SUSTAINABILITY, RESILIENCE, AND COMPETITIVENESS OF THE SUEZ CANAL ROUTE FOR FAR EAST–EUROPE CONTAINERSHIPS IN THE CONTEXT OF IMO REGULATIONS 2025 AND THE RED SEA CRISIS

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1. **ABSTRACT:** The Suez Canal (SC) serves as a critical maritime corridor linking Asia and Europe, yet its operational and environmental competitiveness relative to alternative routes, such as the Cape of Good Hope (COGH), remains under pressure during geopolitical crises. This study employs a comparative analytical approach to evaluate the economic and environmental performance of 14,000-TEU containerships transiting between Shanghai and Rotterdam during the ongoing Red Sea crisis and International Maritime Organization regulations 2025. Total shipping costs, including fuel, canal fees, war-risk premiums, capital and operating costs, and inventory-carrying costs, were analyzed alongside CO_2 emissions to assess overall competitiveness. Additionally, the influence of Suez Canal Authority rebate schemes such as Circulars no. 3/2025 and 8/2023, on route attractiveness was quantified using a composite competitiveness index (CI) that integrates economic and environmental dimensions. Results indicate that the SC route provides substantial financial advantages, particularly on the head-haul leg, achieving total round-trip savings of approximately $3.16 million despite Canal fees and war-risk premiums. Environmentally, the SC reduces fuel consumption by 1,856 tons per voyage, lowering CO_2 emissions by 5,780 tons, corresponding to $578,000 in potential carbon cost savings. The CI confirms that the SC route is consistently more competitive than the COGH route across head-haul, back-haul, and round-trips for Far East – Europe trade route. These findings highlight the strategic, economic, and environmental benefits of the SC and underscore the importance of incentive schemes and operational planning in maintaining maritime resilience during crises.
Keywords: Suez Canal, Cape of Good Hope, containerships, Red Sea crisis, IMO regulations 2025, competitiveness index.

2. INTRODUCTION

The global maritime industry underpins over 80% of international trade by volume, serving as a fundamental pillar of the global economy [1]. Among the world's major maritime corridors, the Suez Canal (SC) stands out for its unparalleled strategic and economic significance, linking the Mediterranean Sea to the Red Sea and offering the shortest maritime passage between Asia and Europe [2]; [3]. Approximately, 12% of global trade and nearly 30% of the world's container traffic pass through the Canal [4]. This central role establishes the Canal as a critical artery for the transportation of energy resources, manufactured products, and raw materials between the world's two largest trading regions.

Since its inauguration in 1869, the SC has played a pivotal role in shaping international trade dynamics. By drastically shortening maritime distances between Europe and Asia, it has provided substantial economic and logistical advantages compared with alternative routes such as the Cape of Good Hope (COGH) [5]; [6]. Owing to its strategic position, the Canal has become a focal point for multidisciplinary research encompassing maritime operations, environmental studies, hydrodynamics, and marine biology [7]; [8].

Nevertheless, maritime transport operates within a complex and volatile environment influenced by geopolitical tensions, technology development, fluctuations in fuel prices, and evolving environmental regulations [9]; [10]. Recent disruptions, most notably the Ever-Given grounding in 2021 and the Red Sea security crisis during 2023–2025, have underscored the vulnerabilities of the global supply chain [11]; [12]. These incidents prompted shipping companies to temporarily reroute vessels around the COGH [13]; [14]. Although such diversions can enhance security and operational predictability during crises, they typically result in longer voyage times, higher fuel consumption, and increased greenhouse gas (GHG) emissions, thereby raising concerns over both economic efficiency and environmental sustainability [15]; [16].

The efficiency and reliability of global maritime transport depend heavily on route optimization, fleet deployment, and transit performance, particularly along major corridors such as the SC [17]. The Asia–Europe trade network exemplifies this interdependence, where operational choices between the SC and the COGH have significant implications for cost, time, and environmental impact [18]. The SC's operational dynamics—such as convoy capacity and navigational behavior in its expanded sections—play a decisive role in maintaining seamless traffic flow and ensuring navigational safety [19]. However, recent events, including the 2021 Ever Given incident, have revealed the vulnerability of this strategic passage and its global repercussions, emphasizing the need for greater resilience, proactive risk management, and contingency preparedness within maritime logistics systems [20]; [14]; [21].

COGH route serves as the primary alternative to the SC for Asia–Europe trade, particularly during regional crises. Historically, it was the dominant pathway for Asia–Europe trade prior to the Canal's opening in 1869 [2]. While free of tolls and geopolitical choke points, the Cape route requires vessels to sail an additional 8–10 days, leading to substantially higher fuel and capital and operating costs [22]; [23]. For large containerships, this equates to roughly 40–45% higher voyage costs and 10–15% higher CO_2 emissions, making the Cape route economically viable only under exceptional circumstances—such as major security threats, blockages [24]; [25]; [26].

However, during periods of geopolitical disruption, the economic disparity between the two routes tends to narrow as insurance premiums, security surcharges, and risk-related operational costs escalate sharply [27]. Moreover, while the COGH route may appear to be a viable contingency option, it exposes vessels to additional challenges, including heightened piracy threats in the western and southern African and western Indian Ocean regions, and also exposing containerships to more extreme bad weather off southern Africa, causing loss of some containers. [28]; [29]. These risks not only increase insurance and escort expenses but also raise safety concerns for crews and cargo. On the other hand, the SC route demonstrates a superior advantage when comparing spectral fatigue effects on vessels, as prolonged exposure to rougher sea conditions and longer voyage durations via the Cape exacerbate hull stress, maintenance demands, and crew fatigue [30].

The competitiveness of the SC has traditionally been rooted in its cost-efficiency and its pivotal geographic position within global maritime trade routes [31]. For East Asia–Europe services, such as the Shanghai–Rotterdam route, transiting through the Canal offers a distance saving of approximately 3,318 nautical miles—equivalent to around eight days of sailing time—compared with the COGH route [32]. This substantial reduction translates into lower bunker fuel consumption, shorter voyage durations, and faster vessel turnaround times, collectively enhancing both economic and environmental performance [27]; [33]. Such operational advantages reinforce the Canal's status as the preferred maritime corridor for containerized trade between Asia and Europe.

However, a range of external challenges—such as regional conflicts in the Red Sea, and geopolitical instability—periodically affect the Canal's perceived reliability and erode its cost advantage [34]. To mitigate these risks and preserve its global competitiveness, the Suez Canal Authority (SCA) has implemented adaptive, flexible pricing and marketing strategies through a series of navigational circulars that provide targeted rebates and toll reductions [35]. These circulars are designed to attract wide categories of vessels and trade routes, thereby maintaining traffic flow and market share. Table 1 summarizes containerships navigation circulars issued by SCA, corresponding target regions, and applicable rebate percentage.

Table 1. SC navigational circulars for containerships valid till June 2026

Ship Type	*Circular No.*	*Trade route*	*Discount rate (%)*
Containership	2/2016*	US East Coast (Norfolk and north) – Port Klang eastward	40
		US East Coast (from ports south of Norfolk) – Colombo eastward up to but not including Port Klang	50
		US East Coast (from ports south of Norfolk) – Ports Port Klang eastward	60
	8/2023*	North-West Europe - Port Klang eastward	Exemption from 15% increase in normal tolls (applied in 15th January 2024)
	3/2025**	Ships exceeding 130,000 SC Net Tonnage, loaded or empty, northbound or southbound	15

*Only for southbound voyages. ** from the total SC tolls, Source: SCA, 2025

Maritime route selection increasingly depends not only on economic factors such as voyage cost and time but also on environmental performance, especially under the International Maritime Organization's (IMO) decarbonization targets [36]. Fuel consumption directly influences both operational cost and CO_2 emissions, creating a dual imperative for carriers to optimize efficiency [15]; [19]. In addition, integrating sustainability metrics into cost analyses can better inform policy and routing decisions, particularly under uncertain geopolitical and market conditions [10]; [37].

Figure 1 shows the monthly average world container index. For the Shanghai–Rotterdam (SHA–RTM) route, the index shows significant volatility between October 2024 and October 2025, peaking at $4,816 per 40-foot container in December 2024 before dropping to $4,018 in January 2025, likely due to post-holiday adjustments and capacity rebalancing. From February to May 2025, the index fell sharply to $2,094, reflecting temporary oversupply or reduced demand, then partially recovered to $3,014 in June amid summer shipping demand, before declining again to $1,620 by October 2025—a 66% drop from the December peak—driven by global market softening, lower freight demand, and operational efficiencies. These fluctuations underscore the cyclical nature of container rates on the SHA–RTM corridor, highlighting the need for strategic booking and flexible routing to manage costs and market exposure.

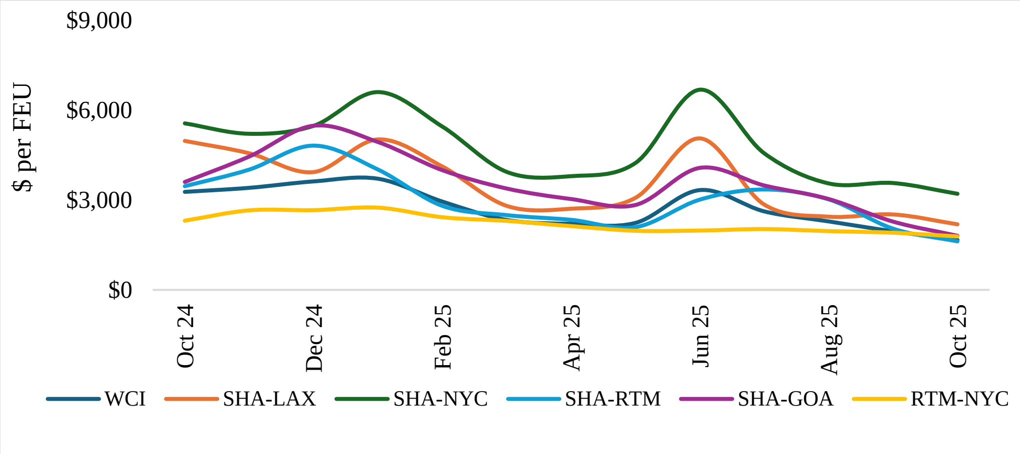

Figure 1: World container index through Oct. 2024- Oct. 2025 (Source: Drewry, 2025)

The IMO has taken a significant step toward establishing a legally binding framework to reduce GHG emissions from ships, with the objective of achieving net-zero emissions by around 2050. The IMO net-zero framework, approved by the marine environment protection committee during its 83rd session held from 7–11 April 2025, represents the world's first initiative to integrate mandatory emission limits with a comprehensive GHG pricing mechanism across an entire industry sector [38].

The framework introduces a new fuel standard for ships and a global emissions pricing scheme which was postponed by one year to be adopted in October 2026 and may enter into force in 2028. These measures will apply to ocean-going vessels exceeding 5,000 gross tonnages, which collectively account for approximately 85% of total Carbon dioxide (CO_2) emissions from international shipping [39].

To support the implementation of these measures, the "IMO net-zero Fund" will be established to collect revenues from emissions pricing. The collected funds will be used to reward low-emission ships, promote innovation, research, and infrastructure development, and ensure a just transition in developing countries. Moreover, the Fund will finance training, technology transfer, and capacity-building activities to advance the IMO's GHG Strategy, while mitigating potential negative impacts on vulnerable countries, particularly small island developing countries and least developed countries [40].

2.1 Research gap and paper objectives

Although numerous studies have examined the strategic importance of the SC and the temporary rerouting of vessels via the COGH during disruptions—such as Tran *et al*. [20], Hamed [37], Hamdan *et al*. [18], Rodriguez-Diaz *et al*. [12], and Chen *et al*. [6]—this literature largely focuses on descriptive analyses, partial cost components, or isolated Red Sea disruptions. Existing studies typically assess economic or environmental performance separately and under relatively stable market conditions, offering limited insight into route competitiveness during acute geopolitical crises characterized by elevated war-risk premiums and the implementation of IMO 2025 carbon regulations. Moreover, prior research seldom provides a comprehensive, direction-based comparison (head-haul, back-haul, and round-trip) that simultaneously incorporates war-risk premiums, carbon pricing, and environmental externalities for large containerships. As a result, the combined effects of geopolitical risk, regulatory pressure, and incentive mechanisms on route competitiveness remain insufficiently explored, a gap that this study explicitly addresses.

In addition, the role of SCA rebate schemes has not been systematically quantified within an integrated economic–environmental framework, especially for large containerships operating on the Far East–Europe trade lane. The combined effects of Canal pricing incentives on route competitiveness therefore remain insufficiently explored.

This study addresses these gaps by providing a comprehensive, direction-based comparison of the SC and COGH routes for 14,000-TEU containerships under Red Sea crisis conditions and IMO 2025 regulations. The novelty of this research can be clarified in (*i*) jointly assessing economic and environmental performance using a unified cost framework, (*ii*) explicitly incorporating war-risk premiums and SCA rebate circulars into route-choice analysis, and (*iii*) proposing and applying a composite CI that integrates cost efficiency and carbon performance. By doing so, the study offers new empirical insights into route selection decisions under extreme market uncertainty and evolving regulatory constraints.

2.2 Paper objectives

This study employs a comprehensive comparative framework that quantifies voyage cost and CO_2 emissions for a representative 14,000 TEU containership across both routes. In addition, a composite competitiveness index (CI) is introduced to integrate economic and environmental performance, providing a robust and transparent tool for evaluating overall corridor efficiency.

Accordingly, the objectives of this study are as follow:

- **Evaluate the economic competitiveness of the SC route compared with the COGH route during the Red Sea crisis and IMO regulations 2025 according to trip directions:** To quantify and compare total shipping costs (fuel, Canal fees, war-risk premiums, capital and operating costs, and inventory-carrying costs) for 14,000-TEU containerships operating in direct service between Shanghai and Rotterdam ports for head-haul, back-haul, and round-trip.
- **Assess the environmental performance of the SC and COGH routes:** To estimate route-specific CO_2 emissions and emission costs using fuel-consumption data and IMO-aligned carbon-pricing assumptions.
- **Examine the influence of SCA rebate schemes on SC route competitiveness:** To determine how Circulars no. 3/2025 and 8/2023 affect voyage cost savings and route-choice decisions for head-haul, back-haul, and round-trip.
- **Develop and apply a composite CI:** To merge economic and environmental dimensions into a unified performance metric and benchmark the relative competitiveness of the SC and COGH routes across trip directions.

The paper proceeds as follows: **Section 3** reviews relevant literature. **Section 4** details the methodology, assumptions, and data sources. **Section 5** presents the findings of economic and environmental analysis, followed by a competitiveness evaluation. While **Section 6** explores the discussion, **Section 7** presents the future work plan. Finally, **Section 8** concludes our study.

3. LITERATURE REVIEW

3.1 Strategic Importance and Operational Efficiency of the SC

The SC has long been recognized as a pivotal maritime corridor, offering the shortest sea route between Europe and Asia and significantly reducing transit time compared with alternative passages such as the COGH (Rodrigue, [2]; Feyrer, [41]; Hamdan *et al*., [27]). Its strategic location positions the canal at the heart of global container shipping networks, with a substantial proportion of global trade volume and container traffic transiting annually (Essallamy *et al*., [42]; Zhang *et al*., [43]; Rusinov *et al*., [44]).

Historical disruptions, such as the SC closure from 1967 to 1975, highlight its critical influence on trade flows, income, and global shipping patterns (Feyrer, [41]; Gerritse, [45]).

Operational efficiency in the canal has been a major focus of research. Convoy management, passage scheduling, and navigational safety are essential for maintaining throughput, particularly under restrictions imposed by vessel size and waterway dimensions. Wang *et al*. [46] estimated the convoy capacity of the canal, while Elsherbiny *et al*. [52] investigated ship squat behavior in the New SC, demonstrating the implications for vessel speed, hull stress, and navigational safety. Additionally, Essallamy *et al*. [8] have explored spectral fatigue impacts on vessels, emphasizing the operational advantages of shorter canal voyages over extended alternatives such as the Cape route.

Beyond physical navigation, operational optimization encompasses network planning, fleet deployment, and voyage scheduling. Hamdan *et al*. [48] analyzed Asia–Europe container networks, comparing Suez and Cape routes under varying market conditions and operational constraints. Some research like Wu *et al*. [53], [54]; Wang *et al*, [55]; Zhao *et al*. [56]; Xiao and Wang [57]; Wen *et al*. [58] have utilized advanced optimization techniques, including nonlinear programming, integer programming, and genetic algorithms, have been applied to optimize fleet deployment, voyage selection, and speed while incorporating environmental considerations such as fuel consumption and CO_2 emissions.

Recent research has also highlighted the integration of sustainability and resilience into operational efficiency analyses. Tran *et al*. [31]; Wan *et al*. [59]; Mechai and Wicaksono [60]; Laih *et al*. [61] have quantified emissions from seagoing vessels, examined risk management strategies during disruptions such as the 2021 Ever Given blockage, and assessed the role of rebate policies in maintaining the canal's competitiveness. Moreover, Ahmed *et al*. [62]; Desoky *et al*. [63]; Ibrahim *et al*. [64] have employed geospatial and remote sensing methodologies to monitor waterway conditions, sediment transport, and environmental impacts, providing data-driven insights for sustainable operational planning.

3.2 Economic and Environmental Competitiveness in Route Selection

Economic efficiency and environmental performance have become pivotal factors influencing maritime route selection, particularly in comparisons between the SC and the COGH. Recent studies highlight that, while the COGH route circumvents canal tolls and avoids potential geopolitical risks associated with chokepoints such as the Red Sea, it is generally less competitive in terms of operating costs and emissions. For instance, Zhang *et al*. [65] reported that voyages via the Cape typically incur 35–45% higher fuel and operational costs relative to the SC, mainly due to extended sailing distances and higher bunker consumption. Similarly, Lee and Yao [66] emphasized that CO_2 emissions for large containerships can rise by 10–20% when rerouting through the COGH, reducing the route's environmental desirability except under crisis conditions such as Canal congestion or security disruptions. Moreover, empirical assessments by Alharbi and Stopford [67] demonstrate that prolonged Cape voyages contribute to greater hull fatigue, increased maintenance costs, and heightened crew fatigue—factors that further consolidate the SC's operational advantage.

The SC's pricing framework and rebate mechanisms have been identified as key determinants influencing global route selection, particularly during periods of market disruption and freight rate volatility. According to Wang and Cullinane [68], the dynamic toll structure adopted by the SCA enables adaptive pricing that reflects fluctuations in bunker costs and global demand, helping sustain the Canal's competitiveness against alternative passages such as the COGH. Similarly, Notteboom and Haralambides [69] emphasized that targeted rebate schemes and temporary fee reductions are strategic tools used by the SCA to retain liner traffic during crises, such as geopolitical instability or global trade slowdowns. More recently, Rahman and Zhang [70] noted that the SCA's issuance of navigation circulars with route-specific incentives—particularly for LNG carriers and Asia–Europe container services—has effectively mitigated diversion risks and stabilized throughput during uncertain market conditions.

Environmental sustainability has emerged as a central factor in maritime route selection, particularly in light of the IMO's decarbonization strategy and the global drive to reduce GHG emissions from shipping. As highlighted by Acciaro and McKinnon [71], environmental performance is increasingly integrated into operational decision-making, influencing route optimization and vessel speed management. Similarly, Qi and Song [72] emphasized that compliance with IMO's carbon intensity indicator and energy efficiency existing ship index requirements has accelerated the adoption of greener routing practices and energy-efficient voyage planning. Recent modeling efforts have applied nonlinear and mixed-integer programming frameworks to optimize fleet deployment, voyage routing, and speed regulation under emission and fuel consumption constraints by Liu *et al*. [73]; Zhang *et al*. [74]. In parallel, studies by Yuen *et al*. [75] showed that incorporating environmental factors—such as weather conditions, emission control areas (ECAs), and low-sulfur fuel zones—into vessel scheduling enhances both operational efficiency and emission performance.

Recent research has increasingly focused on the integrated optimization of vessel deployment, cargo allocation, and fuel bunkering strategies to enhance both the economic and environmental performance of global shipping networks, particularly along the Asia–Europe corridor. According to Yang *et al*. [76], coordinated decision-making in fleet composition and voyage planning can significantly reduce total system costs and carbon emissions by aligning vessel size and speed with route-specific conditions. Similarly, He and Cullinane [77] emphasized the importance of integrating bunkering optimization into route planning, noting that strategic fuel procurement at low-cost ports contributes to both cost efficiency and emissions reduction. In addition, Xu *et al*. [78] demonstrate that multi-objective models capturing the interactions between vessel selection, cargo routing, and environmental regulations yield more resilient and sustainable outcomes under market uncertainty.

3.3 Supply Chain Disruptions and Risk Management

The Ever-Given blockage of the SC in 2021 prompted a surge of research examining the cascading impacts of maritime chokepoint disruptions on global supply chains. Notteboom *et al*. [79]; Haralambides [80]; Panayides and Song [81] have documented significant increases in freight rates, insurance premiums, and port congestion, leading to altered shipping schedules and strategic route diversions. Zhang and Cullinane [82]; Lam and Su [83]; Lee *et al*. [84] emphasized that large-scale maritime disruptions have systemic effects extending beyond immediate trade delays, influencing long-term decisions in fleet deployment, supply chain design, and risk allocation.

Beyond single-incident crises, persistent geopolitical tensions and security risks—particularly in the Red Sea and adjacent maritime zones—continue to challenge the stability and reliability of the SC route. Yuen and Thai [85]; Bichou [86] have shown that regional conflicts, piracy threats, and naval activity can precipitate insurance surcharges, rerouting decisions, and disruptions in cargo flows. Gonzalez-Aregall *et al*. [87]; Liu and Wang [88]; Wang *et al*. [89] have employed advanced risk modeling and scenario-based simulations to assess the vulnerability of container shipping networks under such uncertainty, revealing the strategic importance of diversification, real-time monitoring, and adaptive decision-making frameworks.

Moreover, the scope of supply chain resilience research has broadened to encompass economic, operational, and environmental dimensions. Yang *et al*. [76]; He and Cullinane [77]; Xu *et al*. [78] have been identified integrated strategies such as fleet redeployment, slow steaming, and dynamic route optimization as effective measures to mitigate disruptions while maintaining service reliability and minimizing emissions.

4. METHODOLOGY

4.1 Research Approach

This study employs a comparative analytical approach to assess the economic and environmental competitiveness of the SC relative to the COGH route during the ongoing Red Sea crisis. The analysis focuses on 14,000 TEU containerships, which constitute a significant share of global seaborne trade and are highly sensitive to fluctuations in fuel prices, transit times, and service reliability.

The comparative framework enables the quantification of the effects of route diversion on total voyage costs and GHG emissions, thereby linking short-term crisis impacts and SC incentive strategies to route choice and overall competitiveness.

In response to successive supply chain disruptions—particularly the recent Red Sea crisis—the SCA has implemented various rebate schemes for containerships. Accordingly, this study examines the influence of these incentive strategies on the competitiveness of the SC route before and after the rebate, assessing whether the measures have meaningfully altered its competitive position.

4.2 Reference Vessel and Voyage Assumptions

Table 2 presents a consolidated comparison of the SC and COGH routes, integrating operational, technical, and economic parameters relevant to maritime transport analysis. By combining route characteristics, vessel specifications, cost structures, fuel-related factors, and cargo considerations into a single framework, the table provides a comprehensive basis for evaluating the trade-offs involved in selecting between these two major intercontinental shipping corridors.

Our analysis assumes a 10-year-old, 14,000-TEU containership operating a round-trip between Shanghai and Rotterdam in direct service. The vessel is assumed to maintain a constant speed on both routes, resulting in differing voyage durations. On the SC route, the ship benefits from Circular no. 3/2025 during the head-haul and from both Circulars no. 3/2025 and 8/2023 on the back-haul. These policies provide incentives for vessels to reroute through the SC, particularly during periods of geopolitical tension, such as the Red Sea crisis.

Inventory-carrying costs reflect the economic implications of capital tied up in goods during transit, including storage costs, risks of obsolescence (economic and technical depreciation), and potential damage [91]. These costs are calculated based on the cargo value onboard and an assumed annual time-value rate of 25% of cargo value [90]; [91]. Due to higher cargo values and vessel utilization (90%) on the head-haul leg, inventory-carrying costs are significant for this portion of the voyage. Conversely, the back-haul leg typically involves lower-value cargo and reduced vessel utilization (40%), resulting in lower time sensitivity; therefore, inventory-carrying costs for this leg are considered negligible for the purposes of this analysis.

Capital and operating costs are influenced by multiple factors, including ship-specific characteristics, market conditions, financing arrangements, and trade engagement. Following widely accepted methods, these costs are estimated using regression models based on vessel size, providing a consistent framework for comparative analysis across routes.

Table 2. Ship characteristics and cost components assumptions

Parameter	*SC route*	*COGH route*	*Source*
Average distance (*nm*)	10525	13843	[92]
Voyage duration (*day*)	24	32	
Ship size (*DWT*)	150,000		[93]
Ship capacity (*TEU*)	14,000		
Ship net tonnage (*SCNT*)	140,000		

Average speed (*knot*)		18		
Ship fuel consumption (*ton/day*)		116		
Special drawing rights (*$*)		1.355030		[94]
Capital & operating cost *($/day*)		120,000		[95]
Ship value (*$*)		100,000,000		
Average value per (*$/TEU*)		50,000		[96]
War-risk premium	*% Ship value*	0.5	-	[97]
	value ($)	500,000	-	
SC tolls (*head-haul*) (*$*)	*Before rebate*	1,380,000	-	[98]
	After rebate	1,175,000*	-	
SC tolls (*back-haul*) (*$*)	*Before rebate*	1,080,000	-	
	After rebate	780,000**	-	
HSFO price (*$/ton*)	*Head-haul*	385#		[99]
	Back-haul	393##		
Average ship utilization (*%*)	*Head-haul*	90		[100]
	Back-haul	40		
Additional inventory carrying cost *($/day*)	*Head-haul*	-	437,500	Calculated based on Lambert *et al*. [90]; Robert *et al*. [91]
	Back-haul	-	-	

* Circular no.3/2025, ** circulars no.8/2023, and 3/2025 # Singapore port ## Rotterdam port

4.3 Economic and Environmental Competitiveness Analysis

In maritime economics, total shipping cost (TSC) is typically conceptualized as the sum of three primary components: voyage cost, operating cost, and capital cost [101]; [33]; [102]:

$$TSC = Voyage\ cost + Operating\ cost + Capital\ cost \quad (1)$$

Voyage cost includes variable costs directly tied to a voyage—such as fuel consumption, port charges, and canal dues [33]. Operating cost encapsulates the fixed daily expenses associated with running a vessel, including crew wages, maintenance, insurance, stores, and administrative overhead [102]. Capital cost captures the newbuilding prices of vessel through depreciation, interest payments, or return on invested capital and the vessel's economic life [103]. This three-part structure aligns with frameworks used in contemporary, sustainability-oriented studies of shipping economics [104].

Environmental performance is assessed through voyage-based CO_2 emissions, calculated using an emission factor of 3.114 t CO_2 per ton of HSFO consumed [19]; [105]; [106]; [107]. Total CO_2 emissions are therefore expressed as:

$$CO_2\ emission = HSFO\ Consumption \times 3.114 \quad (2)$$

4.4 Competitiveness Index (CI)

To capture both economic and environmental dimensions, a composite CI is proposed [108]; [109]:

$$CI = w_1\left(\frac{TSC_{Suez}}{TSC_{COGH}}\right) + w_2\left(\frac{CO_2C_{Suez}}{CO_2C_{COGH}}\right) \quad (3)$$

Where, TSC: total shipping cost, CO_2C: CO_2 emissions cost, w_1, w_2: weighting coefficients for shipping cost and emissions respectively, $w_1+w_2=1$.

This index provides a transparent tool for benchmarking maritime corridor performance across multiple criteria—cost, risk, and sustainability [108]; [109]. If CI is less than 1, this indicates that SC route is more economically and environmentally competitive to COGH route.

5. FINDINGS

5.1 Economic Competitiveness

Table 3 shows that, for the head-haul comparison, the SC route is financially superior, saving $3.13M per trip despite war-risk and SC fees; although the COGH route avoids these charges, its higher fuel consumption, greater capital and operating costs, and especially the $3.5M inventory carrying cost from longer transit time make it significantly less competitive overall.

Table 3. Shipping cost for the head-haul trip (SHA » RTM)

Cost component ($)	*SC Route*	*COGH Route*	*SC Saving*
Fuel cost	1,088,071	1,431,084	343,013
SC fees	1,175,000	-	-1,175,000
War-risk premium	500,000	-	-500,000
Capital & operating cost	2,880,000	3,840,000	960,000
Additional inventory carrying cost	-	3,500,000	3,500,000
Total head-haul trip cost	5,643,071	8,771,084	3,128,013

Figure 2 shows that, the head-haul trip uses a single rebate circular offered by the SCA, totaling $205,000. The SC route still yields positive savings even without this rebate; however, the rebate serves a marketing purpose by encouraging more containerships to return to the SC and enhance the SC savings, especially during the Red Sea crisis.

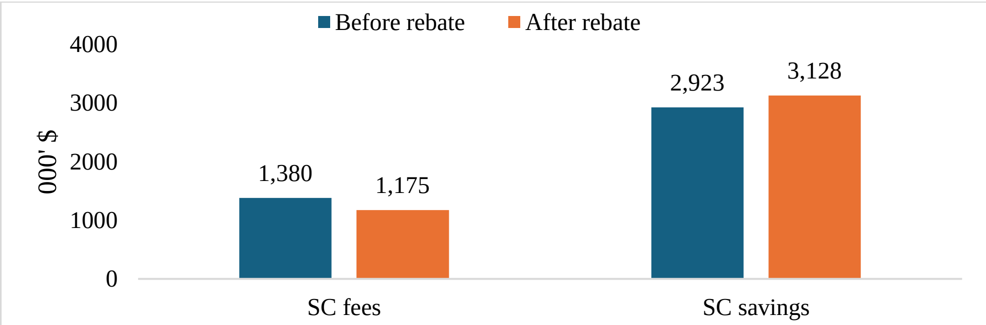

Figure 2: Effect of rebate Circular no. 3/2025 on SC route savings on the head-haul trip

Table 4 shows that, for the back-haul comparison, the SC Route and COGH Route are nearly cost-neutral, with the SC Route offering only a modest $31,900 saving; although COGH avoids SC fees and war-risk premiums, these benefits are almost fully offset by its higher fuel consumption and greater capital and operating costs, leaving only a marginal overall difference between the two routes.

The additional inventory carrying cost is shown as null on the back-haul because this leg typically carries much lower-value and non–time-sensitive cargo, such as repositioned empties or low-priority loads, meaning that any additional transit time does not meaningfully impact working capital which reflected in lower ship utilization and lower freight rate. In contrast, the head-haul usually transports full, revenue-generating shipments, so a longer route keeps higher-value inventory tied up for more days, creating a real and material inventory carrying cost. Even when some cargo is present on the return leg, its lower value and limited urgency mean the cost of capital tied up during transit is negligible.

Table 4. Shipping cost for the back-haul trip (RTM » SHA)

Cost component ($)	*SC Route*	*COGH Route*	*SC Saving*
Fuel cost	1,116,332	1,468,255	351,923
SC fees	780,000	-	-780,000
War-risk premium	500,000	-	-500,000
Capital & operating cost	2,880,000	3,840,000	960,000
Additional inventory carrying cost	-	-	-
Total back-haul trip cost	5,276,332	5,308,255	31,923

Figure 3 illustrates the effectiveness of the SC's marketing and pricing strategies for back-haul containership voyages on the Far East–Europe route. The back-haul trip uses two rebate circulars offered by the SCA, totaling $300,000. Without these rebates, the SC route would be less competitive compared with the COGH route.

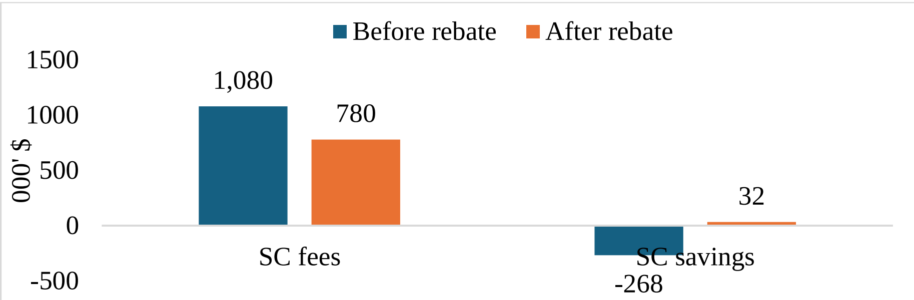

Figure 3. Effect of rebate Circulars no. 8/2023 and 3/2025 on SC route savings on the back-haul trip

Table 5 shows that, shows that the SC Route remains far more cost-effective than the COGH Route, delivering $3.2M in savings per round-trip despite incurring SC fees and a war-risk premium. While COGH avoids these charges, its higher fuel use, significantly higher capital and operating costs, and especially the $3.5M inventory carrying cost driven by longer transit time make it substantially more expensive overall.

Table 5. Shipping cost for the round-trip (SHA»«RTM)

Cost component ($)	*SC Route*	*COGH Route*	*SC Saving*
Fuel cost	2,204,403	2,899,339	694,936
SC fees	1,955,000	-	-1,955,000
War-risk premium	1,000,000	-	-1,000,000
Capital & operating cost	5,760,000	7,680,000	1,920,000
Additional inventory carrying cost	-	3,500,000	3,500,000
Total round-trip cost	10,919,403	14,079,339	3,159,936

Figure 4 shows total SC savings of $505,000, resulting from the two rebate circulars applied to the containerships servicing a round-trip on the ASIA–Europe route.

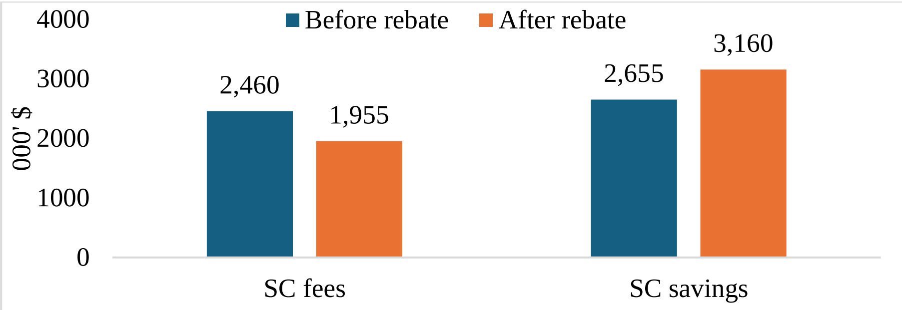

Figure 4. Effect of rebate Circulars no. 8/2023 and 3/2025 on SC route savings on the round-trip

SCA issued Circular no. 3/2025, granting a 15% discount on transit tolls for containerships traveling north or south (laden or ballast) transiting the SC with a net tonnage of 130,000 tons or more, effective from May 15, 2025. This rebate serves as an incentive to encourage large containerships to return to the SC route that had diverted COGH route to cover and compensate the additional cost due to the security threats in the Red Sea crisis. Circular no. 3/2025 has successfully attracted 33 containership voyages to transit the canal and benefitted from the discount granted under this circular, from its issuance on May 15, 2025, until November 15, 2025. These voyages totaled a net tonnage approximately 5M tons.

On the other hand, Circular no. 8/2023 had benefitted 34 containership transits from the exemption granted to containerships from the 15% increase in the tolls under this circular, since applied on Jan 15, 2024, until November 15, 2025. These voyages totaled a net tonnage approximately 1.7M tons.

5.2 *Environmental Competitiveness*

Table 6 illustrates the comparative fuel consumption, CO_2 emissions, and corresponding emission costs between the SC and COGH routes for a representative round-trip. The results show that the SC route is significantly more energy-efficient, with fuel consumption reduced by approximately 1,856 tons, corresponding to a 5,780 ton decrease in CO_2 emissions. This translates into a potential emissions cost saving of about $578,000 per voyage, assuming a carbon price of $100 per ton of CO_2, which aligns with the proposed IMO carbon levy for international shipping [110]; [111]; [112]. Beyond direct cost implications, the results underscore the climate mitigation advantage of shorter maritime routes through the SC, reinforcing its role as both an economically and environmentally optimal passage for global trade.

Table 6. Comparative environmental benefits of SC Route and COGH route for the round trip (SHA»«RTM)

Component	*SC Route*	*COGH Route*	*SC Saving*
Fuel consumption (*ton*)	5,568	7,424	1,856
CO_2 emissions (*ton CO_2*)	17,338	23,118	5,780
CO_2 emissions cost (*$*)*	1,733,800	2,311,800	578,000

*Carbon price = 100 $/ton

5.3 Competitiveness Index (CI)

- For head-haul trip,

$$CI_{head-haul} = 0.5\left(\frac{5{,}643{,}071}{8{,}771{,}084}\right) + 0.5\left(\frac{866900}{1155900}\right) \tag{4}$$

- For back-haul trip,

$$CI_{back-haul} = 0.5\left(\frac{5{,}276{,}332}{5{,}308{,}255}\right) + 0.5\left(\frac{866900}{1155900}\right) \tag{5}$$

- For round-trip,

$$CI_{round-trip} = 0.5\left(\frac{10{,}919{,}403}{14{,}079{,}339}\right) + 0.5\left(\frac{1{,}733{,}800}{2{,}311{,}800}\right) \tag{6}$$

Table 7 clearly demonstrate the economic and environmental advantages of the SC Route over the COGH Route. On the head-haul, the SC Route has a CI of 0.697, corresponding to a competitiveness rate of 43.47%, reflecting significant cost savings from lower fuel use, shorter transit time, and reduced inventory carrying costs. On the back-haul, the CI rises to 0.872 with a competitiveness rate of 14.67%, indicating a much smaller advantage since there is no inventory cost and operational differences are less pronounced. Overall, the round-trip CI of 0.763 and a competitiveness rate of 31.06% show that the SC Route remains substantially more economical and environmentally favorable, combining lower costs and reduced emissions due to the shorter, more efficient route compared with the longer COGH Route.

Table 7. CI output for SC on different trip directions

Trip direction	*CI*	*SC route competitiveness rate (%)*
Head-haul (SHA » RTM)	0.697	43.47
Bach-haul (RTM » SHA)	0.872	14.67
Round-trip (SHA»«RTM)	0.763	31.06

6. DISCUSSION

The results of this study highlight the multifaceted advantages of the SC over the COGH route, both economically and environmentally, under the ongoing Red Sea crisis. By analyzing 14,000-TEU containerships on the Shanghai–Rotterdam trade corridor, the study demonstrates that route selection is influenced not only by direct operating costs but also by inventory-carrying costs, environmental considerations, and incentive schemes implemented by the SCA.

The SC route exhibits clear economic superiority, particularly on the head-haul leg, where shorter transit times, lower fuel consumption, and reduced inventory-carrying costs result in total savings of approximately \$3.13 M per voyage compared to the COGH route. Although the back-haul leg shows a smaller difference, the cumulative round-trip savings of \$3.16 M reinforce the strategic value of the SC as the preferred maritime corridor. These findings are consistent with previous studies like Psaraftis *et al*. [15]; Mechai *et al*., [60] emphasizing the importance of transit time and inventory costs in determining route competitiveness.

The role of SCA rebate schemes is particularly noteworthy. Circulars 3/2025 and 8/2023, by partially offsetting SC fees, incentivize shipping companies to maintain SC traffic even during periods of geopolitical instability or market downturn. This aligns with literatures such as Tran *et al*., [31]; Wan *et al*., [14], on pricing strategies as effective tools for route retention and market share protection.

The results confirm that carbon costs under IMO 2025 disproportionately penalize longer routes such as the COGH, while the SC remains competitive despite high war-risk premiums, supporting previous findings reported by Wang *et al*. [89] and Liu *et al*. [73]. Unlike earlier studies emphasizing rerouting after the SC blockage, as shown by Notteboom *et al*. [79] and Haralambides [80], this study demonstrates that SCA rebate schemes and emission pricing reduce the economic advantage of diversions. By integrating direction-specific costs, emissions, and incentives, the analysis advances the literature on route choice under combined geopolitical and regulatory pressures, in line with scenario analyses by Liu and Wang [88].

The study confirms that shorter routes translate into substantial environmental benefits. The SC route reduces fuel consumption by approximately 1,856 tons per round-trip, resulting in 5,780 tons lower CO_2 emissions. These reductions not only lower operational costs through potential carbon pricing savings but also contribute to global decarbonization efforts, supporting IMO's net-zero goals. The findings underscore the critical role of route optimization in mitigating shipping-related GHG emissions, highlighting a dual economic–environmental incentive for the SC.

The composite CI offers a holistic measure, combining economic and environmental performance. A CI below 1 for head-haul (0.697), back-haul (0.872), and round-trip (0.763) confirms that the SC route is more competitive across all voyage types. The analysis shows that the head-haul is most sensitive to inventory-carrying costs, while the back-haul is primarily influenced by operating costs and fuel consumption, providing nuanced insights for operational decision-making.

The findings suggest that shipping companies should integrate multiple criteria—cost, emissions, risk, and incentive schemes—when making routing decisions. During crises, such as the Red Sea disruption, reliance solely on traditional cost measures could underestimate the value of shorter, strategically managed routes like the SC. Moreover, the SC's ability to maintain traffic under volatile conditions demonstrates the importance of proactive infrastructure management and incentive policies in supporting global supply chain resilience.

Under the current conditions of the shipping market—characterized by extremely high war-risk premiums, relatively low bunker prices and freight rates, and the lower bound of the projected carbon price—this study confirms that the SC route remains the optimal choice for 14,000-TEU containerships operating on the Far East–Europe trade lane. In fact, these conditions can be considered among the most unfavorable for the competitiveness of the SC. Any improvement in these circumstances, such as the end of the Gaza war in October 2025, a potential reduction in war-risk premiums, and a recovery in the shipping market, would further enhance the competitiveness of the SC route compared with alternative routes.

7. FUTURE WORK

Despite its contributions, this study has several limitations. It considers only 14,000-TEU containerships, so the results may not generalize to vessels of different sizes. Operational assumptions such as constant vessel speeds, fixed fuel consumption, and static loading/unloading times may not fully capture real-world variability. Market conditions, including bunker prices, freight rates, and war-risk premiums, are modeled as scenario-based and may fluctuate dynamically. Additionally, only the SC and COGH routes are analyzed, and environmental impacts are limited to CO_2 emissions, excluding other pollutants. The analysis also assumes predictable application of SCA rebate schemes, and longer-term or repeated crises could alter route competitiveness differently.

While this study provides a comprehensive assessment of the economic and environmental competitiveness of the SC versus the COGH route for 14,000-TEU containerships, several opportunities exist for extending and refining the analysis:

- **Expansion to different vessel classes:** Include smaller feeder ships, ultra-large containerships, or other carriers to evaluate whether the SC's economic and environmental advantages persist across diverse vessel types.
- **Integration of real-time operational data:** Incorporate automatic identification system and other traffic data to dynamically model transit times, congestion, and fuel consumption, yielding more accurate and operationally relevant results.
- **Comprehensive assessment of shipping and supply chain costs:** Quantify the additional costs incurred by vessels diverted via the longer COGH route, particularly after the resolution of the Red Sea crisis.
- **Assessment of multi-crisis scenarios:** Explore the combined effects of geopolitical disruptions, natural hazards, and port congestion on route selection to better understand supply chain resilience.
- **Comprehensive environmental analysis:** Extend beyond CO_2 emissions to include sulfur oxide (Sox), nitrogen oxide (NOx), and particulate matter for a more holistic evaluation of maritime environmental performance.
- **Policy and incentive modeling:** Investigate the long-term effectiveness of SC rebate schemes and other pricing strategies under variable market conditions to inform optimal incentive design.
- **Sustainability and decarbonization strategies:** Simulate adoption of alternative fuels, energy-efficient technologies, or carbon-pricing mechanisms to examine their impact on route competitiveness and global shipping sustainability.

By addressing these areas, future work can provide a more nuanced, data-driven understanding of global maritime route choice, support sustainable shipping practices, and strengthen policy recommendations for major trade corridors like the SC.

8. CONCLUSIONS

This study provides a comprehensive assessment of the economic and environmental competitiveness of the SC relative to the COGH route for 14,000-TEU containerships operating directly between Shanghai and Rotterdam, particularly under the context of the ongoing Red Sea crisis. The analysis demonstrates that the SC route remains the superior option for global maritime trade, offering significant cost savings and reduced environmental impact despite war-risk premiums and Canal fees.

The SC route provides substantial savings on the head-haul voyage, primarily due to shorter transit times, lower fuel consumption, and reduced inventory-carrying costs. Although the back-haul leg shows only marginal cost differences, the overall round-trip savings amount to approximately $3.16M, highlighting the financial advantage of the SC even during periods of geopolitical disruption.

The SC route reduces fuel consumption by approximately 1,856 tons per voyage, resulting in 5,780 tons lower CO_2 emissions. This translates into notable emissions cost savings, reinforcing the Canal's role as a more sustainable alternative compared to the longer COGH route.

Circulars 3/2025 and 8/2023 effectively enhance the attractiveness of the SC route, encouraging shipping companies to maintain traffic through the Canal during crises. These incentives provide a tangible economic benefit while supporting operational resilience and continuity of trade flows.

The composite CI confirms that the SC route is consistently more competitive than the COGH route across head-haul, back-haul, and round-trip voyages. The head-haul exhibits the highest relative advantage, while the back-haul remains slightly advantageous, reflecting the interplay between operational costs and cargo value.

The findings underscore the strategic importance of the SC for global trade and demonstrate how operational planning, route selection, and policy incentives can jointly enhance both economic and environmental outcomes. Shipping companies and policymakers can leverage these insights to optimize route decisions, improve sustainability, and maintain resilience during geopolitical and market disruptions.

Subsequent studies could expand the analysis to other vessel classes, incorporate real-time shipping data, or assess the combined impact of multiple global crises on route choice. Integrating broader environmental metrics, such as SOx and NOx emissions, would also provide a more holistic evaluation of maritime sustainability.

9. ACKNOWLEDGMENTS

We extend our sincere appreciation to the leadership and colleagues within the SCA for their continued support throughout the preparation of this study. The availability of accurate operational and cost data, together with the constructive guidance provided during the research process, played a central role in enabling a comprehensive and reliable assessment of the route's competitiveness.

10. APPENDIX

Table. List of Suez Canal Renewed Rebate Circulars valid until June 2026

Ship Type	*Circular No.*	*Trade route*	*Discount rate (%)*
Dry Bulk	3/2018	US E.Coast (N.of Savannah)–West Indian ports from Karachi to Cochin	10
		US E.Coast (N.of Savannah)– Ports east of Cochin up to Port Klang	40
		US E.Coast (N.of Savannah)– Ports from Port Klang eastward	55
		US (Savannah, southward) – West Indian ports up to Cochin	25
		US (Savannah, southward) –east of Cochin up to Port Klang	65
		US (Savannah, southward) – Ports from Port Klang eastward	75
	2/2021	West Africa– Gulf Arab ports	15
		West Africa – West Indian ports from Karachi to Cochin	25
		West Africa – Ports beyond Cochin and eastward	75
		West Africa– Gulf Arab ports	70
		West Africa– Indian ports from Karachi eastward	75
	2/2017	Northwest Europe ports – Ports from NW Cairns to Darwin	25
		NW Europe – Ports west of Darwin	55
		NW Europe – Ports in SW, S, and E Australia	75
	9/2023	Egyptian Red Sea ports – Ports from Ghana up to Nigeria	20
		Egyptian Red Sea ports – Cameroon ports and southward	45
Liquefied petroleum gas (LPG)	4/2020	US East Coast (north of Miami) – Ports east of Cochin up to Port Klang	25
		US East Coast (north of Miami) – Port Klang and eastward	35
		US Gulf– West India & Maldives to Cochin	25
		US Gulf – Ports east of Cochin to Port Klang	55
		US Gulf – Port Klang and eastward	75
Crude Oil	1/2018	US Gulf– Gulf Arab ports	25
		US Gulf – West Indian ports (Karachi to Cochin)	35
		US Gulf – Ports east of Cochin	75

		Latin America– Asia (from Karachi eastward)	75
Liquefied natural gas (LNG)	7/2017	US East Coast (north of Miami)– West Indian ports (Karachi to Cochin)	10
		US East Coast (north of Miami) – Ports east of Cochin	35
		US Gulf– Gulf Arab ports	30
		US Gulf – Ports east of Cochin up to Port Klang	60
		US Gulf – Port Klang and eastward	75
Chemicals & Other Liquids	3/2023	US East Coast (north of Miami)– Ports east of Cochin up to Port Klang	25
		US East Coast (north of Miami)– Port Klang and eastward	35
		US Gulf – West Indian ports (Karachi to Cochin)	25
		US Gulf – Ports east of Cochin up to Port Klang	55
		US Gulf – Port Klang and eastward	75
Petroleum Products (*loaded tankers only*)	2/2023	US Gulf– West Indian ports (Karachi to Cochin)	30
		US Gulf – Ports east of Cochin up to Port Klang	65
		US Gulf – Port Klang and eastward	75
		Latin America– Asia (from Karachi eastward)	75
Car Carriers	10/2023	Ports from Norfolk north – Port Klang and eastward	40
		Ports south of Norfolk – Port Klang and eastward	55

11. DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES:

The author(s) declare that some generative AI or AI-assisted tools were used during the preparation of this work in checking the plagiarism, rephrasing some sentences and search for literatures.

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