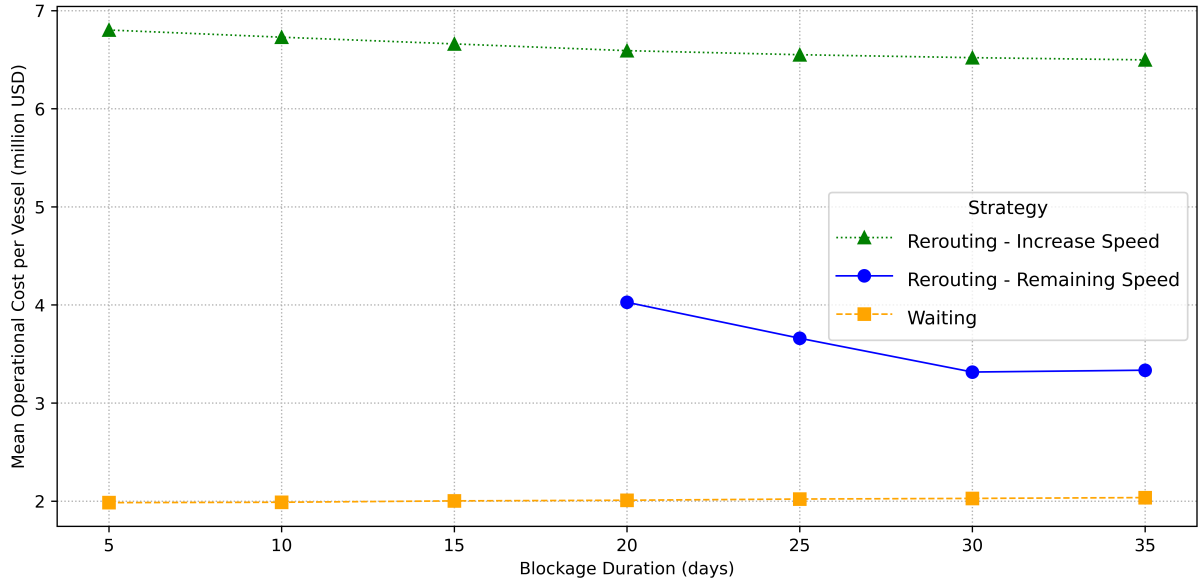


Figure 5 – Operational cost of shipping for each blockage duration scenario

Source: Author

337 The variation in operational costs between the 'RT' and 'W' scenarios remains approximately
 338 constant at 44.2 million USD. A different picture is observed for the 'RN' scenario: operational
 339 costs rapidly decline from approximately 4 to 3.3 million USD, resulting in a difference of about
 340 12.3 million USD depending on the blockage duration.

341 4.3 Emissions cost

342 As discussed, longer blockage durations result in more vessels rerouting and consuming
 343 higher volumes of fuel, leading to increased CO₂ emissions. This creates a strong dependency
 344 on emissions, fuel consumption, and speed, particularly in the case of the 'RT' strategy. As
 345 shown in Figure 5 for direct cost and in Figure 6 for CO₂ emissions, the results are highly
 346 correlated.

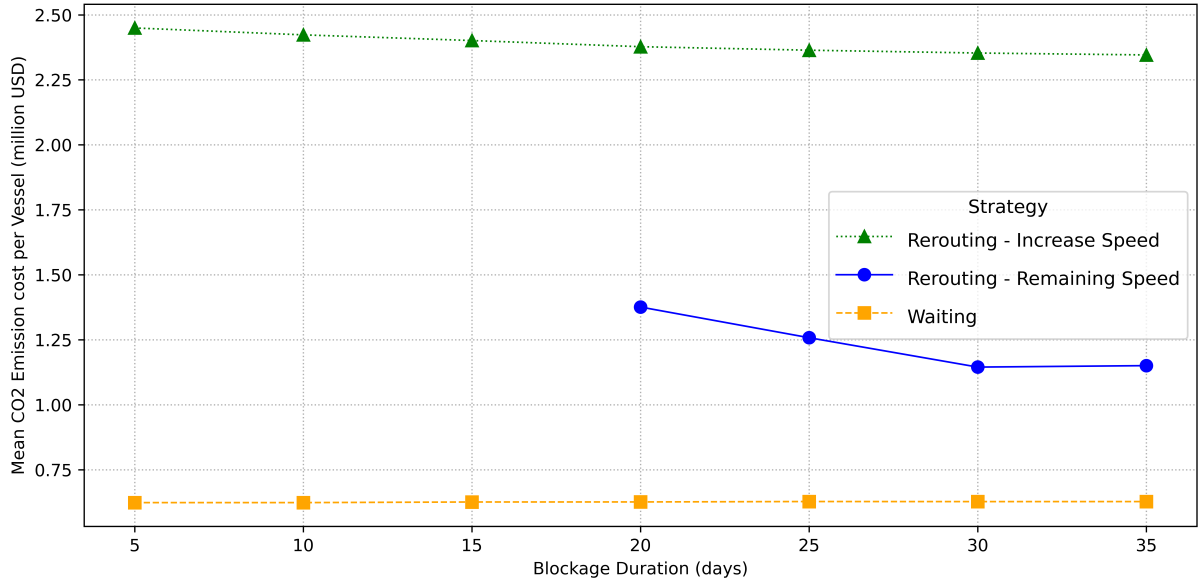


Figure 6 – CO_2 emissions of shipping for each blockage duration scenario

Source: Author

347 The average variation in CO_2 emissions costs between 'RT' and 'W' is in the range of 34
 348 times (1.71.8 million USD). Meanwhile, the 'RN' strategy results in lower mean emissions with
 349 prolonged blockage durations. For the longest blockage duration of 35 days, fuel consumption and
 350 consequently, emissions cost differs by approximately 0.53 million USD, whereas the difference
 351 between 'RT' and 'W' for the same duration is about 1.7 million USD.

352 4.4 Societal cost

353 For society as a whole, the optimal strategy in this study is defined as the one that minimizes
 354 the sum of operational cost (see Section 4.2), time cost (see Section 4.1), and CO_2 emissions
 355 cost (see Section 4.3) for different blockage durations.

356 Based on the results, for all blockage durations shorter than 25 days, the waiting scenario
 357 shows the lowest societal costs. This is due to the substantial operational and CO_2 emissions
 358 costs of rerouting strategies compared with the 'W' strategy. However, time costs are higher for
 359 'W' compared with the 'RT' and 'RN' strategies. Overall, given the magnitudes chosen for the
 360 SC (see Section 2), the 'W' scenario is the most preferable for short blockage durations. Thus,
 361 for short blockages, the best strategy for society as a whole is to wait for the end of the blockage
 362 rather than reroute.

363 A different situation arises for blockages longer than 25 days. In such cases, the 'RN' strategy
 364 dominates, showing a sufficient decrease in SC compared with the 'RT' strategy by 3.3 million
 365 USD and compared with the 'W' scenario by 0.5 million USD.

366 Results for societal cost are visualized in Figure 7.

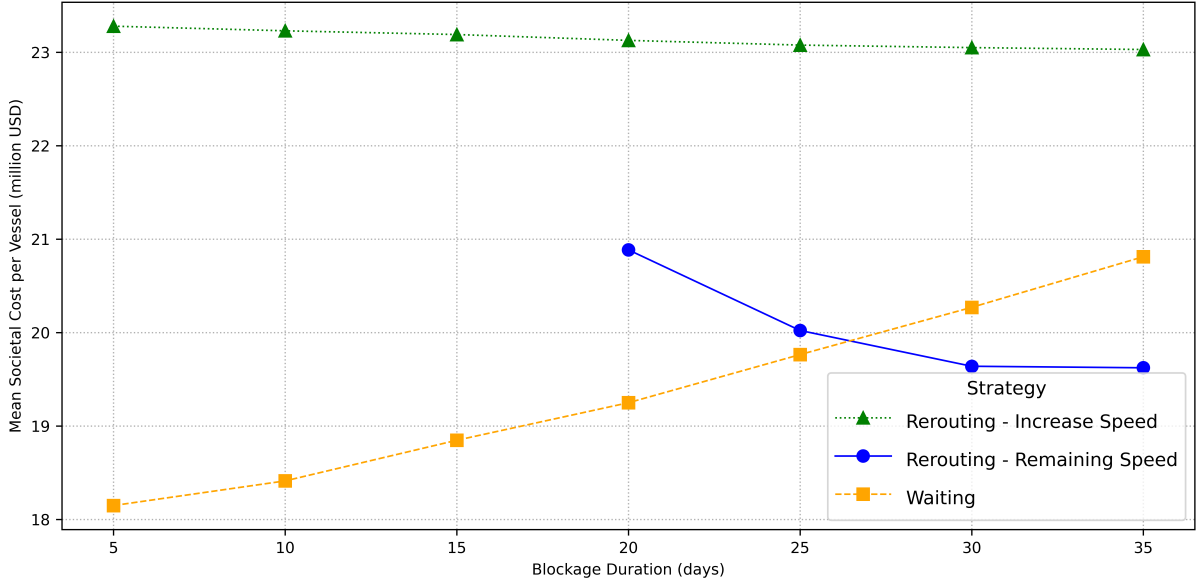


Figure 7 – Mean societal cost of shipping for each blockage duration scenario

Source: Author

As shown in Figure 7, there is a substantial gap between the 'RT' strategy and the two other considered strategies, corresponding to approximately 2.15 million USD ('RT' vs. 'W') and 2.23.2 million USD ('RT' vs. 'RN'). This occurs mainly due to differences in operational and CO₂ emissions costs. The benefits of the 'RT' strategy cannot offset this imbalance, making 'W' the best strategy for blockages shorter than 25 days and 'RN' the best strategy for blockages longer than 25 days.

5 Sensitivity analyses

As discussed in the "Literature Review" section (see Sections 2.1 and 2.2), the SC value highly depends on the magnitude of the coefficients for operational, emissions, and time costs. Due to this, this section examines the impact of technical vessel characteristics, including the Energy Efficiency Design Index (EEDI), freight rates, depreciation, and time charter costs, as well as the fuel cost impact on the mean SC per vessel for each blockage mitigation strategy. The following subsections discuss this impact and provide an overview of the suitable strategy for different blockage durations, considering various parameters that influence the SC for sailing or fuel consumption, which accounts for approximately 70.80% of shipping costs.

Sensitivity analyses in Section 5.1 consider the real case of disruptions at primary choke-points, where freight, charter rates, and container costs are affected by shipping disruptions such as the Suez Canal closure (Li *et al.*, 2021, Notteboom *et al.*, 2024). This implies neglecting static consideration of parameters and requires more sophisticated planning of blockage mitigation strategies.

5.1 EEDI and Freight rate, depreciation, and charter costs

The analyzed parameters for freight rates, combined with depreciation, time charter costs, and EEDI, are represented as $\theta_{i,j}$ with a 0.4 step, where θ corresponds to the decrease of

390 parameters, i corresponds to the EEDI, and j to freight rate, depreciation, and time charter
391 (FDT) costs. Results are presented in the subfigures in Figure 8. Each subfigure grid cell's
392 abbreviation represents the strategy with the lowest SC across the three blockage mitigation
393 strategies.

394 The 'RT' strategy dominates all blockage duration scenarios only in the case of the most
395 energy-efficient vessels. This highlights the importance of vessel characteristics and the dom-
396 inance of fuel consumption in determining the preferable choice of the 'RT' strategy. For all
397 blockages lasting 20 days or less, the dominant strategy for modestly efficient vessels remains
398 'W', except when higher FDT costs are considered at 20 days, where the 'RN' strategy shows
399 the lowest SC. Starting from the 25-day blockage scenario, the 'RN' strategy becomes dominant
400 for modestly energy-efficient vessels depending on FDT costs. Specifically, the 'RN' strategy
401 shows the lowest cost when FDT increases by at least 0.4, or for all values at 25 and 30-35 days.
402 Vessels with modestly low EEDI can consider rerouting at normal speed when FDT is increased
403 by at least 0.4, and for all values at 30 and 35 days. Finally, the least efficient vessels can reroute
404 at normal speed only in the case of the longest considered blockage (35 days) and the highest
405 FDT costs.

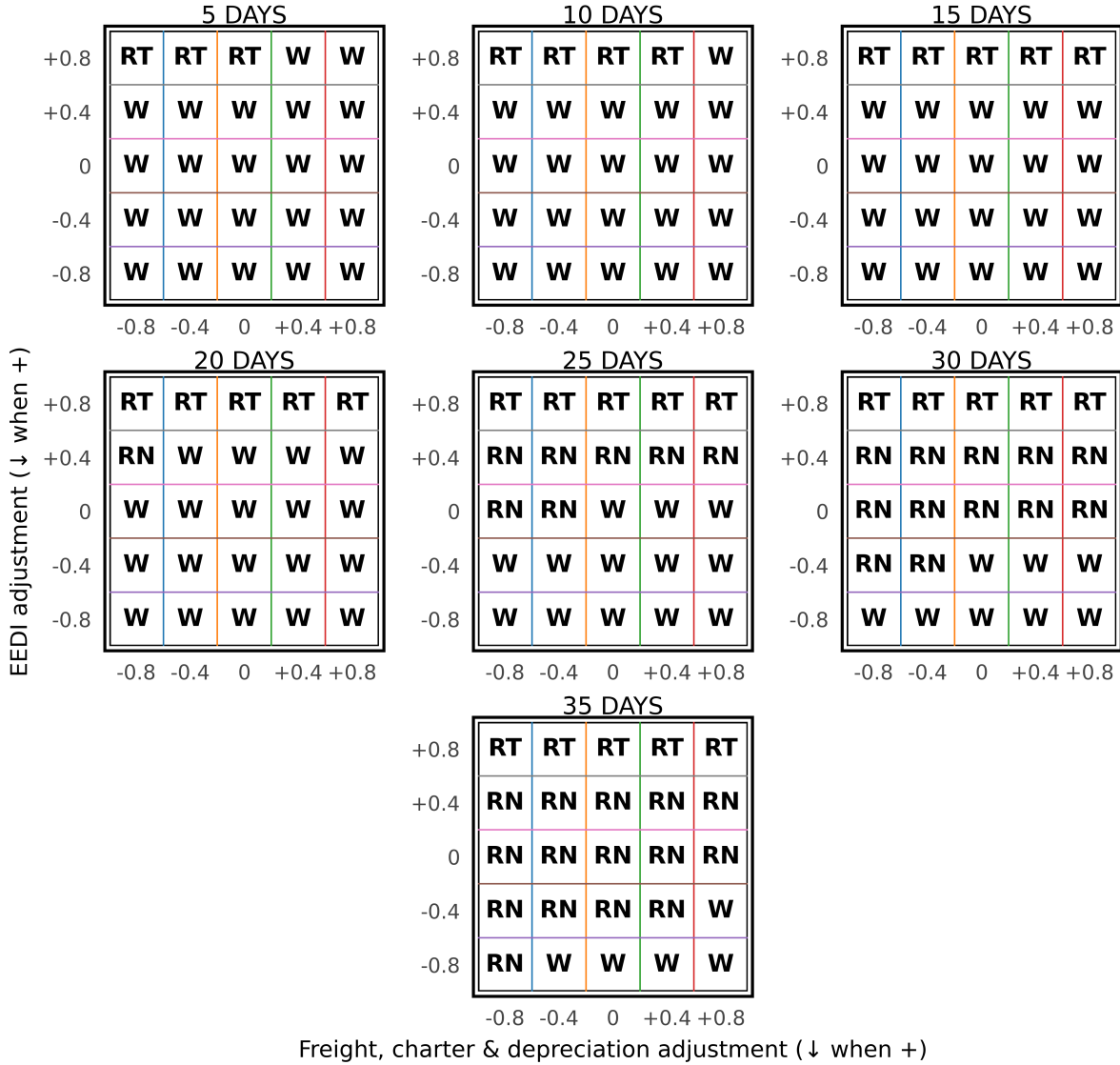


Figure 8 – Sensitivity analyses of freight rates, depreciation, and time charter costs for the preferable strategy for different blockage duration scenarios

Source: Author

5.2 EEDI and Fuel cost

406

407 The next parameters considered are associated with the same technical characteristics as
 408 in the previous subsection (EEDI of vessels) and the market component of fuel cost (bunker
 409 price). The same sensitivity setup $\theta_{i,j}$ with a 0.4 step is used, but with i corresponding to EEDI
 410 and j to the fuel cost decrease. Sensitivity results for EEDI and fuel cost are presented in the
 411 subfigures in Figure 9.

412 Sensitivity results for EEDI and fuel cost indicate the same winning strategy for all block-
 413 age durations for highly efficient vessels (high EEDI) the 'RT' strategy. Additionally, modestly
 414 efficient vessels can consider rerouting in the case of low fuel cost for blockages lasting at least
 415 25 days. For blockages of at least 30 days, vessels with the considered EEDI can start to reroute

416 except in cases of high fuel cost.

417 Moreover, for longer blockages, less efficient vessels may consider rerouting at normal speed
 418 when fuel prices are relatively low for blockages of 3035 days, or at normal fuel prices for
 419 blockages longer than 30 days.

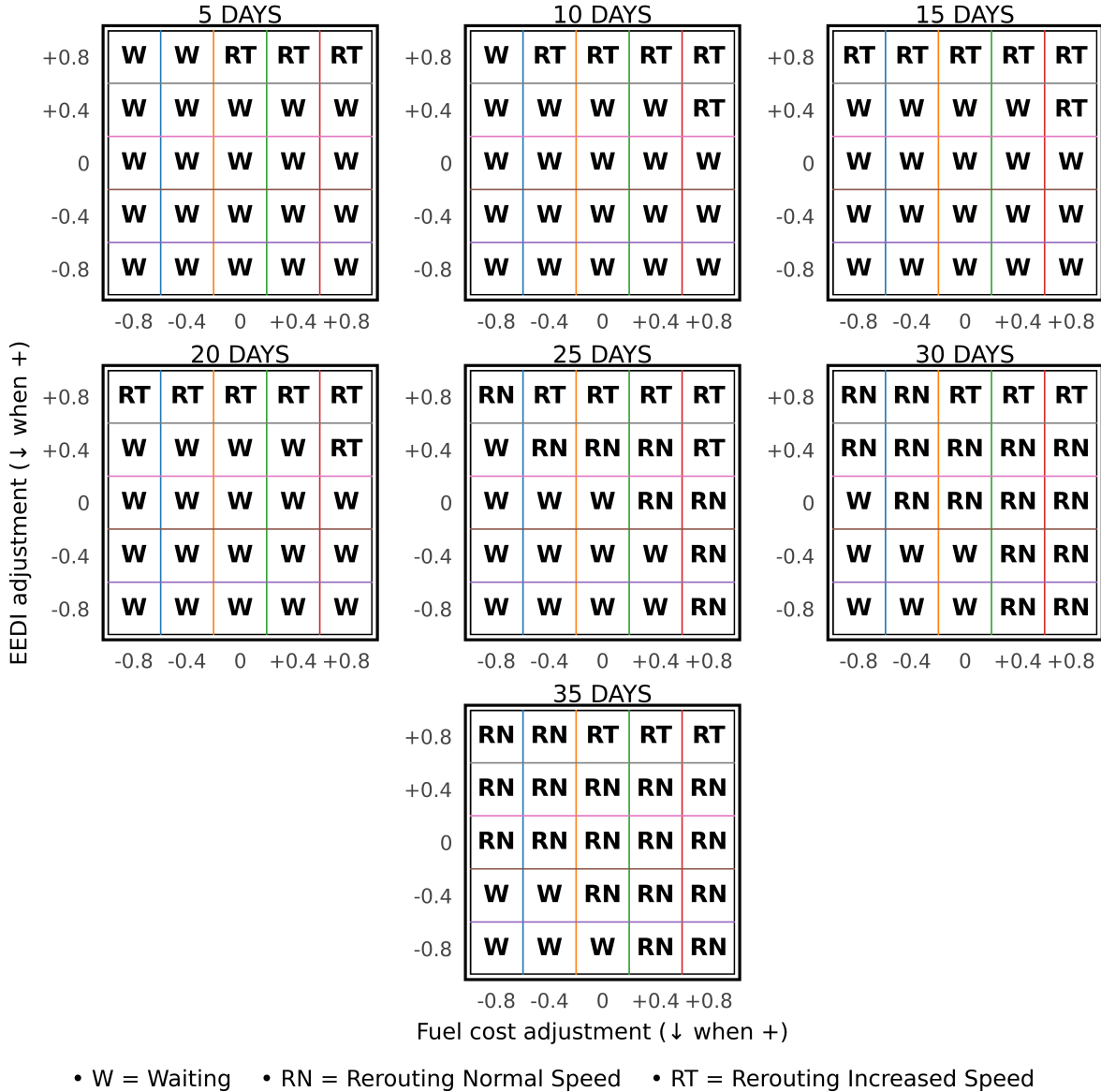


Figure 9 – Sensitivity analyses of fuel cost for the preferable strategy for different blockage duration scenarios

Source: Author

420 5.3 Random Forest analyses

421 Random Forest (RF) is a method widely used in transport-related studies (Aghaabbasi
 422 *et al.*, 2020). This method is employed to assess the relevance of each factor, such as market
 423 components (e.g., freight rate, inventory cost, charter rate) and vessel technical characteristics.
 424 The method is chosen due to its accuracy in predictions and low risk of overfitting. The RF

425 analysis is conducted for six parameters in total, forming a matrix with six features: [Freight
426 rate, Charter rate, Depreciation, Fuel, Inventory, EEDI] for each rerouting strategy ['W', 'RN',
427 'RT']. The analysis is performed for one iteration and four blockage scenarios (5, 15, 25, and 35
428 days) due to calculation complexity limitation. As is common in data analysis, the dataset is
429 split into two parts: 75% for training and 25% for testing. Each strategy is analyzed separately.

430 To obtain the highest model accuracy, the following hyperparameters are tuned using the
431 Randomized Search Cross Validation method (5 folds) with 40 random configurations: number
432 of trees, maximum depth of trees, maximum features per split, minimum samples per split, and
433 minimum samples per leaf (Svetnik *et al.*, 2003).

434 Results for the 'W' strategy across all considered blockage scenarios indicate high impor-
435 tance of freight rate and inventory cost on SC (removing these values reduces model accuracy).
436 Moreover, the impact of inventory cost increases substantially with longer blockage durations
437 (0.23 for a 5-day blockage and 0.4 for a 35-day blockage).

438 For the 'RT' strategy, the most important factors are EEDI, freight rate, and fuel cost,
439 ranked in that order.

440 The 'RN' strategy results indicate the highest importance of freight rate for model prediction,
441 followed by inventory cost and EEDI.

442 The normalized results (where the sum of factors equals 1 and the highest value indicates
443 the most important factor for mitigation strategy and each considered blockage duration) for
444 permutation importance across blockage scenarios and mitigation strategies are shown in Table
445 2.

Table 2 – Normalized permutation importances for cost determinants

		Rerouting			
		Waiting (W)	Increase Speed (RT)	Remaining Speed (RN)	Parameter
Blockage Duration	5	0.67	0.26	-	Freight rate
		0.23	0.10	-	Inventory
		0.05	0.39	-	EEDI
		0.03	0.24	-	Fuel
		0.01	0.00	-	Charter rate
		0.00	0.00	-	Depreciation
		15	0.62	0.27	-
0.28	0.10		-	Inventory	
0.05	0.39		-	EEDI	
0.03	0.24		-	Fuel	
0.01	0.00		-	Charter rate	
0.00	0.00		-	Depreciation	
25	0.56		0.28	0.46	Freight rate
	0.35	0.11	0.24	Inventory	
	0.05	0.38	0.18	EEDI	
	0.03	0.23	0.11	Fuel	
	0.02	0.00	0.01	Charter rate	
	0.00	0.00	0.00	Depreciation	
	35	0.51	0.27	0.48	Freight rate
0.40		0.11	0.25	Inventory	
0.04		0.38	0.16	EEDI	
0.03		0.23	0.10	Fuel	
0.02		0.00	0.01	Charter rate	
0.00		0.00	0.00	Depreciation	

Source: Author

6 Conclusions and further research

The rapid changes in the maritime business, from a disruption-events perspective as well as from regulations aimed at reducing the impact of shipping on emissions, necessitate consideration of the trade-off between 'business-as-usual' and regulatory compliance. For this purpose, not only do the costs associated with shipping and emissions play a crucial role in the choice of mitigation strategy for blockages, but these events also lead to disruption of the consequent chain of cargo delivery and delays.

This research primarily aims to develop the method which helps to evaluate and identify the optimal strategy for shippers in scenarios involving varying durations of blockages in vital trade routes. The assessment is conducted from four key perspectives: time, operational, emission, and societal costs. In the context of a Suez Canal blockage, this study examines two rerouting strategies, comparing their effectiveness against the traditional approach of waiting for the blockage to resolve. Two core methods are employed in the research to achieve this aim:

459 the A-star shortest pathfinding algorithm for shipping and rerouting, and the DES model with
460 simulated flow through the Suez Canal, based on historical throughput data.

461 The results (for vessels affected by blockages) indicate the efficiency of rerouting strategies
462 compared to the waiting strategy from both the shipping time and time-cost perspectives. The
463 benefits of rerouting compared to waiting until the end of the blockage range from 1.5 to 4 million
464 USD and 0.5 to 15 days of shipping for rerouting with increased speed, and from 0.9 to 1.2 million
465 USD and 3 to 5 days of shipping for rerouting at normal speed. However, rerouting strategies
466 imply a significant amount of additional fuel consumption, resulting in nearly 4.54.8 million
467 USD (33.5 times) higher operational costs for the increased-speed strategy and an increase of
468 1.52 million USD (1.752 times) for rerouting at normal speed. The consequence of additional
469 fuel consumption also leads to higher CO₂ emission costs approximately 2 million USD for the
470 increased-speed strategy and approximately 0.6 million USD for the normal-speed strategy.
471 However, societal cost, as the combination of all previous costs, indicates that the waiting
472 strategy is the most preferable option for all blockage duration scenarios. Overall, the best
473 scenario, given the set parameters (e.g., fuel, CO₂, crew, and freight costs), is the waiting
474 strategy. The rerouting with increased speed scenario shows an increase in societal cost of
475 approximately 5.2 million USD across all considered scenarios, whereas rerouting at normal
476 speed has a relatively small gap in societal cost compared to waiting 12 million USD.

477 Sensitivity analyses, considering the impact of vessel technical efficiency and market com-
478 ponents such as freight and charter rates, depreciation costs, and fuel costs, reveal the influence
479 of these parameters on the choice of blockage mitigation strategy across all considered blockage
480 duration scenarios. For highly energy-efficient vessels, rerouting with increased speed is observed
481 for all blockage scenarios regarding vessel technical characteristics and fuel cost. For modestly
482 efficient vessels, rerouting at normal speed can be a preferable strategy only for fleets with mod-
483 est or average technical characteristics, and depending on market components (freight, charter,
484 depreciation, and fuel cost).

485 Furthermore, the Random Forest analysis of factor permutation importance highlights the
486 high importance of freight rate across the 'W' and 'RN' strategies, and its ranking as the second
487 most important factor for the 'RT' strategy. The EEDI factor is the most critical for the 'RT'
488 strategy and the third most important in the 'RN' strategy. Inventory cost plays a crucial role
489 in the 'W' and 'RN' scenarios. The fuel factor is the least important among the major factors
490 for the 'RN' strategy and the second least important for the 'RT' strategy. The two remaining
491 factors, charter rate and depreciation cost, have almost zero impact on societal cost.

492 The current research relies on several assumptions in developing the model; therefore, the
493 following limitations are highlighted. First, the blockage duration is predefined and known from
494 the beginning. This may overlook real blockages that occurred in the Suez Canal in the past.
495 It is suggested to consider stochastic optimization models that can overcome this predefined-
496 duration limitation. Second, following from the first point, the A-star pathfinding algorithm
497 could be extended to consider the dynamic choice of blockage and suggest a more optimal route
498 based on probabilities of disruption duration and vessel rerouting decisions. Furthermore, future
499 studies could consider more complex shipping patterns, such as visiting ports en route to the

500 final destination, as well as different blockage mitigation strategies, including port-skipping and
501 swapping.

502 While this research considers the Suez Canal as the case study, the modeling framework and
503 A-star pathfinding algorithm can be applied to other global maritime chokepoint disruptions.
504 For instance, the methodology could be applied to disruptions of the Panama Canal, Arctic sea
505 routes, or inland transport corridors.

506 **A Appendix: Considered countries in the analyses**

507 The Appendix A lists the countries considered in the case study, including European and
 508 Asian countries that exhibit high engagement in maritime trade flows between Europe and Asia.
 509 The list of these countries is presented in Table 3.

Table 3 – *Considered European and Asian countries in the case study*

	European countries		Asian countries	
	Country	Port names	Country	Port names
1	Belgium	Port of Antwerp	China (except Hong Kong)	Port of Shanghai
2	Denmark	Port of Aarhus	Japan	Port of Nagoya
3	Germany	Port of Hamburg	South Korea	Port of Busan
4	Estonia	Port of Tallinn		
5	Ireland	Port of Dublin		
6	France	Port of Le Havre		
7	Latvia	Port of Riga		
8	Lithuania	Port of Klaipda		
9	Netherlands	Port of Rotterdam		
10	Poland	Port of Gdask		
11	Finland	Port of Helsinki		
12	Sweden	Port of Gothenburg		
13	Norway	Port of Oslo		
14	United Kingdom	Port of Felixstowe		

Source: Author based on Eurostat (2024).

510 B Appendix: Fuel Consumption and Emission

511 Design fuel consumption

512 Fuel consumption for vessels is calculated based on the methodology presented by [International Maritime Organization \(IMO\) \(2018a\)](#). The report outlines the procedure for calculating
 513 the Energy Efficiency Design Index (EEDI), which is designed to assess a vessel’s energy effi-
 514 ciency based on key technical parameters, such as sailing speed, specific fuel consumption of
 515 engines, and deadweight tonnage ([Georgoudakis *et al.*, 2025](#)).

517 The calculation consists of the summation of energy produced by all engines on the vessel,
 518 sailing speed, and vessel capacity. Equation 3 represents the calculation of a vessel’s EEDI.

$$\begin{aligned}
 \text{EEDI} = & \frac{\left(\prod_{i=1}^M f_i\right) \left(\sum_{i=1}^{N_{ME}} P_{ME_i} \cdot C_{ME_i} \cdot \text{SFC}_{ME_i}\right) + (P_{AE} \cdot C_{AE} \cdot \text{SFC}_{AE})}{f_i \cdot \text{Capacity} \cdot V_{\text{ref}} \cdot f_w} \\
 & + \frac{\left(\prod_{i=1}^M f_i \cdot \sum_{i=1}^{N_{PTI}} P_{PTI(i)}\right) - \left(\sum_{i=1}^{n_{\text{eff}}} f_{\text{eff}(i)} \cdot P_{AE_{\text{eff}(i)}}\right) C_{AE_{\text{eff}(i)}} \cdot \text{SFC}_{AE}}{f_i \cdot \text{Capacity} \cdot V_{\text{ref}} \cdot f_w} \quad (3) \\
 & - \frac{\left(\sum_{i=1}^{n_{\text{eff}}} f_{\text{eff}(i)} \cdot P_{\text{eff}(i)}\right) \cdot C_{ME} \cdot \text{SFC}_{ME}}{f_i \cdot \text{Capacity} \cdot V_{\text{ref}} \cdot f_w}
 \end{aligned}$$

519 ME and AE parameters refer to the main and auxiliary engines. P_{ME_i} , C_{ME_i} , and SFC_{ME_i}
 520 refer to the main engine’s power, carbon intensity, and specific fuel consumption (required
 521 volume of fuel to produce 1 kWh). The same calculation is applied for the auxiliary engine fuel
 522 (P_{AE} , C_{AE} , SFC_{AE}). V_{ref} denotes the vessel’s design speed, and Capacity denotes the vessel’s
 523 capacity.

524 Additionally, some parameters in equation 3 are used to calculate specific vessel features
 525 (e.g., ice-class vessels, general cargo vessels equipped with cranes, and correlation factors for
 526 specific-purpose vessels). According to [International Maritime Organization \(IMO\) \(2018a\)](#), the
 527 capacity factor (f_i) and cubic capacity correlation factor (f_c) should be assumed to be one if no
 528 specific values are available. Information about shaft generators is lacking; thus, it is assumed
 529 that they are not installed on the vessels.

530 The inclusion of the carbon intensity factor (C_{ME_i} , C_{AE}) of the fuel used by the vessel allows
 531 the calculation of relevant emissions. In this study, the analyzed emission is CO₂ (t-CO₂/t-Fuel).
 532 According to [International Maritime Organization \(IMO\) \(2018a\)](#), the carbon intensity factor
 533 is set to 3.114 for Heavy Fuel Oil and 3.151 for Light Fuel Oil.

534 Vessel’s speed consumption Cubic Law

535 Cubic Law describes the exponential increase in fuel consumption with sailing speed. This
 536 formula is commonly used in maritime transportation to assess the impact of speed reduction
 537 on emissions ([Taskar & Andersen, 2020](#), [Adland *et al.*, 2020](#)). Equation 4 represents the cubic
 538 law. Some authors suggested a relation of 2.73.3 for fuel consumption between design and actual
 539 speeds (β) ([Wang & Meng, 2012b](#)), while others reported values of 3.5 for feeder vessels, 4 for
 540 medium-size container vessels, 4.5 for the largest container vessels ([Zhen *et al.*, 2016](#)), and even
 541 5 ([Psaraftis & Kontovas, 2013](#)).

542 The exponential coefficient between design and actual speeds used in this research is set to
 543 value 3.

$$FC_a = FC_d \left(\frac{S_a}{S_d} \right)^\beta \quad (4)$$

544 **Where:**

- 545 • FC_a Actual fuel consumption [tonnes];
- 546 • FC_d Design fuel consumption [tonnes];
- 547 • S_a Actual sailing speed [knots];
- 548 • S_d Design sailing speed [knots].

549 Fuel consumption during anchorage

550 For waiting and anchorage while passing the Suez Canal, the calculation method presented
 551 by [Tran *et al.* \(2025\)](#) was implemented in this study. This method is based on the framework
 552 of ([International Maritime Organization \(IMO\), 2020](#)). Anchorage fuel consumption for the
 553 main engines is assumed to be zero. However, coefficients for auxiliary engines and boilers are
 554 considered in equations 5 and 6, respectively.

$$FC_i^{\text{aux}} = \text{SFOC}_{AE} \cdot P_{AE(x)} \cdot t_c \cdot 10^{-6} \quad (5)$$

$$FC_i^{\text{boiler}} = \text{SFOC}_{BE} \cdot P_{BE(x)} \cdot t_c \cdot 10^{-6} \quad (6)$$

555 **Where:**

- 556 • $\text{SFOC}_{AE}, \text{SFOC}_{BE}$ Specific fuel oil consumption of auxiliary engine and boiler [g/kWh];
- 557 • $P_{AE(x)}, P_{BE(x)}$ Power output of auxiliary engine and boiler during anchorage at time x [kW];
- 558 • t_c Duration of anchorage [hours];
- 559 • 10^{-6} Conversion factor from grams to tonnes.

C Appendix: Cost calculation methods

Fuel cost

Two types of fuel remained for the vessels after data cleaning and preparation: IFO380 and VLSFO. The cost of both fuels was obtained on February 28th. The costs for IFO380 and VLSFO were 464 and 549.5 USD, respectively. The cost calculation is presented in equation 7.

$$C_{\text{total}} = \sum_{i=1}^N (FC_{i,\text{open}} + FC_{i,\text{adj}} + FC_{i,\text{anchor}}) \cdot (\alpha_i \cdot P_1 + (1 - \alpha_i) \cdot P_2) \quad (7)$$

Where:

- C_{total} Total fuel cost for all vessels [USD];
- N Total number of vessels;
- $FC_{i,\text{open}}$ Fuel consumed by vessel i when sailing in open water at design speed [tonnes];
- $FC_{i,\text{adj}}$ Fuel consumed by vessel i when sailing in open water or via the canal at adjusted speed [tonnes];
- $FC_{i,\text{anchor}}$ Fuel consumed by vessel i during anchorage [tonnes], where $FC_{i,\text{anchor}} = FC_i^{\text{aux}} + FC_i^{\text{boiler}}$;
- α_i 1 if vessel i uses IFO380, 0 if vessel i uses VLSFO [$0 \leq \alpha_i \leq 1$];
- P_1 Price per tonne of IFO380 [USD/tonne];
- P_2 Price per tonne of VLSFO [USD/tonne].

Crew cost

Crew roles and their numbers are based on the methodology from Kooij & Hekkenberg (2022). Table 4 presents the crew roles and their numbers.

Table 4 – Required crew and their numbers

Position	Master	Chief engin.	Chief officer	Second Engin.	Second Officer	Bosun	Cook	Able bodied seaman	Ordinary Seaman	Deck Boy
Crew number	1	1	1	1	1	1	1	2	0	2

Source: Kooij & Hekkenberg (2022)

Calculation of crew cost for a vessel is presented in Liu *et al.* (2024) and equation 8.

$$C^{\text{crew}} = \sum_{j=1}^r \left(n_{c,j} \left(c_{w,j} + \frac{c_{w,j} \cdot p_{ex}}{1 - p_{ex}} \right) \right) \quad (8)$$

Where:

- C^{crew} Crew cost;
- r Crew roles;

- 583 • $n_{c,j}$ Number of crew members in role j ;
- 584 • $c_{w,j}$ Wage per crew member in role j [USD/month] based on the average wage in 2024 from
585 [Maritime Zone \(2025\)](#);
- 586 • p_{ex} Employment-related cost percentage of the basic salary, assumed to equal 0.3 ([Liu et al.,](#)
587 [2024](#)).

588 Emission cost

589 CO₂ emissions in this study are calculated as the sum of fuel used in each segment of sailing
590 (open water, canal, anchorage), multiplied by the average EU Emissions Trading System cost
591 for 2024, 61.03 USD/tCO₂ ([World Bank Group, 2025](#)).

592 Transit toll cost

593 Vessels passing through the Suez Canal are required to pay a toll. [Suez Canal Authority](#)
594 (2025) publishes parameters to calculate transit tolls for each type of vessel based on its Suez
595 Canal Net Tonnage (SCNT). SCNT ($SCNT_i$) for each vessel is calculated based on the regression
596 analysis results from [Chen et al. \(2018\)](#) and is shown in equation 9.

$$SCNT_i = 10.356 \cdot TEU_i - 2279.3 \quad (9)$$

597 The relation between SCNT and transit tolls is visualized in Table 5. All vessels are assumed
598 to be loaded and carrying cargo (laden); thus, only laden values are presented in Table 5 and
599 used for calculating the canal passage cost.

Table 5 – *Relation between SCNT and Transit Tolls*

Vessel Type	SC Net Tonnage (SDR / SCNT)							
	First 5000	Next 5000	Next 10000	Next 20000	Next 30000	Next 50000	Next 60000	The Rest
	Laden	Laden	Laden	Laden	Laden	Laden	Laden	Laden
Container Ships	11.04	7.58	5.89	4.13	3.82	3.01	2.94	2.88

Source: [Suez Canal Authority \(2025\)](#)

600 Time cost

601 Opportunity cost is used to evaluate one of the time cost components in shipping. According
602 to [Koacz et al. \(2024\)](#), it represents the revenue loss incurred when a container is unavailable
603 for the next delivery due to delays in the previous delivery, or, in other words, when the ship is
604 used unproductively, reducing its daily revenue ([Stopford, 2009](#)).

605 The Daily Maritime Earnings (DME) calculation in opportunity cost is based on two values
606 of $Freight\ rate_t$, corresponding to the monthly spot rates for the Shanghai Containerised Freight
607 Index (SCFI) route Shanghai-Europe. Minimum and maximum values for the period between
608 September 2018th and 2022nd are obtained from the report. The resulting DME is shown in
609 equation 10.

$$DME_{TEU,day} = \frac{FR_{TEU,voyn}}{T_{voyage}}. \quad (10)$$

610 where T_0 is the baseline voyage time in days.

611 Daily depreciation cost of containers is calculated following the methodology described in
612 Koacz *et al.* (2024). The calculation method is provided in equation 11.

$$DC_{container, average} = \sum_{t=0}^{DP} \frac{P_{Container}}{DP_{Container} - t} / \frac{1}{2} \cdot DP_{Container} \quad (11)$$

613 **Where:**

- 614 • $P_{Container}$ New container price;
- 615 • $DP_{Container}$ Depreciation time of container.

616 Inventory-carrying cost is formulated based on the assumptions in Tran *et al.* (2025). Daily
617 inventory carrying cost (equation 12) is defined as a fraction of cargo value on board (CV_{TEU})
618 and assumed time value (r). The cargo value, as assumed in Tran *et al.* (2025), is $CV_{TEU}^{east} =$
619 49,531 USD for the eastward direction and $CV_{TEU}^{west} = 49,747$ USD for the westward direction.

620 The voyage inventory carrying cost is then obtained by multiplying daily inventory cost by
621 voyage time.

$$IC_{TEU,day} = \frac{r}{365} CV_{TEU} \quad (12)$$

622 The vessel's time cost is the product of voyage time and daily value per TEU (equation 13),
623 scaled by the number of loaded containers on board (equation 14).

$$OC^{TEU} = T_{voyage} (DME_{TEU,day} + DC_{TEU,day} + IC_{TEU,day}). \quad (13)$$

$$OC^{vessel} = T_{voyage} [N_{TEU} (DME_{TEU,day} + DC_{TEU,day} + IC_{TEU,day}) + H_{TC,day}]. \quad (14)$$

624 Following the assumptions and calculation method in Lindstad *et al.* (2011), the time charter
625 cost per day is based on the newbuilding cost of the container. Approximate values for the
626 newbuilding cost are set based on the data in (Solakivi *et al.*, 2024). The time charter formula
627 per day is shown in equations 15 and 16, where TC is the annual time charter and CAPEX is
628 the newbuilding cost (Lindstad *et al.*, 2011).

$$TC_{annual} = 0.12 \times CAPEX. \quad (15)$$

$$H_{TC,day} = \frac{TC_{annual}}{350} = \frac{0.12 \times CAPEX}{350}. \quad (16)$$

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Algorithm 1: A* Pathfinding Algorithm

Data: Graph G , Start Node $start$, Goal Node $goal$
Result: Shortest Path from $start$ to $goal$ and its total cost
Initialize priority queue $frontier$;
Insert $start$ into $frontier$ with priority 0;
Set $came_from[start] \leftarrow None$;
Set $cost_so_far[start] \leftarrow 0$;
while $frontier$ is not empty **do**
 Dequeue node with the lowest priority ($current$) from $frontier$;
 if $current == goal$ **then**
 break;
 end
 foreach neighbor $next$ of $current$ in G **do**
 Calculate $new_cost \leftarrow cost_so_far[current] + G[current][next][weight]$;
 if $next$ is not in $cost_so_far$ **or** $new_cost < cost_so_far[next]$ **then**
 Update $cost_so_far[next] \leftarrow new_cost$;
 Calculate $priority \leftarrow new_cost + heuristic(next, goal)$;
 Enqueue $next$ into $frontier$ with $priority$;
 Set $came_from[next] \leftarrow current$;
 end
 end
end

Algorithm 2: Reconstruct Path from Node Connections

Data: $came_from$, Start Node $start$, Goal Node $goal$
Result: Shortest Path as a list of nodes
Initialize empty list $path$;
Set $current \leftarrow goal$;
while $current \neq start$ **do**
 Append $current$ to $path$;
 Set $current \leftarrow came_from[current]$;
 if $current$ is $None$ **then**
 return empty list $[]$;
 end
end
Append $start$ to $path$;
Reverse $path$;
return $path$;



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