



Geopolitical disruptions and maritime transitions: Environmental and economic costs of rerouting

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ABSTRACT

This study examines the environmental, operational and economic implications of crisis-induced rerouting in maritime shipping, focusing on the 2024 Red Sea crisis as a case study. Contributing to the literature by linking operational modelling with transition theory, offering new insights into how geopolitical crises can accelerate or constrain sustainability transitions in global shipping. Within the socio-technical transitions framework, it explores how landscape-level geopolitical disruptions interact with regime inertia and create opportunities for niche innovation. Using an activity-based bottom-up model integrated with AIS data, the study quantifies GHG emissions, costs and voyage durations for vessels rerouting via the Cape of Good Hope, covering three major Eurasian routes (Asia–West Europe, Asia–West Mediterranean, and Asia–East Mediterranean). Emissions cost analysis is combined with scenario modelling to assess trade-offs between environmental and economic impacts across different innovation pathways. Results show that rerouting increases GHG emissions at least 46 %, economic cost at least 51 % of entire route fleet and extends round-trip durations by 20–34 days. Despite this, most shipping companies increased vessels' speeds, reflecting institutional inertia that prioritises short-term efficiency over sustainability. Scenario simulations reveal that incremental innovations (e.g. operation optimisation) reduce excess emissions by 8–10 %. Whereas, transformative innovations such as LNG fuel and shore power cut emissions by up to 23 %, with combined deployment achieving up to 33 % reductions. These findings highlight the limited impact of incremental measures under sustained disruption and underscore the potential of transformative innovations to accelerate sustainability transitions in global shipping.

1. Introduction

The maritime shipping industry is pivotal to the global economy, carrying approximately 80 % of international trade by volume (UNCTAD, 2024). As this sector faces increasing environmental challenges, it is under growing pressure to transition toward sustainability, particularly in light of international commitments to significantly reduce greenhouse gas emissions (Abouarghoub, 2023). Shipping is more than a logistical activity, it is a deeply embedded socio-technical system shaped by path dependencies, regulatory frameworks, technological innovations, and economic structures (Pettit et al., 2018). The Red Sea crisis and the subsequent rerouting

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of vessels via the Cape of Good Hope constitute a landscape level disruption within this system, one that warrants analysis through the lens of the multi-level perspective (MLP) on socio-technical transitions. (IMO, 2020).

According to Pettit et al. (2018), shipping has undergone incremental eco-efficiency improvements but has resisted fundamental regime shifts that could reduce greenhouse gas (GHG) emissions at a transformative level. The crisis-driven shift in routing reflects a landscape-level disruption, as described in transitions theory, forcing actors to adapt to new operational constraints. However, rather than accelerating an industry-wide transformation, such disruptions reinforce existing maritime structures and strategies. This perspective aligns with the empirical findings of the Red Sea case study, which demonstrates how increased costs and emissions resulted from adapting to new geopolitical risks. Similarly, Wells et al. (2020) argue that macro-level disruptions, such as COVID-19, can either reinforce the existing economic order (business as usual) or create space for alternative transition pathways (managed transition, degrowth, or chaotic restructuring). The Red Sea crisis serves as a case study of how external shocks test the resilience of maritime logistics and highlight the need for adaptive governance mechanisms to balance economic efficiency with sustainability objectives. The crisis reveals the industry's reliance on path-dependent strategies prioritising efficiency and cost minimisation over fundamental transitions to more sustainable shipping practices. Drawing on the MLP framework, this study explores how shipping companies have responded to this disruption and assesses the environmental and economic implications of these adaptations.

The Red Sea crisis, which started on November 19, 2023, in the Bab-el-Mandeb Strait, the southern entrance to Egypt's Suez Canal, has significantly disrupted the movement of global trade. This waterway is vital for international commerce and strategically important to the global economy (Pratson, 2023). Major shipping companies have strategically reevaluated their routes in response to heightened security risks, bypassing the Red Sea in favour of the Cape of Good Hope to mitigate threats. Fig. 1 and Table 1 provide a comprehensive overview of the monthly vessel count and a year-over-year comparison of Suez Canal traffic categorised by vessel type. The data covers the period from January 2018, to December 2024. All data analysed in this study is sourced from the Refinitiv (2025) database. Findings reveal a considerable decline in container ship traffic in the Red Sea region, particularly since mid-January 2024. Monthly container ship traffic has decreased sharply by nearly 71 %, contributing to an overall reduction of 40 % in total traffic. Tankers have also been significantly affected, with a 45 % drop in throughput, whereas bulk carriers have been the least impacted, still experiencing a 42 % reduction. Given the substantial impact on container ships, this paper particularly focuses on assessing the environmental and economic implications of the Red Sea crisis on container ships.

Under normal circumstances, the Cape of Good Hope route extends round trip times by 14–21 days compared to the Suez route, covering nearly 30 % more distance (Schøyen & Bråthen, 2011). To offset such delays during the Red Sea crisis, many shipping companies increased average fleet speeds. While this mitigated schedule disruption, it significantly raised transportation costs and GHG emissions, posing additional challenges to meeting the International Maritime Organisation's (IMO) 2050 decarbonisation strategy. Higher GHG emissions also increase environmental costs (Corbett et al., 2009; Zhu et al., 2018; Cheaitou et al., 2020; Joseph et al., 2021; Sun et al., 2025b). Estimating these environmental costs serves multiple purposes: it quantifies the societal impacts of specific maritime activities (Sieber & Kummer, 2008; Antturi et al., 2016), informs corporate decision-making (Krozer et al., 2003) and improves cost-benefit assessments during emergencies such as policy changes, geopolitical conflicts, or natural disasters (Rosendahl, 2004; Hanley et al., 2009). Therefore, accurate quantification of environmental and economic impacts from crisis-induced rerouting is crucial to strengthening the resilience and sustainability of global maritime supply chains. Within the socio-technical transition framework, we integrate sensitivity analysis and scenario simulation to evaluate emission reduction effectiveness across different niche innovations, providing robust empirical support for designing transition pathways in the maritime sector.

Using real-time AIS data for container ships rerouted via the Cape of Good Hope from three major Eurasian trade routes (Asia–West Europe, Asia–West Mediterranean, and Asia–East Mediterranean), we apply an activity-based bottom-up model to estimate GHG emissions compared to the traditional Suez Canal route. This analysis quantifies the additional environmental and economic costs incurred. While a sensitivity analysis examines how operational adjustments, such as changes in vessel speed and fleet size, can mitigate delays and costs while reducing environmental burdens. Beyond incremental operational optimisation, a scenario-based

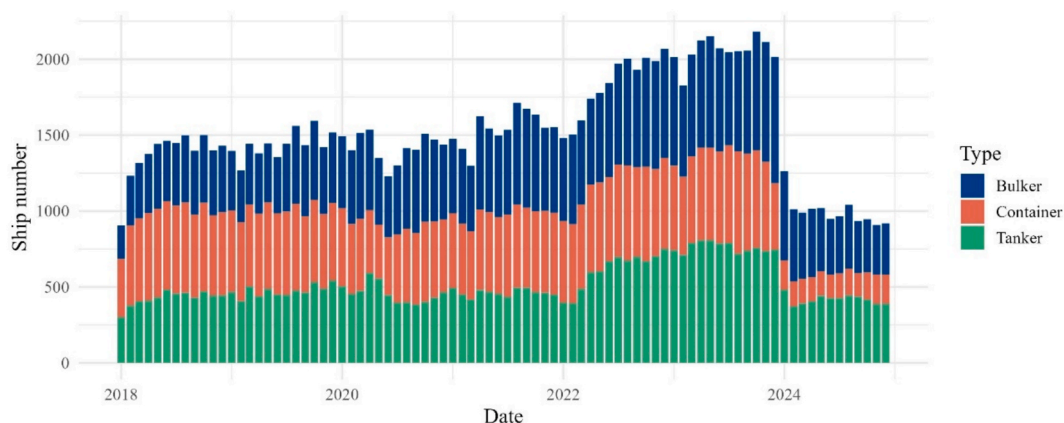


Fig. 1. Daily vessel entries into the Suez Canal by type.

Table 1
Year-Over-Year changes in Suez Canal vessel numbers by type.

Vessel type	2018	2019	2020	2021	2022	2023	2024	2023/2024 change (%)
Bulker	4,703	5,142	6,041	6,741	7,624	8,457	4,884	−42.25 %
Container	6,581	6,403	5,503	6,184	6,937	7,083	2,049	−71.07 %
Tanker	5,122	5,711	5,512	5,579	7,352	9,140	5,027	−45.00 %

assessment considers transformative niche innovations, such as alternative fuels and shore power, to explore their potential for systemic decarbonisation. Framed within the socio-technical transitions perspective, the analysis examines how geopolitical disruptions interact with maritime regime inertia and create opportunities for niche innovation.

This paper makes three main contributions. First, it extends socio-technical transition theory to the maritime transport domain by situating the Red Sea crisis within a multi-level perspective, illustrating how landscape-level shocks interact with entrenched regime structures. Second, it offers a novel empirical assessment quantifying the environmental and economic trade-offs of rerouting decisions using high-frequency AIS data. Third, it presents a structured scenario analysis contrasting incremental and transformative innovations, offering actionable insights into how sustainability-oriented technologies can gain traction under sustained disruption. Together, these contributions provide a new analytical lens for understanding maritime resilience, while informing industry practice and policymaking for sustainable and crisis-resilient shipping.

The remainder of the paper is structured as follows. [Section 2](#) reviews the literature, integrating socio-technical transition theory with prior studies on maritime transport and geopolitical disruptions. [Section 3](#) details the methodology. [Section 4](#) describes the case study background. [Section 5](#) reports and discusses the results. [Section 6](#) discusses the policy implications, highlighting the window of opportunity for maritime decarbonisation under sustained disruption. [Section 7](#) concludes the study.

2. Literature review

2.1. Socio-technical transition theory

Socio-technical transition theory provides a framework for analysing how socio-technical systems undergo long-term, fundamental change, particularly in the context of sustainable transitions ([Kemp et al., 1998](#)). It explains how emerging innovations (niches) can break through the stability of existing systems (regimes) under external pressures (landscape), triggering systemic transformation. Maritime transport operates within a complex socio-technical system shaped by interactions among technology, regulation, market forces, and institutional behaviour. The Multi-Level Perspective (MLP), developed by [Geels \(2002\)](#), offers a structured lens to analyse such transitions, as shown in [Fig. 2](#).

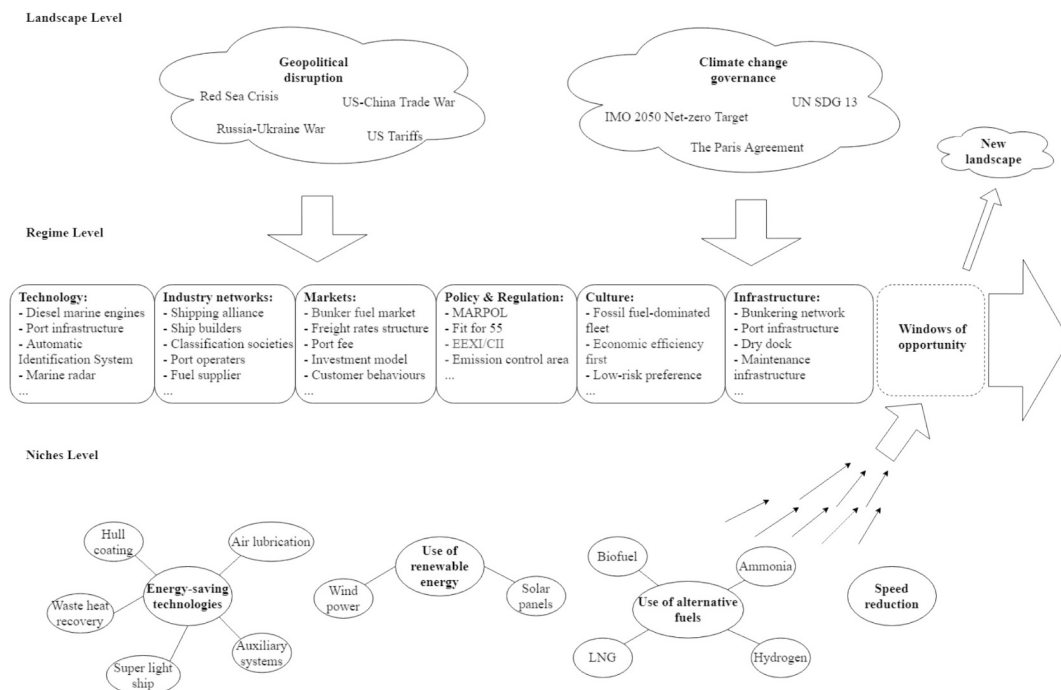


Fig. 2. The Multi-Level Perspective of socio-technical transitions applied to shipping (adopted from [Pettit et al 2018](#)).

The MLP applied to maritime systems distinguishes three levels: socio-technical landscape (external macro-level drivers such as climate change and geopolitical shocks), the socio-technical regime (established industry structures, technologies, networks, market arrangements, and cultural norms that maintain stability and resist rapid change), and niches (protected spaces where innovations and experimental practices emerge, including energy-efficiency measures, renewable energy integration, alternative marine fuels (e.g., LNG), shore power, and operational strategies such as speed reduction).

At the landscape level, geopolitical disruptions and climate change governance are exerting increasing pressure on the maritime regime. While the regime's structural features create inertia, cracks can appear under sustained pressure, opening windows of opportunity for niche innovations to challenge and eventually reshape the dominant regime. The following sections apply the MLP to analyse how the shipping industry's ongoing decarbonisation transition is unfolding under geopolitical disruptions such as the 2024 Red Sea crisis.

2.2. Landscape-level geopolitical disruptions in maritime transport

For centuries, maritime transport has been regarded as the safest and most efficient mode of transportation for moving large volumes of cargo and passengers. According to [Hargroves and Smith \(2013\)](#), maritime technology has evolved through five major waves of technological diffusions, as shown in [Table 2](#). Each wave not only reflects advancements in vessel design, propulsion systems, and operational methods but also coincides with geopolitical disruptions that served as catalysts for systemic transition.

The first wave (1785–1845) centred on innovations in waterpower, textiles, and iron. During this period, the Napoleonic Wars (1803–1815) and the War of 1812 triggered widespread naval blockades. These pressures prompted the development of more robust and faster vessels capable of sustaining long-distance trade, culminating in the construction of the SS Great Britain in 1845, the world's first transatlantic iron-hull steamship ([Pettit et al., 2018](#)). The second wave (1845–1900) was driven by the widespread adoption of steam engines and coal-powered vessels. The American Civil War (1861–1865) disrupted global cotton trade through Union blockade forcing the United Kingdom and other nations to diversify sourcing from Egypt and India ([Beckert, 2004; Allin, 2019](#)). The opening of the Suez Canal in 1869 further transformed maritime trade routes, accelerating the shift from sail to steam and promoting standardised vessel design ([Fletcher, 1958; Geels, 2002](#)). The third wave (1900–1950) coincided with the advent of internal combustion engines and electrification. The two World Wars inflicted severe losses on merchant fleets simultaneously creating the impetus for technological renewal. Wartime destruction and post-war rebuilding led to the rapid adoption of advanced propulsion systems and more standardized, efficient vessel types ([Smil, 2007; Heidbrink, 2012](#)). The fourth wave (1950–1990) was marked by the wide adoption of containerisation, bulk shipping, and the emergence of ultra-large vessels. Geopolitical instability in the Middle East, such as the Suez Crisis (1956), the Six-Day War (1967), and the Yom Kippur War (1973), rendered the Suez route unreliable and revived the use of the Cape of Good Hope route. Conflicts like the Iran–Iraq War and Gulf War heightened war risk premiums, promoting shipping companies to adopt tanker and container technologies, slow steaming and energy-efficient operational practices ([Stopford, 2008; Saito et al.,](#)

Table 2
Geopolitical disruptions across technology waves.

Technology Wave	Geopolitical Disruption	Environmental and economic impact	Niche development
1st Wave (1785–1845)	Napoleonic Wars (1803) War of 1812 (1812)	Widespread naval blockades	• New vessel design • Iron-hull steamship
2nd Wave (1845–1900)	U.S. Civil War (1861) Opening of the Suez Canal (1869)	Disrupt global cotton trade Restructure maritime trade routes	• Adoption of steamships • Standardised hull designs
3rd Wave (1900–1950)	World War I (1914) World War II (1939)	Major parts of pre-war commercial shipping fleets destroyed	• Internal combustion engine • More standardized vessel
4th Wave (1950–1990)	Suez Crisis (1956) Six-Day War (1967) Yom Kippur War (1973) Iran–Iraq War (1980)	Suez Canal blockade for several months Suez Canal blockade for 8 years 557 vessels were attacked; Disrupt global oil trade; Inflating insurance costs	• VLCC • ULCC • Slow steaming strategy • Containerisation
5th Wave (1990–Now)	Gulf War (1991) Somali Piracy (2008) U.S.–China Trade War (2018) Strait of Hormuz Tanker Attacks (2019) Suez Canal Blockage (2021) Russia–Ukraine War (2022) Panama Canal Drought (2023)	War risk premiums to rise from 1–2 % to 3 % 30 % reduction in Far East–Europe trade volume; 18 % of shipments rerouted via the Cape of Good Hope; Annual loss of USD 30 billion 41.28 % decline in US-China maritime trade 10–20 % increase in shipping costs £7 billion in daily trade losses Disrupt global food trade 30–64 days delay; Decrease in Cargo Volume	• Network design redundancy • Third country transport • Risk avoidance strategy
6th Wave (Future)	Red Sea Crisis (2024) ...	Suez Canal blockade ...	• Sustainability • Resilience • ...

2022; Haralambides, 2024).

The fifth wave (1990–present) is defined by digitalisation, integrated logistics, and the emergence of mega-vessels. While large-scale wars have become less frequent, events such as Somali piracy (2008), the 2019 tanker attacks, the Russia–Ukraine war, and the 2021 Suez blockage have exposed new vulnerabilities in global maritime supply chains. Trade tensions; such as the U.S.–China trade war, which reduced bilateral trade by 41.28 % (Zou et al., 2025) have also reshaped global shipping patterns. These disruptions have prompted the industry to incorporate redundancy and risk-avoidance strategies into network design, moving beyond a sole focus on efficiency (Bueger & Edmunds, 2017). Simultaneously, structural changes in global trade have led to an increased reliance on third countries, resulting in approximately 0.23 % to 0.34 % increase in total maritime transport distances (Guo et al., 2021). These historical cases reveal that geopolitical instability poses ongoing threats to maritime trade, which is highly dependent on secure and efficient access through key chokepoints.

According to UNCTAD (2024), approximately 80 % of global trade by volume and over 70 % by value is transported by sea, frequently passing through critical maritime corridors such as the Suez Canal, Panama Canal, and the Malacca Strait. Disruptions at these chokepoints can have cascading effects on global supply chains, further underscoring the fragility of maritime transport under the current socio-technical regime. Historically, major geopolitical disruptions, such as the closure of the Suez Canal in 1967–1975 or the oil crises of the 1970 s have acted as catalysts for systemic transitions in the shipping industry. In this context, present-day disruptions, including armed conflicts, environmental instability, and strategic rivalries, may similarly trigger what could be described as a sixth wave of technological transition. This prospective wave is likely to focus on the green shipping transition, encompassing zero-emission vessels, alternative fuels (e.g., LNG, hydrogen, ammonia), shore power, smart port systems, and new governance models aimed at enhancing the resilience and sustainability in global maritime transport.

2.3. Emerging cracks in the maritime regime

The socio-technical landscape refers to the macro-level environment situated above the regime layer, encompassing factors such as political culture, climate change, the macroeconomy, and societal values (Auvinen & Tuominen, 2014). While these forces typically evolve gradually, they can manifest as sudden and intense shocks. At present, climate change governance and geopolitical disruptions, are two converging landscape pressures that are shaping the maritime sector. On one hand, institutions such as the IMO and the European Union are accelerating the implementation of decarbonisation policies (Cariou et al., 2021; Jimenez et al., 2022; Tol, 2023), driving global shipping towards low-carbon development. On the other hand, geopolitical disruptions, such as the Red Sea Crisis, a classic landscape shock, disrupting key maritime routes, reshaping global trade patterns, and forcing a reassessment of supply chain resilience and sustainability of supply chains (Notteboom et al., 2024). Together, these forces create landscape-driven transition potential: decarbonisation policies provide a long-term regime trajectory, while geopolitical disruptions expose the vulnerabilities of fossil fuel dependency, making green technology and regime transformation a necessity rather than a choice.

Despite mounting pressure, the maritime sector exhibits strong regime inertia, remaining deeply anchored in a fossil-fuel-based regime (Geels et al., 2017; Van Leeuwen & Monios, 2022). This stability is maintained by an interdependent configuration of technology, infrastructure, industry networks, market structures, regulatory frameworks, and cultural values that collectively produce strong lock-in mechanisms. These interlocking elements reinforce path dependency and institutional inertia, making structural change highly resistant. Technological and infrastructural dependence on conventional propulsion systems remains widespread; low-speed diesel engines account for 96.75 % of the global fleet, while only 11.53 % of vessels are equipped with upgraded environmental technologies (Clarkson, 2025). Onshore power infrastructure is scarce, particularly in developing countries, and facilities for alternative fuels such as LNG and methanol are limited to a few major hubs, such as Singapore and Rotterdam (Ismail et al., 2024). These entrenched systems create prohibitive switching costs, restricting the scalability and commercial viability of greener technologies even for shipowners willing to invest in them.

Industry networks and market structures further reinforce behavioural inertia. Strategic alliances between major carriers, such as the 2 M Alliance and THE Alliance, have established stable cooperation models that integrate capacities and routes. These arrangements, along with the interdependence of ports, shipyards, classification societies, and fuel suppliers, prioritise the reduction of uncertainty and the mitigation of market risks (Shi et al., 2021; Chen et al., 2022). Within this tightly knit ecosystem, social and cognitive lock-ins tend to emerge, with actors focusing on incremental improvements to existing systems rather than pursuing potentially disruptive alternatives (Nelson, 2008). Most companies have not yet committed to renewable marine fuels such as ammonia or wind propulsion, instead favouring dual-fuel vessels that partially reduce emissions while maintaining reliance on fossil fuels (Urban et al., 2024). These strategies lead to lack of financial support and market demand for radical innovation.

Regulatory and cultural factors also contribute to institutional inertia. Existing policy frameworks are often designed to accommodate incumbent technologies and the interests of established actors. For example, compliance with the Energy Efficiency Existing Ship Index (EEXI) can be achieved through slow steaming, avoiding the need for retrofits or fuel switching (Lee, 2024). Global-level measures such as an IMO carbon levy remain stalled due to disagreements over distributive justice (Wang & Countryman, 2025), creating uncertainty that dampens industry confidence in investing in transformative technologies. Culturally, the sector continues to prioritise economic efficiency, reliability, and risk aversion, with performance indicators such as schedule reliability reinforcing a focus on operational cost minimisation over environmental performance (Meng et al., 2023; Johansen et al., 2025). Without strong economic incentives or a clear long-term roadmap, many companies and regulators continue to opt for low-risk, reversible strategies that align with the existing regime.

As Wells et al. (2020) noted, major disruptions such as global pandemics or political crises can either reinforce existing structures or trigger systemic transitions, depending on how actors respond within the multi-level configuration. The 2024 Red Sea crisis illustrates

this dynamic by exposing the sector's institutional rigidity. Most mainstream companies and regulatory bodies responded with incremental measures, such as rerouting and speed adjustments, reflecting the “absorption” and “adaptation” strategies identified in the supply chain resilience literature, rather than adopting transformative responses (Sheffi & Rice Jr, 2005; Pettit et al., 2018). This also raises important theoretical questions about whether geopolitical disruptions can drive long-term transitions or whether they reinforce existing structures.

Nevertheless, cracks are beginning to appear in the regime architecture that suggest the current balance may be unsustainable. A growing mismatch between technology and policy is evident, as rerouting to mitigate geopolitical risks increases voyage distances and directly contradicts IMO energy efficiency targets (e.g. EEOI). Commercial logics are also coming into conflict, with the pursuit of navigational safety through rerouting resulting in higher emissions and operational costs. Furthermore, energy infrastructure remains misaligned, with port and fuel supply systems still dominated by fossil fuels, constraining the operational viability of alternative fuel vessels. These misalignments create regime tensions that are forcing shipping companies, governments, and ports to explore greener innovations such as LNG propulsion, shore power, engine retrofitting, and other clean energy technologies. While these niche innovations have not yet displaced the dominant fossil fuel system, the visible cracks in the regime architecture have opened a genuine window of opportunity for their expansion and broader recognition (Geels, 2012; Geels et al., 2017). Under these conditions, maritime transformation is no longer a purely theoretical possibility, but a realistic pathway shaped by evolving policy, shifting market dynamics, and accelerating technological advancement.

2.4. Development of niche innovations

Amidst mounting environmental pressures and geopolitical instability, several niche innovations are emerging that challenge the fossil-fuel-dominance of the maritime regime. Table 3 summarises a range of potential technologies identified by the IMO, spanning energy-saving measures such as hull and propeller optimisation and waste heat recovery (Abadie et al., 2017; Lion et al., 2020; Bai et al., 2025), renewable energy integration, including wind-assisted propulsion and photovoltaic systems (Diab et al., 2016; Li & Tang, 2024), and the adoption of low-carbon or zero-carbon alternative fuels such as LNG, methanol, ammonia, and hydrogen (Seddiek & Elgohary, 2014; Elgohary et al., 2015; Ammar & Seddiek, 2017). In addition, speed reduction represents a relatively simple operational measure with far-reaching implications for fuel consumption and emissions reduction (He et al., 2017; Taskar & Andersen, 2020; Yu et al., 2022).

These innovations challenge the fossil fuel lock-in that underpins the current regime (Van Leeuwen & Monios, 2022) by introducing decentralised, variable, and zero-carbon energy inputs. Their implementation necessitates changes in vessel design, operational planning, and crew training, thereby fostering new actor-networks and competencies (Nuttall et al., 2014). They also require institutional and infrastructural adaptations, such as redesigning port services and expanding energy storage capacity (Buonomano et al., 2023), contributing to a broader systemic reorientation toward climate-aligned innovation pathways. While still at varying stages of maturity, these niche innovations reflect a growing search for alternative solutions capable of reducing the sector's carbon footprint and enhancing resilience. However, their ability to scale and effect systemic change is contingent upon technological viability, cost competitiveness, and the responsiveness of the wider socio-technical landscape. As climate governance becomes more stringent and geopolitical disruptions more frequent, the resulting external pressures are increasingly exposing cracks within the maritime regime, misalignments that could either accelerate or constrain the adoption of these emerging solutions.

2.5. Environmental and economic impacts of geopolitical disruptions

Geopolitical turbulence, ranging from regional conflicts to global pandemics, has become an increasingly important determinants

Table 3
Decarbonisation strategies in maritime transportation (Source: IMO2020).

Categories	Niche innovations	Contribution to maritime transitions
Energy-saving technologies	Main engine improvements Auxiliary systems Steam plant improvements Waste heat recovery Propeller improvements Propeller maintenance Air lubrication Hull coating Hull maintenance Optimisation of water flow hull openings Super light vessel	Improve efficiency; support evolving design norms and regulatory frameworks
Use of renewable energy	Reduced auxiliary power demand Wind power Solar panels	Introduce new propulsion paradigms; challenge fossil fuel dependency
Use of alternative fuels	Use of alternative fuel with carbons Use of alternative fuel without carbons	Enable new fuel systems; foster cross-sectoral collaboration and regulatory shifts
Speed reduction	Speed reduction	Reshape operational logic; support behavioural and organisational change

of volatility and uncertainty in maritime transport. These disruptions have significant environmental implications, particularly through their influence on emissions. Maritime emissions and economic performance are deeply intertwined, as the cost structure of international shipping shapes operational decisions that, in turn, determine emissions levels (Abouarghoub, 2023). The academic literature on maritime geopolitical risks has grown substantially in recent years, with most studies concentrating on their economic consequences. For example, Chen et al. (2025) constructed a news-based maritime risk index using text mining of media reports to examine the interaction between the maritime system and the broader economy. Lim and Chiu (2024) analysed the effects of chokepoint disruptions on operational losses and market responses through questionnaire and interview surveys, while Drobetz et al. (2021) employed a Bayesian VAR model to estimate the dynamic effects of geopolitical risks and economic policy uncertainty on shipping freight rates. Similarly, Rodríguez-Díaz et al. (2024) combined qualitative and statistical methods to assess the economic impact of geopolitical events in the Red Sea and Suez Canal regions on maritime transport efficiency and operational patterns.

Other studies have explored the propagation mechanisms of geopolitical risks through global trade flows and transport networks. Meza et al. (2022) used agent-based modelling to simulate the impact of disruption events on LNG trade flows and export patterns. Notteboom et al. (2021) examined global supply chains, port throughputs, and container shipping networks responses to the COVID-19 pandemic and the 2008 financial crisis. Pratson (2023) integrated GIS-based sea lane data with bilateral trade datasets to estimate the effects of chokepoint blockades (e.g., the Strait of Malacca, the Suez Canal) on global trade flows. Yap and Yang (2024) analysed how the closure of international maritime chokepoints reshapes shipping network structures.

More recently, research has begun to address adjustment and recovery strategies for maritime operations in the face of geopolitical shocks. Achurra-Gonzalez et al. (2019) developed a quantitative model to evaluate the impact of disruptive events on liner networks and proposed a container allocation framework that minimises total route costs. Li et al. (2023) introduced a mixed-integer programming model incorporating multiple recovery strategies, including speed adjustment, port skipping, and port switching. Guo et al. (2024) applied a closed Jackson network model with mean-value analysis to evaluate the impact of port and route disruptions on congestion and recovery efficiency.

Despite these advances, the environmental consequences of geopolitical disruptions remain relatively underexplored. While such events can cause large-scale rerouting and emissions displacement, only a small number of studies have addressed their environmental implications. Peng et al. (2024), for example, examined carbon leakage risks under the EU Emissions Trading System (EU-ETS) arising from container ships rerouted via the Cape of Good Hope, while Hu et al. (2024) integrated environmental impact parameters into route disruption recovery models in order to incorporate emissions reduction goals into scheduling optimisation.

2.6. Significance of this work

Although existing studies have provided valuable insights into maritime emissions, supply chain resilience, and the effects of geopolitical risks, most remain focused on aggregate indicators such as freight rates, trade volumes, or port throughput. Environmental impacts are often treated qualitatively or inferred from broad assumptions rather than quantified using high-resolution operational data. Moreover, few studies address economic and environmental dimensions simultaneously while incorporating environmental governance into the analysis, particularly in relation to behavioural responses at the real-time route level. To the best of our knowledge, no prior research has quantified the combined environmental and economic impacts of geopolitical disruptions such as the 2024 Red Sea crisis using AIS-based vessel activity data.

This paper addresses this gap by estimating the environmental and economic costs of rerouting container vessels via the Cape of Good Hope during the Red Sea crisis. The analysis integrates an activity-based bottom-up model with AIS data to produce high-resolution estimates of GHG emissions and associated costs. A sensitivity analysis is conducted to evaluate how operational adjustments—specifically changes in sailing speed and fleet deployment—can minimise delays, costs, and emissions. In addition, scenario simulations assess the effectiveness of both incremental and transformative niche innovations, such as operational optimisation, LNG propulsion, and shore power, in reducing excess emissions and costs. Framed within the socio-technical transitions perspective, the study demonstrates how landscape-level disruptions interact with entrenched maritime regimes, creating potential windows of opportunity for systemic change. By combining a robust theoretical framework with empirical evidence, the research advances understanding of regime inertia, identifies emerging cracks in the maritime regime, and offers actionable insights for policymakers and industry stakeholders seeking to strengthen resilience and accelerate the green transition in global shipping.

3. Methodology

This study employs an activity-based bottom-up methodology to estimate GHG emissions from container ships operating along the Asia–Europe trade corridor, encompassing three principal routes: Asia–West Europe, Asia–West Mediterranean, and Asia–East Mediterranean. The approach follows established technical reports and regulatory guidelines (ENTEC, 2010; EMEP/EEA, 2019; IMO, 2020; EPA, 2022), which provide best practices and standardised procedures for maritime emission estimation. Emissions are calculated on a route-by-route basis using high-resolution AIS data, enabling the assessment of operational parameters such as vessel speed, engine load, and voyage duration. The resulting GHG outputs are monetised using the environmental cost of carbon factor, allowing for the quantification of environmental externalities at the route level. Economic costs are computed in parallel, incorporating vessel size, round-trip time, and fuel consumption, as well as capital, operational, and fuel cost components. These estimates provide a comprehensive measure of the economic burden associated with crisis-induced rerouting. Building on this empirically derived dataset, a scenario simulation model evaluates the effectiveness of different niche innovations in mitigating these impacts. The scenarios include incremental measures such as speed reduction and fleet size optimisation, alongside transformative options including LNG

propulsion, shore power, and renewable energy integration. This integrated methodological framework links operational modelling with environmental and economic evaluation, enabling a comparative analysis of incremental versus transformative innovation pathways under sustained geopolitical disruption.

3.1. Vessel emissions estimation process

The emission estimation process consists of the followings: *i)* Activity data collection: gathering AIS data on vessel movements, including speed, draft and operational mode. *ii)* Technical data collection: extracting key specifications such as engine power, fuel type, and design speed. *iii)* Data cleaning and processing: ensuring data accuracy by removing errors and aligning activity data with technical parameters by imputing missing data. This study uses a practical imputation method based on previous research (Sun et al., 2025a). *iv)* Emissions estimation: using vessel speed and technical parameters to compute load factors, power output, fuel consumption, and emissions. Detailed process has been shown in Fig. 3.

3.1.1. Emissions estimation methodology steps

The main steps in estimating vessel GHG emissions are:

Step 1: The operational mode of the vessel is identified (Transit, Manoeuvring, Hotelling, Anchorage).

Step 2: Using real-time AIS speed and AIS draft to determine main engine load factors.

Step 3: The main engine's power output is computed using:

$$P_{met} = P_{max} \times \left(\frac{V_t}{V_{max}} \right)^3 \times \left(\frac{D_t}{D_{max}} \right)^{2/3} \times SM, \quad (1)$$

where:

P_{me} = main engine operating power (kW).

P_{max} = vessel's total installed main power (kW).

V = AIS reported speed (kn).

V_{max} = vessel's maximum speed (kn).

D = AIS reported draft (m).

D_{max} = vessel's maximum draft (m).

SM = sea margin, which accounts for average weather conditions, assumed to be 1.10 for coastal operations and 1.15 for at-sea operations (unitless).

t = the value of a variable at a point in time.

Step 4: The output power for auxiliary engines and boilers is determined based on the operational mode.

Step 5: The CO₂ emissions factor is derived from:

$$EF_{CO_2} = SFC \times CCF, \quad (2)$$

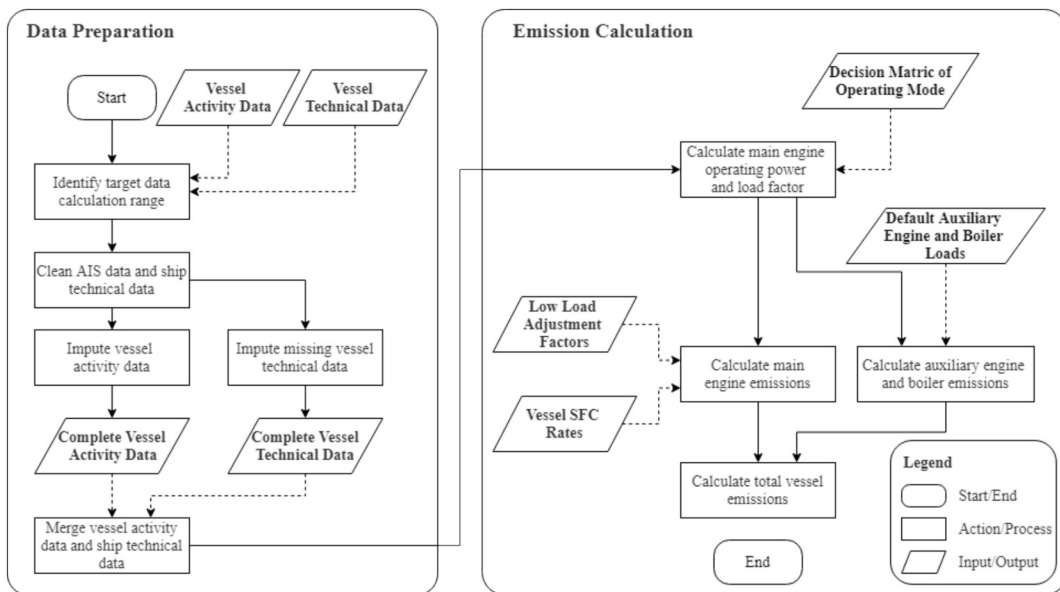


Fig. 3. Flowchart for vessel emission estimation.

where:

EF_{CO_2} = CO₂ emission factor (g/kWh).

SFC = specific fuel consumption (g/kWh).

CCF = carbon content factor (g CO₂/g fuel), set at 3.206 for MGO/MDO (IMO, 2020).

Step 6: Shipping emissions of different engine types computed as:

$$E_t = \sum_i (P_{i,t} \times T_{i,t} \times SFC \times EF_j \times LLAF_j), \quad (3)$$

where:

E = vessel emissions (g).

P = engine operating power (kW).

T = engine operating time (h).

EF = emission factor (g/kWh).

$LLAF$ = low load adjustment factor, a unitless factor that reflects increasing main engine emissions during low load operations (always 1 for auxiliary engines and boilers).

i = engine type (me: main engine, ae: auxiliary engine, bo: boiler).

j = emission type (CO₂, CH₄, N₂O).

3.1.2. Key parameters related to vessel emissions

Emission Factor (EF): The EF represents the amount of emissions per unit of power generated by the engine. It varies based on engine type, speed, fuel type, and pollutant. As this study focuses exclusively on GHGs, the CH₄ and N₂O emission factors (EPA, 2022) are provided in Table 4, while CO₂ emissions are computed using equation 3.

Specific Fuel Consumption (SFC): The SFC measures fuel consumption per unit of power produced by the engine. It serves as a basis for calculating CO₂, SO₂, and particulate matter (PM) emissions (IMO, 2020). Since fuel consumption depends on engine load, vessel speed, and fuel type, accurate SFC values are essential for precise emissions estimation. Table 5 shows vessel SFC rates for different engine types as reported by EPA.

Low Load Adjustment Factor (LLAF): When a vessel's main engine load exceeds 20 % of total installed propulsion power, emission factors remain relatively constant. However, at lower engine loads, efficiency decreases, leading to higher specific fuel consumption (SFC) and increased emissions per unit of power (Yau et al., 2012; Grigoriadis et al., 2021). The LLAF adjusts for this variation, ensuring emissions are accurately accounted for across different operating conditions. Table 6 shows main engine LLAF as reported by EPA.

Vessel Operational Modes (SOM): The emissions generated by a vessel depend on its operational mode, which varies based on speed, location, and engine activity (Toscano & Murena, 2019; Sun et al., 2025c). Table 7 shows considerations for determining operating mode as reported by EPA. Therefore, this study categorises vessel operations into four primary modes. **Transit Mode** – The vessel cruises at service speed, with main engines operating at maximum load while auxiliary engines and boilers remain minimally active. **Manoeuvring Mode** – As the vessel approaches a port, it operates at low speed, reducing main engine power output while auxiliary engines and boilers increase power to support onboard systems. **Anchorage Mode** – The vessel remains stationary at anchorage, relying only on auxiliary engines and boilers for essential functions. **Hotelling Mode** – When docked at berth, the vessel's main engine is inactive, and auxiliary engines sustain operational equipment. Boilers are engaged to maintain engine and fuel system temperatures unless the vessel is equipped with shore power, in which case engine power output is calculated separately.

3.2. Environmental cost calculations

The Environmental cost of carbon (ECC) quantifies the economic impact of GHG emissions, expressed in USD per ton of CO₂e (Nordhaus, 2017). Existing literature reports a wide variability in ECC estimates, ranging from −\$13.36 to \$2,387 per ton CO₂ (Wang et al. (2019)), which reflects difference in regional policies and valuation methodologies. This study derives average ECC values for shipping emissions based on prior research, as reported in Table 8.

The total environmental cost is estimated using:

$$C_{EE} = \sum_j (E_j \times ECC_j), \quad (1)$$

Table 4

Vessel CH₄ and N₂O Emission Factors (g/kWh) (Source: EPA, 2022).

Engine Type	Engine Sub Type	CH ₄ Emission Factor (g/kWh)	N ₂ O Emission Factor (g/kWh)
Main	SSD	0.12	0.029
	MSD	0.01	0.029
Auxiliary	MSD	0.08	0.029
	HSD	0.08	0.029
Boiler	Boiler	0.02	0.075

Table 5

Vessel Specific Fuel Consumption (SFC) Rates (g/kWh) (Source: EPA, 2022).

Engine Type	Engine Sub Type	SFC (g/kWh)
Main	SSD	185
	MSD	205
	LNG	166
Auxiliary	MSD	195
	HSD	215
	LNG	166
Boiler	Boiler	300

Table 6

Main Engine Low-Load Adjustment Factors (unitless) (Source: EPA, 2022).

Main Engine Load Factor (%)	NO _x	HC	CO	PM	CO ₂	SO ₂
<= 2	4.63	21.18	9.68	7.29	3.28	9.54
3	2.92	11.68	6.46	4.33	2.44	6.38
4	2.21	7.71	4.86	3.09	2.01	4.79
5	1.83	5.61	3.89	2.44	1.76	3.85
6	1.60	4.35	3.25	2.04	1.59	3.21
7	1.45	3.52	2.79	1.79	1.47	2.76
8	1.35	2.95	2.45	1.61	1.38	2.42
9	1.27	2.52	2.18	1.48	1.31	2.16
10	1.22	2.20	1.96	1.38	1.25	1.95
11	1.17	1.96	1.79	1.30	1.21	1.78
12	1.14	1.76	1.64	1.24	1.17	1.63
13	1.11	1.60	1.52	1.19	1.14	1.51
14	1.08	1.47	1.41	1.15	1.11	1.41
15	1.06	1.36	1.32	1.11	1.08	1.32
16	1.05	1.26	1.24	1.08	1.06	1.24
17	1.03	1.18	1.17	1.06	1.04	1.17
18	1.02	1.11	1.11	1.04	1.03	1.11
19	1.01	1.05	1.05	1.02	1.01	1.05
>= 20	1.00	1.00	1.00	1.00	1.00	1.00

Table 7

Considerations for determining operating modes (Source: EPA, 2022).

Operating Mode	Geospatial Description	Vessel Speed	Main Engine Load Factor
Transit	Outside the breakwater or restricted speed zone	>1kn	>20 %
Manoeuvring	Between the breakwater and berth or anchorage zone	>1kn	<=20 %
Hotelling	At a berth zone	<=1kn	N/A
Anchorage	In an anchorage zone	<=3kn	N/A

Table 8

Environmental cost of carbon in shipping.

Emissions	Range	Average	Source
CO ₂	9–145	45	(Denisis, 2009; Berechman & Tseng, 2012; Marten & Newbold, 2012; McArthur & Osland, 2013; Song, 2014, 2018; Wang et al., 2019; Government, 2021)
CH ₄	250–2500	1036	(Song, 2014, 2018; Government, 2021)
N ₂ O	2700–28000	12,458	(Song, 2014, 2018; Government, 2021)

where,

 C_{EE} = emission environmental cost (US\$). E_j = emissions of pollutant j (ton). ECC = environmental cost of carbon (US\$/ton).

3.3. Economic cost calculation

Total voyage economic cost includes capital cost, operating cost, fuel cost, and port cost (Chang & Wang, 2014). As port costs are not relevant to this study, they are excluded in alignment with previous research. This paper adopts the formulas proposed by Tran and Lam (2022) to calculate shipping operating and capital costs, which are based on the findings of Tran and Lam (2022) and Ros Chaos

et al. (2021) that establish a linear relationship between these costs and vessel size. Eq. 5 and Eq. 6 demonstrate a positive correlation between capital costs and operating costs with vessel size. The fuel cost is determined by estimating the vessel's fuel consumption based on AIS data and multiplying it by the average price of IFO 380 from February 2023 to February 2024, set at \$500 per ton.

Capital cost is the cost of owning or leasing the vessel and is calculated using:

$$C_{cap} = 0.5977 \times TEU + 4835.7, \quad (5)$$

where C_{cap} = capital cost (US\$/day), TEU = Twenty-foot Equivalent Unit.

Operating cost includes crew salaries, maintenance, and insurance and are calculated using:

$$C_{ope} = 1.093 \times TEU + 1249.3, \quad (6)$$

where C_{ope} = operating cost (US\$/day)

Fuel cost is based on fuel consumption and market fuel price and derived using:

$$C_{fuel} = FC \times P_{fuel}, \quad (7)$$

where:

C_{fuel} = fuel cost (US\$).

FC = fuel consumption of vessel (ton).

P_{fuel} = price of fuel (US\$/ton).

3.4. Scenario set-up

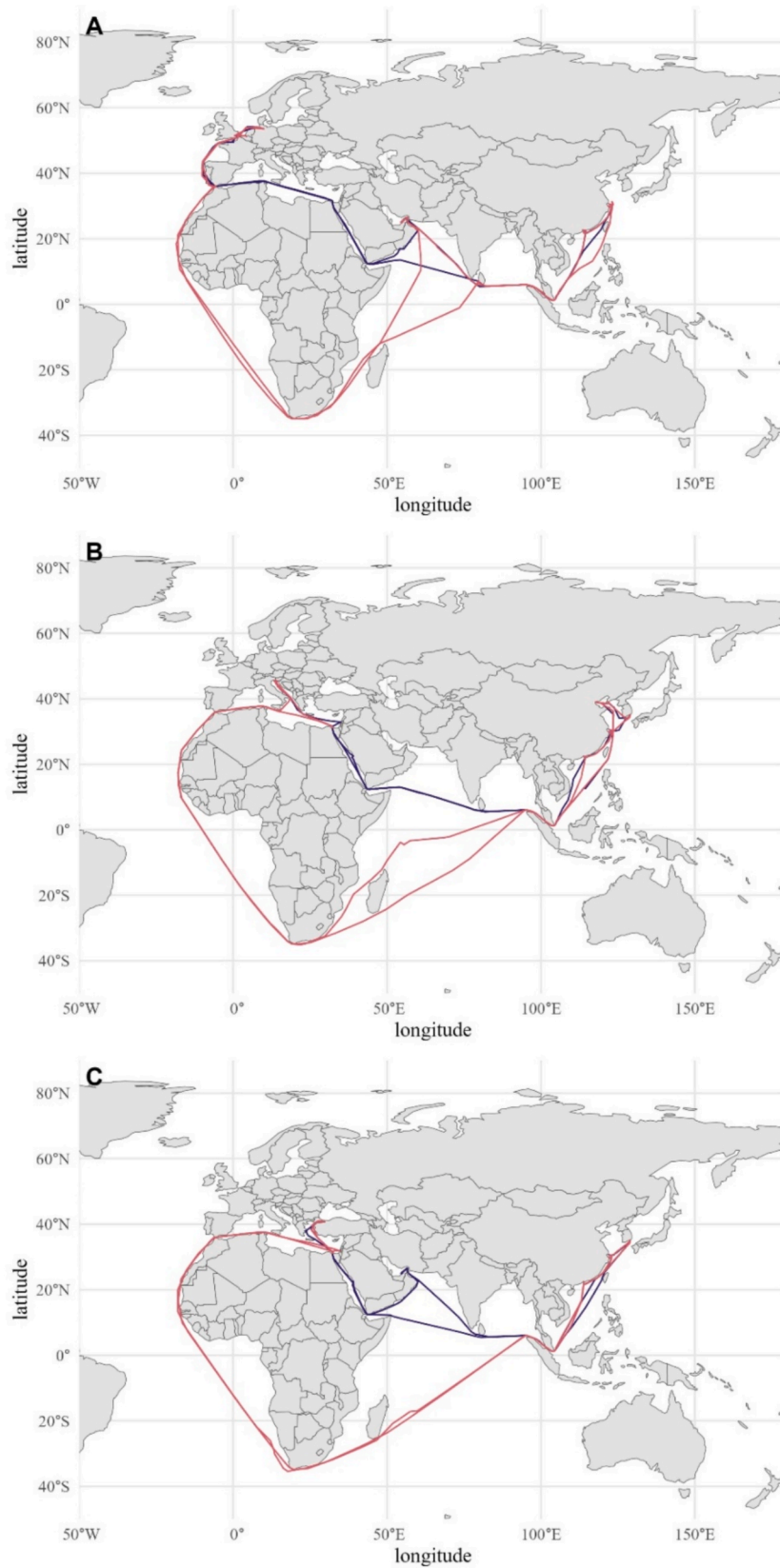
Following the environmental and economic cost calculations, five alternative scenario simulations were conducted using actual AIS data to evaluate potential mitigation strategies. First, the speed optimisation scenario involved adjusting vessel speeds to balance the dual objectives of mitigating delays and reducing environmental costs (Wang & Meng, 2012; Dong & Lee, 2020). Second, the fleet adjustment scenario examined the impact of increasing the number of vessels on the route to achieve a one-week departure interval for the container liner service (Kim et al., 2019). Third, a combined optimisation scenario integrating the adjustments from both speed optimisation and fleet expansion to identify the most cost-effective and environmentally sustainable configuration. Fourth, the shore power scenario assumes that vessels utilise clean alternative energy sources while berthed at ports, under which auxiliary engines could be treated as near-zero emission sources (Hoang et al., 2022). Fifth, the alternative fuel scenario simulated the use of alternative fuels during navigation, with LNG selected as a representative case, applying the latest emissions parameters from the U.S. Environmental Protection Agency (EPA, 2022). The first three scenarios represent incremental niche innovations within the current maritime regime, focusing on operational efficiency improvements without altering the dominant fuel or port infrastructure systems. By contrast, the shore power and alternative fuel scenarios constitute transformative niche innovations, directly challenging incumbent fuel supply chains and port energy infrastructures. This distinction reflects the niche-level dynamics of the socio-technical transition framework, providing a structured basis for comparing the potential of incremental versus transformative measures under sustained geopolitical disruption.

4. Case study

This case study examines eight container shipping routes operated by a total of 108 vessels primarily serving trade between East Asia and Europe. As illustrated in Fig. 4, these routes can be categorised into three main directional groups: Western Europe, Western Mediterranean, and Eastern Mediterranean. The Western European routes typically call at ports in the United Kingdom, Germany, and other Northern European countries. The Western Mediterranean routes generally serve ports in Spain and southern Italy, while the Eastern Mediterranean routes include destinations in southern Europe, Turkey, and Egypt. All services originate from East Asia and pass through Singapore or Malaysia. Under normal conditions, eastbound and westbound voyages transit the Suez Canal, as shown in purple in Fig. 4. However, beginning on 2 January 2024, several major operators, including A.P. Moller – Maersk announced the suspension of all vessel transits through the Red Sea and Gulf of Aden due to heightened security risks. Vessels were instead rerouted southward around the Cape of Good Hope, as represented by the pink route in Fig. 4. This diversion significantly increases voyage distances, fuel consumption, GHG emissions, and associated environmental costs. The next section outlines the technical parameters of the vessels involved and the AIS-based vessel activity data used in the analysis.

4.1. Vessel technical information

The technical specifications of the vessels included in this case study are summarised in Table 9. Key parameters reported include the vessel's IMO identification number, Deadweight Tonnage (DWT), Main Engine Power (MEP), Draft, Length Overall (LOA) and Breadth (BEAM). These characteristics directly influence fuel consumption profiles and are therefore critical inputs for emission estimation in the activity-based bottom-up modelling approach. Descriptive statistics indicate a high degree of homogeneity in vessel size, with most vessels clustered around 200,000 DWT, suggesting a relatively uniform carrying capacity across the fleet. While main engine power shows some variation, the majority of vessels fall within the 60,000 to 80,000 kW range, reflecting modest differences in



(caption on next page)

Fig. 4. Map of container shipping routes (A: Asia-West Europe; B: Asia-West Mediterranean; C: Asia-East Mediterranean; Purple: Via Suez Canal; Pink: Via Cape of Good hope). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 9

Vessel technical information for the container shipping fleet (study sample).

Vars	Mean	SD	Median	Min	Max
DWT	202,058	25,589	200,970	146,000	241,143
MEP	65,377	9,104	62,000	44,187	80,905
Draft	16.13	0.84	16.50	14.50	18.00
LOA	391.39	16.32	399.00	349.00	399.99
BEAM	58.40	3.08	59.00	51.00	62.00
TEU	18,875	2,791	18,720	12,876	24,000

propulsion capability. The average container capacity is 18,875 TEU, with the largest vessels accommodating up to 24,000 TEU, confirming that the sample comprises ultra-large container ships (ULCS) deployed on major intercontinental trade routes. Given the technological uniformity, the dataset can be considered broadly representative of the global (ULCS) fleet currently in operation, supporting the generalisability of the study's findings to similar vessel classes worldwide.

4.2. Vessel activity data

The vessel activity dataset analysed in this paper spans from January 1, 2023, to December 31, 2024. It includes essential vessel parameters, such as IMO identification, real-time latitude and longitude coordinates, AIS timestamps, AIS speed, AIS heading and AIS draught, and the vessel's geographical location and activity classification (entry, within zone, exit). Leveraging this comprehensive dataset allows for determining the vessel's operational mode and main engine load, crucial factors for the subsequent calculation of the vessel's emissions.

5. Experiment results

5.1. Emission and environmental cost calculation result

The calculations of emissions and environmental costs are summarised in [Table 10](#). The data represent the average parameters for a single vessel completing one round trip. For each row, Route Direction indicates the departure and destination ports, while Route Type specifies whether the vessel transited the Suez Canal or was rerouted via the Cape of Good Hope. A third category, labelled 'Mixed' refers to voyages vessels had already passed through the Suez Canal on the outbound leg but completed the return leg via the Cape of Good Hope. GHG emissions are measured in tonnes of CO₂ equivalent (CO₂e), incorporating CO₂, N₂O and CH₄ emissions, and are converted using the Global Warming Potential (GWP) factors provided by the IPCC (IPCC, 2021). Environmental costs are derived directly from these emissions values. Round trip time reflects the duration required for the vessel to complete a round trip, while Average Speed denotes the vessel's average speed in open waters. In total, the analysis covers 542 round trips, providing a sufficiently

Table 10

GHG emissions and environmental costs of single-vessel round trips.

Route Direction	Route Type	Round Trip Time (Day)	GHG Emission (t CO ₂ e)	Environmental Cost (\$)	Average Speed (Knot)	Sample Count
Asia-East Mediterranean	Good Hope	119.94	46,299	2,083,526	16.04	27
Asia-East Mediterranean	Mixed	110.87	30,531	1,373,957	14.30	3
Asia-East Mediterranean	Suez Canal	85.69	22,441	1,009,881	14.97	59
Asia-West Mediterranean	Good Hope	117.28	44,433	1,999,559	15.91	60
Asia-West Mediterranean	Mixed	112.85	38,791	1,745,658	15.97	8
Asia-West Mediterranean	Suez Canal	96.21	29,587	1,331,484	14.69	53
Asia-West Europe	Good Hope	111.68	41,670	1,875,228	16.34	152
Asia-West Europe	Mixed	112.00	40,789	1,835,580	15.91	24
Asia-West Europe	Suez Canal	91.72	29,628	1,333,331	15.60	156
Total Average	Good Hope	114.02	42,886	1,929,972	16.20	239
Total Average	Mixed	112.09	39,453	1,775,459	15.79	35
Total Average	Suez Canal	91.28	28,038	1,261,758	15.28	268

large sample size across all route groups to ensure robust results. The findings reveal that rerouting via the Cape of Good Hope substantially increased voyage durations and environmental externalities. Round-trip time was extended by 20 to 34 days relative to Suez Canal baseline, while GHG emissions and associated environmental costs rose by between 41 % to 106 %. The East Mediterranean routes recorded the most pronounced increases, driven by their longer baseline voyage distances, whereas the West European routes experienced the smallest relative changes and, as indicated by the sample count, carried the largest share of trade volume. Across all routes, vessels increased their operating speeds by an average of 0.77 to 1.07 knots, further amplifying emissions growth. The Mixed category of voyages displayed intermediate values for both emissions and costs, falling between the Suez and Cape outcomes. This suggests that at the onset of the crisis, when rerouting measures were first adopted, the immediate impact was less severe, with the full effects materialising once the Cape route became the dominant alternative. Collectively, these results highlight that the 2024 Red Sea crisis has imposed substantial and lasting environmental pressures on the maritime sector, amplifying the regime's reliance on fossil fuel-intensive practices.

5.2. Single vessel round trip speed simulation for the Cape of Good Hope route

Utilising the AIS data, a simulation model was developed to assess the increase in environmental costs for vessels rerouting via the Cape of Good Hope at different cruising speeds. In the model, open-sea speeds were selectively adjusted while port and manoeuvring were held constant, thereby replicating realistic operational profiles. Fig. 5, plots average cruising speed on the horizontal axis against the percentage changes in round-trip time and environmental costs relative to the Suez Canal baseline. The results show a clear positive correlation between vessel speed and environmental costs. Reducing the average cruising speed to between 9.87 and 13.32 knots would lower emissions sufficiently to match environmental cost of the original Suez Canal route. However, as shown in the left panel of Fig. 5, this reduction alone cannot offset the additional costs imposed by rerouting.

When economic costs are considered in parallel, the results are illustrated in Fig. 6. Total voyage costs decrease as cruising speed is reduced, since fuel consumption, the primary cost component declines sharply with slower operations (Chang & Wang, 2014; Wang et al., 2018; Tan et al., 2020). Environmental costs also decline for the same reason. However, slower speeds increase voyage duration, which in turn raises operating and capital costs. In Fig. 6, the vertical black line marks the optimal cruising speed that minimises total cost, while the horizontal red line indicates the cost level of the original Suez Canal benchmark. This finding highlights the structural limitations of operational optimisation and reinforces the conclusion that speed reduction, while beneficial in reducing emissions, cannot by itself resolve the inefficiencies and environmental burdens created by geopolitical rerouting.

5.3. Whole fleet round-trip route simulation and optimisation

Building on the speed optimisation analysis, the fleet adjustment model examined how total route costs vary with speed and fleet size. Fleet requirements for each directional service were determined by dividing the round-trip duration by the intended service frequency. To preserve on-time liner schedules, it was assumed that every seven-day increase in round-trip time relative to the Suez baseline required the deployment of an additional container vessel, thereby adding both environmental and economic costs. The simulation results are shown in the Fig. 7. In the figure, the red line represents fleet size and the vertical black line indicates the speed that minimises total cost. The results demonstrate that the optimal configuration is achieved at a cruising speed of 14.4–15.0 knots, corresponding to a fleet size of 17–18 vessels per route. This implies the addition of three to five vessels compared with pre-rerouting conditions. Although slower cruising reduces fuel and environmental costs, these savings are offset by the capital and operating costs of the additional vessels. Consequently, as summarised in Table 11, even after optimisation, rerouting via the Cape of Good Hope still increases GHG emissions by at least 46 % and economic costs by at least 51 % compared with the Suez Canal route. Notably, observed vessel behaviour aligns more closely with the “Best Economic Speed” than the “Best Speed,” indicating that companies prioritise short-

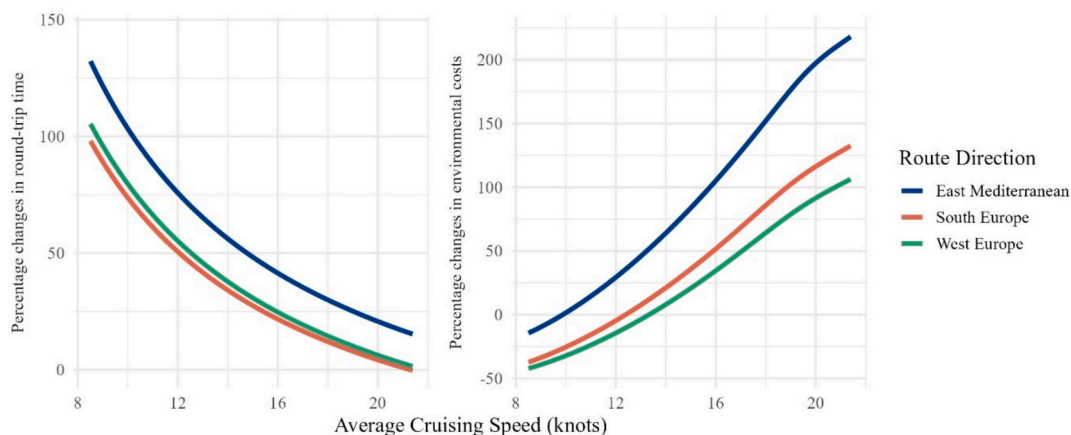


Fig. 5. Relationship between average cruising speed, round-trip time change (%), and environmental cost.

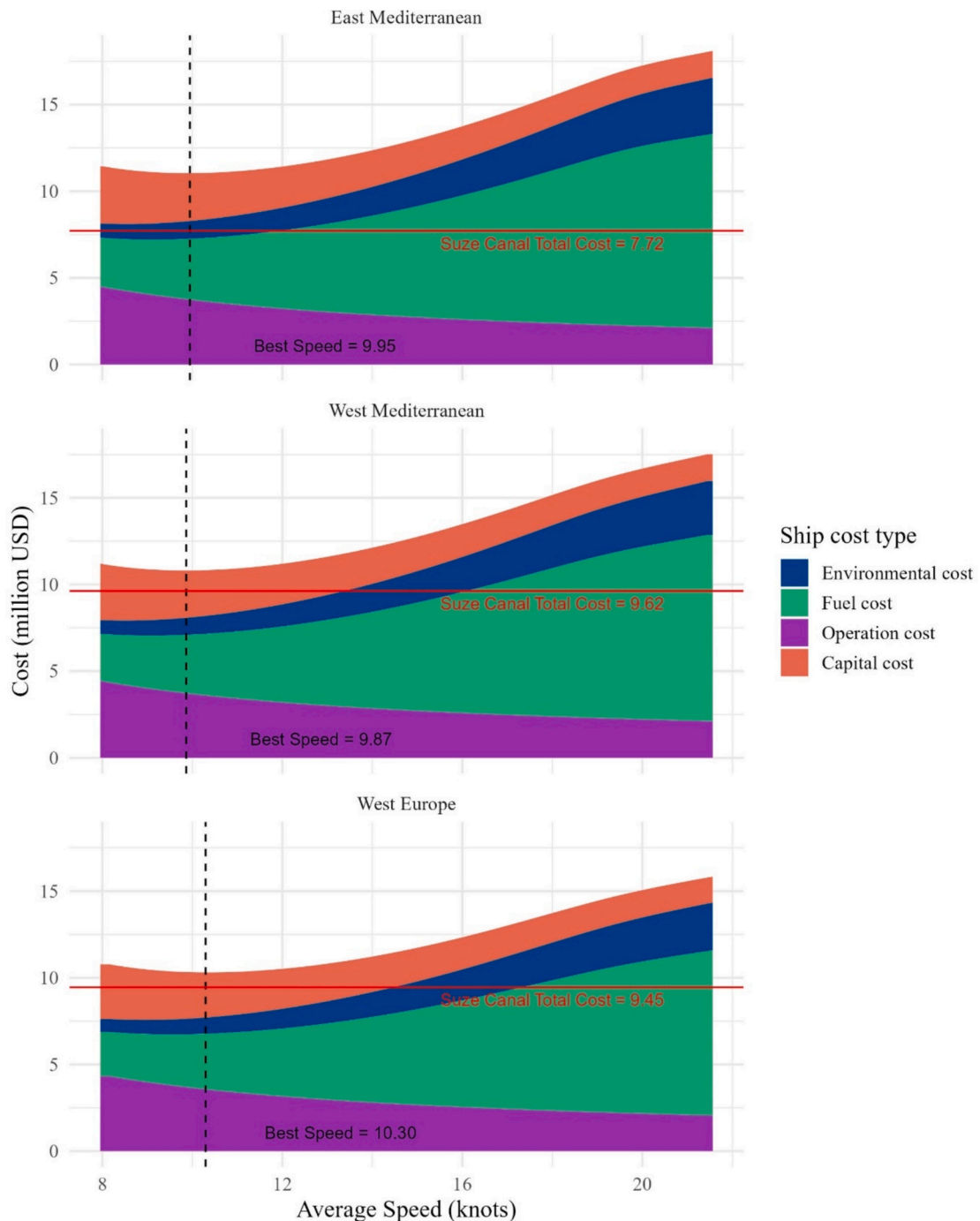


Fig. 6. Relationship between average speed and total cost.

term economic efficiency over minimising total cost. This behaviour illustrates a typical adaptive response within the current socio-technical regime, where incremental operational adjustments are favoured over systemic transformation. At the same time, if disruptions persist, the compounding costs may exacerbate regime tensions and open windows of opportunity for more radical innovation.

To assess the decarbonisation potential of transformative innovations in response to geopolitical disruptions, Table 12 presents percentage reductions in GHG emissions from different scenarios relative to the baseline Cape of Good Hope route. Operational optimisation through speed and fleet size adjustments reduce emissions by 8 % to 10 %, underscoring the limited mitigation potential of incremental improvements under regime lock-in. By contrast, transformative options demonstrate greater effectiveness, such as LNG

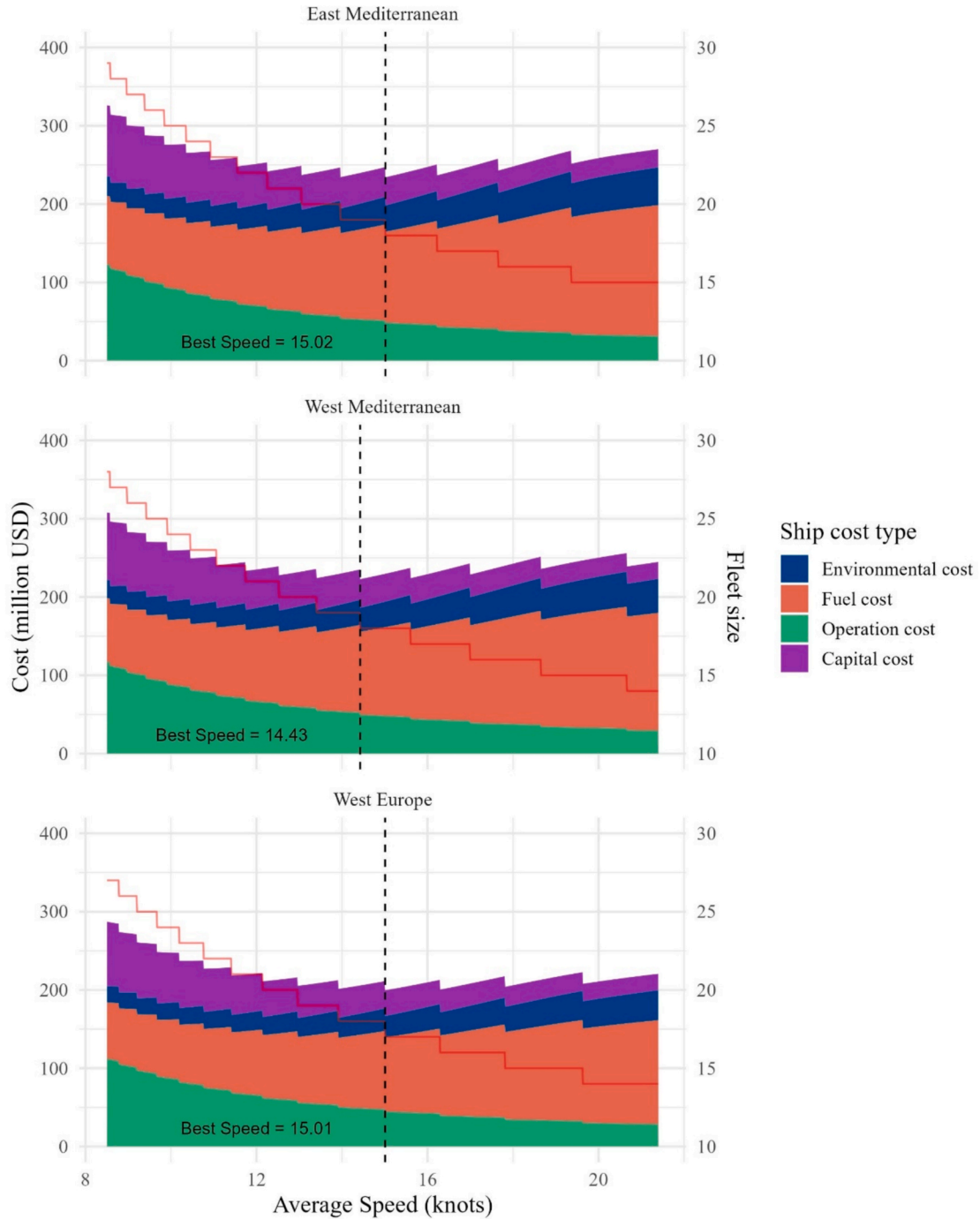


Fig. 7. Vessel line simulation results considering speed and fleet size.

propulsion, that can reduce excess emissions by approximately 23 %, while shore power adoption lowers emissions by 2.5 % during port stays. Most significantly, when these strategies are combined, particularly on Asia–Western Europe routes, total emissions increase is curtailed to below 6 %, bringing overall emissions close to pre-crisis levels.

These findings highlight the sharp contrast between incremental and transformative pathways. Incremental operational measures alleviate some of the immediate pressures of rerouting but are insufficient to counter the broader environmental and economic burdens. Transformative niche innovations, particularly when deployed in combination, show far greater potential to realign the maritime sector with decarbonisation trajectories. In a system characterised by strong path dependence and regime inertia, the high mitigation potential of transformative technologies provides a compelling rationale for their integration into the mainstream regime,

Table 11

Environmental and economic impacts considering speed and fleet size optimisation.

Route Direction	Best Speed (Knot)	GHG Emission Difference (%)	Economic cost Difference (%)	Best Econ Speed (Knot)	Actual Speed (Knot)
Asia-East Mediterranean	15.02	154.89 %	130.33 %	16.22	16.04
Asia-West Mediterranean	14.43	63.58 %	65.67 %	15.60	15.91
Asia-West Europe	15.01	46.73 %	51.43 %	16.29	16.34

Table 12

GHG emissions changes under different niche innovation scenarios.

Route Direction	Operation optimisation	Shore power	LNG	Combined	Suze Canal
Asia-East Mediterranean	−10.77 %	−2.49 %	−23.27 %	−33.21 %	−64.99 %
Asia-West Mediterranean	−10.30 %	−2.59 %	−23.28 %	−32.92 %	−45.16 %
Asia-West Europe	−7.94 %	−2.58 %	−23.28 %	−31.11 %	−37.26 %

facilitated by the window of opportunity created by geopolitical disruption.

6. A window of opportunity for maritime decarbonisation policy

This study quantifies the real-world economic and environmental costs of rerouting decisions prompted by the 2024 Red Sea crisis. The case study provides empirical evidence that such geopolitical disruptions not only generate immediate operational impacts on the maritime sector but also impose longer-term structural pressures. At the same time, climate change governance, led by international organisations and national authorities, is intensifying pressure on the existing maritime regime, gradually exposing internal cracks and creating windows of opportunity for transformation.

Despite these pressures, the industry's short-term responses remain largely incremental. Operational optimisation strategies, such as adjusting speed and fleet size, can only partially mitigate the burdens caused by rerouting. By contrast, transformative niche innovations demonstrate far greater potential to challenge regime inertia. The combined scenario modelled in this study illustrates how deploying alternative fuels, shore power, and operational adjustments together can initiate a structural decarbonisation pathway. These results highlight how innovations that once appeared peripheral are increasingly positioned to break fossil fuel lock-ins and gain legitimacy under conditions of disruption. In this context, geopolitical crises that were once perceived as threats are now being reframed by policymakers as catalysts for systemic change. Recent policy developments confirm this dynamic. In Europe, European Union incorporates maritime transport into the EU Emissions Trading System (EU ETS) and introduces the FuelEU Maritime Initiative, which mandates progressive reductions in the greenhouse gas intensity of marine fuels starting in 2025, with a 75 % reduction target by 2050 compared to 2020 levels (Christodoulou & Cullinane, 2022). Geopolitical crises such as the Red Sea disruption and the war in Ukraine have reinforced the urgency of reducing fossil fuel dependency (Li et al., 2024; Liu et al., 2024). In response, major European ports such as Rotterdam, Genoa, and Antwerp have accelerated investments in LNG and hydrogen bunkering facilities as well as shore power systems (Hentschel et al., 2018; Hoang et al., 2022). Meanwhile, shipping companies such as Maersk and CMA CGM are also deploying dual-fuel vessels and committing to long-term green fuel procurement contracts (Johansen et al., 2025).

Similar trends are evident in Asia, where Singapore, China, Japan, and South Korea are integrating green shipping initiatives with broader energy security and competitiveness goals. Singapore and China have spearheaded the creation of green corridors in partnership with ports such as Rotterdam and Los Angeles, promoting the coordinated adoption of low- or zero-carbon fuels (Ismail et al., 2024). The Maritime and Port Authority (MPA) of Singapore has pledged major investments to prepare for green ammonia and hydrogen bunkering (Ng et al., 2023), while Japan and South Korea are piloting ammonia-fuelled shipping trials (Ishimoto et al., 2020; Seo et al., 2024). In North America, regulatory leadership has been led by California, where the At-Berth Regulation requires vessels to use shore power while docked (Hoang et al., 2022), complemented by federal initiatives to establish clean shipping corridors (Ismail et al., 2024).

Taken together, these regional developments illustrate how policy acceleration under crisis conditions is neither coincidental nor geographically isolated, but instead reflects phased socio-technical transitions. Governments and port authorities increasingly treat green innovation not only as an ecological necessity but also as a strategic tool for competitiveness and resilience. Multi-level governance structures are thus converting systemic shocks into long-term sustainability policies, allowing niche technologies such as zero-emission vessels, LNG propulsion, and electrified port operations to gain legitimacy within the dominant regime. By combining landscape shocks with regime misalignments, geopolitical disruptions create windows of opportunity through which niche innovations can transition from experimentation to mainstream adoption, reshaping the trajectory of the maritime sector.

7. Conclusions

This study has examined the 2024 Red Sea crisis through the lens of socio-technical transitions, combining bottom-up emission

modelling with scenario simulations to quantify the economic and environmental consequences of crisis-induced rerouting. By situating the disruption within the multi-level perspective, the study contributes to a deeper understanding of how geopolitical shocks interact with entrenched regime structures and shape the trajectory of maritime decarbonisation.

The empirical findings demonstrate that rerouting vessels via the Cape of Good Hope imposes substantial environmental and economic costs. Average round-trip voyage times increased by 20–34 days, while GHG emissions and costs rose significantly, in some cases exceeding pre-crisis levels by more than 100 percent. Companies responded by increasing vessel speeds, further amplifying emissions, which is evidence of the regime's tendency to prioritise short-term efficiency over structural change. Scenario analysis confirmed that incremental adjustments, such as speed optimisation and fleet expansion, provide only limited relief, even under optimal conditions, meaning that rerouting still resulted in higher emissions and costs compared with the Suez Canal route. By contrast, transformative niche innovations showed far greater decarbonisation potential. LNG propulsion reduced excess emissions by roughly 23 percent, and when combined with operational optimisation and shore power, overall emissions on some routes nearly returned to pre-crisis levels.

These results highlight the structural inertia of the maritime regime, where incumbent practices are reinforced rather than overturned during crises. At the same time, the persistence of high costs and emissions creates tensions that may open windows of opportunity for more radical innovation. Geopolitical disruptions, once regarded primarily as external threats, are increasingly recognised as catalysts for change. Policy responses in Europe, Asia, and North America illustrate how governments and port authorities are accelerating investment in alternative fuels, shore power, and clean shipping corridors, thereby transforming crisis pressures into long-term sustainability pathways. These dynamics demonstrate how multi-level governance structures can mainstream niche innovations and gradually reconfigure the regime.

Beyond the theoretical contribution, the study provides practical insights for shipping companies and policymakers. Integrating socio-technical theory with empirical modelling offers a framework for designing strategies that balance operational resilience with long-term sustainability. The findings suggest that only through the adoption and combination of transformative innovations can the maritime sector reconcile economic performance with climate objectives under conditions of geopolitical turbulence.

Future research should expand the analysis to a wider set of vessel types and trade routes, and investigate longer-term adaptation strategies that integrate supply chain resilience with decarbonisation. Further development of predictive models could provide industry decision-makers with tools to evaluate trade-offs between cost, emissions, and resilience, supporting the transition toward more sustainable and crisis-resilient global shipping.

CRediT authorship contribution statement

Ruikai Sun: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Wessam Abouarghoub:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Emrah Demir:** Writing – review & editing, Supervision. **Andrew Potter:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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