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The costs of maritime supply chain disruptions: The case of the Suez Canal blockage by the 'Ever Given' megaship

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ABSTRACT

In March 2021, the six-day blockage of the Suez Canal, caused by the grounding of Evergreen's 'Ever Given' containership, created chaos in global trade. The 400-m giant lodged horizontally in a 265-m wide stretch of the canal and the efforts to dislodge and refloat it were unprecedented, involving dredging, towing and lightering. The accident marked one of the most severe disruptions at a key chokepoint in the international shipping network. Using ship voyage data, this research introduces a model to quantify the economic losses of a carrier's containership fleet, caused by such a disruption. The studied impacts include ship costs, environmental costs, and inventory-carrying costs. The model is applied to Maersk Line's East-West network, with 69 vessels (0.84m TEUs) affected by the blockage, either by having to reroute via the Cape of Good Hope or by the delays caused during and after the blockage. The results point to an additional 44,574 tonnes of CO_2 produced by the extended trips and extra waiting times of the Maersk ships. The total losses incurred amount to \$88.79m, comprising ship costs of \$8.04m, environmental costs of \$4.46m and, most strikingly of all, inventory-carrying costs of \$76.29m, stemming from the high value of goods onboard (\$26.5bn). Ship deviations also resulted in revenue losses for the Suez Canal Authority (SCA) of \$5.86m, from Maersk crossings alone. Additionally, the research findings shed light on the vulnerabilities of maritime supply chains, particularly concerning prolonged roundtrips, changes to port call patterns, and extended cargo delivery times.

1. Introduction

1.1. Disruptions in maritime transport

Maritime transport plays an indispensable role in global commerce given that about 80% of international trade by volume and 70% by value moves on water (UNCTAD, 2018). Being the slowest transport mode, shipping offers very low freight rates (transport costs), originating also from the scale economies of using very big ships.

Any disruption in maritime transport will inevitably put a strain on the many parties involved along supply chains. As a node in maritime transport systems, a port is also highly vulnerable due to its natural conditions as well as by being a multimodal platform hosting many traffic flows.

Ronza et al. (2009) estimate the economic losses affecting people, the environment and port infrastructures as a result of major accidents that occur in port areas. Gurning and Cahoon (2011) classify disruptions along the Australian–Indonesian wheat supply chains in four broad categories: (1) delay, (2) deviation, (3) stoppage and (4) loss of service platform. Hsieh (2014) and Hsieh et al. (2014) study the vulnerability of Taiwanese ports in terms of transport accessibility, equipment capability, operational efficiency, business growth and energy supply. Lam and Su (2015) analyse disruptions that occurred in selected Asian ports in three categories: natural disasters, human-caused accidents and port

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strikes. Disruptions chiefly stem from the latter two categories. Natural disasters have been rare but, nonetheless, they have all had extremely high impacts on cargo throughput.

Disruptions in maritime transport and ports come in various forms linked to natural causes (e.g., droughts, hurricanes/typhoons, floods, earthquakes, volcanic eruptions), or to human activity (e.g., vessel groundings and other accidents, explosions in port areas, economic and geopolitical crises, wars, terrorist attacks, pandemics, cyberattacks, and labour disputes and strikes). Disruptions induced by climate change often combine natural and man-made causes. Some disruptions are endogenous to the maritime transport industry, while others are exogenous. Disruptions can be predictable or random. Black Swan events are the most difficult random disruptions to predict and assess and, depending on their nature and geographical scope, their ramifications for shipping and ports can range from local to global and from light to severe. Extant literature provides insights into the impacts of a wide range of disruptions on the shipping sector and ports (see e.g. Wu et al., 2019; Zhang et al., 2020).

One of the most discussed anthropogenic Black Swan events was the Covid-19 pandemic, resulting in major pressures on shipping, ports and global supply chains (see e.g. Notteboom et al., 2021; Cullinane and Haralambides, 2021; Ayaz et al., 2022; Cullinane et al., 2023). At the beginning of 2021, the unavailability of empty containers prevented producers in Southeast Asia from exporting rice to North America (Goodman et al., 2021). In May 2021, a COVID outbreak in Shenzhen reduced handling capacity in the port of Yantian, an export gateway of more than 90% of electronics products (La Rocco, 2021). The decline caused a queue for both vessels and export containers, and the ensuing congestion affected seasonal (Christmas) products, often shipped from China during the summertime (Leonard, 2021).

Their coastal locations make ports vulnerable to natural catastrophes and severe weather conditions. Na and Shinozuka (2009) propose a model to quantify earthquake effects on a container terminal's operational performance. Paul and Maloni (2010) simulate the effects of a port disaster from 14 to 120 days in the North American container port network, with the increased costs ranging between \$58m and \$1.4b. Cao and Lam (2018) study the economic losses of the port of Shenzhen, caused by severe weather such as wind, rain, fog, and typhoon. Zhang et al. (2020) propose a model to compute economic losses due to port disruptions originating from typhoon-induced wind disasters. Losses are relevant to reputation, clients, ship operators, and ports. Due to the devastating Sendai earthquake and tsunami in 2011, Japanese ports sustained severe damage, hindering various industrial activities, especially those reliant on container and tank shipping (Mogi and Fabi, 2011). Chang (2000) analyses the impacts of the 1995 devastating earthquake at the port of Kobe, in terms of damages, as well as the port's declining role in the global shipping network. The incident shut down the port and it took more than two years for the restoration of port services. In addition to economic losses, the port also experienced losses in traffic, especially transhipment containers, to other ports in East Asia.

Cao and Lam (2019) assess the impacts on Tianjin port, in the aftermath of the 2015 explosion, in two periods: one day and four months after the incident. Sadek et al. (2022) measure the impacts of the 2020 Beirut explosion on port infrastructure and activity. In 2015, a protracted labour dispute halted the operations of 29 ports on the US West Coast, including Los Angeles and Long Beach. It is estimated that each shutdown day cost the US economy \$2bn (Shabad, 2015). A wholesaler of fabric, curtains and decorative pillows saw its shipment stuck in the congested ports for three weeks, instead of four to five days (Khouri, 2015). Utilising both Automatic Identification System (AIS) data and official port statistics on container handling, Svanberg et al. (2021) analyse the impact of the labour disputes at the port of Gothenburg during 2016 and 2017. They find quite significant short and medium-term effects on port competition in Sweden, in terms of gateway container traffic, port user profiles, and port efficiency levels.

Cyberattacks have become a major threat to port operations, given the large number of stakeholders, activities, and transactions in port areas. According to Bastug et al. (2023), cyberattacks are ranked fourth on the list of shipping risks and constitute a major challenge to maintaining the integrity of maritime supply chains. Chenarak (2024) reviews 15 cases of port cyber attacks and concludes that ports are prime targets of cyber warfare, irrespective of their size, cargo handled, ownership structure, and geographical location. The author describes the striking case of the NotPetya attack on Maersk's global shipping network in 2017, costing the Danish shipping group about \$ 250m–300m and months of major disruptions at key container terminals in its network.

The extant literature on maritime disruptions focuses primarily on disruptions in ports. Another component in the shipping network, however, is related to connections or links *between* ports. Kajitani et al. (2013) propose a framework to evaluate the economic impact of accidents in key shipping links. Their framework is applied to estimate losses in case a chemical facility in the Straits of Malacca and Singapore would explode. Wu et al. (2019) simulate the negative consequences of disruption on critical maritime infrastructures, namely The Malacca Strait, Suez Canal and Panama Canal, in terms of transportation time (cf. also Haralambides, 2024).

In 2023 and 2024, the Panama Canal faced an unprecedented drought, drastically cutting transit capacity. Daily transits decreased to 22 vessels in December 2023, compared with a regular number of 36 transits per day (Panama Canal Authority, 2023). In addition, the authorized draft was set to 13.41 m from a maximum of 15.24 m. These restrictions triggered vessel queues on both canal entrances, causing the total waiting and transit time to jump from 1.7 to 6 days (Project 44, 2023).

Another major disruption in late 2023 and early 2024 occurred when Houthi militia started attacking commercial ships transiting the Red Sea and the Strait of Bab al-Mandab as retaliation to the Israeli attacks on Gaza. Between November 2023 and late February 2024, more than 40 attacks were launched using drones, anti-vessel missiles or gunmen on speedboats. At the time of writing, there was no sign that this crisis would end anytime soon. More than 80% of container vessels that used to transit the canal were diverted around the Cape of Good Hope, thereby resulting in longer transit times, higher freight rates and air emissions, and additional types of surcharges (see Notteboom et al., 2024 for a detailed analysis).

Disruptions can occur at any point in the global shipping system due to various reasons. Over the past four years, several notable disruptions have caused far-reaching consequences for local economies and global trade. These include the Suez Canal blockage, the Red Sea crisis, the Francis Scott Key Bridge collapse in Baltimore, and the significant recent drop in the Panama Canal transit capacity due to limited rainfall and consequent drought affecting water availability and drafts, needed for lock operations. In the context of our research, we focus specifically on the 2021 incident at the Suez Canal, which is discussed in detail in the next section.

1.2. The grounding of the Ever Given and the subsequent Suez Canal blockage

The whole world was fixated on the Suez Canal blockage, lasting from 23 to March 29, 2021. Fully laden and *en route* from East Asia to Europe, the bow of the three-year-old containership Ever Given got stuck in the eastern bank of the canal and blocked the 120-mile-long canal (Fig. 1). The mega-ship had a size of 20,124 TEU (twenty-foot equivalent unit) and an overall length of 400m.

Since the 2016 investments at a cost of \$8.2bn, the 120-mile canal now allows the passage of ships with a draft of 22.1 m and a maximum loaded deadweight tonnage of 240,000. This essential waterway accommodates 61.2% of the world's tanker fleet, 92.7% of the bulk carrier fleet, and 100% of the containerships operating between Asia and Europe (Suez Canal Authority, 2023). Notably, the bypath length,

Fig. 1. An Ordinary Voyage of Ever Given in China-Europe-Mediterranean Service (CEM) of the Ocean Alliance (Cosco, CMA CGM and Evergreen) Source: Evergreen's route platform.[11]

permitting two-way traffic, has reached 70 miles, compared with 17 miles in 1956 and 49 miles in 2001. As a result, the minimum southbound transit time has decreased from 18 h to 11 h, and vessel waiting times have also become shorter.

Unfortunately, the incident occurred in the southern section of the canal, which has only one navigation lane. The salvage efforts to dislodge and refloat the grounded ship became a focal point of breaking news across various prominent media outlets. The Suez Canal blockage can be categorized as a man-made Black Swan event, which triggered widespread disruption in global supply chains. At the time, the latter chains were already plagued by severe Covid-19 effects, including vessel and equipment capacity shortages and high port congestion levels.

The Suez Canal is undisputedly one of the most crucial arteries in the international shipping network, connecting Asia and Europe and to a lesser extent Asia and North America (Fig. 2). It is a strategic link from the Asian export regions to the main consumption areas in Europe and North America. Exporters include East Asia, home to the biggest suppliers such as China (number 1 in terms of export value in 2021), Japan (number 4), South Korea (number 5) and Taiwan (number 11). The canal is also a key trade route to South Asia, which includes India, the world's most populous country, alongside burgeoning manufacturing hubs in Pakistan, Sri Lanka and Bangladesh. Moreover, the canal also serves as a key interoceanic link in energy trades, connecting the Middle East, which houses leading exporters of crude oil and gas, to major markets in the west. In 2019, this intensively used waterway facilitated 18,880 vessels carrying 1.03bn tonnes of cargo, or about 9.3% of total seaborne trade (Suez Canal Authority, 2023).

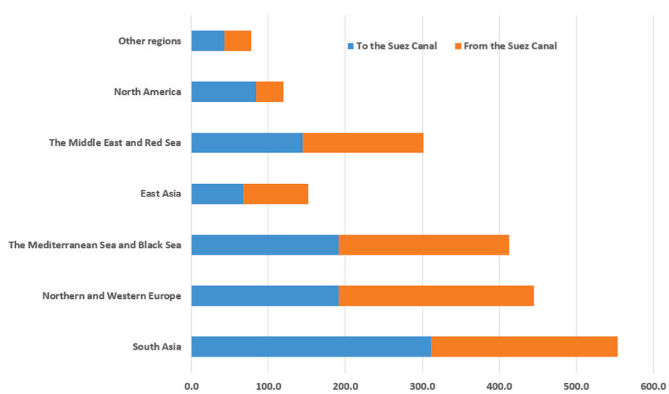

Fig. 2. Freight flows (million tons) through the Suez Canal in 2019. Source: based on Suez Canal Authority (2023).

The Suez Canal is particularly important in accommodating the intercontinental movement of containers, thanks to its unique position as a bridge on the Europe-Asia trade route, the second-largest intercontinental container trade route after the Asia-North America one. In 2019, about 28% of global container freight (i.e., 0.5bn out of 1.85bn tonnes) passed through this man-made waterway (Suez Canal Authority, 2023; UNCTAD, 2021).

Due to the canal's pivotal role in global shipping networks, the Ever Given incident was bound to have a great impact not only on the shipping industry and the Egyptian economy, but also on various stakeholders such as manufacturers, retailers, wholesalers, and their customers. The sectors most affected were foodservice establishments, construction, wholesale trade in Europe, and department and grocery stores in the USA (Segal, 2021). The obstruction resulted in a long queue of 422 ships waiting for passage on both sides of the canal (Suez Canal Authority, 2021). Among these, 89 containerships were waiting: 40 northbound from the Gulf of Aden, and 49 southbound from the Mediterranean Sea. Even after the Ever Given had been dislodged, it took nearly a week to clear the backlog, which was cascading on other ships arriving after the crisis (for a detailed analysis see Lind et al., 2021). On a normal day, some 50 ships transit the Suez Canal. To clear the backlog, the canal's capacity was pushed to the limit of more than 100 transits per day. A report by Allianz Research reveals that the canal's six-day closure may have curtailed global trade by 0.2%–0.4% per annum (Subran et al., 2021).

1.3. Research problem

The Ever Given accident was not the first time the Suez Canal choked trade since its inauguration in November 1869: a grand international event, frequented by royals and dignitaries, immersed in the divine sounds of Verdi's Aida. The canal was since closed three times, in 1956 (the Suez Crisis); 1967 (the Six-Day War); and in 1973 (the Yom Kippur War), and whenever there were concerns about the security of navigation and naval deployments (Haralambide and Merk, 2020; Notteboom et al., 2024; Haralambides, 2024). The impacts of closures have been substantial due to the number of shipping routes involved. From a network perspective, the canal is unlike any other ordinary maritime link or system node (port), playing instead the role of a strategic bridge.

Our aim here is to study how a major disruption at a chokepoint could affect container shipping operations in terms of ship costs, emissions, and trader inventories. We develop a comprehensive approach to quantify the impacts of the accident on the various stakeholders in maritime supply chains, including shipping lines, their customers, the environment and the Suez Canal Authority. Carriers, in particular, incurred extra costs due to unscheduled waiting for the convoy, or ship deviation via the Cape of Good Hope. Additionally, unplanned operations consumed more fuel, meaning higher CO_2 emissions. Longer transit times, finally, implied higher inventory carrying costs for cargo onboard and at shipper warehouses.

We propose a model to quantify ship costs, environmental costs, and inventory carrying costs pertaining to a fleet of containerships. We use ship voyage data of arrival/departure times in particular ports or shipping passages. The model estimates the economic losses relevant to Maersk vessels sailing on the company's East-West network. The Danish carrier has consistently taken first or second place in container shipping rankings since the beginning of the 2000s, with a market share of over 16% (Tran, 2022).

Our research addresses a major concern in global supply chains today: disruptions in a strategic shipping hub, transoceanic passage or major maritime artery. Over the past four years, a series of major disruptions in maritime supply chains have drawn worldwide attention due to their far-reaching impacts on shipping and world seaborne trade. We develop a data-rich bottom-up framework to measure the extensive impacts in real-life cases by combining multiple models of shipping economics, emissions accounting, and container cargo inventories, as well as utilising a wide range of liner operational data. Although our research framework is applied to the Suez Canal Blockage of March 2021, it can also be used in other contexts and for other disruptions, such as the more recent Red Sea crisis involving countless vessel attacks by the Houthi militia. The framework is also useful in evaluating the impacts of delays and similar disruptions in port operations on immobilized ships, such as the deadly collapse of the Francis Scott Key Bridge in Baltimore caused by the containership Dali, causing over 40 ships to be stuck inside port areas.

The remainder of the paper is organised as follows. The next section describes the research methodology and the data collection process, which are the groundwork for estimating the losses of Maersk Line's fleet caused by the Ever Given incident. Next, Section 3 presents key findings, mainly on the impacts of the blockage on delayed and re-routed vessels. Section 4 discusses the implications of the research outcomes for supply chain stakeholders. The concluding section highlights the key research takeaways and final remarks on the contribution and relevance of the presented study.

2. Research methodology and data

Our research framework consists of three stages, to study the impacts of a major disruption on a fleet of containerships (Fig. 3). In the first stage, input data is collected related to ship specifications, ship voyages, and nautical distances. The second stage analyses ship voyage data to identify how they were affected by the incident: (i) vessel delays in canal transit, (ii) vessel rerouting via the Cape of Good Hope, or (iii) no impact. The third stage quantifies the financial losses of both delayed and re-routed ships.

2.1. Data collection

The input data consists of three main sets. The first includes ship data from the Clarksons ship database: vessel capacity (TEU), design speed (knots), and main engine power (kWh). Ship capacity is used to estimate capital and operating costs, whereas the other two inputs are used to calculate ship fuel consumption. The second data set consists of the voyage data of each vessel, including ports/canals of call and the corresponding arrival and departure times (Table 1). The schedules are available on the liner service platform of Maersk Line[2]. The voyage data determine transit times between ports and whether a vessel traverses the Suez Canal or sails around the Cape of Good Hope. The last dataset involves nautical distances between ports, and between ports and the Suez Canal. These are retrieved from the SeaRoutes platform by inputting the origin and destination of a voyage, both via the Suez Canal and the Cape of Good Hope.[3] For instance, the distance from Tanjung Pelepas to Algeciras (via the Cape of Good Hope) is 10,783 NM, and from the Suez Canal to Tanjung Pelepas is 4971 NM.

2.2. Ship voyage analysis

According to our voyage data, a total of 201 ships in Maersk Line's shipping network sailed through the Suez Canal in the first half of 2021. Of these, 69 were impacted by the blockage. Twelve ships followed the conventional route via the Suez Canal (the Suez route) but were compelled to re-route via the Cape of Good Hope (the Cape route) during the blockage period. A void in our arrival/departure data at the Canal implies a deviation of the journey between the northern and southern ports of the canal. For instance, we identify such missing data on Magleby Maersk's re-routed voyage from Tanjung Pelepas to Algeciras. Twenty-eight ships arrived at the canal during the incident and waited until the blockage was cleared (e.g., Majestic Maersk). Twenty-nine ships arrived after the incident but their canal transit time exceeded the typical plan (16 h) due to the backlog of ships waiting on both sides of the canal (e.g., Maersk Kinloss).

In East-West trades, a containership crossing the Suez Canal mainly serves the trades of Asia/Europe and Asia/North America. On both these routes, the westward direction from Asia is the head haul, owing to the prominent role of Asian exporters. Based on the head haul utilisation rates in 2021 (Linerlytica, 2023), we assume that a ship departing from Asia to Europe is 90% full and 87% from Asia to North America. The ratios of head haul and backhaul traffic determine the utilisation rate in the eastward direction (Table 2). Accordingly, the utilisation rate from North America to Asia stands at 25.6% (24.1m TEUs vs. 7.1m TEUs in 2021), and that from Europe to Asia is 37.9% (18.5m TEUs vs. 7.8m TEUs). These utilisation rates refer to loaded containers and thus exclude the repositioning of empties. Following the statistics of Lloyd's List, 2021 concerning the container throughput and cargo value via the Suez Canal, the average values per TEU in the eastward and westward directions are estimated at $49,531 and $49,747, respectively. The total cargo value on board a specific ship is the product of her capacity, utilisation rate and value per TEU.

2.3. Quantifying the economic losses of the affected ships

The losses pertaining to delays and reroutes are measured by the additional ship costs, inventory-carrying costs, and environmental costs. In particular, the losses of a ship held up in the canal are measured during its waiting time for clearing the grounded ship and traffic congestion, calculated as the difference between the total hours in the canal and 16 h (the regular planned time). To estimate the losses due to rerouting, we compare this with the conventional voyage via the Suez Canal, to quantify the higher costs due to the lengthier itinerary.

2.3.1. Cost specifications

Based on prior, widely accepted, models on liner shipping costs (Cullinane and Khanna, 1999; Ge et al., 2021; Jansson and Shneerson, 1987; Stopford, 2009; Tran and Haasis, 2015), we assume that the shipping costs of a service include capital costs, container costs,

[1] https://ss.shipmentlink.com/tvs2/jsp/TVS2_ServiceProfile.jsp?line=CEM&segment=E.

[2] https://www.maersk.com/schedules/vesselSchedules

[3] https://searoutes.com/routing-api/.

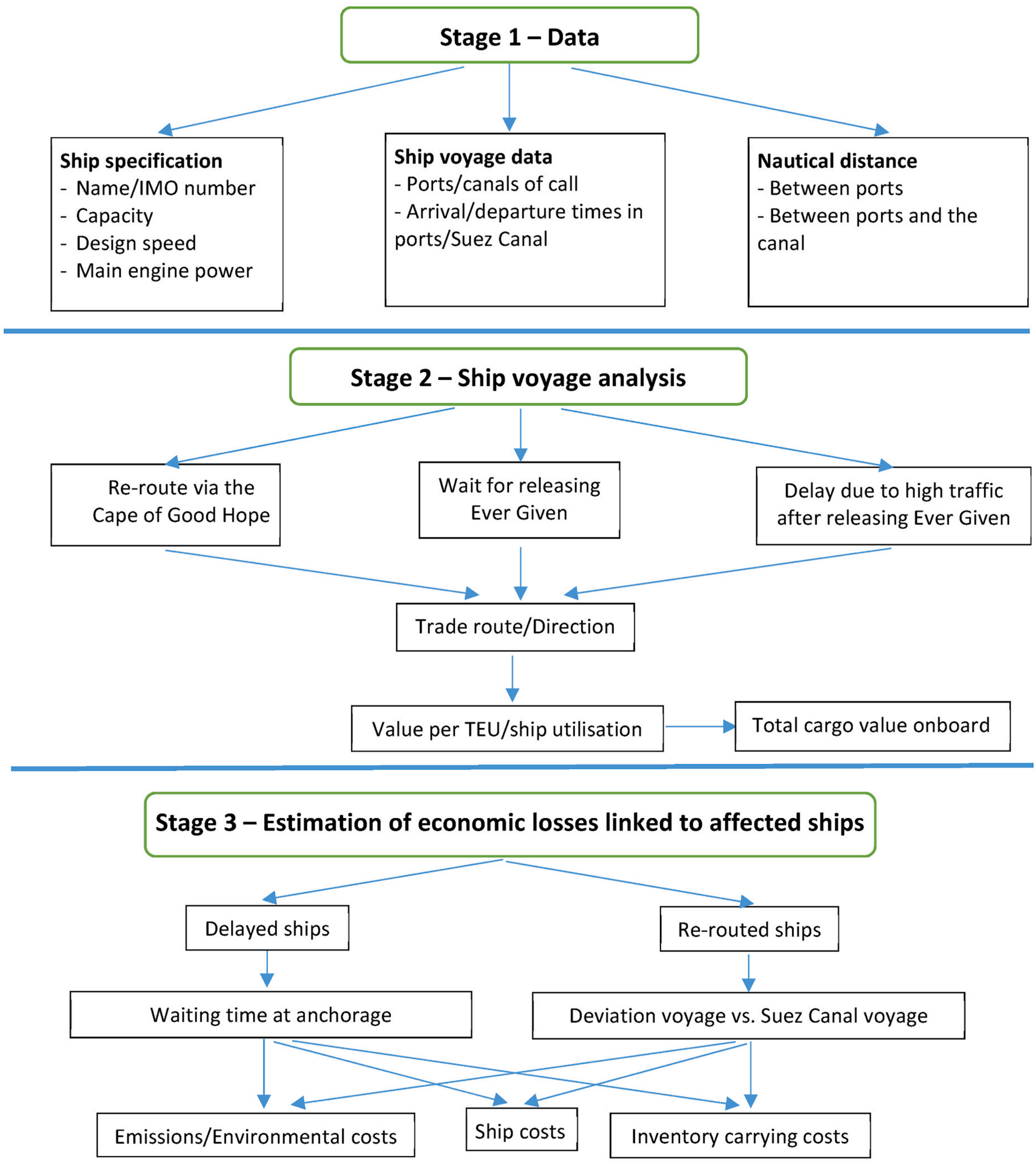

Fig. 3. Research framework.

operating costs and fuel costs. Additionally, shipping lines must pay canal fees when their vessels navigate through the Suez Canal. The latter fees are obtained from the Wilhelmsen platform[4], considering ship size and designated trade route. Capital and container costs concern the core assets of the shipping service, i.e., ships and containers. Operating costs consist of multiple items such as manning, repairs and maintenance, management and administration, lubricating oils, and insurance (Drewry, 2018).

Capital and operating costs can vary according to various other factors such as the ship operator themselves, market conditions, financing options, and engaged trades (Stopford, 2009; Tran, 2022). However, data limitations only allowed us to build an estimation based on ship capacity, an approach that has also been used in earlier works. Hence, we follow the method applied widely in prior studies (Cullinane and Khanna, 1999; Jansson and Shneerson, 1987; Tran and Haasis, 2014) to estimate capital and operating costs by building power regression models between ship size and such costs, from prominent maritime research consultancies, like Clarksons and Drewry, (Table 3).

In addition to determining the fuel cost of carriers, the fuel consumed at anchorage or transit determines the amount of ship emissions (Table 4). Subsequently, the environmental costs are calculated utilising the European Commission's external cost model for transport (Essen et al., 2019). Detailed calculations of fuel consumption are presented below.

Inventory-carrying costs include factors such as costs tied-up in goods in transit, storage costs, risk of obsolescence (i.e., economic and technical depreciation), and damages (Lambert et al., 1998). These costs

[4] https://www.wilhelmsen.com/tollcalculators/suez-toll-calculator/.

Table 1
Examples of input data.

Port/Canal	Country	Arrival	Departure
Magleby Maersk (Re-routing via the Cape of Good Hope from Tanjung Pelepas to Algeciras) Capacity: 18,340 TEUs Design speed: 22.5 knots Main engine power: 59,360 kWh			
Port/Canal	Country	Arrival	Departure
Ningbo	China	March 10, 2021 10:48	March 11, 2021 16:00
Yantian	China	March 16, 2021 15:25	March 17, 2021 09:55
Tanjung Pelepas	Malaysia	March 20, 2021 13:32	March 22, 2021 00:13
Algeciras	Spain	April 14, 2021 14:06	April 15, 2021 12:33
Gdansk	Poland	April 20, 2021 17:45	April 22, 2021 03:20
Majestic Maersk (Waiting and transit time: 101 h) – arrival at the Canal during the blockage Capacity: 18,340 TEUs Design speed: 22.5 knots Main engine power: 59,360 kWh			
Bremerhaven	Germany	March 13, 2021 12:11	March 15, 2021 22:40
Rotterdam	The Netherlands	March 18, 2021 12:20	March 20, 2021 05:10
Suez Canal	Egypt	March 27, 2021 23:00	April 01, 2021 20:12
Tanjung Pelepas	Malaysia	April 12, 2021 04:00	April 13, 2021 13:20
Shanghai	China	April 20, 2021 05:45	April 21, 2021 07:25
Maersk Kinloss (Waiting and transit time: 80 h) – arrival at the Canal after the blockage Capacity: 6478 TEUs Design speed: 24 knots Main engine power: 57,200 kWh			
Salalah	Oman	March 25, 2021 03:33	March 26, 2021 02:16
Suez Canal	Egypt	March 30, 2021 15:00	April 02, 2021 22:37
Algeciras	Spain	April 08, 2021 01:43	April 09, 2021 04:38
Newark	USA	April 17, 2021 14:10	April 18, 2021 19:47
Charleston	USA	April 23, 2021 05:12	April 23, 2021 17:48

Source: Based on input datasets

Table 2
Operational parameters.

	Asia to North America	North America to Asia	Asia to Europe	Europe to Asia
Container traffic (m TEU)	24.1	7.1	18.5	7.8
Ship utilisation	87.0%	25.6%	90.0%	37.9%
Average value per TEU (USD)	49,531	49,747	49,531	49,747

Source: Based on UNCTAD (2021); Lloyd's List (2021); Linerlytica (2023).

are calculated based on the value of cargo onboard and an assumed value of time of 25% p. a. of the value of cargo (Lambert et al., 1998; Robert et al., 2009).

2.3.2. Ship fuel consumption

International Maritime Organisation – IMO (2021) provides a framework to compute the fuel consumption of ships' main engines, auxiliary engines and boilers in two operational phases: (i) at anchorage, waiting for the convoy and (ii) transit at sea or along the canal. The main engines only burn fuel during transit (while sailing). Their consumption depends on sailing speed and design engine power. Auxiliary engines consume fuel in both phases, whereas boilers do so only in anchorage. Power outputs are taken from the reference value of International Maritime Organisation – IMO (2021) tailored to a specific capacity in an operational phase (Table 5).

2.3.3. The economic losses of a re-routed ship

The losses of a re-routed ship are defined by comparing the costs on the Suez route and the Cape route. Fig. 4 illustrates a deviation journey from Tanjung Pelepas (Malaysia) to Algeciras (Spain) and a conventional journey via the Suez Canal.

Analyzing a deviation voyage includes four steps.

(i) Identify the deviation voyage between a western- and an eastern port based on ship voyage data
(ii) Calculate the transit time (the difference between departure time and arrival time between the two ports) and calculate the transit speed (the quotient of nautical distance to transit time)
(iii) Calculate fuel consumption and emissions at sea
(iv) Calculate ship costs, inventory-carrying costs, and environmental costs

An ordinary voyage via the Suez Canal is broken down into three parts: (i) the voyage to the canal, (ii) transit through the canal, and (iii) the voyage from the canal. The sailing speed at sea is the same as that of the Cape route. Along the canal, we assume a transit speed of 7.5 knots. This assumption is based on Maersk Line's typically planned transit time of 16 h for a transit distance of 120 nautical miles, without considering ship waiting time. There are three steps in analyzing an ordinary voyage.

(i) Calculate sailing time at sea
(ii) Calculate fuel consumption/emissions at sea and during canal transit
(iii) Calculate ship costs, canal fees, inventory carrying costs, and environmental costs

3. Results and analyses

3.1. A review of east-west fleet effects

The main East-West routes are the most crucial for shipping and trade, connecting the three economic powerhouses of North America, Europe and Asia (Haralambides, 2019). In 2021, together, the three regions accounted for around 40% of total containerised trade (UNCTAD, 2022), while since China's entry into the World Trade Organisation in 2001, more than 50% of international trade is now intra-Asian. At the time of the Ever Given incident, east-west routes were in the hands of three strategic alliances, namely 2M Alliance (Maersk Line and MSC), THE Alliance (ONE, Hapag Lloyd, Yangming, HMM) and Ocean Alliance (CMA-CGM, COSCO, Evergreen). The nine (largest) carriers share among themselves more than 80% of the total container slot capacity (Tran, 2022). In particular, they control nearly 100% of the fleet capacity on the Europe/Asia trade routes and 89% of the Asia/North America trades (Alphaliner, 2022).

From our input data, together with carriers' updates on the Suez Canal blockage, we calculate that the six-day Ever Given incident directly affected a total of 145 vessels (1.71m TEUs) of the three alliances, either by lining up for transit convoys (1.33m TEUs) or re-routing (0.38m TEUs) to the Cape route. These vessels represented 7% of global capacity (24.43 mil. TEUs). Note that the actual number of impacted vessels was higher due to the rippling effect on other vessels arriving at the canal after the re-opening. Using trade route, sailing direction, and vessel capacity, we estimate that the blockage delayed the carriage of $51.1bn of goods (Table 6). The impacted vessels varied in size, ranging from 4369 TEUs (Maersk Utah) to nearly 24,000 TEUs, the largest capacity in the industry at the time (HMM Gdansk; HMM Dublin).

The majority of ships (109 units) sailed between Europe and Asia,

Table 3
Estimations of daily capital cost and operating cost.

Size (TEU)	1000	1700	2750	3700	4800	6600	8800	13,000	21,000
Newbuilding price (10^6 USD)	20	26	35	42	53	72	90	115	149
Daily capital cost (USD)	2712	3603	4795	5685	7260	9863	12,260	15,753	20,411
Power regression model: *daily capital cost* = 20.971*ship_size$^{0.6988}$ R^2 = 0.9919									
Size (TEU)	500	2000	4000	6000	9000	11,500	14,000	16,500	20,000
Daily operating cost (USD)	4070	4350	5240	6340	6850	7260	7560	7900	8570
Power regression model: *daily operating cost* = 952.9*ship_size$^{0.2162}$ R^2 = 0.9316									

Source: Based on the survey of newbuilding prices (Clarkson, 2019) and an assumption of ships' economic life of 20 years and 350 operating days per year (Stopford, 2009); and the survey of daily operating costs (Drewry, 2018).

Table 4
Cost components.

Item	Formula	Source
Daily capital cost (USD)	20.971*ship_size$^{0.6988}$ R^2 = 0.9919	Based on newbuilding prices of various ship sizes (Clarkson, 2019) and an assumption of ships' economic life of 20 years and 350 operating days per year.
Daily operating cost (USD)	952.9*ship_size$^{0.2162}$ R^2 = 0.9316	Based on operating costs of various ship sizes (Drewry, 2018).
Daily container cost (USD)	0.6358* ship_size	Based on an average price per TEU of $3.481 (Hapag Lloyd, 2021) and an assumption of containers' economic life of 15 years and 365 operating days per year.
Daily fuel cost (USD)	387.5 * daily fuel consumption	Based on the average bunker price of global 20 ports (1st and 2nd quarters 2021) of Ship& Bunker[a]
Daily inventory carrying cost (USD)	Cargo value* 0.25/365	Based on an assumption of time value of 25% per year (based on Lambert et al., 1998; Robert et al., 2009)
Daily CO2 emissions (tonne)	3.114 * daily fuel consumption	Based on the emission rate (tonne per tonne of fuel) provided by International Maritime Organisation – IMO (2021)
Daily environmental cost (USD)	100 * Daily CO_2 emissions	Essen et al. (2019)

[a] https://shipandbunker.com/prices/av/global/av-g20-global-20-ports-average.

whereas the remaining 36 ships were involved in the carriage of boxes between Asia and North America (Table 7). Nearly 26% of fleet capacity serving the Europe/Asia trade was affected by the incident, while the corresponding figure for the Asia/North America trade stood at 7%. The disparity can be attributed to the fact that the shipping routes linking Asia and North America primarily traverse the Pacific Ocean to reach the ports along the North American West Coast or, via transit through the Panama Canal, the ports along the US East Coast.

3.2. Impacts on Maersk Line's shipping network

3.2.1. Transit delay in the canal

The stranding of the Ever Given forced 57 vessels on Maersk Line's East-West schedules to halt at both canal entrances or in the Great Bitter Lake. Thirty-three vessels (0.41m TEUs) arrived before or during the blockage (Fig. 5), nine of which had to wait more than six days for transit convoy, and 20 ships waited between four and six days. Additionally, 24 vessels (0.29m TEUs) arrived after the obstruction had been freed, ten of which were caught up in the backlog for two days or more. While the canal was closed, vessels continued to approach it, and this resulted in severe queues in both directions. According to the Suez Canal Authority's 2021 report, the average transit rate per day was 57 vessels whereas the canal's maximum capacity is 105 vessels (Habibic, 2022; Sawy, 2021). The long queue of 422 vessels implied that the congestion could not be cleared immediately because less than 50 ships could leave the queue each day. On the April 2, 2021, 227 vessels were still waiting in the anchorage zones (Maersk Line, 2021). Operational data shows that it was not until ten days after the re-opening of the canal (8th April), that transits returned to normal.

Our research findings indicate that the majority of delayed Maersk ships incurred a cost of $6.84m, in terms of capital cost, operating cost, container cost and fuel cost (Fig. 6). Seven ships experienced additional expenses of $200k-246k, and 26 units between $100k-200k. In addition to higher bunker prices, increased fuel consumption led to higher emissions. Fuel consumption at anchorage is much lower than during

Table 5
Fuel consumption of main engines, auxiliary engines and boilers (unit: tonne).

Phase	Main engine	Auxiliary engine	Boiler
Anchorage	0	$SFOC_{AE}*PA_{AE(x)}*t_c*10^{-6}$	$SFOC_{BE}*P_{BE(x)}*t_c*10^{-6}$
Transit	$SFOC_{ME}*P_{ME(x)}*\left(\frac{s}{sd}\right)^3*\frac{1}{nw}*\frac{1}{nf}*t_s*10^{-6}$	$SFOC_{AE}*PT_{AE(x)}*t_s*10^{-6}$	0

$SFOC_{ME}$, $SFOC_{AE}$, $SFOC_{BE}$ (gram per kWh): specific fuel oil consumption of main engines, auxiliary engines and boilers with corresponding values of 175, 195 and 340 (International Maritime Organisation – IMO, 2021) *s*: transit speed (knot) – based on the voyage data
sd: designed speed of a ship (knot) – based on ship specification.
t_s: transit time at sea (hour).
t_c: waiting time in the canal (hour).
$PA_{AE(x)}$, $PT_{AE(x)}$: auxiliary engine's power output during anchorage and transit (kW) – based on IMO reference value for ship capacity of *x* TEUs (International Maritime Organisation – IMO, 2021).
$P_{BE(x)}$: boiler's power output during anchorage (kW) – based on IMO reference value for ship capacity of *x* TEUs (International Maritime Organisation – IMO, 2021) *nw*, *nf*: weather correction factor and fouling correction factor with corresponding values of 0.867 and 0.917 for container ships (International Maritime Organisation – IMO, 2021)

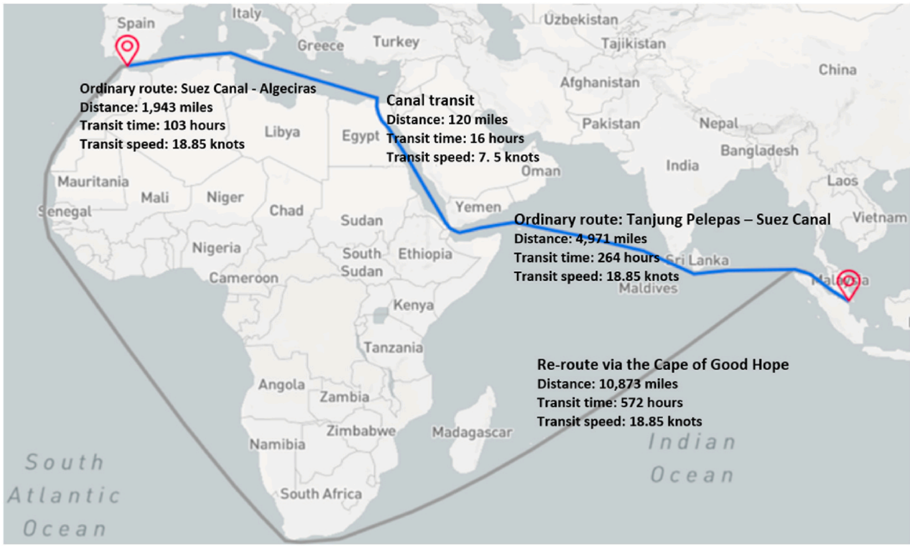

Fig. 4. The Suez route vs. The Cape route.

Table 6
The strategic alliances' fleet affected by the incident.

Vessel capacity (TEU)	2M Alliance			Ocean Alliance			THE Alliance		
	Unit	Fleet capacity (TEU)	Cargo value (10^9 USD)	Unit	Fleet capacity (TEU)	Cargo value (10^9 USD)	Unit	Fleet capacity (TEU)	Cargo value (10^9 USD)
Less than 10,000	36	280,392	6.82	18	143,381	4.33	18	120,574	3.76
10,000–15000	9	111,597	3.61	15	194,802	5.65	16	218,593	6.07
15,000–20,000	16	278,692	10.28	2	35,200	1.08	1	19,870	0.89
≥20000	3	67,279	1.88	7	144,897	4.32	4	95,512	2.41
Total	64	737,960	22.59	42	518,280	15.37	39	454,549	13.14

Sources: the authors. Affected ships, together with their service trade and direction, are collected based on our input data and shipping lines' updates on the incident. Ship capacity (TEU) is retrieved from Clarkson's ship database. Cargo value on board a ship is estimated using the model presented in Section 2.2.

Table 7
Breakdown of the impacted fleet by ship status.

Trade	Direction	Unit	Fleet capacity (TEU)	Cargo value (10^9 USD)
Waiting at the Canal entrances or Great Bitter Lake				
Asia – Europe	Eastward	49	595,832	11.25
Asia – Europe	Westward	46	541,436	24.14
Asia – North America	Eastward	15	139,104	1.77
Asia – North America	Westward	6	55,853	2.41
Deviating via the Cape of Good Hope				
Asia – Europe	Eastward	5	82,103	1.55
Asia – Europe	Westward	9	158,479	7.06
Asia – North America	Eastward	11	99,607	1.27
Asia – North America	Westward	4	38,375	1.65
Total fleet in Asia-Europe		328	5,253,868	–
Affected fleet		109	1,377,850	44.0
Total fleet in Asia-North America		547	4,870,321	–
Affected fleet		36	332,939	7.1

Sources: the authors

sea operations because vessels turn off their main engines and burn fuel only for the running of auxiliary engines and boilers. Nevertheless, the substantial number of queued ships and the lengthy waiting times resulted in nearly 2400 tonnes of fuel, equivalent to 7474 tonnes of CO_2 and an environmental cost of $0.75m, considering only CO_2 emissions. Finally, nearly $22 billion worth of goods were carried onboard the impacted ships, exerting pressure on clients by extending the logistics pipeline which translated into additional inventory-carrying costs of $51.7m.

3.2.2. *Re-route via the Cape of Good Hope*

Instead of anchoring at the Suez Canal during the time it was closed, 12 Maersk vessels were rerouted via the Cape route. Four vessels (71,830 TEUs) were sailing from Asia to Europe (westbound), six (50,995 TEUs) traversing from Asia to North America (westbound) and two vessels (16,481 TEUs) were to sail in the opposite direction (Table 8). The deviation of these ships resulted in an additional 33,845 miles (nearly 80 sailing days) and an increase in fuel consumption of 11,914 tonnes, emitting 37,101 tonnes of CO_2 over and above the normal transit route via the Canal, adding $7.05 mil. to shipping costs. Ship diversion raises concerns about piracy risks near the Horn of Africa (primarily near the coast of Somalia) and West Africa (in particular near Nigeria), which increase insurance premiums. However, the main targets have been bulk carriers and tankers. For instance, only 11 container vessels were attacked by pirates in 2022, compared with 50 bulk carriers and 30 tankers out of 115 attacks in 2022 (ICC International Maritime Bureau, 2023). We note that none of the rerouted Maersk vessels was affected by piracy during their voyages.

We should note, however that, according to our comparisons, in several cases (such as Marchen Maersk, Maren Maersk, Maersk Skarstind), the Cape route was cheaper than the Suez transit thanks to the expensive canal fees that were saved ($0.8m for a one-way transit of Magleby Maersk (18,340 TEUs) or $0.73m for Elly Maersk (16,810 TEUs)). The re-routing helped Maersk avoid this cost, amounting to a total of $5.86m for the detoured ships. Consequently, the final increase in ship costs was just $1.2m, lower than inventory-carrying costs ($24.56m) and even environmental costs ($3.51m) (Fig. 7).

The vessels from Asia to Europe bore the brunt of the substantial rises in voyage distances, especially to southern European ports, as ships had

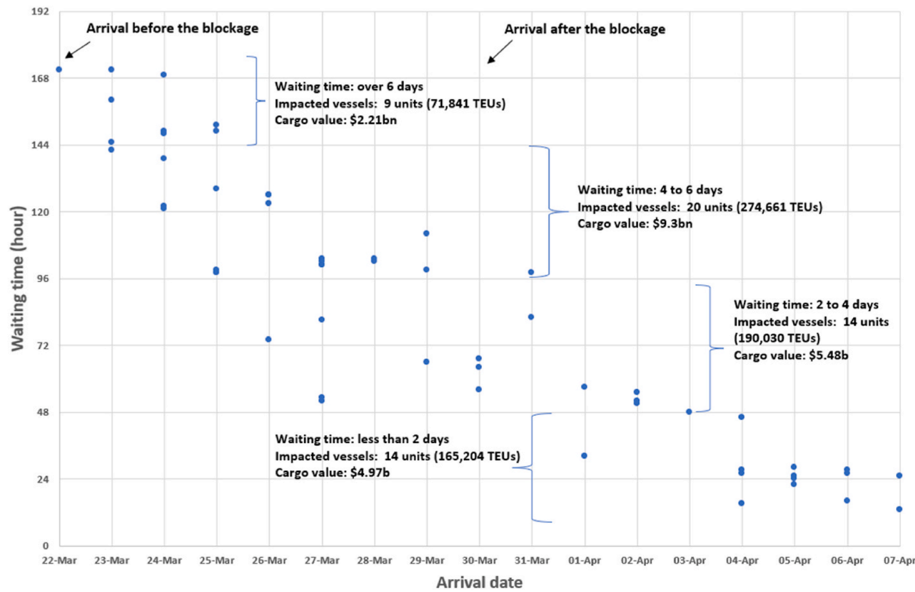

Fig. 5. Vessels held up in the Canal. Source: the authors based on the input data.

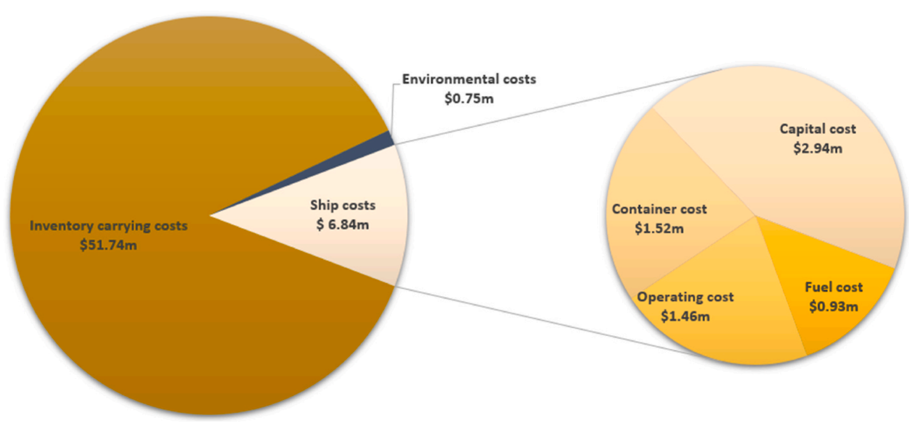

Fig. 6. Breakdown of delay costs.

now to approach them via the Strait of Gibraltar. The extra distances were somewhere between 3400 and 3966 nautical miles (8.2–9.5 sailing days), compared with 1681 to 3566 extra miles on the Asia/North America routes (4.1–8.4 days). Elly Maersk saw a 70% extension of her trip (Colombo to Tangier); Marchen Maersk 40% (Tanjung Pelepas to Rotterdam); compared with 16% for Maersk Santana (Savannah to Tanjung Pelepas) and 19% for Maersk Algo (Newark to Singapore). The lengthened voyage, together with the deployment of giant vessels on the head haul leg (westbound), made total inventory-carrying costs in the Asia/Europe vessels extremely high, over $4.5m for each vessel.

In contrast to the previous sector, but as one might expect, ships from North America to Asia experienced an insignificant rise in all cost items; for example, less than $0.6m in inventory-carrying costs. This route is characterised by small deviation distances and lower cargo values onboard (on the backhaul Asia/North America route). Consequently, these vessels do not benefit much from the Suez Canal, except those calling at the Middle East and South Asian ports.

3.2.3. Cascading effects on maritime supply chains

As we explained above, the congestion at the canal increased the transit time of ships. For example, the detoured Maren Maersk experienced a 6.4-day increase in her East Asia/Europe roundtrip; Maersk Hamburg, stuck in the Southside congestion, experienced a 4-day prolongation of its East Asia/Mediterranean voyage. Our analysis shows that the extension of the affected voyages lay in the range of 3.2–5.6 days (at a 95% confidence level). Containerships must adhere strictly to long-term plans regarding ports of call and the timetable of arrivals/departures (Zhen et al., 2017; Haralambides, 2019). Any delay will hamper subsequent calls as well as ship carrying capacity. In certain trade legs, Maersk Line had to suspend short-term bookings (e.g., North America to the Middle East and South Asia) or restrict booking acceptances (e.g., Europe to Asia) to manage capacity shortages during the first week of April 2021.

The extended delivery times of goods were a direct consequence of the blockage. By analysing the average transit time for 35 trade lanes across 217 port-to-port connections, we find that all lanes faced an increase in delivery times. The only exception was the Mediterranean/South Asia route, where the impact was mitigated mainly by skipping several intermediate port calls. For instance, Maersk Kalmar, after leaving the Suez Canal, skipped two scheduled stops in the Middle-East (Doha and Jebel Ali) and headed directly to Mundra (India). Such bypasses compensated for the blockage time and even resulted in a shorter transit time than scheduled (i.e., nearly one day faster). Thirteen lanes reported a moderate increase from 1 to 3 days, while sixteen faced more substantial delays from 3 to 6 days. Furthermore, four lanes were significantly affected, suffering delays from 7 to 11 days: Southeast Asia

Table 8
Operational parameters on the Cape route and the Suez route.

Vessel	Itinerary	Size (TEU)	Cargo Value (10^6 USD)	Cape route			Suez route			
				Distance (nm)	Time (hour)	Fuel (tonne)	Distance (nm)	Time (hour)	Fuel (tonne)	Canal fee (10^6 USD)
ELLY MAERSK	Colombo – Tangier	16,810	749	9465	547	3392	5499	318	1971	0.73
MAGLEBY MAERSK	Tanjung Pelepas – Algeciras	18,340	818	10,783	572	4598	7034	373	2999	0.80
MARCHEN MAERSK	Tanjung Pelepas – Rotterdam	18,340	818	11,872	701	3766	8468	505	2714	0.80
MAREN MAERSK	Tanjung Pelepas – Rotterdam	18,340	818	11,872	716	3619	8468	511	2581	0.80
MAERSK KOWLOON	Salalah – Newark	7831	337	10,787	616	3335	7241	413	2238	0.43
ARNOLD MAERSK	Colombo – Newark	8650	373	12,796	678	5386	10,253	543	4181	0.47
GUNHILDE MAERSK	Newark – Salalah	8788	112	10,799	557	4638	7233	373	3106	0.48
MAERSK ALGOL	Freeport - Tanjung Pelepas	10,232	130	11,874	613	5079	9971	515	4265	0.33
MAERSK SANTANA	Savannah - Tanjung Pelepas	7670	98	12,449	731	3962	10,768	633	3427	0.29
MAERSK SKARSTIND	Savannah - Tanjung Pelepas	8555	109	12,449	781	2688	10,768	675	2325	0.30
BREMEN	Newark – Singapore	7805	100	12,454	746	3548	10,253	614	2921	0.21
MSC BILBAO	Newark – Singapore	7464	95	12,454	723	3582	10,253	595	2949	0.20
Total		138,825	4556	140,054	7981	47,592	106,209	6069	35,678	5.86

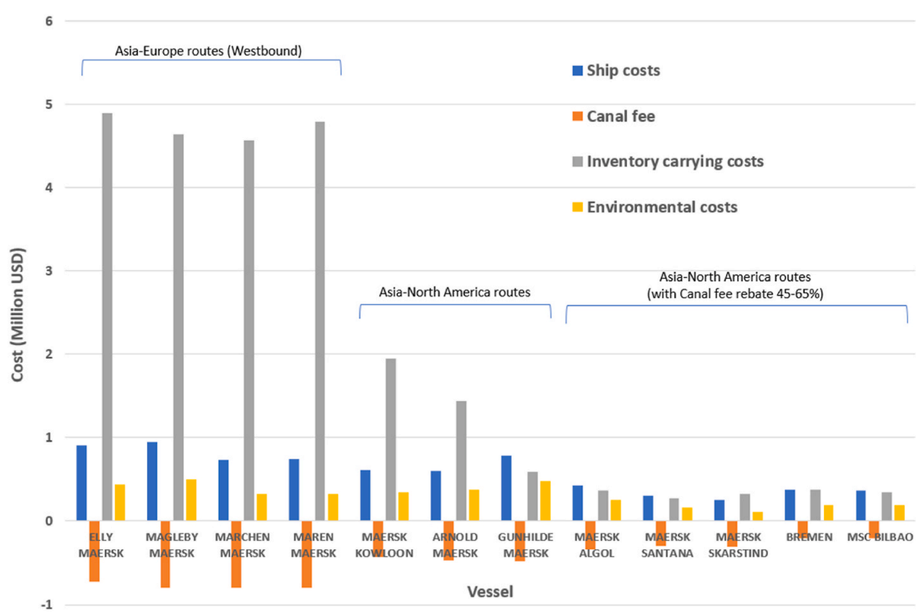

Fig. 7. Cost changes of re-routed vessels.

(SEA) to East Coast North America (ECNA) (7.6 days); South Asia to Europe (nearly 8 days); SEA to Europe (8.2 days); Northeast Asia to ECNA (10.12 days) (Fig. 8).

Cancelling or skipping a port call is a common tactic to maintain schedule integrity, as well as compensate for waiting times (Table 8). Among the vessels hit by the blockage, 40 units bypassed at least one port in their scheduled itineraries. The ports affected the most were the transshipment hubs of Salalah and Jebel Ali (7 times each), Shanghai, Ningbo, Abu Dhabi, and Baltiysk (4 times). In a port range with multiple regional calls, vessels opted to omit one or more stops. For example, they only visited either Ningbo or Shanghai, Felixstowe or London, Newark or Norfolk, and cancelled the second, normally scheduled, port call.

In addition, cutting an entire port range could reduce not only turnaround times in ports but also reduce significantly nautical distances travelled. Given the considerable deviation from the international shipping axis between East Asia and Europe, the middle eastern ports were often bypassed. Out of a total of 62 port call cancellations (in 31 ports), 21 instances took place in the Middle-East (6 ports). By bypassing this region, specifically Abu Dhabi and Jebel Ali, the *MSC Mirjam* shortened the distance by 1559 miles and saved 4.5 days on the round voyage (Table 9). Baltiysk (Russia), located in the Baltic Sea, suffered from four cancellations on Asia–Europe services due to its remote location.

4. Implications

This section aims to provide practical implications for supply chain stakeholders in the aftermath of the Suez Canal blockage. Section 4.1 discusses the diverse impacts on various players. Section 4.2 highlights the critical role of efficient salvage missions in a port or canal to prevent

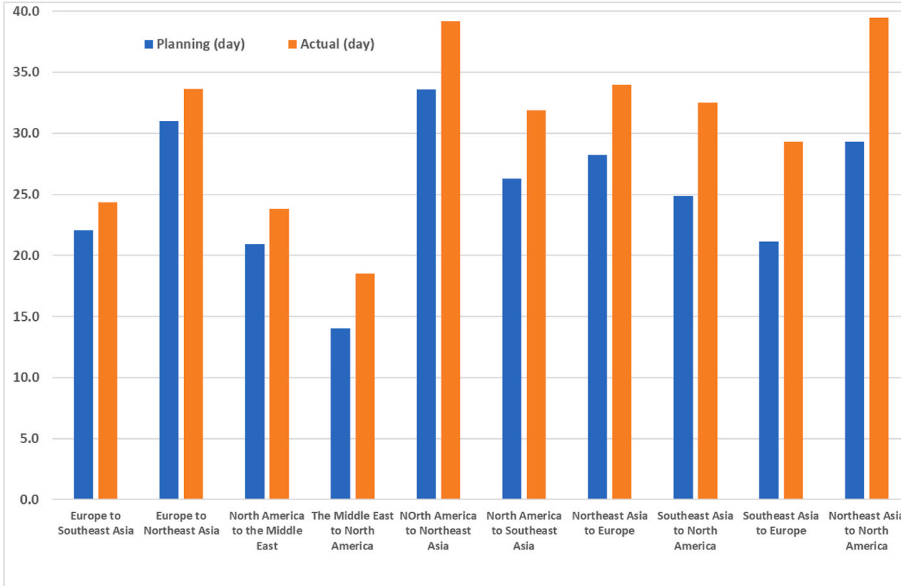

Fig. 8. Extended delivery time in Maersk Line's selected trade lanes.

Table 9
Examples of port call cancellations and skippings.

Vessel	Original journey	Revised journey	Saving distance	Saving voyage time
Magleby Maersk	Gdansk – **Baltiysk** – Bremerhaven	Gdansk – Bremerhaven	66 nautical miles	2.2 days
Gunde Maersk	Xiamen – **Ningbo** – Shanghai	Xiamen – Shanghai	12 nautical miles	1.7 days
Maersk Denver	Charleston - **Savannah** – Houston	Charleston – Houston	72 nautical miles	1 day
Munich Maersk	Ningbo – **Shanghai** – Tanjung Pelepas	Ningbo – Tanjung Pelepas	91 nautical miles	3.2 days
Maersk Houston	King Abdullah Port – **Salalah** – Singapore	King Abdullah Port – Singapore	188 nautical miles	2.7 days
MSC Mirjam	King Abdullah Port – **Abu Dhabi** – **Jebel Ali** – Singapore	King Abdullah Port – Singapore	1559 nautical miles	4.5 days
Maren Maersk	Bremerhaven – **Baltiysk** – Gothenburg	Bremerhaven – Gothenburg	849 nautical miles	3.3 days

Source: authors based on ships' voyage data

a long-lasting incident. Section 4.3 analyses a choke point's vulnerability to underscore the need to develop alternative transport options. Lastly, Section 4.4 addresses the environmental consequences of a disruption.

4.1. Far-reaching implications for supply chain stakeholders

Maritime supply chains involve a multitude of stakeholders beyond just shipping lines (Talley and Ng, 2013; Talley, 2014; Lam and Gu, 2016). As such, disruptions are bound to have far-reaching impacts. Again, our research estimates the total economic losses attributed to the 69 vessels on Maersk Line's shipping network at $88.79m: ship costs ($8.04m); environmental costs ($4.46m) and clients' inventory-carrying costs ($76.29m).

Prolonged ship voyages, caused by congestion in the canal, or the route deviation, were the obvious factors influencing the increased ship costs of carriers. Moreover, the Cape rerouting of 12 vessels (0.14 m TEU) also led to a significant ($5.86m) revenue drop for the Suez Canal Authority (SCA). Note that this amount was only a fraction of the entire losses. According to SCA's update, 48 vessels modified their usual course during the blockage, with 29 of them (0.38m TEU) being containerships sailing along the East-West axis.

Inventory-carrying costs accounted for nearly 86% of the additional costs of the affected vessels. A vast amount of goods ($26.5b) trapped in those vessels resulted in $76.3 mil. of inventory-carrying costs. This figure once again highlights the important role of these costs in supply chain optimization, aligning with insights of earlier research (Hassel et al., 2016; Harrison and Fichtinger, 2013).

The delay in the delivery of goods has also had a profound effect in terms of extending pipeline inventory and putting more financial strain on clients (Maloni et al., 2013; Tran and Lam, 2022). On a Trans-Atlantic service, Tran and Lam (2022) simulated that a one-day increase in transit time would raise inventory-carrying costs by $37.5 per TEU. In a survey of Maersk Line (2012) , a global retailer revealed that his cargo (worth $30,000 per container) was losing on average 25% of its value for every week of postponement and the delay was particularly severe for time-sensitive and perishable goods. Furthermore, delays erode liner schedule integrity, obliging clients to hold more safety stock to face delivery uncertainty and a shortage of merchandise (Vernimmen et al., 2007; Zhang and Lam, 2014). In the first half of 2021, global liner schedule reliability declined to extremely low levels (less than 40%); a stark contrast to over 65% reliability observed in the preceding period 2018–2020 (Sea-Intelligence, 2023). This worrisome fact was the result of the supply chain crisis caused by the COVID-19 pandemic. Finally, we may also note that unexpected changes in port call patterns (e.g., cancellation of certain port calls or changing the order of port calls) disrupt not only customer supply chains by prolonging transit time through container rollings or container cargo rerouting, but also by the re-direction of feeder/inland transportation services. For example, in the aftermath of the blockage, void sailings at Krishnapatnam (India) in some Hapag Lloyd's IEX services forced outbound containers in South Asia to be delayed for at least a week, or to be re-routed and trans-shipped via Singapore. It should be noted, however, that the costs associated with the impact on these third parties do not form part of the analysis carried out here, since this would require a significant and complex global disaggregate data collection process that would probably render the calculation analytically intractable.

Based on the framework presented in Section 2, we calculate ship costs and emissions of 57 vessels in the fleet of Maersk Line affected by the temporary blockage of the Canal. Such a framework requires numerous calculation steps. The simplified functions are built using power regression analysis from these outcomes with very satisfactory results. These can be useful in computing additional ship costs (USD) and CO2 emissions (tonnes) for a given ship capacity (TEUs) and delay times (hours) in a particular location: $\textit{hip costs} = 7.291 * \textit{size}^{0.558} * \textit{time}^{1.011}$; $\textit{emissions} = 0.606 * \textit{size}^{0.022} * \textit{time}^{1.101}$. At an average delay time of 118 h, we estimate that the delay of other container vessels (84 units, 0.92m TEUs) belonging to OCEAN Alliance and THE Alliance, arriving at the Canal from 23rd to 29th March, resulted in additional ship costs of \$13.3m, emissions of 15,090 tonnes, and inventory-carrying costs of \$88m.

4.2. The critical role of the salvage mission in the era of mega-ships

Since the mid-1990s, the deployment of mega-ships, together with mergers/acquisitions and strategic alliances, have been important carrier strategies, aiming at better cost control and higher efficiency (Haralambides, 2019; Tran, 2022). At the beginning of 2023, mega-ships of over 10,000 TEU accounted for 28.1% of the world containership capacity (7.32m TEUs), compared to only 12.7% (2.07m TEUs) ten years earlier (BRS, 2013, 2023). In 2013, Maersk Line launched the first Triple-E class vessels. Today, the largest containerships (e.g., MSC Irina and her sister ships) can carry in excess of 24,000 TEUs.

The scale economies of giant ships have been widely acknowledged (Cullinane and Khanna, 1999; Ge et al., 2021; Haralambides, 2019; Tran and Haasis, 2015). However, there have also been questions raised about the operational challenges they pose, particularly in port. These include costs of nautical-technical services in port (Chang, 2020); handling equipment (Saanen, 2013); call sizes and berth utilisation (Haralambides, 2019), inland transportation (Stopford, 2002; Sys et al., 2008); ship utilisation (Drewry, 2009); service frequency (Tran et al., 2017) and last but not least the impact of megaships on port connectivity (UNCTAD, Review of Maritime Transport, various issues).

The Suez Canal blockage revealed further challenges of these behemoths when encountering delays or incidents, especially for salvage operations. Carrying nearly \$1bn of goods, the Ever Given got stuck in the Canal for 106 days. After being dislodged and refloated, she could not continue her voyage to Europe until July 7, 2021, when the shipowner and the Suez Canal Authority reached an agreement on compensation.

In the Canal, ship incidents have not been uncommon, with 75 cases reported in the 2010s (Allianz, 2021). However, most incidents have typically caused rather short traffic stoppages, thanks to the timely intervention of the in-house tugboats and dredgers. For instance, in 2017, the container vessel OOCL Japan (21,413 TEUs) encountered a malfunction in its steering gear, causing it to go off course; the titan vessel was freed within hours. Similarly, in January 2023, the bulk carrier Glory, carrying grain from Ukraine to China, faced a technical problem that briefly halted Canal traffic. Four months later, another bulk carrier was stranded for nearly 4 h. Before the Ever Given incident, the most serious shutdown occurred in 2004 when the tanker Tropic Brilliance obstructed the two convoys of 101 vessels for three days. The transit operation only returned to normal after many efforts were made to remove sand alongside and under the tanker, as well as pumping out nearly a quarter of the crude oil onboard.

Never before had an incident in the Canal created so many troubles as that of the Ever Given; its sheer size presented a significant challenge in dislodging it (400m long, 58.8m wide, a draft of 16m, and an air draft of 57m). The salvage mission could not be pursued by in-house resources alone, as in previous cases, and efforts only succeeded with the assistance of Royal Boskalis, a prominent Dutch dredging and salvage firm, and two powerful seagoing tugboats, coming from the Red Sea. Had the last attempt during high tide failed, the ultimate plan was to lighten Ever Given using floating cranes (lifting height above 57m) to discharge containers. In that case, the crisis would have lasted longer because of the transportation of suitable cranes, the complexity of handling operations, and the suitable relocation of many containers, once unloaded on the bank of the Canal without proper facilities.

The incident has underscored the critical role of salvage missions in canals and ports, particularly upstream ports, in avoiding long-lasting disruptions of shipping operations. There is indeed a need to react swiftly to an incident, in order to negate impacts on other vessels and infrastructure. In 2016, the container vessel CSCL Indian Ocean (18,980 TEUs) ran aground *en route* from Felixstowe to Hamburg and it took six days to refloat it. Fortunately, navigation along the Elbe River was only partially affected, otherwise it would have been a near catastrophe, due to the river's critical role as a unique link between Hamburg and the North Sea. In 2017, another incident in an upstream port happened when CSCL Jupiter (13,300 TEUs) got stuck for half a day due to mechanical failure while navigating along the river Scheldt leaving the port of Antwerp. The grounding led to a disrupted access to/from this Belgian hub for about 24 h.

After Ever Given's incident, the Suez Canal Authority had to revamp the salvage operation by strengthening the Canal's existing mooring stations as well as building five more stations in order to better and faster respond to any malfunctioning vessel (The National News, 2021). In addition, new powerful dredgers and tugboats were added to enhance the Canal's rescue capability (Reviera, 2021).

4.3. The vulnerability of a chokepoint

The Suez Canal is among the few vital chokepoints of international shipping, alongside others such as the Panama Canal, the Bab el-Mandeb Strait and the Malacca Strait (Haralambides, 2024). Notteboom et al. (2022) consider the Malacca Strait as the world's most important shipping passage, accommodating about 30% of global seaborne trade. In 2022, 24.2 mil. TEUs on the Asia-Europe trade were transported via the Suez Canal and the Bab el-Mandeb Strait, equivalent to 15% of global container traffic (UNCTAD, 2023). In 2023, 290 mil. tonnes of cargo were transported via the Panama Canal, of which nearly 212m tonnes of US imports and exports (Panama Canal Authority, 2024).

These strategic conduits accommodate a substantial number of vessels but also face various physical and navigational constraints. The Malacca Strait has always been a piracy hotspot, with 55 out of 115 incidents around the world in 2022 (ReCAAP ISC, 2022; ICC International Maritime Bureau, 2023). The expanded Panama Canal has resolved the long-standing Panamax limit (ships with a length of 294m and beam of 32.3m), allowing the transit of Neo-Panamax vessels (wider than 32.3m) since 2016. Nevertheless, recently, the Panama Canal has been struggling with unprecedented low water levels, leading to drastic cuts in transit capacity.

The Suez Canal experienced a mega expansion in 2016, but the two single shipping lanes (50 miles in total) on both sides continue to be bottlenecks (Fig. 9). On the one hand, they have created daily cut-off times (11 p.m.) for vessels to join convoys. On the other hand, any incident occurring in these stretches will disrupt the entire navigation system. Ever Given crashed into a bank at the Suez entrance, impeding the transit of all 15 vessels behind her in the northbound convoy and all in the southbound one (Fig. 9).

Due to the strategic role of chokepoints in global shipping networks, closure or disruptions would clog international trade, causing costly reroutings. Earlier studies have simulated the potential impacts of chokepoint disruptions (Kajitani et al., 2013; Wu et al., 2019). However, with the exception of the grave piracy incidents in the Strait of Malacca some years back, and the current (2024) crisis in the Red Sea and the Gulf of Aden, the Ever Given's grounding marked a rather unique, critical disruption. The economic losses calculated above underscore the vulnerability of an East-West shipping corridor, highlighting the

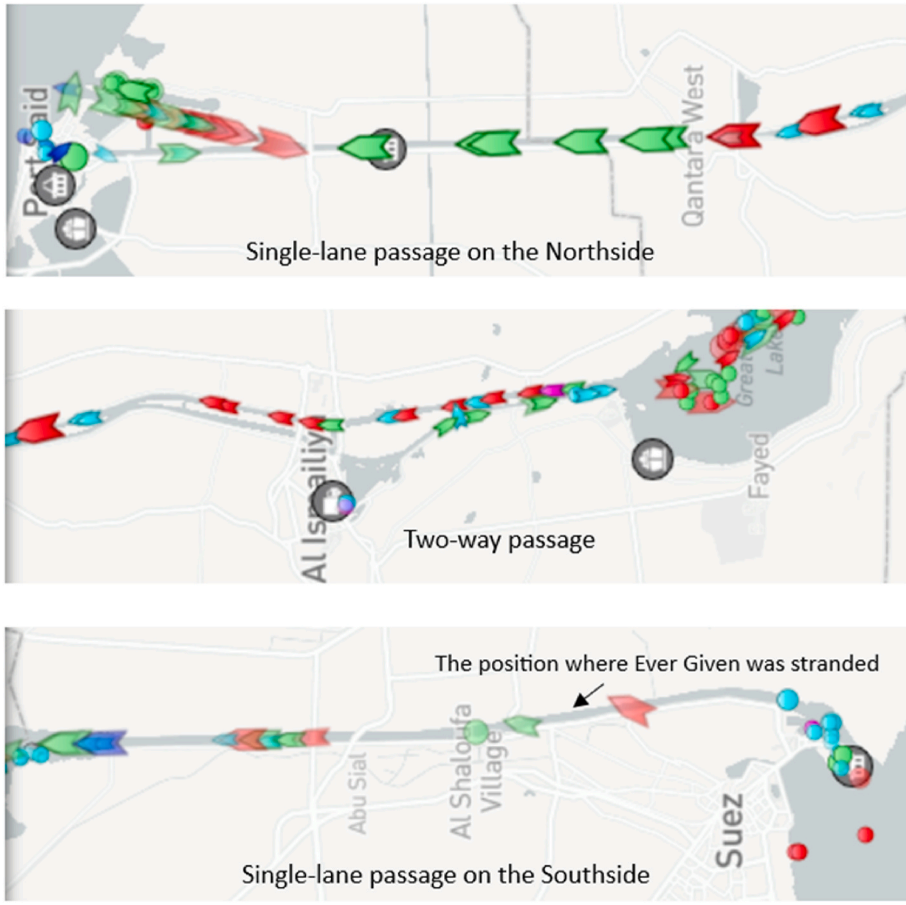

Fig. 9. Navigation along the Canal. Source: The authors based on the Marine Traffic platform.[51]

profound implications for global trade and supply chains in overcoming these bottlenecks.

Although fully bypassing the Suez route is not a preferred scenario, the blockage showed a strong need to develop alternative transport options to reduce the heavy reliance on this route as well as to deal with long-lasting disruptions. Global warming has opened up opportunities for the use of the Northern Sea Route (NSR) (Keltto and Woo, 2020; Joseph et al., 2021; Sibul and Jin, 2021; Xu and Yin, 2021). Cargo volume, mainly liquefied natural gas, grew significantly from 3.1 mil. tonnes in 2011 to 34 mil. in 2022 (Artic-Lio, 2023). Despite such growth, container ships have not utilised NSR so far, although its feasibility has been discussed in several studies (Verny and Grigentin, 2009; Zhang et al., 2016, 2024; Tseng and Cullinane, 2018). Critical voices, however, are also heard loudly, mostly due to environmental concerns, high shipbuilding costs of ice-class vessels, fees of Russian control stations, and preparedness of western European ports to serve this traffic. A number of carriers too have stated that they will never use this alternative (Haralambides, 2024).

Supported by the Belt and Road Initiative (BRI), launched in 2013 by Chinese president Xi Jinping, freight trains have increasingly become a viable option between China and Europe for some cargo types, to overcome the expensive freight rates of air transport and the long transit time of sea transport (Zhang and Schramm, 2020; Yang et al., 2023; Zhang et al., 2023). According to the statistics of China State Railway Group, China-Europe freight trains carried 1.9m TEUs in 17,000 trips in 2023 (New Silkroad Discovery, 2024). In 2022, Maersk Line launched an intermodal rail-sea service connecting these two markets through Central Asia and the Black Sea. Finally, one needs to also note the IMEC project (India-Middle East-Europe Corridor), tabled at the 2023 G20 meeting in Mumbai, India. This $20b project bypasses Suez by i) a sea-leg from the west coast of India to Dubai; ii) a rail link from there to Israel, traversing Saoudi Arabia; and iii) a final sea-leg connecting Israel's port of Haifa to the South Mediterranean ports of the European Union, notably Piraeus and Genoa (Haralambides, 2024).

The Cape route has shown to be able to compete with the Suez route in certain instances. Notteboom (2012) identifies 11 trade lanes for which the Cape route outperforms Suez, for instance, West Africa – Oceania, West Africa–East Africa, East Coast South America - Oceania. Our outcome in Section 3 reveals only a small difference between the two routes in terms of ship costs and voyage distances in the trade between North America and Asia. In practice, the Suez Canal Authority has offered rebates, ranging from 45% to 65%, to attract certain back-haul traffic on this trade corridor. For example, a containership returning to the Far East was granted a rebate of (i) 45% if it came from Norfolk, Virginia (or any port further north along the North American East Coast) and (ii) 65% if coming from a port south of Norfolk. In order to increase the Suez Canal's competitive advantage and prevent an incident like the 2021 blockage, the Suez Canal Authority conducted a preliminary study in March 2024 to plan another extension to double canal capacity at the bottleneck parts.

The Kra Canal in Thailand (Peng Er, 2018) and the Nicaragua Canal (Yip and Wong, 2015; Chen et al., 2019) have a long history as potential new interoceanic passages, to reduce reliance on the Malacca Strait and the Panama Canal respectively. However, both projects have been shelved for the time being.

4.4. *Operational disruption and increased ship emissions*

Shipping is instrumental as a facilitator of global trade but also a significant source of greenhouse gas emissions (GHGs) and toxic pollutants, affecting human health and the environment, and aggravating global warming, and climate change (Cullinane and Cullinane, 2013). International Maritime Organisation – IMO (2021) reports that international shipping activities in 2018 released 2.89% of global emissions. Since the 2000s, accounting for emissions has been crucial in monitoring the negative externalities of shipping (Yin et al., 2021). While a few studies have addressed ship emissions on the global shipping network (Cariou et al., 2019; Tran and Lam, 2022; Tran and Tran, 2023; International Maritime Organisation – IMO, 2021), the majority have dealt with emissions in specific locations such as cruise ships in Las Palmas Port (Tichavska and Tovar, 2015); in Greek ports (Papaefthimiou et al., 2016); container ships in the port of Shanghai (Song, 2014), Singapore (Tran et al., 2022) and Taiwanese ports (Cullinane et al., 2016).

Our research highlights the environmental concerns associated with operational disruptions in shipping, in addition to conventional transport activities. Using the International Maritime Organisation – IMO (2021) emission rates, we estimate that the increased fuel consumption (14,314 tonnes) of Maersk Line's affected vessels released 44,574 tonnes of CO_2 and other pollutants, such as 117 tonnes of SO_X, 223 tonnes of NOx, and 17 tonnes of Particulate Matter (PM) (Table 10).

Such emissions could arise during ships' anchorage time in the Suez Canal or the additional sailing distances of vessel reroutings via the Cape. Approximately 17% of the increased emissions (7615 tonnes of CO_2 and other pollutants) occurred in the Suez Canal: In addition to traffic disruption and revenue decline, the Canal had to face this problem too. While CO_2 emissions contribute to global warming, other pollutants can cause severe health problems in urban areas, in agricultural activities, biodiversity decline, and damage to construction facilities (Essen et al., 2019). Again, efficient salvage operations are critical for the Canal or any port, not only to restore transit operations quickly, but also to limit ship emissions, which are closely tied to ships' waiting time.

Although only 12 Maersk vessels were rerouted, they contributed to over four-fifths of the increased emissions of Maersk's affected fleet (37,101 tonnes of CO_2). These ships released much more emissions than the 57 Maersk ships stuck at the Suez Canal, because of the higher fuel consumption of their main engines during sea operations; main engines are turned off at anchorage. According to our calculations, the diversion of a Triple – E class vessel (18,340 TEU) on an Asia - Europe trip via the Cape increases fuel consumption by 1037 to 1598 tonnes. In the case of the Red Sea crisis, the Cape route diversion implied a huge spike in emissions of the Asia-Europe fleet with 328 units totalling 5.25 mil. TEU. Consequently, such a shift jeopardizes the global ambition to cut emissions or decarbonise shipping operations. Industry experts evaluate that the maritime industry can face an increase in fuel consumption for diverted ships by 1 million tonnes per month (Labrut, 2024).

The inclusion of shipping in the EU Emissions Trading System (EU ETS) has been effective since January 1, 2024 (Meng et al., 2023). This 'cap and trade' policy is a cornerstone in combating climate challenges by reducing greenhouse gas emissions. EU ETS covers all emissions produced by ships (above 5000 GT) during their movement between EU ports and visits at an EU port. In addition, EU ETS counts 50% of emissions from voyages between an EU port and a non-EU port. While this is several years after the Suez Canal blockage, any current or future disruption in the maritime network affecting European waters and ports will have a financial implication associated with the EU ETS. This scope will significantly increase carbon taxes for diverted container ships between Asia and Europe due to longer journeys to/from an EU port. For instance, at 18.9 knots and the extended distance between Tanjung Pelepas and Algeciras of 3749 miles, CO_2 emissions produced by a Triple-E class vessel amount to nearly 5000 tonnes. At an EU ETS price of $96.29 per tonne, the additional costs will be $95,872 when the liability is only 40% (in 2024) or $239,679 when the system will be fully implemented from 2026 onward (Table 11).

5. Conclusions

The grounding of the mega-containership Ever Given, and the subsequent blockage of the Suez Canal, attracted much attention due to the critical role of the Suez Canal in international shipping and trade. This research quantified the impacts of the blockage by proposing a model to estimate the losses of a containership fleet based on ship voyage data.

The model was applied in the case of Maersk Line's East-West shipping network, with a total of 69 vessels affected by the crisis, either because of the need to reroute via the Cape of Good Hope, or due to the delay for the transit convoy during or after the blockage. The total losses suffered by these vessels amounted to $88.79m, together with nearly 44,574 tonnes of CO_2 emitted into the atmosphere due to extra waiting time or extended trips. The losses consisted of ship costs ($8.04m), environmental costs ($4.46m) caused by prolonged voyage duration, and most significantly clients' inventory-carrying costs ($76.29m), in view of the vast amount of goods onboard the affected vessels ($26.48bn). In addition, the detour of vessels resulted in a significant revenue drop for the Suez Canal Authority ($5.86m).

Total losses for the entire container shipping industry could not be assessed in this research due to restricted access to confidential commercial data. Therefore, our results regard a subset only of the affected fleet, representing about 32% of the total capacity of all containerships directly impacted by the blockage (0.55m out of 1.71m TEUs). Our findings shed light only partly on the vulnerability of this chokepoint of international shipping and trade, given the large number of ships and goods passing through it. The in-depth exploration attempted here highlights the impacts on maritime supply chains in terms of prolonged ship voyages, blank sailings, and extended delivery times in most trade lanes.

The Suez blockage lasted six days and the majority of the ships had to wait at the canal's two entrances. Only a handful of ships detoured via the Cape of Good Hope (28 out of 144 affected units). The ongoing Red Sea crisis is disrupting maritime supply chains for a much longer period, compelling shipping lines to alter their conventional Suez route. Given the large number of detoured vessels, the losses are much more substantial in terms of inventory-carrying costs and CO_2 emissions. Once the Red Sea Crisis is over, researchers can apply our framework to accurately assess the costs to shipping and global supply chains associated with this major disruption in the global shipping network.

We acknowledge that, as with all such works, ours too has certain limitations. First, we consider the impact of a major disruption by focusing on the affected fleet of one carrier only, i.e., Maersk. Future research could benefit from incorporating operational data from additional shipping lines to provide a more comprehensive understanding of maritime supply chain disruptions. Secondly, new directions can be approached to study the impacts of skipped ports or the change of loading/unloading ports on supply chain costs. Thirdly, ship costs are critical input factors for our model. We have estimated these costs using a proven and widely-used approach. Future research might attempt to collect actual ship costs from shipping lines to improve accuracy even further.

CRediT authorship contribution statement

Nguyen Khoi Tran: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hercules Haralambides:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Theo Notteboom:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Kevin Cullinane:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Conceptualization.

[5] https://www.marinetraffic.com/en/ais.

Table 10
CO_2 emissions and other pollutants of the affected vessels.

Pollutant	CO_2	NO_x	SO_x	PM	CO	N_2O	CH_4
Emission rate (tonne per tonne of fuel)	3.114	0.093	0.04943	0.00701	0.00277	0.00016	0.00006
Amount (tonne)	44,574	223	117	17	40	2.29	0.85884

Table 11
The impact of re-route on EU ETS cost.

	Size (TEU)	Speed (Knot)	Itinerary	Increase			Increase of EU ETS cost (USD) (*)		
				Distance (NM)	Fuel (Tonne)	CO_2 (Tonne)	2024 (40%)	2025 (70%)	From 2026 (100%)
ELLY MAERSK	16,810	17.3	Colombo - Tangier	3966	1421	4426	85,245	149,178	213,112
MAGLEBY MAERSK	18,340	18.9	Tanjung Pelepas – Algeciras	3749	1599	4978	95,872	167,776	239,680
MAREN MAERSK	18,340	16.6	Tanjung Pelepas – Rotterdam	3404	1038	3231	62,226	108,896	155,565

(*) Average EU ETS carbon price in 2023 (https://carbonpricingdashboard.worldbank.org/compliance/price).

Data availability

Data will be made available on request.

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