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“Towards Resilient Maritime Supply Chains: Analyzing Risks and  
Response Strategies.”

Pantelis Kollias (523694)

Supervisor: Efstratios Papadimitriou

Athens, Greece, January 2025

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# Towards Resilient Maritime Supply Chains: Analyzing Risks and Response Strategies

Pantelis Kollias

Supervising Committee

Supervisor:

Efstratios Papadimitriou

Co-Supervisor:

Konstantinos Tasias

Athens, Greece, January 2025

## Abstract

Maritime supply chains have a special place among factors driving global trade’s growth, facilitating around 90% of goods traded internationally. However though, due to the high complexity of the nodes that form the maritime supply networks, these systems are highly volatile to a wide range of risks, including operational inefficiencies, geopolitical tensions, environmental hazards, and technological vulnerabilities. The purpose of this study is to delve into the factors that trigger aforementioned risks and vulnerabilities and examine response strategies and good practices that enhance resilience within the maritime networks.

By thoroughly analyzing existing literature on theoretical and practical frameworks, the study examines historical developments and emerging challenges faced by maritime networks. Particular emphasis is given on disruptions such as the Suez Canal blockade and the COVID-19 pandemic, highlighting their effects on the maritime systems. Technological advancements, such as blockchain technology, are examined as transformative tools for enhancing transparency, adaptability, risk mitigation and finally resilience within maritime logistics.

This study is using a qualitative approach from case studies along with quantitative analyses to evaluate the effectiveness of resilience strategies, significant attention is being given to risk management frameworks, by presenting proactive and reactive strategies. These include diversifying supply chain routes, collaborative governance models, and advanced predictive analytics to mitigate risks.

In conclusion, the study observes the impacts of global disruptions in maritime supply chains under the prism of resilience and their ability to adapt, respond to and evolve to a better level of performance.

**Keywords:** Maritime resilience, risk assessment, vulnerabilities, maritime disruptions, defining resilience, supply chain, risk mitigation strategies, technology, blockchain, transparency, visibility, infrastructure, port resilience, bullwhip effect

## Περίληψη

Η ναυτιλιακή εφοδιαστική αλυσίδα κατέχει ιδιαίτερη θέση μεταξύ των παραγόντων που συμβάλουν στην ανάπτυξη του παγκόσμιου εμπορίου, διευκολύνοντας περίπου το 90% των αγαθών που διακινούνται διεθνώς. Ωστόσο, λόγω της εγγενούς υψηλής πολυπλοκότητας που χαρακτηρίζει τα ναυτιλιακά δίκτυα εφοδιασμού, τα συστήματα αυτά είναι ιδιαίτερα ευαίσθητα σε ένα ευρύ φάσμα κινδύνων, συμπεριλαμβανομένων των επιχειρησιακών δυσλειτουργιών, των γεωπολιτικών εντάσεων, των περιβαλλοντικών κινδύνων και των τεχνολογικών κινδύνων. Σκοπός της παρούσας μελέτης είναι να διερευνήσει τους παράγοντες που προκαλούν τους προαναφερθέντες κινδύνους, καθώς και να εξετάσει στρατηγικές ανταπόκρισης και καλές πρακτικές που ενισχύουν την ανθεκτικότητα των ναυτιλιακών δικτύων.

Μέσα από διεξοδική ανάλυση της υπάρχουσας βιβλιογραφίας σχετικά με θεωρητικά και πρακτικά πλαίσια, η μελέτη εξετάζει τις ιστορικές εξελίξεις και τις αναδυόμενες προκλήσεις που αντιμετωπίζουν τα ναυτιλιακά δίκτυα. Ιδιαίτερη έμφαση δίνεται σε διαταραχές, όπως ο αποκλεισμός της διώρυγας του Σουέζ και η πανδημία COVID-19, υπογραμμίζοντας τις επιπτώσεις τους στα ναυτιλιακά συστήματα. Οι τεχνολογικές εξελίξεις, όπως η τεχνολογία του blockchain, εξετάζονται ως εργαλεία για την ενίσχυση της διαφάνειας, της προσαρμοστικότητας, της μείωσης κινδύνων και τελικά της ανθεκτικότητας στις ναυτιλιακές εφοδιαστικές διαδικασίες.

Η μελέτη χρησιμοποιεί ποιοτική ανάλυση μέσω περιπτώσιολογικών μελετών μαζί με ποσοτικές αναλύσεις για να αξιολογήσει την αποτελεσματικότητα των στρατηγικών ανθεκτικότητας. Ιδιαίτερη προσοχή δίνεται στο πλαίσιο γύρω από την διαχείριση των κινδύνων, παρουσιάζοντας προληπτικές και αντιδραστικές στρατηγικές. Οι στρατηγικές αυτές περιλαμβάνουν την διαφοροποίηση των δρομολογίων, τα μοντέλα συνεργατικής διακυβέρνησης και τις προσαρμοσμένες αναλυτικές προβλέψεις για τη μείωση των κινδύνων και την ενίσχυση της ανθεκτικότητας.

Συμπερασματικά, η μελέτη παρατηρεί τις επιπτώσεις των παγκόσμιων διαταραχών στις ναυτιλιακές εφοδιαστικές αλυσίδες υπό το πρίσμα της ανθεκτικότητας και της ικανότητάς τους να προσαρμόζονται, να ανταποκρίνονται και να εξελίσσονται σε ένα καλύτερο και πιο αποτελεσματικό επίπεδο απόδοσης.

**Λέξεις – Κλειδιά:** Ναυτιλιακή ανθεκτικότητα, αξιολόγηση κινδύνων, ευπάθειες, ναυτιλιακές διαταραχές, ορισμός ανθεκτικότητας, αλυσίδα εφοδιασμού, στρατηγικές μετριασμού κινδύνων, τεχνολογία, blockchain.

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# 1. Introduction

## 1.1. The Importance of Maritime Transport

Maritime transport plays a crucial role in international commerce, being accountable for nearly 90% of global goods trade and over 70% of trade value. Its importance goes beyond just economics, it facilitates the smooth movement of essential commodities such as food, energy, and manufactured products (Xiao et al., 2024). Over the years, advancements in maritime capabilities, from small cargo vessels to massive containerships, have broadened market access for importers and exporters. This efficient mode of transport enables businesses and countries to participate in international trade, providing access to diverse markets and creating opportunities for economic growth through better resource allocation and fostering industrialization. In fact, according to the UNCTAD Review of Maritime Transport (2024), a 10% increase in maritime transport has been linked to a 1.6% rise in GDP per capita.

Maritime shipments and their related activities have a significant impact on the economy, as they directly or indirectly influence many industries by transferring resources to manufacturing sources (Fratila et al., 2021). The advent of containerization has transformed maritime logistics, allowing large-scale cargo to be transported by sea in vast quantities, which reduces per-unit costs compared to other transport methods. With lower fuel consumption per ton/kilometer than road or air, maritime transport is more sustainable and efficient, creating economies of scale and a clear competitive advantage (Ferarri et al., 2023). Consequently, the affordability and efficiency of maritime transport have greatly contributed to trade globalization, enabling markets and countries that specialize in producing goods, to become more competitive through maritime trade.

Moreover, maritime transport is versatile, accommodating a wide range of cargo types, from bulk items like oil, coal, and agricultural products to containerized goods such as manufactured items, electronics, and consumer products, as well as specialized cargo, like LNG (liquefied natural gas), chemicals, and automobiles. This diversity is crucial for energy security and sufficiency for many countries that rely on timely and uninterrupted maritime shipping.

Another vital aspect of sea transport is its ability to provide resilience and redundancy in global supply chains. It allows for strategic adaptability and long-term planning to address disruptions such as the COVID-19 pandemic, the Suez Canal blockade, or the need for alternative routes and ports to avoid congestion and geopolitical tensions (Vaggelas, 2023). Today, these

capabilities are further enhanced by technological advancements in the sector, including blockchain and Artificial Intelligent (AI) in port operations, along with smart shipping solutions and real-time tracking systems for improved traceability, fortify resilience and redefine global trade.

While maritime transport remains more efficient than other means of transport, it faces numerous modern challenges that threaten its resilience and efficiency. With global concerns rising over the effects of climate change, the industry is under constant pressure to reduce greenhouse gas emissions and comply with strict environmental and marine pollution regulations. There is also an increasing demand for the adoption of new and sustainable practices, such as green technologies in both shipbuilding and port operations (Fratila et al., 2021).

In recent years, global supply chain disruptions have also increased, directly impacting the resilience capabilities of maritime transport. Events like the Covid-19 pandemic and the Suez Canal blockade, along with geopolitical tensions and new forms of piracy from regimes such as the Houthis, have revealed significant vulnerabilities in maritime supply chains, including severe port congestion, logistical shortcomings, and reliance on a limited number of efficient routes (Xiao & Xu, 2024).

As economies become more interconnected and globalization accelerates, the role of shipping transport will continue to grow. Addressing these challenges while leveraging technological advancements will be essential for ensuring the resilience and sustainability of maritime transport, securing its position as a driving force in global commerce.

## **1.2. Maritime Supply Chains: An Overview**

Maritime Supply Chains are defined as complex networks that facilitate the transportation of a large variety of goods via sea routes, integrating ports, shipping lines, logistics providers, and other stakeholders to enable efficient and cost-effective global trade (Stopford, 2009). These interconnected networks have been evolved through the centuries driven by factors such as market demand, disasters, geopolitical changes and technological advancements.

Throughout history maritime supply chains have played a crucial role in driving evolution and economic development. From the ancient trade routes of the Mediterranean and the Indian Ocean to the Age of Exploration, these supply chains have significantly influenced the

economic and cultural landscapes of various civilizations (Frankopan, 2015). The era of industrialization marked a transformative period, introducing steam-powered vessels and modern port infrastructure, which greatly enhanced the efficiency of maritime logistics (Stopford, 2009). Moving into the mid-20th century, containerization represented another revolutionary cornerstone for global trade by standardizing cargo handling and facilitating integration between sea and land transport (Levinson, 2006).

The key players in maritime supply chains consist of shipping companies, freight forwarders, port operators, and regulatory authorities. Major multinational shipping companies like MSC, MAERSK, and CMA CGM play a crucial role in the industry, overseeing global containerized cargo. Private port operators such as DP World, Hutchinson Ports and PSA International, manage essential port hubs and the associated infrastructure and services. Freight forwarders and logistics providers, including DHL and Kuehne & Nagel, ensure the efficient movement of goods throughout the supply chain. Additionally, independent regulatory authorities, like the International Maritime Organization (IMO), set and enforce standards for safety, environmental compliance, and security (UNCTAD, 2022).

The key elements essential for the smooth and continuous functioning of maritime supply chains are infrastructure, connectivity, and technological innovation. Port infrastructure, which includes berth cranes and storage facilities, plays a crucial role in the efficiency of maritime logistics (Notteboom & Rodrigue, 2020). Connectivity, as defined by Lopez-Navarro (2020), refers to the integration of shipping routes and intermodal transportation, which influences the accessibility of markets and trade hubs. Additionally, technological innovations such as smart port operations, digital freight management, and blockchain for supply chain transparency are increasingly important for optimizing operations and enhancing resilience (Heilig et al., 2017).

According to Stopford (2009), maritime supply chains provide several benefits. These include cost efficiency from economies of scale and improved global connectivity, which links remote markets and boosts international trade and economic growth. Furthermore, innovations in vessel design and fuel efficiency have helped lessen environmental impacts, making maritime transport comparatively more sustainable than other transportation methods (IMO, 2021).

Despite the beneficial effects, maritime supply chains also face significant challenges. Geopolitical issues like trade wars and territorial disputes often disrupt trade routes, leading to increased operational costs and risks (López-Navarro, 2020). Furthermore, climate change presents a serious threat, with rising sea levels and extreme weather events becoming common,

disrupting shipping schedules globally. The recent pandemic also highlighted numerous vulnerabilities, resulting in port congestion, container shortages, and workforce availability problems (UNCTAD, 2021). Lastly, the growing reliance on digitization introduces cyber security risks and exposes supply chains to potential breaches.

As we look ahead to the future, it's clear that maritime supply chains must improve their resilience and sustainability, and technology plays a crucial role in this effort. The digital transformation, fuelled by artificial intelligence, the Internet-of-Things (IoT), and emerging blockchain technology, is expected to revolutionize maritime logistics, enhancing transparency, efficiency, and resilience (Heilig et al., 2017). Additionally, initiatives aimed at making the shipping industry more environmental friendly, such as adopting alternative energy sources and developing zero-emission vessels, are designed to reduce the environmental impact and respond to the growing demand for a sustainable future. Furthermore, diversifying maritime supply chains through investments in smart port infrastructure is a key strategy to mitigate risks and adapt to future changes and challenges (Notteboom & Rodrigue, 2020).

In summary, maritime supply chains are vital to global trade and economic development. Their historical development, essential components, and key players highlight their complexity and importance. While challenges arise, innovative solutions and strategic adjustments pave the way for a more resilient and sustainable future.

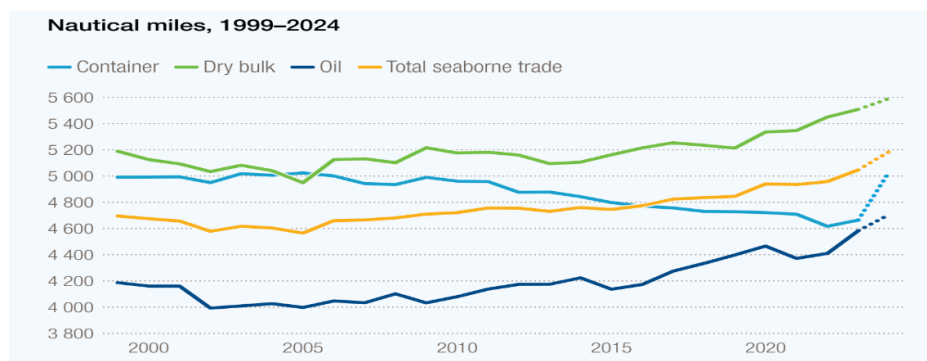
### **1.3. Problem Statement**

#### **1.3.1. Inherent Vulnerabilities, Consequences of Disruptions and Dependency on Chokepoints**

As already mentioned maritime supply chains are systems characterized by high levels of complexity and interconnections, thus making them highly vulnerable to several risks and disturbances. A study by Wilson (2007) states that, disruptions in maritime supply chains may occur due to external supply or demand shocks. Disruptions may as well be a result of natural disasters, labor differences, cyber and terrorist attacks, piracy, supplier threats, health pandemics, economic fluctuations and rapid changes in consumer preferences (Chopra and Sodhi, 2004). Disruptions in maritime logistics can spread across multiple sectors, magnifying economic, social, and environmental consequences (Notteboom & Pallis, 2021). As per Ponomarov (2009), disruptions can be categorized as either slow progressive or sudden-

progressive events. Van Wassenhove (2006), stretches the importance of the repentance and duration of a disturbance as crucial factor of the magnitude effect on the supply chain. Time is an important factor in categorizing disruptions as slow-onset events. On the other hand, sudden-onset events are evolving suddenly and without any previous warning leaving little room for counter or preventive actions. Such events could be failures in essential infrastructure or unexpected events such as major transport accidents.

Thus it becomes quite apparent that one of the most significant vulnerability of the maritime supply chains is their dependence on port infrastructure or important hubs and chokepoints. Ports act as critical intersection points in the maritime supply chain where, cargo is being loaded – unloaded, stored and transferred to inland or air transport systems. Ports are highly volatile to extreme weather conditions and as per UNCTAD (2024), around 38% of global container port activity occurs in such areas. Storms, hurricanes heat waves, floods and snowstorms can affect their operational efficiency causing closures and delays for hours or even days. Nevertheless those facilities operate twenty four hours a day and seven days a week close to maximum capacity risking accidents that would cause the disruption of continuity of the supply chain for weeks (Heiland et al., 2021). Disruptions at the major maritime chokepoints is for sure another source of vulnerability. A blockade or conflict in such areas could have amplified economic repercussions, particularly for energy markets, leading to price surges and shortages (Crampon et al., 2022). Key shipping routes are facing severe disruptions, causing rerouting, delays and raising costs. As per UNCTAD (2024) traffic through the Panama and Suez Canals, critical chokepoints global trade, dropped by over 50% by mid-2024, compared to their peaks, meanwhile, the tonnage of ships moving through the Gulf of Aden and the Suez Canal fell by 76% and 70% respectively, compared to late 2023. A decline mainly driven by climate change affected low water levels in the Panama Canal and the outbreak of conflict in the Red Sea region affecting the Suez Canal. As shown in Figure 1 below, disruption in main chokepoints for total seaborne trade have been following a relevantly steady line since 2000 but clearly seem to have an increasing tendency from 2020 and onwards.



**Figure 1: Black Sea, Red Sea and Panama Canal disruptions increase shipping distances**

*Source: UN Trade and Development (UNCTAD), calculations are based on data from Clarksons Research*

Of course not to forget the recent Ever Given mega containership event in 2021 that caused the blockade of the Suez Canal that severely disrupted maritime routes for several weeks, revealing with the harshest way how vulnerable is maritime supply chain, causing extreme bottlenecks in ports considered to be main global hubs and delaying billions of dollars' worth of goods daily.

Piracy is another key source of maritime supply chain vulnerability. Even though, piracy seemed to be a problem under control, recently it has been re-appeared, seriously affecting routes and increasing costs. UNCTAD (2024) research states that the most dangerous areas are amongst others the Gulf of Guinea and the Gulf of Aden where piracies are becoming not only more common but more violent and more sophisticated.

Another vulnerability occurs from the increasing use of new technologies and the continuous digitization of maritime operations. However the importance and the positive impact of technology, cyberattacks have emerged as major risk, compromising sensitive information and create instabilities for terminal's operating systems and cargo management tools. As Krishnamurthy et al (2020), state at their work, the NotPetya ransomware malware attack incident in 2017, that targeted Maersk, considered to be amongst the largest container shipping companies in the world, is estimated that it had a negative financial result of more than 300 million dollars losses and significant delays amongst its nodes. As Pownall (2019) states, the incident affected over 45.000 personal computers and around 4.000 servers, leading around 76 port terminals to cease operations.

Of course natural disasters and climate change play as well a vital role in destabilizing the maritime supply chains. Global warming leads to rising sea levels and increases the intensity

and duration of storms and hurricanes that threaten port infrastructure and continuity of routes (Lai et al., 2022). Moreover extreme weather conditions and disruptions due to climate change not only cause possible delays and accidents, but as well is an important factor of increased insurance costs and operational uncertainties (Becker et al., 2021).

Maritime supply chains are highly volatile to disruptions emerging due to geopolitical changes, tensions and turmoil. Geopolitical instabilities can directly disrupt maritime supply chains by affecting routes ports and its infrastructure. For instance late Russian-Ukrainian conflict has affected Black Sea routes and paralyzed Odessa port, considered to be a main hub in the area. Additionally the Houthis regime’s attacks in the Red Sea area has directly influenced the Suez Canal passage. (CSIS, 2024).

The human factor remains as well an important vulnerability source. Workforce shortages and labor strikes may severely disrupt operations in ports, as well as shipping lines schedules. Disputes and strikes in major port hubs can cause delays and bottlenecks disrupting seaborne trade and raising costs for shippers and consumers (Rodrigue, 2022). On top of that, the recent Covid-19 pandemic, revealed a series of vulnerabilities, including human factor, with crew shifting becoming a quite challenging procedure and quarantine protocols leading to unexpected delays. According to the International’s Maritime Organization (IMO) research in 2020, crew shortages during the pandemic severely impaired maritime logistics, forcing many companies to reroute or cancel shipments.

In conclusion, vulnerabilities in maritime supply chains are multifaceted, arising from technological, geopolitical, operational, and natural factors. These vulnerabilities create risks that will be later on analyzed and when realized, can spread rapidly across global maritime systems, highlighting the critical need for resilient maritime logistics. Addressing these risks requires coordinated efforts among stakeholders, investments in infrastructure and technology, and the development of a robust contingency planning. The evolving nature of global trade demands ongoing attention to fortify maritime supply chains against future disruptions.

## 1.4. Objectives

The main goal of this dissertation is to explore the essence of resilience in maritime supply chains by identifying key risks and examining effective response strategies. Resilience will be analyzed, under the prism of existing literature, in terms of the maritime supply chains' ability



to anticipate, adapt, and recover from disruptions while ensuring operational continuity. This research will also seek to pinpoint vulnerabilities within supply chain networks, focusing on both external disruptions, such as geopolitical conflicts and extreme weather events, as well as internal inefficiencies like operational bottlenecks and technological shortcomings. It will evaluate how resilience measures can help mitigate risks and improve supply chain efficiency.

A vital part of achieving this goal is the inclusion and detailed examination of case studies related to past maritime disruptions and the role of technology in enhancing resilience. Events like the 2021 Suez Canal blockade and the COVID-19 pandemic, which significantly disrupted maritime supply chain nodes, will serve as key case studies to analyze the impacts of these disruptions and the effectiveness of the mitigation strategies that were implemented. This dissertation will also explore how technological advancements, such as blockchain for traceability, Artificial Intelligence (AI) for predictive analytics, and Internet-of-Things (IoT) for real-time monitoring can enhance resilience capabilities.

By connecting theoretical foundations with practical applications through case studies, this research aims to contribute to both academic literature and industry best practices, evaluating a comprehensive approach to building resilient maritime supply chains in an increasingly uncertain and complex environment.

## **2. Literature Review**

### **2.1. Defining Resilience**

#### **2.1.1. Theoretical Framework**

The last decades the aspect of resilience in supply chains has been emerging as an evolving field of study, especially the apparent ability of some supply chain networks to recover from inevitable disruptions more effectively than others has more recently triggered an open debate about supply chain resilience.

The word “resilience” originates from the Latin “resiliere” which actually means returning back to shape or position (Besinovic, 2020). The term of resilience alone, has a lot of different concepts depending on the scientific framework that it’s being examined. From sociology’s

point of view resilience is used to identify what makes social networks throughout disaster and recovery (Aldrich & Meyer, 2015). Bruneau et al. (2003), use resilience to identify and measure built infrastructure. In economics Rose & Wei (2013), associate resilience with the ability of industry's local business sectors to endure during economic cycles. Xu et al. (2023), noticed that resilience is commonly adopted throughout the literature to describe the ability of a system to return to its normal operations, recover from a disruptive event and sustain its position under external forces. According to McAllister (2016), the term of resilience in general, is usually associated with the ability of an entity or a system to recover from a disturbance or a disruption, therefore the following definition is being commonly used:

*"Resilience is the ability to predict, prepare for, and adapt to altering conditions and endure, respond to, and recover rapidly from disturbances while maintaining operational activities."*

As Vaggelas (2023), states in his recent work, the concept of resilience is closely linked with terms such as *agility, flexibility, and lean*. Agility refers to the time of adaptation process, when a system faces changes and disruptions, immediate or small adaptation time leads to increased agility. Flexibility is the ability of the system to provide innovative solutions in order to respond to sudden disruptions and offer a smooth recovery. Lean can be described as the continuous improvement of a process that eliminates waste leading the system to a better performance.

And finally Carpenter et al. (2001) came to the conclusion that resilience has three main properties: (a) the amount of change that a system can go through while retaining the same structure and function, (b) the extent to which the system is capable of organizing itself without assistance from external factors, (c) the extent to which a system develops the capacity to learn and adapt in response to disturbances.

In order to understand the concept of supply chain resilience, we have to analyze and define its components, theoretical foundations, and models that have been proposed to enhance it. The academic literature on supply chain resilience has significantly evolved over the past decades, stimulated by theories of systems thinking, risk management, and organizational adaptability.

As mentioned above, the theoretical framework of supply chain resilience draws from the systems theory. Complexity is inherent to supply chain networks as the interconnection amongst its entities is evident. For suppliers, manufacturers, distributors, retailers, and customers and so on so forth, the level of resilience depends on the system's ability to absorb shocks, adapt to new conditions, and recover to a functional state. Walker's et al. (2004) argument, that resilience is determined by the capacity to absorb disturbances and still maintain

the same basic structure and functions, has been recently transferred to supply chain management environment and has been emphasized with key attributes enhancing resilience, such as robustness, flexibility, and agility.

Christopher and Peck (2004), through their influential paper "*Building the Resilient Supply Chain*", describe modern supply chains as dynamic networks of interconnected firms where no single entity can operate independently, and even carefully managed procedures are ultimately dependent on the interconnected components that connects them, optimal efficiency relies on robust and dependable transportation and communication infrastructures.. While moving on Christopher and Peck provide as well a short but commonly accepted and inclusive definition of supply chain resilience "*The ability of a supply chain to return to its original state or move to a new, more desirable state after being disturbed*". The most important aspect of this definition is that it focuses both on recovery as well as improvement, taking into consideration that disruptions within the supply chains may create opportunities for innovation and improvement rather than merely necessitating a return to a pre-disruption baseline. The need for such capabilities is evident in highly complex global supply chains, where disruptions can ripple across multiple tiers and create significant damage.

Continuing in the same contexts as Christopher and Peck, Sheffi and Rice (2005) make a statement that supply chain resilience encompasses not only the capacity to mitigate risks but also the potential to surpass competitors and capitalize on disruptions.. They also elaborated on the dimensions of resilience by emphasizing the trade-offs between efficiency and flexibility. They argued that highly lean and cost-efficient supply chains tend to lack the redundancy necessary for quick recovery during disruptions. This observation, often referred to as the resilience-efficiency paradox, emphasizes the tension between minimizing costs and maintaining sufficient buffer capacity or alternative solutions to deal with potential disturbances.

Ponomarov and Holcomb (2009), provide another cornerstone definition of supply chain resilience as "*The adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function*". They see supply chain resilience as a multidimensional phenomenon and their work links resilience to risk management, adaptability, and recovery strategies while providing a structured approach to

identifying resilience-enhancing factors such as visibility, collaboration, and integration across the supply chain.

Erol et al. (2010) and Tukamuhabwa et al. (2015) extended these theoretical foundations by emphasizing the need for resilience strategies tailored to specific risk profiles. They identified key dimensions of resilience, including vulnerability reduction, robustness, agility, and adaptability, and argued that these dimensions could be dynamically balanced to achieve optimal outcomes. Vulnerability reduction involves proactive identification and mitigation of risks, whereas robustness focuses on building the inherent strength of the supply chain's infrastructure. Agility, in this framework, refers to the supply chain's ability to respond rapidly to changes, while adaptability involves longer-term adjustments to changing conditions and structural shifts.

Maritime supply chain resilience has gained significant attention as global trade relies heavily on maritime transport. The literature focuses, as well as, on resilience strategies to mitigate risks such as disruptions caused by natural disasters, cyber-attacks, geopolitical tensions, and pandemics. Studies about maritime supply chain resilience seem to be much scarcer as this is an emerging field in progress.

Pettit et al. (2010), set a conceptual framework about maritime supply chains that include resilience capacities like redundancy, flexibility and collaboration. Later on Fan & Stevenson, (2018) associate resilience in maritime supply chain as the ability to prepare for, respond to, and recover from disruptions while maintaining operational performance.

According to Gu & Liu (2023), maritime supply chain resilience signifies the capability of an organization or specific segment in maritime transportation to undergo disruptive incidents and recover to a satisfactory performance level. This encompasses discussions on port resilience, maritime networks resilience, and overall resilience of the maritime supply chain. Li et al. (2023) examined the resilience of maritime networks under the framework of risk analysis in maritime transport systems, including different aspects like operational security, technical considerations, organizational components, and natural factors.

Ghani et al. (2021), build their framework on maritime transport resilience by identifying and quantifying types of risks and vulnerabilities (internal, external etc.). Kersten et al. (2017), elaborated on emerging technologies like blockchain and Internet-of-Things (IoT) are increasingly researched for their potential to enhance visibility and traceability across maritime networks that led

to increased resilience respectively, while Ivanov & Dolgui (2020), refer to Artificial Intelligence (AI) capabilities for predictive analysis in order to anticipate and respond to disruptions. Finally Sheffi and Rice (2005), explored advantages from collaborative good practices among stakeholders, including ports, shippers, and policymakers and how effective governance and shared risk management frameworks could be proved beneficiary for maritime transport resilience.

Iftikhar et al. (2022) highlighted that by utilizing cutting-edge technologies to aid in data analysis, businesses can better manage the complexities and rapid changes of the external environment, thereby strengthening their resilience and adaptability. In the maritime sector, some firms have expanded their network reach and gained a competitive edge by adopting advanced information and communication technologies. Others have introduced new offerings, such as cargo tracking and monitoring of carbon emissions. These innovations not only diversify their service portfolios but also improve supply chain visibility, which in turn enhances flexibility and resilience (Acciaro and Sys, 2020). Furthermore, digitalization and automation have revolutionized the shipping industry, significantly improving the precision and timeliness of maritime intelligence. These advancements empower companies to address risks more effectively and reinforce supply chain robustness and resilience.

### **2.1.2. Supply Chain Resilience Models**

Resilience models often operationalize aforementioned theoretical frameworks to provide practical tools for supply chain effective management. Pettit et al. (2010), developed the Supply Chain Resilience Assessment and Management model (SCRAM) that has been widely referenced in academic papers. SCRAM, evaluates resilience based on specific resilience enhancers, such as flexibility, redundancy, collaboration, visibility, and risk awareness, and resilience inhibitors, such as reliance on single sources, lack of transparency, and rigid processes. By mapping these factors against the supply chain's ability to overcome and recover from disruptions, the model provides a comprehensive tool for resilience assessment.

The Resilience Maturity Model (RMM) introduced by Carvalho et al. (2012), encompasses a development model, stating that supply chains progresses through different stages of resilience maturity. From reactive to proactive and ultimately to predictive and transformative levels, the model outlines how organizations can build their resilience capabilities over time. Lee's (2004), Triple-A framework focuses on the dynamic nature of resilience that is further captured

through the concept of agility, often framed as a critical enhancer of resilience. The notion of agility, defined by Lee, as the ability to respond rapidly to environmental changes and market fluctuations, complements the broader understanding of resilience by emphasizing real-time adaptability and responsiveness. This framework has been widely adopted in analyzing how supply chains can synchronize operations with demand while maintaining flexibility to adjust to disruptions.

Towards the further operationalization of resilience in supply chain networks, predictive analytics and digital tools have become indispensable. Ivanov and Dolgui (2020), introduced the concept of the “Adaptive Supply Chain” model, as digitized system capable of modeling, simulating and responding to disruption and disturbances in real-time, through data analytics and artificial intelligence. Those kind of technologies enhance visibility and minimize decision-making time, which are crucial for increased resilience. For instance, digital twins, virtual representations of physical supply chains, allow for scenario planning and stress-testing, providing insights into the potential impacts of disruptions and optimal recovery options (Wang et al., 2022).

Another critical aspect of resilience is collaboration across the supply chain network. Internal collaboration enhances resilience by promoting shared risk awareness, joint problem solving, and resource pooling. Collaborative models emphasize the role of trust and information sharing among supply chain partners as key enablers of effective coordination during disruptions. Scholten and Schilder (2015), argued that collaboration acts as a multiplier of resilience by facilitating proactive risk management and dynamic response strategies.

Despite the progress in understanding and modeling supply chain resilience, challenges remain. Measuring resilience, especially quantitatively is inherently complex due to its multidimensional nature. Various metrics have been proposed, such as recovery time, cost impact and customer service levels, but a universally accepted measurement framework is not evident. Qualitative methods are more theoretical, for instance, analysis of concept related definitions, properties or theoretical frameworks and case studies. Omer et al. (2012) proposed a model for assessing the resilience of the Maritime Transport System by considering cargo, time, and cost factors. In contrast, Justice et al. (2016) and Shaw et al. (2017) utilized case studies using data from the United States and the United Kingdom to examine the response of port systems to disruptions. As per the work of Hossain et al. (2020) and Wang et al. (2023), qualitative methods, amongst others include Bayesian networks, complex networks,

mathematical modeling, simulations and game theory. As for the factors that are being usually qualitatively measured Li et al. (2024), summarizes the most common ones to be absorptive capability, recovery time, restorative capability, robustness, reliability, responsiveness and resourcefulness. Furthermore, the integration of resilience into supply chain strategy often involves trade-offs with other performance objectives, such as cost efficiency and speed. Managing these trade-offs effectively requires an approach that considers the specific context of each supply chain and the types of risks it faces.

Future research in supply chain resilience could focus on several promising aspects such as sustainability. Sustainable supply chains are inherently designed to minimize environmental and social risks, which can contribute to long-term resilience. However, achieving both objectives simultaneously can be challenging, given the potential conflicts between environmental goals and the need for redundancy or flexibility. The concept of “resilient sustainability” could provide a framework for balancing these priorities in supply chain design.

In conclusion, resilience in supply chains encompasses the capacity to prepare for, respond to, and recover from disruptions while adapting to new conditions. Theoretical frameworks grounded in systems thinking, risk management, and organizational adaptability provide the foundation for understanding resilience. Models such as the Supply Chain Resilience Assessment and Management (SCRAM), Resilience Maturity Model, and Lee’s Triple-A framework operationalize resilience, offering practical tools for assessment and enhancement. Digital technologies and collaboration further augment resilience capabilities, although challenges related to measurement and trade-offs persist. As global supply chains continue to face unprecedented challenges, the importance of resilience as a strategic objective will only intensify, necessitating further research and innovation in this critical field.

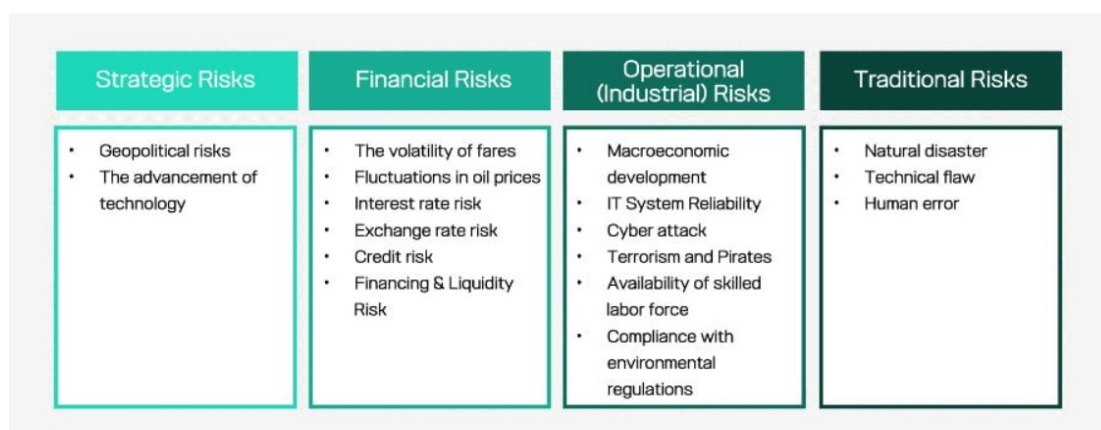
## **2.2. Types of Risks in Maritime Supply Chains**

Maritime supply chains are inherently susceptible to numerous risks due to their complexity and the fact that they stretch over longer and longer distances, which makes them vulnerable compared to other supply chains (Vilko and Hallikas, 2012). In recent years, academic studies have focused on exploring both traditional and emerging risks as well as elaborating on strategies in order to address, understand and mitigate them. In order to understand how to



build a possible pathway to maritime supply chain resilience, we will go through recent literature and thoroughly analyze those risks.

Bernstein (1996), defines risk as the product of the likelihood of an event occurrence (its probability) and its consequences. Walters (2007), in his work states that risks in supply chain are unpredictable events that might interrupt the smooth flow of materials. When products are being delivered there always the inherent risk that the delivery will be later than promised, goods are damaged or lost, wrong products are being delivered or to wrong place and their immediate symptoms can cause a widespread effect throughout the chain. One of the most common ways, is to classify risks under two categories, internal and external risks. Christopher & Peck (2004), elaborated on the fact that supply chain risks can be categorized in many ways depending on the perspective and suggested a simple categorization as internal to a company, driven by process and control factors, external to the company but inherent to the supply chain network enhanced by demand and supply disruptions, and external ones, affected by upstream and downstream environment. Throughout the literature we can find many kind of classification about types of risks affecting maritime supply chain but the most common ones can be summarized to operational risks, geopolitical, environmental and natural risks, technological or cybersecurity, demand-supply and economic risks.



**Figure 2: The Type of Shipping Risk**

Source: <https://cello-square.com/en/blog/view-226.do>

### 2.2.1. Operational risks

Operational risks may emerge from inefficiencies and disturbances that arise from day to day logistics activities in maritime supply chains and are the most dealt in the literature. Those type of risks include port congestion, equipment failure, human error in cargo handling, long waiting



hours, stowage, all of which can lead to delays and financial losses (Chang, 2022). As per Van de Voorde & Vanelander, (2020) port inefficiencies are one of the most significant operational risks, especially in ports considered to be logistic hubs or in high traffic regions where insufficient port infrastructure struggles to serve increased trade volumes. For instance equipment breakdown, such as cranes, container barges and cargo handling machines can severely affect and delay operations increasing lead times and causing port congestion. Poor intermodal connectivity at ports further intensifies the risk of delays and disrupts continuity of supply chain flow (Rodrigue, 2022). Recent data from the World Bank also highlight that port inefficiencies cost global trade billions of dollars annually (World Bank, 2021).

The maritime workforce plays an essential role in ensuring operational efficiency, yet the sector is dealing with chronic labor-related risks. Strikes from labor unions forms another important operational risk, having profound implications for the whole maritime supply chain. Jaffe (2023), refers to the example of the dockworkers strike at the port of Los Angeles in 2023, one of the busiest U.S ports, which led the port to cease operations completely causing massive backlogs and delays. Furthermore, insufficient training and non-compliance with international standards such as the International Safety Management (ISM) magnify operational risks, particularly in regions with regulatory oversight (ILO, 2022). A study by Cahoon et al. (2022), indicates that those kind of disruptions can result not only in direct and obvious implications in lead time, as well as financial ones, but also reputational damage, as maritime supply chain main stakeholders perceive such incidents as indication of unreliable service.

Maritime accidents, such as vessel collisions, groundings, and sinking, are also a form of operational risk. For example, the grounding of the Ever Given in the Suez Canal in 2021 resulted in a six-day blockade of one of the world's busiest trade routes, causing delays in the delivery of goods and an estimated 10 billion dollars loss per day for global trade (Khalid, 2021). Such incidents highlight the fragility of maritime chokepoints and their vulnerability to operational risks.

Efforts to mitigate these risks often require coordinated international responses, encompassing regulatory frameworks, technological investments, and workforce development (IMO, 2023). Despite these measures, operational risks persist due to the inherent complexity of maritime logistics and the dynamic nature of global trade.

### 2.2.2. Geopolitical Risks

Geopolitical risks are inherent in maritime supply chains due to its reliance on stable international relations, secure trade routes and predictable regulatory environments. Geopolitical events and tensions often disrupt these factors, leading to increased costs, delays, and vulnerabilities for maritime stakeholders (UNCTAD, 2023).

Rahman & Tsamenyi (2010) stretch out the importance geopolitical risks, such as territorial disputes in significant waterways like the South China Sea and the Strait of Hormuz. Especially the South China Sea, facilitating almost one third of global trade, has been a point of long-lasting dispute among several nations including China, the Philippines and Vietnam. Such disputes can disrupt severely maritime routes and cause unexpected costs and delays (Lee, 2021). Same case is the Strait of Hormuz, a major chokepoint of oil trading routes, which has been affected by the tensed U.S.A.-Iran relations, including incidents of vessel seizures and sabotage, which significantly affect maritime logistics (Smith et al., 2020). The ongoing Russia - Ukraine conflict has significantly disrupted maritime routes. A paper by the European Parliament’s Research Service (2022), stretches out the importance of the closure of major Ukrainian ports, especially in the Black Sea area and the severe impact on the maritime logistics routes and connectivity. This disruption has led to main routes alternation causing substantial delays and affecting supply chains across Europe by raising freights and final product’s prices. The most important implications of this conflict though, have been profound on the energy maritime transportation supply chains. Europe’s dependency on Russian natural gas and crude oil, as well as on their transportation routes and methods, has made evident the vulnerabilities in maritime energy transportation. This fact has highlighted these risks, leading to increased scrutiny and the need for alternative routes. The International Maritime Bureau (IMB) reports that the Gulf of Guinea accounted for 95% of global kidnappings of seafarers in 2021, posing a direct threat to crew safety and increasing insurance rates for vessels transiting these waters (IMB, 2022). This situation underscores the maritime supply chain's critical role in energy security (Kalish, 2022). As Cong et al. (2024) note, the global maritime industry respond to these challenges by adapting and exploring alternative routes and ports to maintain supply chain continuity. This adaptation has led to an overall increase in maritime activities in certain regions, reflecting the industry's resilience. However, the long-term sustainability of these adjustments remains uncertain.

Another form of geopolitical risks include economic sanctions and trade wars. For instance Jones et al. (2017), refer to the impact of economic sanctions imposed by the western countries to Russia following the Crimea conflict in 2014. He concludes that sanctions disrupted maritime operations and as a matter of fact not only targeted countries were affected but also countries depended on the later ones.

Piracy and Maritime crime is as well an emerging geopolitical risk as despite all the efforts, it remains persistent in some regions that are crucial for the maritime supply chain. The International Maritime Bureau (IMB) reports that while incidents have declined in areas such as the Gulf of Aden due to increased patrols, new hotspots have emerged such as the Gulf of Guinea. Another highly affected area is the Red Sea that is being terrorized by the Houthi rebel's regime of Yemen, as it is the direct passage towards the Suez Canal. This has a direct effect to maritime routes, as companies and traders have to choose between the non-safe passage, which comes with increased risk as well as increased insurance fees, or the longer route that passes all around Africa, through the Cape of Good Hope which of course comes with substantial delays and extra costs.

Geopolitical risks profoundly impact maritime transport by disrupting trade routes, escalating costs, and threatening the security of maritime assets. As global interconnectivity intensifies, the stakes for managing these risks grow higher, requiring proactive and collaborative approaches.

### **2.2.3. Environmental risks**

Environmental risks in maritime supply chains stem from both natural and anthropogenic factors. Climate change, has played a vital role as it intensified the frequency and intensity of extreme weather conditions, such as hurricanes and typhoons. In particular, Notteboom & Rodrigue (2021), refer to the typhoon Haiyan of 2013 that severely affected shipping routes in Southeast Asia. Such events profoundly increase vulnerability and disrupt maritime supply chain continuity and increase cost in order to adhere those effects. Studies indicate that hurricanes, typhoons, and other natural disasters disrupt port operations and maritime transit routes, leading to significant economic losses (Becker et al., 2013).

Studies project that rising sea levels, coupled with the increasing frequency and intensity of tropical storms, will amplify risks for port infrastructure and shipping lines in the coming decades (Becker et al., 2023). Ports such as Rotterdam and Shanghai that are low-lying cities

are increasingly exposed to flooding risks, which of course could cause disruptions and backlogs in cargo handling (Becker et al., 2023). Addressing these risks requires substantial investment in adaptive infrastructure, such as sea walls and elevated facilities, as well as adopting land-use policies to mitigate long-term impacts (Nicholls et al., 2019).

Human-induced environmental risks also impact maritime supply chains. Oil spills, chemical leaks, and marine pollution, damage ecosystems, often resulting in fines, legal liabilities, and reputational harm. For instance, the Deepwater Horizon oil spill in 2010 led to widespread environmental degradation and billions of dollars in remediation costs (Chalvatzis & Ioannidis, 2017). Regulatory frameworks such as the International Convention for the Prevention of Pollution from Ships (MARPOL) impose strict requirements on shipping operators to minimize these risks. Compliance, however, involves substantial costs, particularly for retrofitting of vessels in order to meet new standards, thereby challenging smaller shipping companies (Schlag et al., 2020). These risks necessitate a combination of mitigation and adaptation strategies that incorporate resilient infrastructure, stringent regulatory compliance, and proactive international cooperation.

#### **2.2.4. Technological risks**

Rapid advancements in digital technologies have transformed maritime supply chains but also introduced new vulnerabilities. Cybersecurity risks have emerged as a paramount concern, with studies showing that the frequency and severity of cyberattacks on port systems and vessels have risen substantially over the last decade (Kessler, 2022). As shortly referred earlier, the cyberattack on Maersk’s IT systems in 2017 disrupted the company’s global operations and resulted in an estimated \$300 million loss (Chang, 2022). Another important risk arises from technological obsolescence. Vanelslander et al. (2020) stretch out the fact that outdated systems can suspend technological transformation and can jeopardize safety, as seen in incidents where older navigation systems failed to provide accurate data during emergencies.

Beyond cybersecurity, the adoption of autonomous vessels and other forms of automation raises questions about system reliability and accountability during system failures (Zhou & Wang, 2021). Recent studies highlight the risks posed by software malfunctions and insufficient safeguards during autonomous navigation, which can lead to collisions or cargo mishandling (Meng et al., 2023).

The Internet-of-Things (IoT), has been proved integral to digitalization and modern maritime transport by offering a lot of predictive maintenance capabilities. A research by Trelleborg et al. (2021), underlines that while Internet-of-Things (IoT) reduces costs and improves efficiency, it significantly elevates the risk of data compromise and system manipulation. Additionally, overreliance on Internet-of-Things (IoT) could lead to disruptions in cases of system failure, where manual overrides are no longer feasible due to eroded human expertise. For all the above reasons enhanced cybersecurity frameworks, investments in technology upgrades, and adaptive regulatory standards are essential to ensure the resilience and sustainability of maritime transport in the face of evolving technological challenges.

#### **2.2.5. Demand-Supply and Economic risks**

Demand and Supply risks in maritime transport have their roots primarily on differences between the supply of shipping capacity and tonnage and the demand for transportation services and goods. Global trade's fluctuations significantly influence those risks and their occurrence probability. Stepford (2009), examines periods of economic downturn, such as the 2008 credit crunch, and noticed a significant drop-in in global trade's volumes resulting to excess shipping capacity, lower freights and significant losses for shipping companies. On the contrary unexpected surges in demand, such as the ones occurred during COVID-19 pandemic, led to significant capacity shortages and skyrocketed freight rates creating enormous bottlenecks, as ports and shipping lines were struggling to coop with the unprecedented demand for e-commerce goods (Notteboom & Pallis, 2021). Additionally seasonality effects, such as high demand during holiday seasons, further enhance those risks urging for flexible and adaptive capacity planning, resulting to higher resilience levels.

On the contrary, economic risks include broader financial and macroeconomic factors that directly influence profitability and sustainability of maritime supply chains. Sabri et al., (2012), elaborate on the case of exchange rate volatility that can significantly affect operating costs and revenue streams for shipping lines as well as other significant players across the maritime supply chain. Moreover, oil price fluctuations directly influence fuel costs, which are considered to be a substantial percentage of a ship's operating expenses. Chang & Lee (2020), in their study have proved that sharp increases in oil prices led to higher freight rates and reduce competitiveness.

### 2.2.6. Recent Trends and Conclusion

Recent studies reveal emerging trends towards mitigating risks within maritime supply chains. One prominent trend is the adoption of digital technologies. Blockchain, artificial intelligence (AI), and Internet-of-Things (IoT) technologies offer enhanced transparency, predictive capabilities and traceability. Blockchain for instance permits secure and efficient data sharing across supply chain stakeholders, reducing the risk of scam and delays (Bian et al., 2022).

Furthermore, climate change adaptation measures, such as the implementation of resilient port infrastructure, are gaining points among maritime supply chain stakeholders. Ports are investing in flood defenses, renewable energy sources and digital technology to improve resilience and prepare for extreme weather events (Becker et al., 2023).

In addition to resilience-building measures, trends in de-carbonization are reshaping the maritime risk landscape. While compliance with new IMO regulations presents immediate operational challenges, it also drives technological innovation in cleaner fuels and energy-efficient vessel designs (IMO, 2021) and automation and electrification of port equipment contribute to reducing the carbon footprint of maritime operations (Pawlik et al., 2021).

By closing this chapter, it becomes obvious that maritime supply chains are indispensable to global commerce, but for this reason they are extremely vulnerable to diverse and interconnected risks. Operational, economic, environmental and geopolitical factors play significant role in shaping the vulnerabilities of these supply chains. As the global trade evolves though, recent trends and studies showing an increasing tendency towards the development of proactive and adaptive strategies in order to mitigate risks effectively. Building more robust and resilient maritime supply chains, will be pivotal ensuring sustainable growth in international trade and an effective risk management framework.

## 2.3. The Maritime Network and Essential Stakeholders

The Maritime network is serving international logistics as the main way of transportation of goods around the globe. It is a complex and dynamic system comprising of ports, shipping routes, vessels, shipping owners and companies, forwarders regulatory authorities and other various stakeholders, and is being held responsible for transporting 90% of global trade (The Maritime Resilience Breakthroughs, November 2022). At its very core though, the maritime network is being consisted of three main elements; seaports, shipping routes and vessels. Ports

serve as critical nodes within the network, linking the intermodal transportation system. Major hub ports, such as Shanghai, play critical role in global trade, handling over 47.3 million TEUs (twenty-foot equivalent units) in 2022, making it the world’s busiest port (Shanghai Port Authority, 2023). Shipping routes connect ports through sea pathways. These routes follow economic and geographic constraints, with critical chokepoints like the Strait of Malacca and the Suez Canal playing disproportionate roles in trade volumes, as according to IMO (2020), around 20% of global trade passes through the Strait of Malacca annually. Such nodes and routes are inevitably characterized by their high dependency and potential for disruption. The vessels themselves, ranging from container ships to bulk carriers and tankers, are inherent to maritime transport. Continuous technological advancements throughout the years, in ship design and automation have significantly increased their efficiency, further driving economies of scale (Stopford, 2020).

Containerization, has profoundly transformed the maritime industry by enhancing efficiency, minimizing costs and reshaping global trade’s patterns. As per Rodrigue & Notteboom (2008), in 1980 total container throughput around the world barely exceeded 40 million TEU’s and raised to just 75 million by 1990, carrying approximately 3,000-8,000 TEU’s per vessel. Since then and until 2020, there has been an exponential increase of around 1,500%, in carrying capacity per vessel reaching to 24.000 TEU’s (Allianz Safety and Shipping Review, 2024).



**Figure 3: Safety and Shipping in Global Maritime Trade**

*Source: Allianz Safety and Shipping Review, 2024*

Containerization, standardized cargo handling, allowing for rapid and efficient procedures and reduced loading-unloading time by up to 85% (Notteboom, 2004). As per Rodrigue et al. (2020) the standardization of containers have also reduced shipping costs by approximately 20%-30% compared to break-bulk methods. Finally, Ducruet & Merk (2013) in their work, conclude that containerization enhanced infrastructure upgrades, such as deeper ports and specialized terminals. They also found out that ports accommodating container ships have seen GDP growth correlations, with countries like China witnessing a 15% economic growth boost linked to port expansion. The World's Bank research in 2020, further supported those findings by stating that adoption of upgrades and new technologies has led to productivity gains of 45% in major global ports.

The maritime network is essential to global economic systems and it has strategic implications for national security and energy supply. Approximately 60% of global crude oil is transported via



maritime routes, highlighting the significance of securing these pathways for energy-dependent economies (BP Statistical Review of World Energy, 2023). The COVID-19 pandemic and recent geopolitical tensions, such as the Russia – Ukraine conflict, have further emphasized the



criticality of the maritime network in maintaining the resilience of supply chains (Notteboom & Pallis, 2023).

### 2.3.1. Maritime Shipping Companies

Shipping companies are indeed the backbone of maritime supply chain. They own and generally operate a vast fleet of different ships that help transport cargo around the world. They are fundamental in influencing global supply chain by determining capacity volumes, and speed of seaborne transport. Stopford (2009) mentions in his work that shipping companies are essential contributors of global trade, providing transportation services with competitive prices, thus enabling international trade networks to grow. According to data from the International Chamber of Shipping (ICS), around 70,000 vessels transport over 11 billion tons of goods annually, underlining the critical role of shipping companies in maintaining the smooth movement of international trade.

The importance of shipping companies extends beyond mere transportation. Shipping companies play a crucial role in overseeing the efficient movement of goods within the supply chain, ensuring the smooth transit of freight, information, and financial exchanges throughout the entire process. These companies collaborate closely with multiple stakeholders, including carriers and ports, as highlighted by Lam (2008).

Shipping companies play a critical role in enhancing maritime transport resilience by ensuring the continuous movement of goods through dynamic risk management strategies, particularly when facing disruptions (Oliviero & Mastromarco, 2017). As per Vijayan et al. (2021), during the COVID-19 pandemic, shipping companies were forced to adapt quickly, adjusting to changing demand patterns, lockdowns, and port congestion. The ability to adjust is a key determinant of supply chain resilience. This kind of evidences may be strengthened by the application of lean supply chain good practices, such as the implementation of Just-in-Time (JIT) that merely relies on timely deliveries to reduce costs and improve supply chain efficiency and resilience eventually. However, JIT can be disrupted by shipping delays, indicating the essential need for shipping companies to manage uncertainties, effectively. Thus it becomes more than evident that the resilience of maritime transport is closely tied to these companies' ability to mitigate disruptions, while maintaining the smooth flow of goods.

### 2.3.2. Freight Forwarders

Freight forwarders have the vital role of acting as intermediaries in the shipping process, handling the complex coordination of international cargo on behalf of shippers and product owners. So, freight forwarders are not considered to be active carriers but third-party logistics services providers, by using their professional expertise to handle and prepare documentation, customs, storage, management packaging, insurance and all relevant details required for the on time and in full delivery of products. As Skiba (2020) mentions, a sea freight forwarder is a professional who is able to arrange efficient transport services and proactively solve or minimize any kind of problems that may occur in the process. The result should be, best quality services at the lowest possible cost.

As per a research from the International Transport Forum (2020), the freight forwarding industry is highly correlated to the performance of the global maritime logistics sector. According to the same research the contribution of the freight forwarding field is about 8% of the global GDP.

Xue et al, (2022), correlates freight forwarders with efficiency within maritime supply chain. Their expertise in managing logistics networks is leading towards mitigating risks occurring from delays, extra costs and potential disruptions.



**Figure 4: What do freight forwarders manage?**

*Source: [freightos.com/freight-resources/what-services-do-freight-forwarders-offer](https://freightos.com/freight-resources/what-services-do-freight-forwarders-offer)*

### 2.3.3. Port Operators

Port operators manage the daily operations of ports, handling the loading and unloading of cargo, vessel scheduling, and maintaining port infrastructure. As per Notteboom et al. (2021), port or terminal operators are usually private entities and can be grouped into three main categories; pure stevedores, maritime shipping companies and financial holdings.

PSA International of the port of Singapore is the most well-known example of a global terminal operator coming from a stevedore background, followed by Hutchison Ports, in Hong Kong.

Stevedores account for about 50% of ports controlled by terminal operators. Maritime shipping lines invested a lot of funds into port operating business, such as APM Terminals, an A.P. Moeller-Maersk's company, which is one of the largest global terminal operators from a maritime shipping background. Shipping lines account for about 31% of the port terminals controlled by terminal operators, as noticed by Notteboom et al. (2021). The last big category is financial holdings, the majority of which have an indirect approach by acquiring the port and only keep the management part of the job.

The efficiency of port operators significantly impacts the efficiency of the maritime supply chain, as inefficient ports result in increased dwell time for vessels and higher transportation costs. Research indicates that improving port efficiency by just 10% can lead to a 2.5% increase in a country's trade volume (Rodrigue & Notteboom, 2008).

The efficiency of port operations is also closely linked to the automation and digitization of port services, with investments in technologies such as port management systems (PMS), container tracking systems, and electronic data interchange (EDI). The greatest example is the port of Rotterdam that has implemented the world's first automated container terminals, proving that technological advancements by port operators can lead to significant efficiencies in handling larger volumes of cargo and enhancing maritime resilience (Port of Rotterdam, 2020).

#### **2.3.4. Regulatory Authorities**

Regulatory authorities are responsible for ensuring that the maritime industry operates safely, securely and with regard to the environment, and thus their primary focus is to minimize risks in maritime operations, including risks of accidents, pollution and security threats. These authorities, including the International Maritime Organization (IMO), set standards for ship safety, pollution prevention, and operational efficiency on a global scale, while national bodies, including the United States Coast Guard (USA) or Maritime and Coastguard Agency (UK), implement and monitor compliance locally. They are responsible for setting the legal frameworks that regulate shipping operations for overseeing international conventions, such as the International Convention for the Safety of Life at Sea (SOLAS), the International Maritime Solid Bulk Cargoes Code (IMSBC) and the International Convention for the Prevention of Pollution from Ships (MARPOL), which aims to promote the safe and efficient operation of vessels and prevent accidents (Hess et al., 2022).

Moreover, regulatory authorities also play a critical role in enhancing innovation and adaptation to emerging challenges in maritime transport. With the rise of climate change and technological advancements, the shipping industry faces pressure to decarbonize and digitize its operations. In addition, digital transformations, including e-navigation and cybersecurity measures, have been included into regulatory frameworks to enhance operational efficiency and resilience against cyber threats (IMO, 2021). As Stopford (2009) mentions in his work, regulatory authorities continuously updating regulations and collaborating with industry stakeholders, ensure that the maritime sector evolves in line with international goals and sustainability principles, paving the way for a safer and more resilient future for global maritime transport.

### **3. Risks and Disruptions Analysis in Maritime Supply Chains**

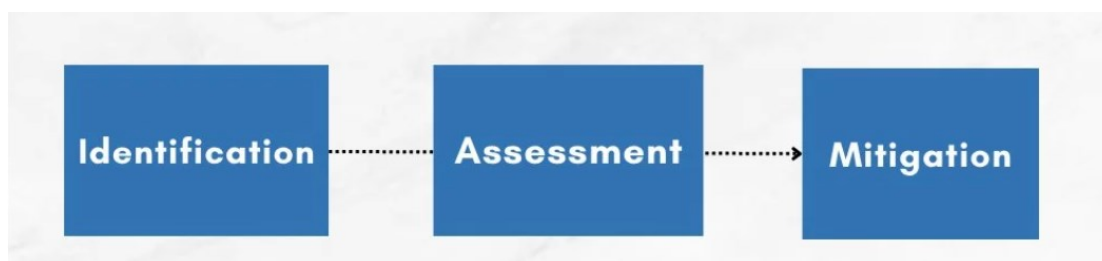
#### **3.1. Resilient Maritime Supply Chain Risk Management**

The importance of resilience in maritime supply chain risk management has grown significantly over recent decades. However, the inherent vulnerabilities of maritime supply chains, arising from the complexity of its multiple interconnected nodes, including exposure to disruptions from natural disasters, geopolitical conflicts, cyberattacks, and pandemics, demand broad risk management approaches to ensure continuity. In this framework, resilient maritime risk management has emerged as a critical factor to ensure the sustainability and adaptability of maritime supply chains.

Hollnagel (2014), refers to the resilience applied to maritime risk management, as the capacity of maritime systems to anticipate, absorb, adapt to, and recover from adverse events while maintaining critical operations. Under this concept, maritime risk management is laying emphasis rather in proactive and adaptive measures than solely focusing on risk avoidance or mitigation. According to Sheffi (2005), resilience is being characterized by two main features; resistance, which minimizes the immediate impact of a disruption, and recovery, which ensures a smooth return to normality. The dynamic nature of global trade requires maritime systems to be not only robust but also agile in responding to evolving threats (Becker et al., 2018). Resilience, therefore, serves as a multidimensional framework that combines risk assessment, operational flexibility, and collaborative problem-solving.

### 3.1.1. Risk assessment Frameworks in Maritime Supply Chains

Maritime risk assessment is a systematic process that identifies, evaluates, and mitigates risks within maritime supply chain to enhance operational safety, efficiency, and resilience.



**Figure 5: Supply Chain Risk Management Phases**

Source: <https://www.vem-tooling.com/supply-chain-risk-management/>

As per Sheffi and Rice (2005), effective risk management begins with the identification and classification of risks. This phase aims to pinpoint potential threats to maritime operations, assets, personnel, and the environment. Sheffi and Rice (2005), continue by classifying risks into internal and external; internal risks include operational inefficiencies or technological failures, while external risks include natural disasters and geopolitical instability. Lu & Shi (2018), in their research refer to various systematic techniques used Hazard and Operability Studies (HAZOP), Fault Tree Analysis (FTA), and Failure Modes and Effects Analysis (FMEA). These techniques analyze possible risk scenarios by considering system vulnerabilities and failure paths.

The second phase moves on with risk analysis and assessment, which examines quantitative and qualitative criteria of the likelihood and consequences of the already identified and classified hazards. The evaluation process classifies risks according to their intensity, recurring time and possible impacts, in order to prioritize the one's requiring immediate actions. Hassan & Folorunsho (2019), highlight the use of Probabilistic Risk Assessment (PRA) and dynamic risk models to forecast risk probabilities and predict their impacts and severity under different conditions.

In the third phase we find risk mitigation. It includes the implementation of different kind of measures in order to eliminate or reduce the impact of the already identified risks to acceptable and manageable levels. Psarros et al. (2011), propose strategies such as, technical upgrades,

staff training, and investment in infrastructure. Collaboration amongst the stakeholders of the maritime supply, including port authorities and regulators, also play a crucial role in this stage to ensure coordinated and effective risk-mitigation strategies.

Maritime risk assessment plays a crucial role in reducing threats to the industry, boosting its resilience, and ensuring sustainability. The combination of international cooperation and compliance with regulations, along with advancements in technology, has led to notable progress in this area.

### **3.1.2. Maritime Risk Management Principles and Strategies**

Christopher and Peck (2004), highlight four essential principles of resilience; flexibility, redundancy, collaboration, and agility. These principles act as the foundation of effective risk management strategies and can support in mitigating disruptions.

Flexibility refers to the ability to modify operational and logistical processes in response to unforeseen disruptions. Ivanov (2020), refers to strategies such as multi-sourcing, flexible contracts, and dynamic routing. With flexibility, companies can easily transit between suppliers or shipping routes when their first options become unavailable due to any kind of disruptions.

Redundancy refers to the practice of having extra resources, like additional inventory or spare capacity. Although redundancy can lead to increased operational costs, it acts as a safeguard against significant disruptions. Lee et al. (2017) argue that establishing redundant port facilities or keeping alternative routes available within the network can mitigate systemic vulnerability.

Collaboration among maritime transport stakeholders, such as shipping companies, freight forwarders, and port operators, improves visibility and traceability and boosts collective problem-solving efforts (Cui et al., 2019). The use of advanced data-sharing platforms and real-time tracking systems, along with technologies like blockchain, can enhance transparency and coordination and eventually resilience.

Finally agility in maritime supply chains refers to their ability to quickly respond to unforeseen disruptions. Agility is usually supported by efficient decision-making and strong contingency plans. Stakeholders in the maritime sector who focused on agile responses during the COVID-19 pandemic were able to adjust their capacity allocations and resource deployments effectively (Notteboom & Haralambides, 2021).

Another important issue to classify different risk management approaches into proactive or reactive strategies. Ivanov & Dolgui (2020) characterize proactive strategies the ones that aim to enhance adaptive capacities before any disruptions happen, which might include investing in predictive analytics and creating redundancy. On the other hand, reactive strategies usually arise after a disruption has occurred.

As per Notteboom and Rodrigue (2020), proactive strategies initially include resilience into the design and operations of supply chains, by diversifying trade routes, investing in multi-modal logistics, and forming partnerships and collaboration among local stakeholders. During their research, Notteboom and Rodrigue (2020) also noticed that ports with access to varied hinterlands demonstrated greater resilience during global crises, including the COVID-19 pandemic.

On the contrary, reactive strategies involve quickly transforming logistics process, speeding up customs clearance in emergencies, and maintaining real-time communication with stakeholders. Examples of adaptive frameworks, like Maersk’s reaction to the NotPetya cyberattack, highlight the importance of having pre-defined contingency plans paired with an agile organizational culture (Smith et al., 2021).

However the importance of an efficient maritime supply chain risk management, there are several challenges to be faced within the implementation process. Investing in advanced technologies, redundancy, and compliance mechanisms can highly increase costs and create financial constraints on stakeholders, making the right balance between resilience and cost-effectiveness, a quite difficult goal. Moreover, establishing collaboration between various stakeholders with different levels of technological expertise is a quite difficult task. Finally, the geopolitical landscape significantly influences the risk environment, bringing unforeseen uncertainties. Issues like trade disputes, piracy, and sanctions lead to increased of operational costs and decrease efficiency, necessitating for quick action and strong contingency planning.

### **3.2. Impact Assessment**

As we have previously referred to, the stability of maritime supply chains is highly affected by global disruptions such as natural disasters, geopolitical conflicts, pandemics, and trade wars. These disruptions deeply affect both the operational and financial dimensions of maritime supply chains, creating significant impacts to their resilience.



As per Notteboom et al. (2022), in order to fully understand the length of these impacts, we need to classify them in two main categories; qualitative and quantitative. Qualitative effects mainly relate to non-numeric aspects, such as disruption in decision-making, coordination process and the relationships between maritime supply chain players. These qualitative elements influence the way stakeholders perceive and respond to risk. On the other hand, quantitative impacts are those that can be measured numerically, such as financial losses, transportation delays, or the costs of inventory accumulation. These categories, taken together, provide a holistic view of the challenges that maritime supply chains face.

### 3.2.1. Qualitative Impacts

From a qualitative point of view, global disruptions often lead to a breakdown of trust and communication between supply chain stakeholders. Specifically, geopolitical instability or an existing public health crisis, such as the COVID-19 outbreak, can disorientate information flow and subsequently influence strategic decisions related to shipping routes, port operations, and supply replenishing. Political tensions, such as trade sanctions or embargos, can worsen the effects of such impacts. An example, is the bad trade relationship between the U.S. and China in recent years, which resulted in increased uncertainty and lead shipping companies to seek alternative routes, further complicating the overall logistics network (Bremmer, 2020).

Another qualitative impact is the change of risk perception and the adoption of broader supply chain resilience enhancing policies in order to respond to disruptions. Christopher and Peck (2004), highlight the fact that disruptions boost companies to reschedule by increasing the emphasis on risk identification, risk avoidance, and agile responses. The grounding of the mega containership Ever Given at the Suez Canal that led to its blockade for several days, revealed the weaknesses in relying on Just-In-Time supply chains and signaled the necessity for companies to incorporate flexibility into their processes to withstand such shocks.

Environmental awareness and sustainability is considered to be another aspect that raises qualitative impacts. Simpson & Zaraket (2020), in their research conclude that disruptions from natural disasters or pandemics, are causing changes in operational strategies which are typically reflected in sustainability commitments. The growing demand for sustainable shipping, facilitated by technological advances in green fuels and eco-friendly design of ships, is a direct consequence of such disruptions. For instance, prior to the COVID-19 pandemic, sustainability in shipping had been viewed more as a public relations effort. Nevertheless, after the major



disruptive effects that the pandemic had, is considered to be a driver for transformations in shipping practices toward resilience and environmental effectiveness.

### 3.2.2. Quantitative Impacts

Quantitative impacts are usually more visible and measurable because they lead in direct costs fluctuations, throughput, and service levels. As per Notteboom & Rodrigue (2009), one of the most common form of quantitative impacts is economic shocks. Container throughput and cargo volumes may dramatically fall during recession times as a result of the decreased demand. A recent example is the economic impact of the 2008 global financial crisis, significantly lowering demand for products, leading to fewer vessels needed, decreased shipping lines' revenues as well as port activities. Another example is of course the COVID-19 pandemic that had as a result labor shortages and operational challenges, creating extended lead times and port congestions. Baker et al. (2020), also noticed that especially the field of oil and chemicals maritime transportation, experienced substantial losses due to low demand.

Another straightforward quantitative impact, is the one of shipping costs, especially in cases of disruption from natural phenomena or disasters. Kumar et al. (2015) mentions the hurricane season in the Gulf of Mexico that raises shipping costs due to port closures, rerouting and severe vessel schedule alternations. The direct cost impact arisen from those kind of disruptions can be easily quantified and monetized. Additionally, there are efficient numeric Key Performance Indicators (KPI), such as vessel turnaround time, total lead time, port delay time, which can also measure the cost impact. Recent bottlenecks in ports, such as the ones caused in 2021 by the Suez Canal blockade, delayed shipments and severely increased monetary costs, fact supported by the research of Veenstra et al. (2022), which provided concrete quantitative evidence that prolonged transit times along with bottlenecks and port congestion have a direct measurable monetary impact on maritime's supply chain stakeholders.

Piracy as well, forms another emerging quantitative impact. As already analyzed, in sensitive regions affected by piracy, such as the Gulf of Guinea and the Strait of Malacca, attacks lead to billions of dollars in annual losses. These of course include ransom payments and increased insurance rates, as well as higher fuel costs due to rerouting and re-scheduling. Each attack delays shipments and reduces supply chain efficiency, leaving a quantifiable mark on global trade flows.

### 3.3. Case Studies: Major Disruptive Events

#### 3.3.1. The COVID-19 pandemic

The World Health Organization (WHO) declared COVID-19 as a pandemic in mid-March 2020. The events following this announcement had been an unprecedented shock to the global economic system. A demand shock followed the supply shock and widespread lockdowns and travel restrictions led to fast-rising unemployment, huge governmental rescue packages to support consumption and finally oil and stock market collapses. According to International Monetary Fund (IMF, 2022), trade volumes reduced by 5.3% in 2020, and the entire world faced the worst global economic recession after the Great Depression. For the maritime supply chain the sudden onset and the prolonged duration of the pandemic, heavily disrupted shipping operations, logistics and port activities and suddenly altered consumer demands patterns.

#### *The Impacts of COVID-19 on Maritime Supply Chains*

Port operations were among the first fields to feel the impacts of the pandemic. During 2020 a lot of important ports globally faced significant labor shortages due to illness, health restrictions and strict quarantine measures. Notteboom et al. (2021), refer as an example to the port of Los Angeles, handling approximately 40% of U.S imports, that faced significant congestion and delays due to lack of personnel. The situation intensified by empty containers, piled in volumes in major ports due to reduced exports from countries considered to be major exporters, such as China.

Another significant impact of COVID-19, was the one on freight rates. Initially at the beginning of the pandemic, uncertainty caused a severe demand shock that almost flattened the demand curve for many goods that were boosting maritime transport, leading freight rates to decline to extremely low levels. This situation profited mainly freight forwarders and ship operators, while shippers and shipping companies faced mounting costs that were often passed along the supply chain. Haralambides (2020) highlights how volatile freight costs boosted inflationary pressures, particularly in commodity-dependent economies, underscoring the pandemic's cascading effect on global trade costs. As the pandemic though altered consumer's preferences, especially towards electronic goods and e-commerce, rising their demand drastically, leading to a surge in freight volumes. The difference between supply of vessels and available containers and demand for consumer goods resulted in extremely sharp increase of freight rates.

As an immediate impact of the pandemic, key shipping routes were as well, disrupted. Border controls and restricted port entries made schedule's alternations and vessels' rerouting a necessity. That, resulted in increased transit times and operating costs. As per a UNCTAD (2022) research, operating costs during the pandemic increased at their fastest pace in the last decade. Average daily operating cost is estimated to have been increased by 4.5% in 2020. In contrast, the equivalent increases of the two previous years, were estimated at 2% and 2.5%, respectively.

One of the most human induced impact was the inevitable shortage in any kind of crew members. Crew shifts in vessels became a nearly impossible procedure, especially in countries with harsh travel restrictions. According to the International Chamber of Shipping (ICS, 2021), at the beginning of the pandemic over 400.000 crew members were stuck to any kind of vessels after their contract had expired. The difficulties faced by maritime workers highlighted the fragile interdependence between human labor and the broader shipping infrastructure.

The rapid shifts in demand, as well as consuming trade patterns, was another impact. Consumer's spending services altered from services to goods and especially e-commerce, technological and home related products, drastically increasing their demand. Consequently maritime supply chain struggled to response to this surge for home appliances and consumer goods, including protective equipment (masks, gloves etc.) due to the, already mentioned, container shortage, extremely prolonged delivery times and port congestion. On the other hand, industries such as the automotive, faced a sudden decrease on demand leading to highly reduced shipping activity and supply for those sectors. Great example can be considered the unprecedented shortage of semiconductors at the automotive industry, both due to lack of raw materials but most importantly, due to lack of transportation means (World Bank, 2021).

### ***Lessons Learnt***

Heiland et al., 2022 noted that one important lesson learnt during the COVID-19 pandemic is the need of digitalization in maritime logistics sector. Ports and shipping companies that had invested in digital technologies for cargo, documentation and communication were better adjusted to COVID-19 challenges. Heiland et al., 2022 also noted that technologies such as blockchain for secure, tamper-proof documentation and Internet-of-Things (IoT) enabled sensors for real-time cargo monitoring, are proving to be essential tools for resilience.

Jübner et al. (2021) noted that another important lesson learnt during the COVID-19 pandemic is the importance of diversification and flexibility in supply chains. Many companies after the COVID-19 pandemic crisis, are exploring ways to diversify sourcing destinations, decrease reliance on individual nations, and create regional supply chain centers, in order to mitigate risks related to localized disruptions (pandemics, geopolitical tensions or natural disasters).

The highly volatile freight rate and their fluctuation made evident the fragility of the maritime supply chain and the need for more resilient and adaptable logistics strategies. Even through freight rates eventually stabilized from the initial shock, it also emphasized the role of geopolitical and in general external factors influencing shipping rates and costs (UNCTAD, 2022).

The pandemic also revealed the immediate need for sustainability in maritime supply chains. The temporary slowdown in global shipping activity during the pandemic, reduced greenhouse gas emissions, giving the industry a chance to re-examine its environmental footprint. The transition to cleaner fuels and adoption of energy-efficient technologies can contribute to global sustainability goals and reduce the dependency of investments on fossil fuels (IMO, 2021).

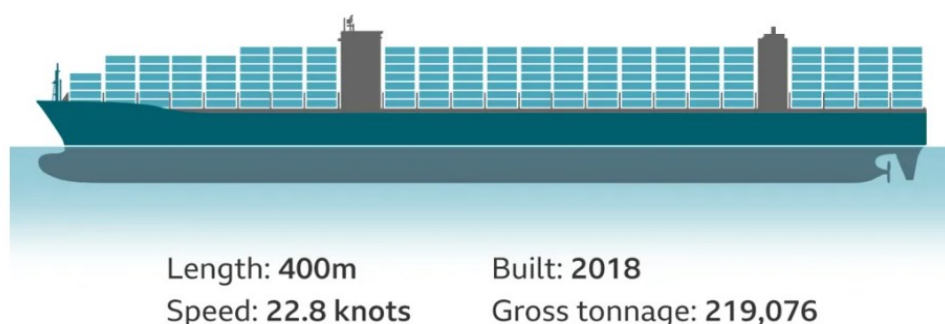
At last but not least, the pandemic highlighted the need to protect the well-being of seafarers. Stakeholders (shipping companies, organizations, etc.) must prioritize mental health, fair wages, and better working conditions for the seafarers. In order to ensure that during a crisis seafarers will not be neglected and crew changes will be made in time, international cooperation is required (ICS, 2021).

## ***Conclusion***

Maritime supply chains disrupted by the COVID-19 pandemic while at the same time revealed the weakness of shipping industry to become more resilient and adaptable. As the global economy recovers, the maritime industry must adopt the lessons learned; embracing digitalization, diversification and flexibility, sustainability and prioritizing human welfare, and become resilient so as to protect global trade system in case of a similar future crisis.

### 3.3.2. The Suez Canal Blockade

On 23 March 2021, the containership *Ever Given*, the world's biggest container by the time, grounded during her passage through the Suez Canal. This caused a six-day blockade of the Suez Canal, causing a "heart attack" in global maritime industry.



**Figure 6: Vessel MV Ever Given**

Source: <https://www.bbc.com/news/business-56559073>

The Suez Canal importance in maritime trade is undisputed, as it is considered to be one of the most crucial passage in the international shipping network, connecting Asia and Europe as well as in lesser degree, Asia and North America. It plays a crucial role in facilitating the movement of all vessels between continents due to its strategic location as the second most significant intercontinental trade route, following the Asia-North America one. In 2019, approximately 28% of the world's container cargo (0.5 billion out of 1.85 billion tones) passed through this artificial canal (Suez Canal Authority, 2023). Handling about 12%-15% of global trade and 20% of container shipments, it approximately reached 9.4 billion dollars in revenue in 2023, highlighting its unparalleled role.

Given the canal's crucial role in global maritime supply chain, the *Ever Given* incident, not only disrupted the flow of goods but also had far-reaching economic, logistical, strategic and environmental implications. Lind et al. (2021), note that the disruption had such an impact that even after a week that the *Ever Given* had been removed, it took almost a week to clear the backlog of the vessels awaiting to pass through the Canal. Moreover Surban et al. (2021), mention a report by Allianz Research revealing that the canal's blockade may had contributed in reducing of global trade by 0.2%–0.4% per year.

The grounding event of the Ever Given may have multiple causes such as structural, operational and environmental. Bad weather conditions played an important role in the ship’s ability to maneuver, taking as well into consideration the vessels’ size, over 400 meters length, and gross tonnage, over 220,000 (Osler et al., 2021). Operational factors had as well a share in this incident. There has been much of a debate over whether the canal’s infrastructure, such as its pilotage and towing capacity, could accommodate such vessels. Furthermore, the human factor, including decision-making by the crew and canal authorities, may have played a role. On the other hand though Cariou & Wolff (2021), strongly argue that the late trend towards mega containerships in order to maximize scale economies, have increased risk of such incidents and made the 2021 blockade more or less a self-fulfilling prophesy, stretching out the interconnectivity factor between technological, human and environmental variables in modern maritime supply chain.

### ***Impacts of Suez Canal blockade on Maritime Supply Chains***

The immediate impact of the blockade was the bottleneck of over 400 vessels including oil tankers, bulk carriers and containerships, at both ends of the canal waiting to pass through (Liu et al., 2022). The daily cost of the blockade was worth 9.6 billion USD approximately, to global trade (Allianz, 2021). That incident had several consequences, such as financial losses for Egyptian economy, maritime companies and various stakeholders as well as environmental impacts.

Due to the six-day blockade of the Suez Canal, many vessels diverted around the Cape of Good Hope, adding 10 to 14 days to their transit times (Psaraftis & Kontovas, 2022). As a result of this diversion, additional fuel was consumed driving the extra miles, generating more greenhouse gases and increasing operating costs. As an example, the diversion around the Cape of Good Hope of 12 vessels of Maersk Lines resulted to revenue drop for the Suez Canal Authority (SCA) of about 5.86 million USD (Tran et al., 2025). This incident resulted in 79.6 billion USD annual net negative impacts worldwide, meaning 0.1% of the world’s GDP. However, the more substantial negative effects of 291.5 billion USD were counterbalanced by positive impacts of 211.9 billion USD. In other words, the larger negative impacts in certain countries are balanced out by positive impacts in others (Gokan et al., 2024).

As a consequence of maneuvering against Europe and late arrivals to ports and terminals which were already congested, ships began to arrive in large volumes leading to enormous

congestions, disorientating port schedules and operations and resulting in further delays. Those delays affected also various stakeholders such as manufacturers, sellers, wholesalers, and final consumers. The industries most impacted were food establishments, building, wholesale trade within Europe, and retail and grocery businesses in the United States (Tran et al., 2025).

The ripple effects extended beyond shipping industry. Rising freight rates following the Ever Given incident were indicative of limited vessel availability and capacity restrictions (UNCTAD, 2021). For example, the cost of shipping a container from Asia to Europe disproportionately affecting small and medium enterprises (Notteboom & Pallis, 2021). Consumers experienced higher prices across various products, such as electronics and clothing as companies transferred the added expenses. The global nature of this incident revealed the vulnerability of trade systems dependent on uninterrupted maritime routes.

The environmental costs of this blockade were multidimensional. Vessels idling in the canal consumed fuel without moving, contributing to CO<sub>2</sub> emissions. Although the bypass route for some ships was operationally necessary, and as a result emissions increased enormously due to extended voyage durations (Cariou, 2022). For instance, although only 12 Maersk vessels were rerouted around Africa, they emitted significantly more pollutants than the 57 Maersk vessels waiting at the Suez Canal, due to the increased fuel usage by their primary engines while operating at sea. As a result, these 12 vessels accounted for more than 80% of the additional emissions from Maersk's affected fleet (37,101 tons of CO<sub>2</sub>) (Tran et al., 2025).

### ***Lessons Learnt***

The Ever Given incident served as a critical stress test for global supply chains, providing several valuable lessons for industry stakeholders.

One important lesson learnt from this incident is the need to modernize maritime infrastructure. Although the Suez Canal Authority (SCA) has already begun expansion projects by widening and deepening specific sections, it may not be enough. Technological upgrade (e.g. real - time monitoring systems and autonomous pilotage) may improve navigational safety (Liu et al., 2022).

Another aspect this blockade highlighted is the need to diversify supply chain routes and strategies. Over-reliance in specific routes, like the Suez Canal, makes the entire global trade vulnerable. Investments in alternative routes like the rail networks connecting Asia and Europe



or the Arctic shipping routes can prevent such future vulnerabilities (Psaraftis & Kontovas, 2022).

Building resilience requires collaboration among stakeholders. Shipping companies, ports and governments must establish effective contingency plans for similar crises in the future. Simulation-based trainings and the adoption of scenario planning has embrace faster and effective responses toward disruptions (Notteboom & Pallis, 2021).

Finally, the environmental implications of the incident highlight the need of low-carbon vessels. Innovations leading to green fuels or energy-efficient vessel designs may reduce the ecological footprint of maritime industry, along with improving resilience.

### ***Conclusion***

The 2021 blockade in the Suez Canal reminded to the entire world of the interdependencies and complexities of global supply chains. By examining the causes, impacts and implications of this incident, the maritime sector can develop routes in order to achieve greater resilience and sustainability. These lessons learned through the lens of this incident, could serve as a blueprint for dealing with future similar crises in a complex and interconnected world.

## **4. Building a Resilient Maritime Network**

The current literature primarily focuses on the general aspects of the Maritime Supply Chain Resilience concept, which is still a relatively fresh a concept. However, this critical sector faces multifaceted risks, including natural disasters, geopolitical conflicts, cyber threats, and operational disruptions. Enhancing maritime resilience is essential in order to mitigate these risks, ensuring supply chain continuity, and supporting global economic development. Hollnagel et al (2022), refers to maritime resilience as the capacity of the maritime industry to anticipate, prepare for, adapt to, and recover from disruptions. It encompasses both physical infrastructure, such as ports and ships, and intangible assets, as well as governance, technology, and human capital. Hsieh (2014) conducted a study focusing on evaluating the risk of port failures through the lens of vulnerability. By using Geographic Information Systems, Hsieh (2014) examined vulnerable factors and the associated risks with port operations, offering valuable insights into quantifying the vulnerability and risk of port failures, providing essential



information for decision makers to formulate strategies and mitigate disaster risks in port settings. Omer et al. (2012), introduced a framework aiming to assess the resilience of maritime transportation systems, proposing strategies that enhance resilience by decreasing vulnerability levels and increasing adaptive capacity. Their work established a comprehensive framework for assessing and enhancing resilience of maritime transportation systems and consequently facilitating decision-making to mitigate the socio-economic impacts during disruptions. Berle et al. (2013) introduced a vulnerability assessment methodology for maritime transportation systems. They employed an assessment framework to evaluate the efficiency of transportation systems as throughput mechanisms for goods and their ability to recover from disruptive incidents, evaluating inherent vulnerabilities and enhancing their ability to effectively mitigate unforeseen threats and hazards and finally boosting resilience.

Moreover Liu et al. (2018), analyzed vulnerabilities in maritime supply chains, aiming to create a framework to efficiently identify and analyze these vulnerabilities. By working through case studies, focusing on A.P. Moeller-Maersk operations, they analyzed maritime network resilience to both random failures as well as international risks and attacks and managed to point out vulnerable network nodes, such as ports and chokepoints. Becker et al. (2015), underlined the importance of including stakeholder perspective and concerns in the planning and policy-making processes for seaport resilience to the effect of climate change. They supported the need of collaborative and participant approach that will elaborate on the effects of natural disasters on ports and their implications for stakeholders in order to develop effective strategies and make resilience inherent to the maritime network. Onwards, Notteboom et al. (2021), managed to compare the impacts of the COVID-19 pandemic and the 2008–2009 financial crisis on container shipping and ports, and their findings stretched out the importance of developing a mechanism for adaptive and robust strategies, which during crisis will work towards stability and resilience. Calatayud et al. (2017), analyzed the vulnerabilities, sourcing from the freight fluctuations within the maritime transportation network, by highlighting the varying levels of vulnerability across different countries and the effect of the complexity that arises. Al Naimi et al. (2022), concluded that the early adoption of practices that boost maritime supply chain resilience will improve in time interventions and measures in order to mitigate risks and impacts. Scholten and Schilder (2015) elaborated on the fact that collaboration is of utmost importance for supply chain resilience. Their findings side with the argument that collaborative activities, such as information sharing, cooperative communication, joint

knowledge creation, and relationship-building, can boost supply chain resilience by improving visibility, speed, and flexibility.

Several other research studies have analyzed the components of supply chain resilience. Erol et al. (2010) worked within the systems theory field, to conclude that resilience involves flexibility, agility, adaptability, and robustness. Elali (2021) and Solis et al. (2023) also support the above findings and focuses on agility. They define supply chain agility as the capacity to resist change without altering the initial configuration and highlight her role as a response mechanism to unpredicted demand shifts. On the other hand, robustness is crucial across the production field, as it refers to the ability to sustain operations despite internal or external disruptions (Kitano, 2004). Alshahrani and Salam (2022) described supply chain flexibility as the ability to adapt swiftly to evolving environmental and stakeholder demands fluctuations and Sanchez and Perez (2005) had previously confirmed the positive correlation between flexibility capabilities and firm performance.

Lam and Bai (2016) finally come to the conclusion that a resilient maritime network is able to sustain operations, handle risks with efficiency, serve customer demands, manage cost fluctuations and smoothly adjust to changing industry conditions. As a result, there is a visible need for the maritime network to embrace the importance of resilience, to enhance risk mitigation and respond to disruptions and disturbances by including agility, robustness, and flexibility into its supply chain strategies, so as to navigate in a highly complex environment.

#### **4.1. Response Strategies**

Resilience is essential in order to mitigate evolving risks inherent to the maritime networks, ensuring supply chain continuity, and supporting global economic development. Unlike traditional risk management, which focuses on prevention, resilience emphasizes to adaptability, flexibility and the ability, to maintain operations under adverse conditions. For instance, as we have showed, disruptions at a major ports or chokepoints, such as the Suez Canal blockade in 2021, can have multiplying effects on global supply chains. The economic consequences of such events highlight the fragility of maritime networks and emphasize the need for robust resilience strategies. Enhancing maritime resilience requires a multifaceted approach that integrates technological, organizational, and policy measures among others response strategies.

## 4.2. Mitigation Strategies

As per Musal et al., (2020) mitigation strategies, play a crucial role in fortifying maritime operations against vulnerabilities such as climate change, geopolitical risks, and pandemics. Those kind of strategies that contribute to enhanced maritime resilience, usually focus on advanced risk assessments, integrated technologies, infrastructure, diversification and collaborative approaches within the industry.

Widespread risk assessment analysis of potential disruptions, give stakeholders the time needed to develop targeted responses in order to mitigate the impacts of unforeseen global events. For instance early warning for natural disasters, such as typhoons, tsunamis or even earthquakes, help shipping companies and ports implement proactive measures, ensuring they are prepared for disruptions. A study by Lam et al, (2015), highlights the significance of real time monitoring and predictive analytics to identify, assesses and mitigate risks emerging from maritime supply chain disruptions. Moreover, risk assessment for risks arising from climate change may identify vulnerable geographic areas and reallocate resources or routes to other safe locations increasing efficiency and resilience. In addition, financial and insurance risk assessment enables stakeholders to develop efficient insurance policies and mitigate possible financial losses due to unexpected cost increase from disruptions. Finally, by the on time and effective identification of vulnerabilities, stakeholders can prioritize their investments in mitigation strategies. Gharehgozli et al. (2016) proposes a scenario-based process in order to prepare for rare but high-impact events such as tsunamis or port shutdowns. These models allow stakeholders to stress their systems under various conditions, offering insights into potential chokepoints and failure modes.

Diversification is, as well, another important strategy. By having suppliers, sources or productions diversified across different and multiple locations, risks can be mitigated more effectively than relying over a single location or supplier (Chopra & Sodhi, 2014). An empirical study of Ivanov & Dolgui (2020), showed that when the supply networks are diversified, they recover easier than those that are dependent on a single node. Such a strategy however requires careful consideration of supplier competencies, geographical reach, as well as the balance between reduced risk and efficiency and / or redundancy (Sheffi, 2005).

A resilient maritime network requires international collaboration among all stakeholders. Through cooperation on disaster response, information sharing, and capacity building,

strengthens overall resilience. It is vital for stakeholders to collaborate and standardize procedures and evaluate risk management processes. Winsett (2020), elaborates on the fact that during periods of crisis, information sharing among essential nodes helps to mitigate uncertainty, reduces recovery time and encourages international cooperation and compliance in global resilience standards.

### **4.3. Adaptive Measures**

Adaptive measures are vital in enhancing the resilience of maritime supply chains, particularly in the face of escalating global challenges. Adaptability involves promoting organizational flexibility, leveraging data-driven decisions, and embracing a culture of continuous learning, including the human capital.

In the post COVID-19 pandemic era, the ability to reallocate resources in a dynamic way is crucial. Terminal operators showed remarkable adaptability by rescheduling cargo operations and adjusting work flow in order to serve the highly fluctuating demand of the time. This kind of dynamic resource allocations minimizes delays and delivery time and support the supply chain continuity (Pu and Lam, 2021).

Engaging into flexible transport mode shift by investing in multimodal transport (sea, rail or road) diversifies risk and increases resilience. By offering alternate routes, multimodal transport limits the effects of maritime delays on the entire supply chain. Reliance exclusively on maritime transport risks compounding disruptions, especially when vital sea lanes or critical chokepoints, such as the Suez Canal, are under crisis. (Notteboom et al., 2021).

Adaptability also requires continuous improvement as well as learning and innovation involving not only learning from past disruptions but also proactively exploring innovative solutions to address recurring disruptions. From that point of view, the human capital has a significant role into developing adaptive strategies. Investing in continuous training and development of the personnel, improves their ability to adapt to new challenges, not common in the past, such as cyberattacks, new technological improvements or evolving environmental regulations (Mitroussi et al., 2014).

#### 4.4. Technological Innovation and Cybersecurity for Enhancing Resilience

The maritime network, is undergoing a rapid digital transformation era that has reshaped its framework. Advanced navigation systems and automated port operations, increasing connectivity of vessels through the Internet-of-Things (IoT), are only some of the technological innovations that have emerged that very last decades. However, this digitalization also increases vulnerability to cyber threats, calling for robust cybersecurity measures.

Technological innovations, especially those in automation, digital twins, traceability and artificial intelligence (AI), boost the resilient capabilities of the network ability to anticipate, withstand, and recover from disruptions. Berle et al. (2013), refers to digital twins, a virtual representations of physical systems that can simulate disruptions and test response strategies in a risk-free environment. In ports, digital twin technology can maximize logistics capabilities by identifying inefficiencies and potential failures, such as equipment failures or delays caused by unforeseen demand fluctuations. The introduction of autonomous vessels is another promising development. Ships, literally without crew members, currently in experimental mode, offer the potential to reduce errors occurring due to human factor while at the same time improving safety and operational reliability (Lloyd's Register, 2021). However, the further development and adoption of such technology necessitates a concrete regulatory framework to address concerns about cybersecurity and liability. Additionally, AI- predictive analytics play a critical role in enhancing decision-making during crises by processing real-time data, such as weather patterns and vessel movements, to provide important decision making information.

Traceability is another important factor, critical for resilience that is fostered by technological innovation. Lee and Rha (2016), argue that traceability contributes to increased resilience by improving maritime supply network visibility and transparency. Visibility gives the option of real time monitoring and identification of potential risks and bottlenecks, such as port congestions natural disasters or other global events and delays. As per Ghorashi & Honarvar (2021), the most important advantage of traceability is that it gives time to stakeholders in order to develop and implement plans to avoid contingency. Finally, traceability is being enhanced by technologies such as blockchain, the Internet-of-Things (IoT) which enables in real time the connectivity of devices such GPS trackers and environmental conditions, the Radio-Frequency Identification (RFID) and Barcoding, which allow for the tagging and tracking of goods, providing real-time location data and status updates.

#### 4.4.1. Cybersecurity

While all the above technological advancements provide significant efficiencies, they also make maritime networks vulnerable to cybersecurity risks and breaches. Not strangely in 2021 the International Maritime Organization (IMO) has classified cybersecurity as an emerging risk in its guidelines (IMO, 2021). Cyberattacks expose vital navigation and communication information and severely disrupt cargo and vessel tracking and compromise port management software.

By paraphrasing a term of resilience by Hollnagel et al (2022), we can say that cyber resilience refers to the ability to anticipate, withstand, and recover from cybersecurity threats. In the maritime context, enhancing cybersecurity can improve the industry's overall resilience and prevent contingency impacts.

Wright et al. (2021) support that by strengthening cybersecurity to prevent attacks on critical infrastructures with the implementation of robust security measures, such as regular software updates, encryption of sensitive data, and multi-factor authentication, create a lot of obstacles to cybercriminals in their effort to exploit vulnerabilities or blind spots. Additionally, Carson et al. (2020), elaborate on the fact that cybersecurity frameworks facilitate stakeholders on the early detection of cyberattacks. For instance, the integration of machine learning algorithms into monitoring system behavior, identify potential cybersecurity threats in real time and improve the speed and accuracy of incident detection. They conclude that early detection ensures faster recovery times and reduces the systemic impact of cyber incidents.

#### 4.5. Sustainable and Climate Resilience Strategies

Maritime networks face a variety of vulnerabilities due to climate change impacts. Ports are particularly vulnerable as they are predominantly situated in low-lying coastal areas. Rising sea levels and extreme weather events amplify the risk of flooding and infrastructure damage, resulting in costly disruptions (Ng et al., 2018). Moreover, maritime routes are highly volatile to shifting climate patterns, which disrupt sailing conditions and increase fuel consumption (Rehmatulla & Smith, 2015).

To underline the vulnerability of maritime infrastructure to climate extreme conditions, the hurricane Katrina in 2005, among other devastating impacts, caused extensive damage to the port of New Orleans by suspending operations for weeks and severely disrupting maritime

routes and continuity, not to mention of course the financial implications as well. Additionally as per the International Maritime Organization (IMO), shipping is to be held responsible for approximately 3% of greenhouse gas emissions, fact that clearly intensifies climate change effects. As per Smith et al. (2014), the role of the maritime network both as contributor and victim of climate change underscores the need of integrating sustainability into maritime operations. By prioritizing sustainability, maritime networks can address vulnerabilities, reduce environmental footprints, and improve operational continuity. It involves the implementation of strategies that reduce climate change effects while at the same time they boost system's ability to withstand disruptions. Usually those strategies focus on green infrastructure, low-carbon technologies, and adaptive governance.

Invest in climate-resilient infrastructure is of outmost importance. Developing ports infrastructure and vessels to endure extreme weather conditions is a principle of maritime resilience. This includes elevating port infrastructure, reinforcing seawalls in ports below to sea level, and deploying weather-resistant materials (Jansen et al., 2023). Such initiatives not only mitigate risks but also ensure continuity in cargo handling and operations.

Green ports and infrastructure play a vital role towards sustainability and resilience. By developing natural solutions such as artificial reefs, ports can be better protected from storm impacts. Van Slobbe et al. (2013), refers to the port of Rotterdam that has developed eco-engineering mechanisms to address flooding risks and biodiversity. Additionally a resilient infrastructure design, by elevating much higher than sea level, critical facilities and machinery, as well as using climate resilient construction materials, may significantly increase sustainability and overall resilience.

Over more, the use of low-carbon innovative technologies reduces greenhouse gas emissions and improves sustainability. Using alternative fuels, such as liquefied natural gas (LNG), hydrogen, and biofuels, add value to decarbonization effort of the maritime transport. Lately, highly innovative all- electric vessels are emerging as an alternative, adding more viable options towards further decreasing of CO<sub>2</sub> footprint and a more sustainable future.

Adaptive measures should align with Environmental, Social, and Governance (ESG) principles to ensure long-term viability. The same can be said for measures such as switching to cleaner fuels and energy-efficient technologies, which will reduce greenhouse gas emissions but also reduce dependence on volatile fossil fuel markets (Ng et al., 2018). Circular



economy principles like, vessels recycling and scraping and minimizing the use of marine pollutant materials, further contribute to a more sustainable and resilient maritime sector.

Governance and international collaboration are essential for adopting sustainability and resilience. Regulatory measures, such as the International Maritime Organization's (IMO) sulfur cap and its targets for reducing GHG emissions by 50% by 2050, set clear benchmarks for the industry (IMO, 2020). Additionally, organizations such as the Sustainable Shipping Initiative (SSI), bring together industry leaders to develop collaborative solutions for sustainable shipping.

However, the implementation and further development of sustainability practices still face a lot of challenges. High upfront costs associated with green infrastructure and low-carbon technologies, negatively affect adoption, especially in developing regions where policymakers should provide financial incentives, such as subsidies and tax cuts, to encourage green innovation.

#### **4.6. Port Resilience: A Key Driver of Maritime Network Resilience**

Ports are critical nodes in the global maritime network, acting as the interface of international trade and the smooth transfer of goods between sea and land. At times, disruptive events may arise within this framework, stemming from diverse factors, including some that are foreseeable, some that are stochastic yet anticipated, and some that are unforeseen. Their ability to maintain functionality during disruptions is of ultimate importance to the resilience of the entire maritime supply chain.

UNCTAD (2022) defines port resilience as the ability of a port to maintain an acceptable level of operations during a disruption (pandemics, natural disasters and cyber or terrorist attacks) and quickly recover and re-establish operations to a similar level or even above, as well as adopting to evolving conditions by continuing to develop and transform.

Port resilience is associated to the port's inherent properties, its absorptive, restorative and adaptive capacities. Absorptive capacity is described as the ability of a port to efficiently absorb disruption's impacts by using the existing infrastructure while at the same time maintaining the same level of services and is highly linked with key attributes such as robustness, redundancy and visibility. Restorative is the capability of a port to recover from a particular disruption to a level of service that is comparable to, or potentially better than the pro-disruptive level. The



first aspect involves the port's capacity to respond to a disruptive incident, largely dependent on its readiness and the available resources, which can be utilized to manage and mitigate the disruption. The second aspect entails the port's ability to restore and resume normal operational activities (UNCTAD, 2022). Adaptive capacity is the capability of a port to modify its procedures and even its administration, in advance of or in response to a disturbance and it encompasses flexibility, agility and collaboration.

Physical, machinery and technological infrastructure of every port is a very significant parameter. Ports designed under the redundancy point of view, including, but not limited to, multiple berth points or alternative energy sources, show better absorptive capacity to external shocks or internal equipment failures (Zhang et al., 2021). Advanced technological innovations such as the Internet-of-Things (IoT), allow ports to have real-time data in order to predict disruptions and develop auto-activated response mechanisms.

Working under strict and updated risk assessment procedures is another factor that allow ports to identify vulnerabilities and respond in timely manner. Notteboom & Pallis (2021), argue that the post COVID-19 era is a case study, on how ports that prioritized proactive risk assessment and developed contingency plans, managed to have quicker recovery times.

Finally, ports do not operate in isolation but they are an important node of the whole maritime network, including a variety of players such as shipping lines, logistics providers, and local governments. Establishing robust collaborations with all stakeholders, enhances resilience by facilitating the sharing of resources, critical information, and coordinated responses to risk mitigation.

According to Chen et al. (2023) building resilient ports comes with great challenges, including high costs, the complexity of stakeholder collaboration, and the uncertainties of emerging risks. However, these challenges usually go with opportunities. Increasing attention to sustainability creates incentives for green and resilient port designs, such as integrating renewable energy or adopting decarbonized shipping technologies. Digital transformation, such as blockchain technologies that enhance transparency and the digital twin virtual representations of physical port allow for advanced simulation and scenario testing and provide valuable solutions for building port resilience. These advancements, along with all other traditional strategies, can further enhance the resilience of ports but also of the entire maritime network.

## 4.7. Case Studies and Good Practices

### 4.7.1. The Blockchain Effect: A Maersk Case Study

The blockchain technology, is mainly associated with cryptocurrencies and the introduction of Bitcoin some years ago. As per Zheng et al. (2017), blockchain could be described as a public ledger where all transactions are being stored in a list of blocks. This chain of blocks may grow as new blocks are added. Cryptography and broad consensus algorithms are used for security and ledger consistency reasons. Blockchain characteristics are, decentralization, persistency, anonymity, transparency and visibility, enabling to minimize costs and increase efficiency.

In 2014 a department of IBM was working on a blockchain project with limited results. Before the project to be terminated, some members of the management, realized that this could be something more than a cryptocurrency technology and could have application into maritime supply chain as well and be used as a way of tracking shipments, transactions and documents. Stakeholders would be keeping their own live version of data, information and documentation without any intermediate's interference, and could immediately see every move or process knowing that their information was accurate and could not be compromised.

Zhao et al., (2023), went one step further and argued that blockchain technology, may have broader impacts on maritime supply chains, working as a lean strategy to eliminate excess waste and "noise" and have a direct impact on mitigating the Bullwhip effect. The Bullwhip effect emerges from market uncertainty and asymmetric information that leads to quantity and eventually demand fluctuations, from downstream to upstream. Zhao et al., (2023), suggested that blockchain could enhance maritime resilience and mitigate the Bullwhip effect by improving the level of maritime services. Their research concluded that blockchain can empower maritime services resilience and minimize uncertainty by increasing visibility and transparency.

The lack of transparency in information is a fundamental issue within the maritime sector that significantly impacts the entire supply chain directly. Coupled with inefficient paper-based processes, this deficiency can result in almost a 20% increase in physical transportation costs (Rajiv & Johnson, 2018).

At times, information may be accessible at the departure point but not at the destination, or details such as the vessel and the Actual Time of Arrival (ATA) of shipments may be known while uncertainty remains regarding whether the shipment has been cleared from the customs.

Inconsistent data sharing across organizational boundaries and blind spots throughout the supply chain obstruct the smooth flow of goods (Rajiv & Johnson, 2018). The majority of unpredictable and extra costs of transportation arise from the lack of transparency.

To address and overcome these challenges in maritime transportation, A.P. Moeller-Maersk decided to invest in technology and established a partnership with IBM. Their strategy revolved around blockchain technology. They introduced a digital platform named TradeLens, tailored for the shipping industry, offering a secure digital solution for exchanging shipping documents and information in real-time, thereby enhancing visibility and transparency not only in transactions but across the maritime supply chain as a whole (Rajiv & Johnson, 2018).

The implementation of blockchain technology in TradeLens offered several advantages. Improved transparency and traceability as it allowed stakeholders to monitor the movement of goods in real-time, thereby reducing uncertainties and enhancing the ability to respond promptly to disruptions. Additionally, digitizing all relevant documentation significantly reduces time that containers/products spend in ports or customs, minimizing delays, operational costs or human errors and eventually improving efficiency. Finally, TradeLens, ensured that no one could alter a single document, record or piece of information without broader consensus increasing security and lowering uncertainty among stakeholders.

Despite these advantages, the adoption of TradeLens faced challenges. At the time the blockchain technology was relatively new and not so popular, much less understood and Maersk and IBM struggled to find early adopters in order to process their plans. On the contrary, they found a lot of reluctance as many companies were afraid to take the risk of embracing an unknown technology. Not to mention of course, the large upfront costs that acted as a significant barrier to small and medium companies.

In conclusion, the joint venture between Maersk and IBM in the development of TradeLens is a great paradigm of the use of blockchain technology to enhance maritime resilience. By amplifying visibility, simplifying record-keeping, and guaranteeing data protection, blockchain tackles numerous enduring obstacles within the maritime sector. Offering a secure, transparent, and effective framework for monitoring shipping operations, TradeLens tried to revolutionize the worldwide supply chain, by addressing inefficiencies and promoting increased cooperation among industry stakeholders.

#### 4.7.2. The Port of Rotterdam Paradigm

In 2020, the Port of Rotterdam handled over 14 million TEUs (UNCTAD, 2022). The capacity of the port was being challenged by the increased size of containerships that consequently accumulated handled volumes and work flow. Up to five 20,000 TEUs mega-containerships could call simultaneously, generating enormous workload peaks, leading human capital working to limits and jeopardizing operations continuity.

Among other factors leading to congestions and disrupting port's operations were, the poor schedule reliability of large vessels, the limited barge capacity for inland haulage, barge capacity that was not predefined leading to demand visibility issues. Moreover, barge and feeder terminals limited working hours created bottlenecks and severe delays in rush hours. Finally seasonality and peaks during summer period were amplified by the fact that port of Rotterdam is considered to be one of Europe's largest hub enlarging any kind of impact (UNCTAD, 2022).

In 2014 a five month congestion, created huge delays and bottleneck. Barges had to wait between 72 hours and 92 hours to process cargoes, leading the vast majority of shipping companies and forwarders to alter their schedules, omitting the port of Rotterdam and consequently disrupting the maritime supply chain, but also creating huge financial costs for the port operating companies and the Dutch authorities.

#### *Response and mitigation measures*

To mitigate those impacts, throughout the coming years, the Rotterdam's port management invested in infrastructure and port upgrades to handle increased barge demand, being steadily monitored, adjusted and fine-tuned to meet expected demand. One of the most notable projects was the Maasvlakte terminal expansion, which incorporated state of the art facilities designed for both economic and environmental resilience (Notteboom et al., 2022). Hinterland extensions and enhanced connectivity resulted today, the port of Rotterdam to manage and oversee an extensive port area exceeding 12,500 hectares and approximately 89 kilometers of quay walls (The Port of Rotterdam, 2024). They focused both on enhancing hinterland connectivity but as well as in measures that boost digital cooperation, involving smart sensors to monitor infrastructure condition in real-time and enabling timely interventions that extend the lifetime of port facilities. Additionally, the port acquired satellite technology to conduct

regular surveys, allowing for accurate monitoring of quay wall displacements and ensuring structural integrity (The Port of Rotterdam, 2024).

Additionally, by embracing digitalization the port of Rotterdam aimed to enhance operational efficiency and resilience. More specifically the development of PortXchange, a digital platform designed to optimize port call operations, providing real-time data exchange among shipping lines, terminals, and service providers, reduced idle times and improved supply chain reliability. Carlan et al. (2018), highlighted that those digitalization efforts are vital into making the maritime supply chain more resilient, efficient, and responsive.

Finally, the port of Rotterdam authorities engaged into collaboration with various stakeholders of the maritime network. The introduction of Portbase, a joint venture connecting the port of Rotterdam, other Dutch ports, freight forwarders and shipping companies, customs offices and other government agencies, enabled automated data exchange along the logistics processes and reduced administrative costs by reducing bureaucracy and processing time. By connecting over 4,700 companies, Portbase facilitates efficient, paperless procedures across Dutch ports, enhancing the resilience of the maritime supply chain (The Port of Rotterdam, 2024).

The strategies and good practices, implemented by the port of Rotterdam in order to respond to disruptions and enhance maritime resilience highlights the importance of a multifaceted approach. Through infrastructure investments, it has physically fortified its operations against both environmental and operational shocks. By including digitalization, allowed the port to anticipate and respond dynamically to disruptions, increasing efficiency and reliability. By investing in collaboration, the port of Rotterdam has adopted a holistic resilience strategy that extends beyond port boundaries, ensuring a coordinated response to global challenges. Finally, by prioritizing sustainable strategies, ports can ensure not only their survival but their leadership in an uncertain and evolving global environment.

## 5. Conclusion

Through the analysis of the resilience of the maritime supply chain, we have observed the complexities and vulnerabilities of the sector. These networks face diverse risks, including natural disasters, geopolitical conflicts, technological disruptions, and operational inefficiencies. The interconnected structure of these maritime network nodes intensifies disturbances, leading to extensive repercussions, as demonstrated by case studies of notable

events like the COVID-19 pandemic and the Suez Canal blockade. These occurrences have underscored the vulnerability of critical chokepoints, the significance of diversification, and the necessity for advanced technological adaptation to ensure seamless operations. Resilience involves not only recovering from disruptions but also adapting to new challenges and seizing opportunities for improvement.

Port resilience has emerged as a crucial element in maintaining the stability of maritime supply chains. Due to their central role in operations, ports are especially susceptible to disruptions such as extreme weather conditions, cyberattacks, labor shortages, and infrastructural bottlenecks. Effective responses include investments in adaptive infrastructure such as flood defenses, enhanced automation, and integrated logistics systems. The case of the port of Rotterdam made clear that when ports prioritize collaboration among stakeholders, transparency through data sharing, and technological innovation, demonstrate a greater capacity to absorb shocks and maintain throughput during crises.

Technological integration is regarded as a two-sided coin. While innovations such as blockchain, Internet-of-Things (IoT), and Artificial Intelligence (AI) substantially improve operational efficiency and supply chain visibility, they also bring about vulnerabilities, particularly in the form of cybersecurity threats. Mitigating these risks requires balancing technological adoption with governance frameworks and proactive risk management strategies. Moreover, effectively managing the equilibrium between cost efficiency and resilience is crucial in order to avoid excess optimization, which can expose systems to unforeseen disruptions.

Future research should prioritize exploring innovative methods to address chokepoint dependencies, diversify trade routes, and implement decentralized models such as regional supply chain hubs. Additionally, greater emphasis on sustainability, through initiatives such as zero-emission vessels, green port infrastructure, and climate-resilient logistics will enhance both environmental performance and operational resilience.

Building maritime supply chain resilience calls for a holistic approach that integrates advanced technology, adaptive infrastructure, and collaborative governance. Continuous investment in resilience measures, including robust port operations and sustainable practices, will fortify maritime networks against future disruptions. By fostering adaptability and continuity, stakeholders can ensure that maritime networks remain the driving force of global trade, contributing to economic growth and stability in an increasingly dynamic world.

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