Maritime Policy & Management

The flagship journal of international shipping and port research

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tmpm20

Resilience analysis of seaports: a critical review of development and research directions

Massoud Mohsendokht, Christos Kontovas, Chia-Hsun Chang, Zhuohua Qu, Huanhuan Li & Zaili Yang

To cite this article: Massoud Mohsendokht, Christos Kontovas, Chia-Hsun Chang, Zhuohua Qu, Huanhuan Li & Zaili Yang (23 Mar 2025): Resilience analysis of seaports: a critical review of development and research directions, Maritime Policy & Management, DOI: 10.1080/03088839.2025.2483410

To link to this article: https://doi.org/10.1080/03088839.2025.2483410

Published online: 23 Mar 2025.

MARITIME POLICY & MANAGEMENT
https://doi.org/10.1080/03088839.2025.2483410

Resilience analysis of seaports: a critical review of development and research directions

Massoud Mohsendokht [a], Christos Kontovas [a], Chia-Hsun Chang [a], Zhuohua Qu [b], Huanhuan Li [a] and Zaili Yang [a]

[a]Liverpool Logistics, Offshore and Marine (LOOM) Research Institute, Liverpool John Moores University, Liverpool, UK; [b]Liverpool Business School, Liverpool John Moores University, Liverpool, UK

ABSTRACT

Given the wide range of hazards or disruptive events, particularly those arising from climate change, that threaten the normal operations of seaports and the continuity of supply chains, the concept of resilience has emerged as a key approach, offering promising strategies to effectively withstand these hazards and recover successfully from their adverse effects. This study aims to investigate the existing body of research on resilience analysis of seaports, focusing on identifying their limitations and challenges, conducting detailed discussions and comparisons, and analyzing approaches, models, and techniques. To achieve this, a critical review of existing studies on seaport resilience analysis is conducted, alongside an examination of seaport network resilience as a complementary aspect. This study makes a significant contribution by identifying research gaps in seaport resilience and highlighting potential directions for future research. The findings of this review serve as a critical foundation for further investigation, offering valuable insights to both academic scholars and industry practitioners. Additionally, the review not only provides practical approaches for implementation but also offers essential references for managing disruptions at both the individual seaport and network levels. The final results indicate that seaport resilience analysis is still in its early stages, with substantial overlap between proposed frameworks and a high degree of conceptual similarity.

ARTICLE HISTORY
Received 21 June 2024
Accepted 12 March 2025

KEYWORDS
Seaport; maritime transportation; supply chain; seaport resilience; resilience analysis

1. Introduction

Maritime transportation and seaport operations serve as the fundamental pillars of global trade and the international economy. It is worth noting that a significant proportion, approximately 80% in terms of volume and around 70% in terms of value, of international trade is conducted via maritime routes (UNCTAD 2023). In this respect, the continuous operation of seaports as the heart of maritime transportation is essential. Any failure or disruption would significantly hinder the flow of goods and disrupt supply chains, both domestically and internationally. The key principles for evaluating seaport performance include reliability, vulnerability, robustness, survivability, safety, and security. These terms cover several technical aspects related to evaluating the functionality of seaport operations but differ in their primary objectives and perspectives. Among these concepts, resilience stands out for its significance and emblematic nature. It has the capacity to cover a wide range of

CONTACT Zaili Yang z.yang@ljmu.ac.uk Liverpool Logistics, Offshore and Marine (LOOM) Research Institute, Liverpool John Moores University, James Parsons Building, Byrom Street, Liverpool L3 3AF, UK

port operation assessments and is of utmost importance in facilitating seamless and effective functioning while maintaining its integrity. Resilience refers to a port's ability to withstand, adapt to, and recover from various shocks and stresses. This involves understanding conceivable hazards, assessing their potential consequences, and implementing measures to enhance the port's capacity to resist and mitigate the adverse effects of disturbances and recover from them.

This paper aims to serve as a comprehensive survey of existing research on resilience studies in seaports. Over the past years, there has been a significant surge in attention surrounding the notion of resilience, making it a topic of interest for this review. Regarding maritime resilience, the existing literature is rather scant. Madhusudan and Ganapathy (2011) conducted a review study on the resilience of transportation infrastructure and seaports in the face of relevant disasters. They concluded that a universally agreed-upon metric for assessing the resilience of transportation infrastructure across various modes of transportation has not yet been established. Wendler-Bosco and Nicholson (2020) conducted a literature review of existing research on the impacts of seaport disruptions on the maritime supply chain. They reviewed a variety of scholarly research and industry sources to gain insights into the impacts of port disruptions on various dimensions of the supply chain, including transportation, inventory management, and customer service. Gu and Liu (2023) conducted a comprehensive literature analysis that specifically examined the notion of resilience in the realm of maritime transportation. Additionally, a bibliometric study was undertaken, providing insights into the elements that contribute to maritime resilience. Recent studies have explored resilience in the context of maritime transportation. Lau et al. (2024) employed bibliometric analysis and a systematic literature review to examine a broad range of issues related to maritime transport resilience. It discusses resilience in maritime transport systems and freight networks, ports and supply chains, and the effects of climate change on port resilience. Liu et al. (2024) also utilized bibliometric analysis and a literature review but focused specifically on the implications of maritime transport resilience for international trade. This study emphasizes the need for more comprehensive economic evaluations using analytical models and simulations to assess the costs and benefits of resilience strategies. Additionally, it identifies a significant gap in research concerning geopolitical risks and their impacts on maritime transport resilience and trade. While both recent papers provide valuable insights into maritime transport resilience, they are limited by their reliance on bibliometric analysis. Although bibliometric analysis is useful for understanding the research landscape, it does not offer in-depth insights into the content, quality, or practical implications of the studies reviewed. This reliance may lead to conclusions that reflect publication trends rather than substantive advancements in the field. Additionally, bibliometric data can sometimes overemphasize certain research areas based on publication volume rather than actual impact or innovation. As a result, the papers face several limitations: a lack of sufficient discussion and categorization of resilience analysis methodologies from an engineering perspective, insufficient exploration of practical implementation of resilience strategies in seaports, and inadequate analysis of the resilience of seaport networks.

In this respect, it is imperative to conduct a comprehensive review study that provides a thorough overview of the advancements in the emerging field of seaport resilience. This study includes a summary of the existing body of knowledge, with particular emphasis on the qualitative and quantitative methodologies that have been developed. Furthermore, it consolidates the findings from various research papers, highlighting future research directions and recognising the current methodological challenges.

To achieve the objectives, a comprehensive critical review with a focus on seaport resilience is conducted, leading to the following significant contributions:

(1) Extensive coverage: A broad array of journal papers published over the past two decades is meticulously surveyed, providing a comprehensive and in-depth review, with the most relevant and research-worthy studies chosen through a rigorous screening process.

(2) Critical analysis: Critical literature review techniques have been employed to facilitate the exploration of previously unaddressed questions in existing research, thereby uncovering significant knowledge gaps in this field.
(3) Extensive discussion on resilience metrics and methodologies: A comprehensive examination of the resilience concept, along with the existing measures, methodologies, and strategies specifically applied within the seaport context, has been carried out, highlighting their complexities and practical applications.
(4) In-depth evaluation: This work extends beyond simple exploration, providing an in-depth evaluation that highlights both the strengths and weaknesses of the topics covered. It also identifies and discusses key challenges, while proposing potential directions for future research, offering valuable insights to the academic community.

The rest of the paper is structured as follows: Section 2 presents the research methodology and the process of literature identification. Section 3 provides the concept, definition, application, and purpose of resilience assessment in the context of seaports. Section 4 particularly concentrates on the methodologies and approaches applied in the resilience analysis of individual seaports. Section 5 discusses the resilience of seaport networks, focusing on how disturbances might affect the interconnectedness and overall functionality of port networks. The discussion for existing challenges, policy implications and future research directions, as well as the conclusions, are provided in Sections 6 and 7, respectively.

2. Methodology

To conduct an in-depth examination of resilience research within the seaport field, a critical review approach has been employed to find relevant publications for evaluation. This approach consists of four phases: 1) the use of online platforms for research studies retrieval and exploration, 2) the systematic evaluation and selection procedure employed to assess the suitability and credibility of sources, 3) the eligibility assessment, and 4) concluding the incorporation of research studies. The relevant studies have been gathered through a search performed using Clarivates's Web of Science, which is known for its robust search capabilities and well-acknowledged reputation for trustworthiness throughout the scientific world. While SCOPUS is widely utilized for research, its citation analysis tools are less robust compared to the Web of Science, offering only basic features. Web of Science's meticulous quality control, including manual indexing, assures researchers of database accuracy. Thus, choosing the Web of Science for locating seaport resilience papers is preferred due to its reliability and comprehensive citation analysis capabilities.

The procedure to search records started by using a combination of keywords as follows: *('seaport' or 'sea port' or 'port') AND ('resilience' or 'resilient' or 'resiliency')* for the resilience analysis of individual seaports, and *('seaport' or 'sea port' or 'port') AND ('Network') AND ('resilience' or 'resilient' or 'resiliency')* for the resilience analysis of seaport networks. The investigation was conducted throughout the timeframe spanning from 2000 to 2024 and yielded a total of 1131 records. Initially, it was decided that our investigation to be limited to only peer-reviewed publications, given that the peer-review process is often regarded as the most reliable means of securing acceptance within the scientific community. To this end, our study purposefully omitted conference proceedings, editorial articles, white papers, and book chapters since these sources are likely to provide retrospective perspectives on the topic matter. Furthermore, the screening process included reviewing the titles and abstracts of the identified articles, and in some cases, doing a cursory reading or scanning of the content. In this phase, a substantial portion of the initially identified research papers were eliminated (967 out of 1131), with a retention rate of only 14% (164 papers) being maintained. In the literature review, stringent screening criteria were applied. The term 'resilience' encompassed various disciplines, necessitating the selection of studies directly addressing seaport resilience. Numerous papers explored related areas, such as supply chain and shipping network resilience, while others focused on broader concepts like economic and coastal community resilience. Additionally, papers from computer science, centered on different 'port' contexts, were excluded. These measures ensured the review's precision, resulting in a refined collection of studies specifically contributing to our understanding of seaport resilience assessment, while mitigating the inclusion of tangential or unrelated research.

In the phase of the eligibility assessment process, the screened records underwent further analysis through full-text review, leading to the elimination of 36 records. Consequently, only 128 publications were deemed to have the possibility for inclusion in our review. In this phase, we used a set of criteria to assess the significance of selected papers. These criteria included inquiries into the papers' pertinence to the overarching objective and their potential for deriving novel outcomes. For instance, in several cases, resilience was seen only as sub-topics or a superficial designation. It is noteworthy that in addition to the aforementioned procedure, some papers were identified using reference tracking, which included examining relevant review studies and highly cited research papers. This methodology facilitated the inclusion of an additional 14 records in our comprehensive literature review. Based on the collected data (i.e. included papers), the top five scholars in the field include 'Z. Yang,' 'E. Miller-Hooks,' 'A.K.Y. Ng,' 'J.S.L. Lam,' and 'K. Barker.' The leading journals which published the most papers are 'Reliability Engineering & System Safety,' 'Maritime Policy & Management,' 'Transportation Research Part E: Logistics and Transportation Review,' and 'Ocean & Coastal Management.' This breakdown shows the number of references associated with each of the top authors and journals, emphasizing their prominence in this literature review.

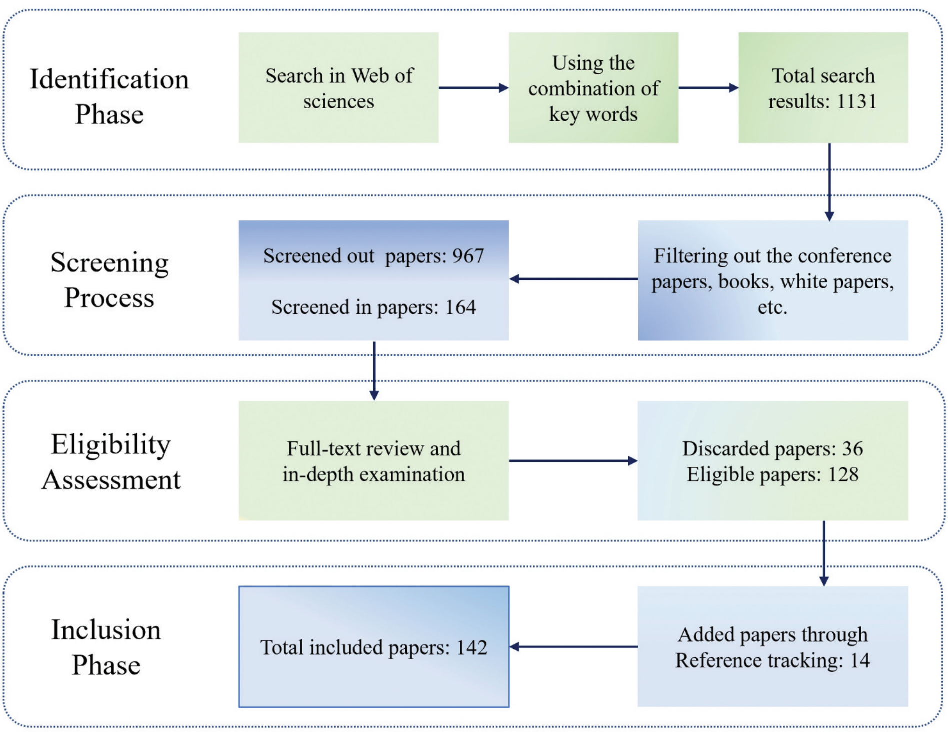

Figure 1. The flowchart of the different phases in the literature review.

Figure 1 illustrates the overall demonstration of the implemented procedure. Following the above four steps, all major studies are included in the analysis.

3. The concept of resilience in seaports

3.1. Definition and terminology

Resilience in many application fields is subject to varying viewpoints and definitions. Within the realm of engineering systems, and specifically in the domain of infrastructures, the concept of resilience encompasses several dimensions and viewpoints, resulting in the absence of a universally applicable definition. For instance, the National Infrastructure Advisory Council (Critical Infrastructure Resilience: Final Report and Recommendations 2009) provided a definition of infrastructure system resilience, characterizing it as the capacity to predict, absorb, adapt, and/or quickly recover from a disruptive event such as natural disasters. Hosseini, Barker, and Ramirez-Marquez (2016) conducted a comprehensive literature review, including research publications that explore the definition, conceptualization, and measurement of resilience across many academic fields, with particular emphasis on engineering systems. Wan et al. (2018) conducted a thorough analysis of prior scholarly investigations, focusing on the elucidation and fundamental attributes of transportation resilience. Out of all relevant resilience definitions, this research aligns with the prevailing viewpoint within the maritime community and the term 'seaport resilience' is defined as the capacity of a port to effectively withstand disturbances, preserve its fundamental structure and operations, adapt to the existing situation, and then restore its service to a satisfactory level within an acceptable timeframe and financial constraints after the occurrence of disruptions. According to the above-mentioned definitions, the features of resilience may be delineated using several terminologies, including, but not limited to, reliability, robustness, redundancy, vulnerability, flexibility, adaptability, and recoverability, among others. In this regard, Biringer, Vugrin, and Warren (2013) proposed three capacity categories of basic system features that contribute to infrastructure resilience and act as defense layers against disruptive events. These categories, namely absorptive, adaptive, and restorative capabilities, serve as a classification framework for different elements of resilience. Figure 2 illustrates the three resilience capacities and their respective elements in the

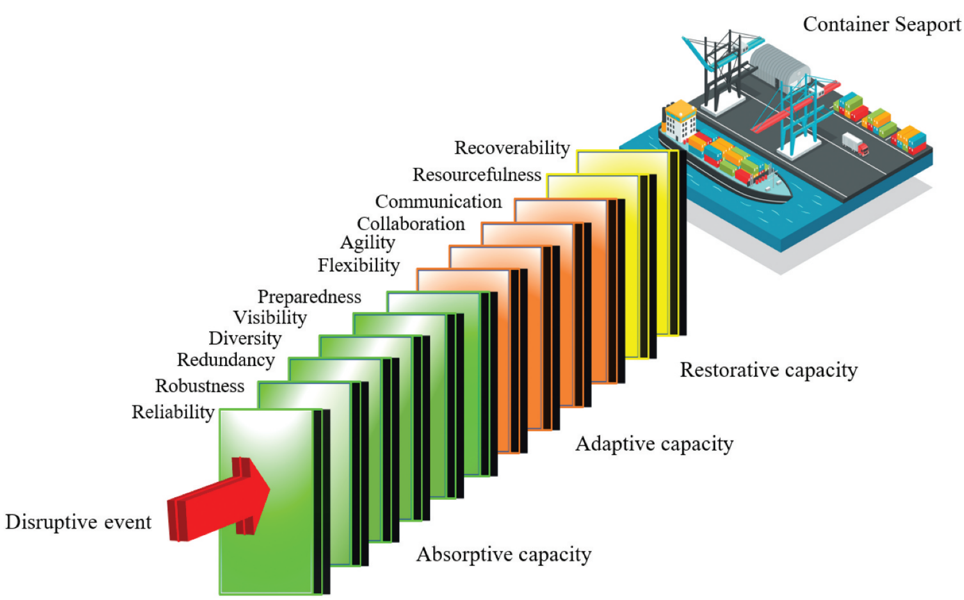

Figure 2. Seaport resilience structure [Authors].

context of seaport operations. The '*absorptive capacity*', as its name suggests, refers to the inherent capability of a system to absorb or endure the effects of any disturbances that pose a risk to its functioning, while also mitigating the resulting repercussions. As an endogenous characteristic of the system, this capacity is widely recognized as the primary mechanism for mitigating the impacts of disruptive events. The analysis of relevant scholarly sources has led us to identify five key components that contribute to this particular capability. These components include reliability, robustness, redundancy, diversity, visibility, and preparedness. The '*adaptive capacity*', as the second line of defense, is the ability of a system to adjust and reorganize itself in response to post-accident scenarios, while using non-standard operating approaches that require more resources and expenses, with the aim of minimizing the impacts of interruptions. Four elements of resilience that can be attributed to the adaptive capacity are identified as follows: flexibility, agility, collaboration, and communication. The concept of '*restorative capacity*' is presented as the last line of defense, denoting a system's capability to undergo repair, recovery, and restoration in a prompt and efficient manner in a way that the repaired system will function at the same level as its original condition. Given the vast array of operations involved in this capacity, including services, methods, procedures, and technologies (resourcefulness), it necessitates a substantial amount of effort and financial investment compared to other capacities. Table 1 presents the definition of the terms related to seaport resilience.

3.2. Temporal phases of seaport resilience

To enhance understanding and facilitate the assimilation of the concept of resilience, as well as to see the role of resilience elements during disruptions, Figure 3 depicts the hypothetical performance level of a seaport and its fluctuations across three distinct temporal phases: pre-disruption, during the actual disruption, and post-disruption. The diagram follows the 'Resilience Triangle' concept (Fan et al. 2024) and aims to integrate the essential characteristics of resilience elements to depict the time-dependent representation of seaport performance. Over the pre-disruption period, a port's functionality depends on factors such as the design configuration, the reliability of its systems, sub-systems, and associated components, as well as the prevailing operating conditions. For simplicity, the system's functionality is represented by a linear model, assuming a steady state and disregarding any transitory deviations from the original state.

Upon the occurrence of disruptive events within the system, namely at time t_e, the absorptive capacity is triggered. This time may be divided into the following two distinct phases: In the first phase, the system demonstrates its ability to withstand the effects of disruptive events by using redundant or diversified capabilities. This enables the system to uphold a minimal threshold of performance, demonstrating that it only fulfills the most basic requirements. In the second phase, depending on the severity of the disruptive event, functionality reduction persists beyond the complete exhaustion of redundant capabilities, resulting in continuous deterioration until time t_d, when the adverse effects of the disruption are fully manifested.

In this scenario, the system's functionality is at its lowest point, determined by the level of systems' robustness. In other words, the extent to which functionality decreases reflects the degree of vulnerability in the system, indicating a lack of robustness. The level of vulnerability shown by a system inversely correlates with the degree of its robustness. Following the point of maximum functional deterioration, denoted as time t_d, a series of adaptive and restorative mechanisms are initiated with the aim of restoring the system's functioning to a stable condition by time t_r.

It is important to acknowledge that the new state does not necessarily have to be at the same level as the initial state. This is because the new state has the potential to attain an alternative equilibrium level, which might be either an enhanced state (i.e. enhanced functionality) or a partially restored state (i.e. reduced functionality). During the recovery phase, the presence of various factors such as the availability of resources (human, technology, budget), agility, flexibility, effective communication, and efficient collaboration are of utmost importance. In

Table 1. Seaport resilience terminology.

Term	Definition	Reference
Absorptive capacity	The ability of a system to absorb or withstand the impacts of any disruptions threatening its operation as well as minimizing the subsequent consequences.	Biringer, Vugrin, and Warren (2013)
Adaptive capacity	The ability of a system to adapt itself to post-accident situations (reorganization) and employ unconventional operational strategies with extra effort and cost to mitigate the effects of disruptions.	Biringer, Vugrin, and Warren (2013)
Restorative capacity	The ability of a system to be repaired, recovered, and restored quickly and efficiently, although requiring the greatest effort and cost.	Biringer, Vugrin, and Warren (2013)
Reliability	The probability of a system to successfully operate at its optimum level of functionality under specific conditions and within a specified period.	Modarres, Kaminskiy, and Krivtsov (2016)
Robustness	The inherent characteristics of a system to withstand and absorb the stress of perturbations and disturbances while maintaining its functionality.	Faturechi and Miller-Hooks (2015)
Redundancy	The ability of a system to substitute its failed components or even sub-systems with the reserved embedded ones to take over the same functions in the same way.	Modarres, Kaminskiy, and Krivtsov (2016)
Diversity	Having multiple independent systems or components that can fulfill the same function, while possessing distinct attributes, to reduce the possibility of common cause failure.	Modarres, Kaminskiy, and Krivtsov (2016)
Visibility	Visibility refers to the ability of systematic monitoring of different operations such as tracking shipments and the corresponding supply information throughout the entire process.	Kim, Choi, and Kim (2021)
Preparedness	The ability to be prepared against disruptions through proactive implementation of specific measures prior to their occurrence.	Kwesi-Buor, Menachof, and Talas (2019)
Flexibility	The capacity to adjust, adapt, reorganize, and reconfigure in response to a disruptive occurrence, via the implementation of contingency strategies. The connotations associated with flexibility differ from those associated with robustness in the context of preserving system performance, rather than specifically preserving system structure.	Lagoudis, Naim, and Potter (2010)
Agility	The capacity to promptly address disruptions with the aim of mitigating the extent of suboptimal performance.	Adam et al. (2016)
Collaboration	The capacity of multiple groups to collectively view and participate in the process of decision-making together, to effectively address the disruptions.	Wang, Wu, and Yuen (2023)
Communication	The process of effective exchange of information for mitigating the consequences of disruptions among relevant groups of decision-makers, both prior to, during, and after such events.	Wang, Wu, and Yuen (2023)
Resourcefulness	Resourcefulness is described as the state or quality of having access to a sufficient quantity of materials, supplies, and personnel in order to effectively restore or maintain functionality.	Reggiani (2013)
Recoverability	The capacity to efficiently recover from disruptions and restore the normal functioning within a reasonable timeframe, while minimizing expenses and resource utilization.	Baroud et al. (2014)
Vulnerability	The deficiency or susceptibility in the structure, design, functioning, and/or administration of a seaport, which makes it prone to damages or a considerable reduction in capacity in the face of disruptive events or diminishes its ability to return to a state of stability.	Pan et al. (2021)
Survivability	survivability refers to the ability of a seaport to resist various stressors, disturbances, or adverse events while maintaining essential functions and minimizing the impact on its overall stability and functionality.	Lagoudis, Naim, and Potter (2010)
Rapidity	Rapidity is a measure of how quickly the system can restore its critical functions and resume regular activities after facing a disruption. A seaport with high rapidity can bounce back swiftly and efficiently from disruptive events, minimizing downtime and negative impacts to supply chains and customer service.	Baroud et al. (2014)

the resilience diagram, the red dashed line indicates the presence of a highly resilient system, which implies that the system's functioning may see considerable improvement in comparison to its initial state. A stronger absorptive capacity not only reduces the vulnerability, but also prolongs the occurrence of minimal functionality ($\Delta t_1' > \Delta t_1$). Furthermore, with enhanced adaptive and restorative capabilities, there can be an observed rise in the rate of recovery, suggesting a more rapid process of repair (see the slope of the recovery line, ($\Delta t_2' < \Delta t_2$)). It is worth mentioning that, following a disruption, the system's functionality may increase to

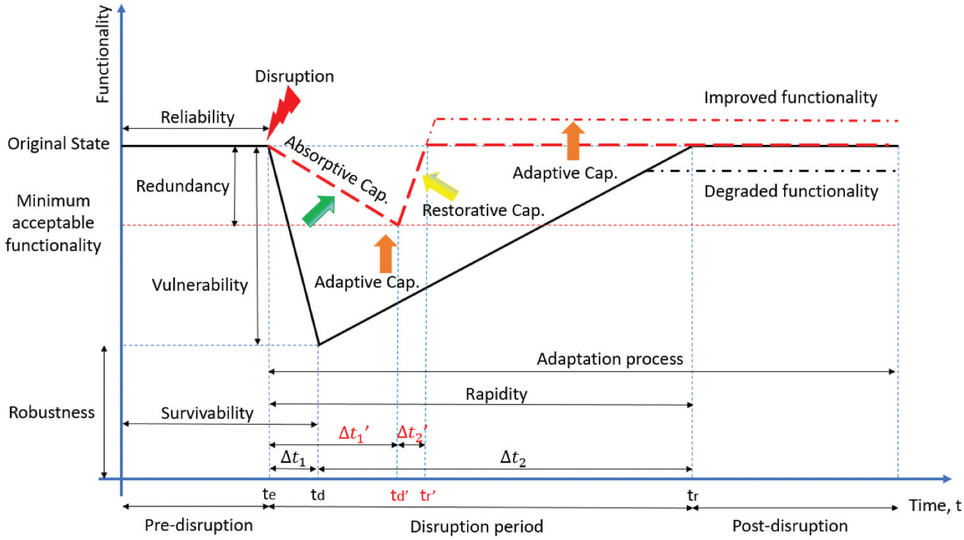

Figure 3. Schematic representation of seaport functionality with consideration of resilience capacities [Authors].

a higher degree and its resilience against future occurrences may be enhanced due to the adoption of advanced adaptive capabilities and the incorporation of lessons learned from prior experiences or during the disruption. All in all, this observation indicates that systems encountering disruptive events and possessing higher resilience exhibit superior performance compared to those with lower resilience when facing the same disruptions.

3.3. Seaport disruptive scenarios

Maritime supply chains in general, and seaports in particular, are subject to numerous sources of risk, resulting in moderate to severe interruptions. There appears to be a growing recognition among academic researchers and industry stakeholders that seaports should not be viewed as merely another set of nodes in the supply chain. Instead, they should be seen as interconnected components and as central components of the maritime transportation system (MTS), with serious repercussions if they fail (Wendler-Bosco and Nicholson 2020).

Given the interconnected operation of different parts in MTS, any disruption in any part will immediately propagate throughout the system, having an immediate impact on supply chains. In this regard, attempting to identify all possible types of hazards threatening the functionality of such important infrastructures is essential. Using lessons learned from research on safety and reliability in other critical fields such as aviation, nuclear, and chemical industries, potential disruptive scenarios in the context of seaports can be identified and classified using a data-driven approach or a qualitative process. In the former, hazards are detected and documented through a systematic process using historical events, allowing for traceability and additional analysis, and in the latter, discussions, interviews, and brainstorming from experts, academics and stakeholders are applied. Due to the nature of ports, the location they are built, the complex systems they consist of, and the sociological environment they operate in, a wide range of risks could impact their functionality. Mansouri, Nilchiani, and Mostashari (2010) stated that hazards to ports can be classified into four main groups: natural disasters, organizational factors, technological failures, and human errors. Each group can also be attributed to different underlying causes originating from either external disturbances or internal perturbation of the ports' boundaries. To enrich the above list of classification, one might introduce the following disruptive scenarios which have received less attention but are critical in a case of occurrence, which are economic factors, land/marine access disruptions, and network disturbances (Grainger and Achuthan 2014). There are several noteworthy studies aiming at analyzing the impact of different hazards on the seaports and discussing their subsequent consequences. With the help of the Automatic Identification System (AIS), Verschuur et al. (2022) analyzed 141 cases of port disruptions caused by natural disasters in 74 different ports throughout the world. Based on the empirical evidence they provided, they concluded that multiple ports at the same time, could be disrupted and even shutdown in case of extreme natural disasters, putting the reserve capacity at potential alternative ports at risk. Cao and Lam (2018) developed a novel framework based on the simulation of seaport operations, historical events and actual data logs to estimate the financial consequences of two major types of catastrophes that occur in ports, namely, natural disasters and human-induced hazards. Adam et al. (2016) conducted a systematic analysis of maritime disruptive scenarios over a period of six decades from 1950 to 2014 to evaluate their scale, time span and subsequent impacts on UK ports and the related areas. They categorized the disruptions into seven major sources, including human errors, technological failures, poor visibility, rough seas, snow and ice, storm surges and windstorms. Lam and Su (2015) provided a comprehensive assessment of port interruptions in East and South Asia from 2001 to 2011. They concluded that natural disasters and labor strikes are the two most frequent reasons for port interruptions, with natural disasters having the most damaging impact on supply chains. In Figure 4, a comprehensive analysis of the existing

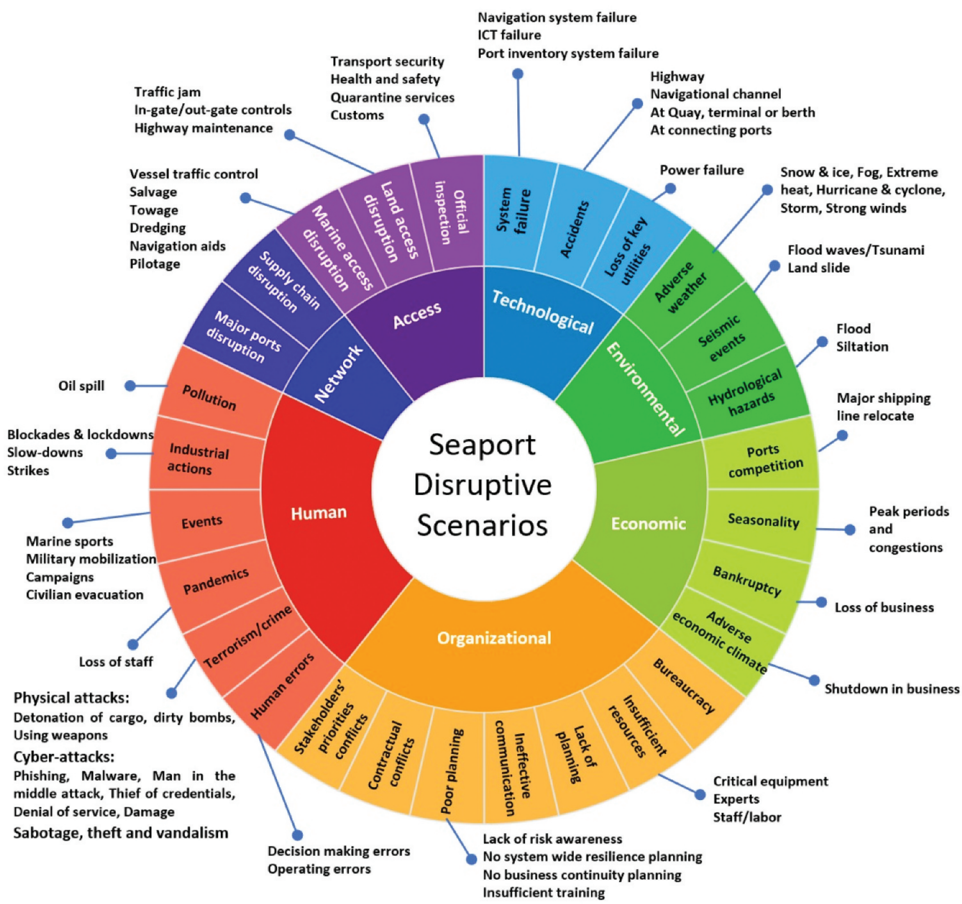

Figure 4. Seaport disruptive scenarios classification [Authors].

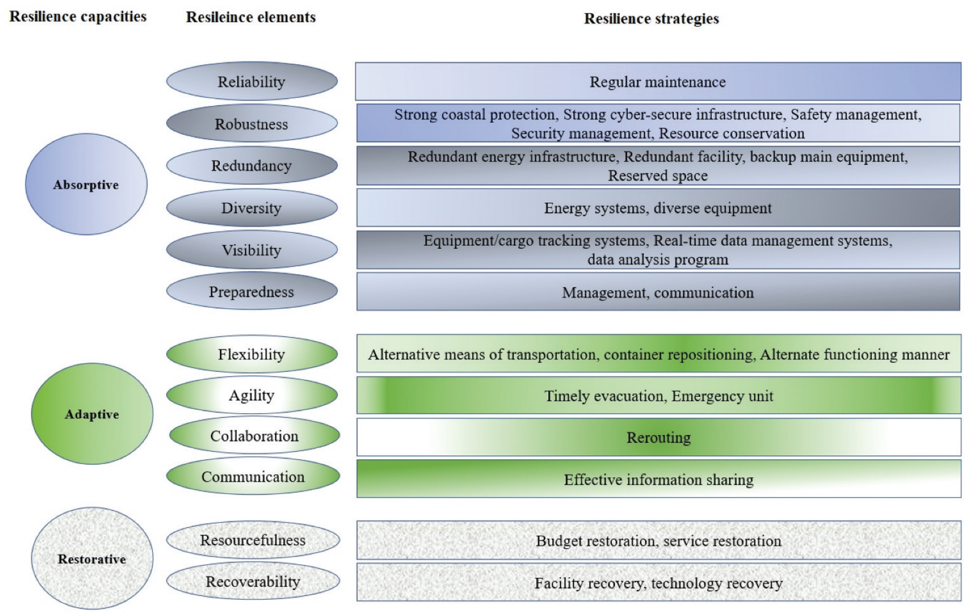

Figure 5. Seaport resilience capacities, elements, and strategies [Authors].

literature has been compiled to identify and categorize seven primary disruptive scenarios and their corresponding sub-factors that pose significant risks to the efficient operations of seaports.

3.4. Seaport resilience strategies

Seaport resilience strategies are a crucial set of protective actions and contingency plans, including both reactive and proactive measures, with the objective of improving the ability of seaports to manage disruptions and swiftly bounce back from adverse events. These strategies encompass various features that are commensurate with the resilience capacities and elements. Figure 5 demonstrates the overall structure of seaport resilience and the relevant strategies. It is to be noted that the resilience strategies are not limited to the examples in Figure 5 and may be customized to the unique features of individual ports and their challenges against various disruptions. In this regard, we have compiled the different resilience strategies adopted in the selected papers in Table 2. Further discussion about the details of these resilience strategies as well as their descriptions and applications are provided in section 6.2.

4. Seaport resilience assessment methodologies

In this section, the primary emphasis is placed on deliberating upon all relevant aspects of resilience assessment in seaports. Utilizing an extensive examination of the relevant literature and following the classification of resilience assessment methods presented in (Hosseini, Barker, and Ramirez-Marquez 2016), the research of seaport resilience may be approached in a similar manner. The approaches to evaluating the resilience of seaports against the above-discussed disruptive scenarios can be classified into three primary categories, namely qualitative, semi-quantitative, and quantitative approaches. The qualitative approaches deliver a general comprehension of the definition of resilience, the interaction between the resilience elements, the identification of causal relationships between various influencing factors in resilience, and the establishment of an overarching framework to categorize resilience strategies based on resilience elements. As guiding principles and

Table 2. List of resilience capacities, elements, and strategies in representative studies.

Study	Resilience capacity	Resilience elements	Resilience Strategies
Hossain et al. (2019)	Absorptive	Redundancy, Robustness	Strong coastal protective measures, Energy redundant facilities, Safety management, Emergency response team
	Adaptive	Adaptability	Quick evacuation, Repositioning, mode flexibility
	Restorative	Resourcefulness	Resource restoration, budget restoration
Hosseini and Barker (2016)	Absorptive	Reliability, redundancy, robustness	Supportive utility systems, additional controling equipment, Storm surge protection, Communication, Space utilization, maintenance, skilled labor management
	Adaptive	Adaptability	Quick evacuation, Repositioning, mode flexibility
	Restorative	Resourcefulness	Resource restoration, budget restoration
Wang, Wu, and Yuen (2023)	Readiness Response	Redundancy, robustness, visibility, agility, flexibility, recovery	Facility, technology and manpower restoration, alternative operation mode, real-time data management system, extra capital equipment, safety management, quick evacuation, alternative transportation mode, emergency response team, redundant facilities, and energy infrastructure
Kim, Choi, and Kim (2021)	Absorptive	Robustness, redundancy, visibility	Situational operation manual, Emergency workforce mobilization plans, establishing backup offloading and transportation machineries, establishment of systematic inspection protocols, the modernization and visualization of IT systems for port operations, the use of cutting-edge technology, such as digital twins.
	Adaptive	Flexibility, collaboration, agility, information sharing	Implementation of alternative operation strategies using big data, machine learning, etc., communication of the port's strategic objectives, consistent identification of client demands, personnel instruction on how to swiftly respond to emergencies, information exchange for the development of collaborative response systems.
	Restorative	Response, recovery	Creating crisis-specific organizational and monitoring structures, Emergency preparedness instruction, devising strategies for funding the recovery of port functions during emergencies, the assessment of the viability of emergency plans preparations using simulation.
León-Mateos et al. (2021)	Absorptive	Diversity, redundancy	Alternative sources of energy, new infrastructures,
	Adaptive	Information sharing, flexibility, collaboration,	Adaptive management, digitalization, transport improvement, Collaboration with insurance providers, consideration of the impacts and costs of the different adaptive plans, long-term proactive strategies, development of strategies to ensure uninterrupted functioning of infrastructure and facilities, relocation.
	Restorative	Response, recovery	Facility and technology recovery, service restoration.
Omer et al. (2012)	Absorptive	Redundancy, robustness, diversity, modularity, capacity tolerance,	Alternative road transportation, increasing the port reserved capacity.
	Adaptive	Information sharing, collaboration, resource allocation, preparedness	Allocation of trains, trucks, and personnel
Mansouri, Nilchiani, and Mostashari (2010)	Prevention	Redundancy, vulnerability	Redundant information systems redundant infrastructure systems, implementation of security monitoring systems,
	Recovery	Support and maintenance	Designing efficient maintenance strategies for the infrastructures
John et al. (2014)	Absorptive	Robustness, redundancy, modularity, visibility	Hardening infrastructure systems, constructing systems that can be attached and detached easily, enhancing the use of vessel traffic management systems, deploying floating harbor cranes, investing in container tracking technology, making infrastructure systems more cognitive,
	Adaptive	Collaboration, resource allocation, information sharing,	Proper allocation of resources to enhance operation, collaborative efforts between stakeholders for an efficient information flow
	Restorative	Resourcefulness,	Increasing staffing in critical areas, consideration of high-capacity tolerance of the systems
Mutombo, Ölçer, and Kuroshi (2017)	Preparedness	Robustness,	Incorporating projected climate forecasts into the planning and construction of port infrastructure.
	Adjusting	Redundancy, diversity,	Rerouting cargoes to a back-up port, using rail line and road interchangeably
	Rebounding back	resourcefulness	Consideration of efficient operations and timely implementation of sophisticated supply networks
Cho and Park (2017)	Preparedness	Robustness	Allowance capacity, substitution by nearby ports
	Recovery	Rapidity, resourcefulness	Allocating enough resources for repairing and recovery

roadmaps, qualitative approaches can assist stakeholders in understanding resilience and recognizing the relevant strategies adopted to improve resilience. However, when it comes to addressing the multitude of variables and discerning precise quantitative correlations between them, qualitative approaches are not sufficient, and there arises a need for a complementary approach. This necessity can be explained by the fact that managers or decision-makers tasked with devising strategies require a solid justification for their decision-making process to optimize resource allocation for strengthening system resilience, a need that qualitative approaches alone cannot fulfill. In this regard, quantitative approaches have the potential to address the aforementioned limitations and offer more compelling and cogent insights. The following sections introduce and discuss the different resilience assessment methodologies developed and applied in the context of seaports and their related superstructures.

4.1. Qualitative approaches

The qualitative approaches in the literature can be further categorized into conceptual frameworks and empirical studies.

4.1.1. Conceptual frameworks

The qualitative assessment of seaport resilience is predominantly carried out through the utilization of conceptual frameworks. This approach deals with a wide range of concept-related subjects, such as terminologies, attributes, conceptual foundations and modeling. The study by Mansouri, Nilchiani, and Mostashari (2010) is considered a seminal study in introducing conceptual frameworks within the realm of seaport resilience. The authors developed a risk management-based decision analysis (RMDA) framework consisting of three main phases, namely vulnerability assessment, resilience strategies development, and cost-effectiveness analysis, to provide the seaport stakeholders with a tool to select the best available policies for the improvement of port infrastructure resilience.

The issue of fragmented information flows among multiple stakeholders in seaports has been widely recognized as a significant barrier to coordinated responses during disruptive events. Various researchers have developed conceptual frameworks to address this challenge, each offering distinct approaches to improving seaport resilience. These frameworks can be categorized into different thematic areas, including decision-making processes, stakeholder engagement, information sharing, and organizational resilience.

In terms of decision-making and process architecture, Mostashari et al. (2011) introduced the Cognitive Process Architecture Framework (CPAF). This framework aims to support the effective perception of changes and events, facilitate the analysis of operational scenarios, enable informed decision-making by accounting for trade-offs, and ensure continuous monitoring of the implementation of selected actions. This approach highlights the need for a dynamic and adaptive framework that evolves with the complexities of seaport operations, making it particularly relevant in scenarios where rapid responses are required. Almutairi et al. (2019) adopted a different approach, emphasizing the fluctuating interests and influences of different stakeholders over time. Their framework integrates stakeholder mapping and disruption scenario modeling to address varying levels of stakeholder participation in response to disruptive scenarios. By recognizing that stakeholders' priorities may shift depending on economic, environmental, and social factors, this framework allows for more strategic planning initiatives aimed at enhancing resilience. Shaw, Grainger, and Achuthan (2017) tackle the issue of information sharing between key seaport stakeholders, including managers, shipping firms, and logistics businesses. Their multi-level case study methodology led to an information-sharing model that leverages both supplier and customer perspectives. The key insight here is that subjective information, when shared effectively, can enhance seaport resilience by enabling stakeholders to act promptly and allocate resources more efficiently. This approach provides a practical solution for optimizing limited resources, emphasizing the operational benefits of improved communication channels among stakeholders during disruptions. Vanlaer et al. (2022), developed a framework that categorizes resilience-building activities into three key phases: anticipation, coping, and adaptation. Their model applies these phases across the policy, economic, and operational domains, offering a comprehensive approach to seaport resilience. By focusing on these domains, the framework ensures that resilience is not only a reactive measure but also a proactive process, embedded within the broader organizational strategy of seaports. This holistic approach suggests that resilience must be built at multiple levels, from policy planning to day-to-day operations, to be effective.

Categorizing the above-mentioned approaches reveals two major focuses: process-driven frameworks (such as CPAF and the information-sharing model) and stakeholder-centric frameworks (as demonstrated in the stakeholder mapping by Almutairi et al. and the organizational resilience model by Vanlaer et al. (2022). Both categories highlight the importance of collaboration and communication, but each addresses different aspects of resilience: process frameworks prioritize efficiency and optimization, while stakeholder frameworks emphasize the need for inclusive and flexible engagement strategies.

Despite the merits of conceptual approaches, such as providing a structured methodology for understanding seaport resilience and helping researchers and practitioners systematically evaluate various dimensions of resilience, their theoretical foundation and limited reliance on quantitative data can weaken the persuasiveness of their conclusions, potentially leading to an incomplete representation of the overall picture.

4.1.2. Empirical studies

Moving away from conceptual approaches, there also exist some survey-based studies that aim to analyze port resilience. Empirical studies provide valuable, data-driven insights into seaport resilience by focusing on real-world events and gathering the perspectives of those directly involved in port operations. These studies offer practical, grounded recommendations for improving resilience, such as identifying common disruption patterns or developing risk management models.

Trepte and James (2014) research found that US seaport disruptions typically last 6 to 20 days. They analyzed cargo concentration, disruption duration, and capacity requirements to reduce port bottlenecks. Additionally, Rice and Trepte (2012) gathered insights from stakeholders, concluding that ports are resilient to daily fluctuations and minor disruptions. However, their study showed that the maritime transportation system lacks sufficient resilience when facing large-scale disruptions, highlighting a gap in preparedness for significant challenges. These works capture the firsthand experiences and perspectives of various stakeholders, such as port managers and users. This provides a comprehensive understanding of port resilience from the viewpoint of those directly involved in operations. The involvement of multiple stakeholders ensures that empirical studies reflect the practical challenges faced during disruptions, making the findings highly relevant to real-world applications. A similar approach, conducted by Loh and Thai (2015), classified the port-related supply chain disruption threats into four categories, namely, infrastructure threats, manpower threats, planning threats and security threats, through interviewing the professional port managers as well as port users. They also proposed a management model to improve the resilience of seaports regardless of their specific cargo handling types, regions, or stages of development. The strength of empirical research lies in its ability to connect theory to practice, validating resilience frameworks through actual disruptions and stakeholder input. However, empirical studies also face challenges. The limited scope of data, potential lack of generalizability, and difficulty in addressing large-scale, complex disruptions present notable drawbacks. Moreover, the reliance on stakeholder interviews and qualitative data can introduce subjectivity, which might hinder the development of universally applicable strategies.

4.2. Semi-quantitative approach

A semi-quantitative methodology seeks to furnish a structured framework for assessing resilience by harmonizing the depth of qualitative understanding with the precision of quantitative analysis. An often-used strategy in semi-quantitative resilience evaluation involves assigning scores or rankings to various resilience indicators or elements. These assessments may draw upon a blend of qualitative assessments, expert insights, and quantitative data.

A semi-quantitative measurement framework to evaluate the resilience of seaports was established by Kim, Choi, and Kim (2021), drawing upon an extensive review of pertinent scholarly literature. This framework was empirically validated through the implementation of both exploratory and confirmatory factor analyses, utilizing a sample of 199 individuals representing various stakeholders within the port industry in South Korea. Based on the findings of the study, they came to this conclusion that the Korean ports possess a certain degree of adaptive and absorptive capabilities for encountering adverse circumstances. However, they exhibit a relatively limited level of restorative capability to respond to such circumstances when they do occur. Mutombo, Ölçer, and Kuroshi (2017) introduced a novel approach that uses resilience scores to assess the resilience of port infrastructure against climate-related hazards. By providing the scores, this approach delivers clear and actionable results. These scores can highlight areas of strength (e.g. adaptive and absorptive capabilities) and weakness (e.g. limited restorative capabilities), helping stakeholders prioritize actions. The weighted scoring system, where preparedness is given a higher priority, allows decision-makers to focus on crucial adaptive measures.

While semi-quantitative methods aim to harmonize qualitative and quantitative aspects, reliance on expert insights and qualitative assessments introduces a level of subjectivity. Additionally, assigning weights and scores, though useful for decision-making, can sometimes oversimplify the complexities of resilience. As a result, the mathematical formulas used to calculate resilience may overlook nuanced factors or interdependencies between resilience elements, potentially leading to an incomplete picture.

4.3. Quantitative approaches

This section provides a discussion of various quantitative methodologies for assessing the resilience of seaports. Based on the literature review, we have identified four major approaches used in the relevant studies: Bayesian networks, multiple criterion decision making, simulation, mathematical modeling and optimization. It's worth mentioning that certain additional approaches have been identified which do not fall into the previously established categories. As a result, they are all addressed under the miscellaneous category heading.

4.3.1. Bayesian networks

A Bayesian network (BN) is a formal probabilistic methodology that is utilized to represent the causal relationships between random variables through the utilization of conditional probabilities (M. Mohsendokht, Li, Kontovas, Chang, et al. 2024; M. Mohsendokht, H. Li, C. Kontovas, C. Chang, et al. 2024). With a diverse array of functions in the domain of risk, reliability and in particular, resilience engineering, as well as its capability to combine various pieces of information, including objective and subjective data, BN has emerged as an advanced tool for uncertainty modelling in the realm of seaport resilience assessment.

Hosseini and Barker (2016) applied BN to assess the resilience of the Port of Catoosa against various disruptions, focusing on the 'Triple Resilience' capacities: absorptive, adaptive, and restorative. They developed strategies for each capacity and validated their model through sensitivity, forward, and backward propagation analyses. Similarly, Hossain et al. (2019) devised a five-phase BN-based resilience assessment for the Port of Pascagoula, incorporating disruptions like natural disasters and cyber-attacks. Their sensitivity analysis highlighted the importance of maintenance practices, alternate routing, and manpower allocation in enhancing port resilience. Building on this, Hossain et al. (2020) expanded their research by integrating interdependencies into a BN model, recognizing geographic, service provision, and repair access as key factors. All the above-mentioned studies emphasize the utility of BN for resilience assessment, highlighting maintenance, interdependencies, and adaptive strategies as essential to enhancing port infrastructure resilience under various disruptive scenarios. The approaches underscore the significance of interconnectedness in port operations and supply chain management.

Wang, Wu, and Yuen (2023) developed a circular four-stage research framework using a BN model to assess the resilience of Shanghai Yangshan Deepwater Port. They categorized resilience capabilities into two main areas: readiness (pre-event actions) and response (post-event actions). To validate their model and gain insights, they conducted sensitivity analysis along with forward and backward inference analyses.

In line with relevant studies, Panahi et al. (2022) developed a BN model to measure the resilience of Hong Kong's Kwai Tsing Container Terminals in the face of the COVID-19 pandemic. They applied similar approaches in BN models, such as sensitivity and propagation analyses, to extract useful insights. The results indicated that the primary variables contributing to the enhancement of seaport infrastructure resilience are port connectivity, training, and service improvement.

It goes without saying that BN offers a powerful framework for analyzing seaport resilience by modeling causal relationships, handling diverse scenarios, and incorporating interdependencies. The ability of BN to blend qualitative and quantitative data makes it a versatile tool in assessing resilience across multiple dimensions, from infrastructure to human factors. However, the success of BN models depends heavily on data quality and the expertise of those building and interpreting the models. To maximize the benefits of BN in seaport resilience analysis, ongoing refinement of models and broader data collection efforts are essential, along with improving accessibility for non-experts in the field.

4.3.2. Multiple criterion decision making

In the realm of seaport resilience assessment, the intricate nature of systems and the multitude of factors at play, necessitate the consideration of diverse techniques, including expert judgment, cost-benefit analysis, collaborative design and modeling of the system. This has resulted in an enhanced assortment and abundance of tools for decision-making, leading to the emergence of Multi-Criteria Decision Making (MCDM) tools. In this regard, the MCDM framework encompasses the integration of qualitative and quantitative data, along with the implementation of suitable resilience strategies, to mitigate the potential impact of disruptive scenarios and improve the overall resilience of seaports. Some illustrative examples of adopting MCDM for seaport resilience analysis can be tracked in the following works. John et al. (2014) proposed a framework combining the Fuzzy Analytical Hierarchy Process (FAHP) and fuzzy TOPSIS to select optimal resilience strategies for seaports, using nine criteria (e.g. cost, safety, reliability) and analyzing 11 strategies. FAHP was used to assign weights, while TOPSIS ranked the strategies. Sensitivity analysis examined the impact of weight variations on rankings. Similarly, Cao and Lam (2019) applied fuzzy Evidential Reasoning (ER) and fuzzy TOPSIS to assess port vulnerability post-2015 Tianjin Port explosion, offering insights into port resilience by addressing both pre- and post-disruption vulnerabilities in uncertain scenarios.

The MCDM approach offers a comprehensive framework for quantitative analysis by integrating both qualitative and quantitative data, enabling a well-rounded assessment of seaport resilience. Additionally, the method can be tailored to various criteria and scenarios, making it adaptable to different contexts and needs. Techniques such as FAHP and TOPSIS provide systematic ways to rank resilience strategies based on multiple factors. However, the process of assigning weights and performing sensitivity analyses can be time-consuming and complex. Furthermore, expert judgment and the selection of criteria introduce subjectivity, which may negatively influence the results.

4.3.3. Simulation

The evaluation, design, and configuration of resilience strategies in seaports pose significant challenges due to various factors such as the geographical characteristics of the port, the unpredictable and diverse nature of disruptive events, the management of investments and allocation of resources, as well as the complex interactions among numerous other variables. In this respect, simulation could be a useful approach to deal with the complexity of the process by executing numerous iterations and experiments to investigate the responsiveness of a model to various scenarios and inputs. Several studies have applied simulation models to assess port resilience, as detailed below.

Folkman et al. (2021) developed a simulation model to examine the adverse impacts of hurricanes on Houston port operations, demonstrating how natural disasters affect TEU throughput and port efficiency. This approach allows stakeholders to explore the effects of disruptions on various aspects of port operations, providing valuable insights into both pre- and post-disruption scenarios. However, the accuracy of simulations depends heavily on the data and assumptions used. Their model may be limited by the availability and precision of real-world data regarding port operations, and the assumptions about recovery timelines and infrastructure capacity can affect the validity of the outcomes.

Zhou et al. (2021) established a decision support system that utilizes digital-twin modeling to assess the resilience of a port in the face of three power supply disruption scenarios with specific levels of power shortage as well as determine the most suitable course of actions to be taken following the disruptions. The findings of the research indicate that neglecting ordinary operational uncertainties in port models can lead to a substantial overestimation of resilience levels, which subsequently will result in misleading conclusions for port operators, falsely indicating that their port possesses a high level of resilience.

Loh and Van Thai (2015) conducted simulations to ascertain the importance of ports in the context of supply chain disruptions. The research aimed to establish a comparative analysis of costs associated with various scenarios, namely, no disruption, waterway accidents, 12-hour delay, and port shutdown resulting from a strike. The findings indicated that the escalation in expenses during an unfavorable occurrence is primarily ascribed to elevated warehousing storage costs, inventory storage costs, labor costs, and transportation costs. The limitations of their study can be succinctly described as the absence of a sensitivity analysis and the exclusive examination of disruption effects on a single category of cargo.

Shafieezadeh and Burden (2014) proposed a comprehensive framework for assessing port resilience through simulation analysis. Their developed framework was specifically designed to evaluate the seismic performance of a hypothetical seaport terminal located on the West Coast of the United States, considering both the during and post-hazard phases. While the study gives port operators insight into vulnerabilities, particularly how berths are more affected than cranes, and highlights the long recovery timelines after significant seismic events, it may not account for other types of disruptions, such as economic or environmental shocks.

Based on the above studies, it can be concluded that simulation is a powerful tool for analyzing seaport resilience due to its ability to model complex real-world scenarios and test responses to various disruptive events. However, its effectiveness is limited by the quality of data, assumptions made during model construction, and the potential omission of key variables or scenarios. To fully maximize the benefits of simulation in resilience assessments, models should be continuously refined with updated data, broader risk considerations, and the inclusion of sensitivity analyses.

4.3.4. Mathematical modeling and optimization

In the context of port resiliency, mathematical modeling-based approaches are well-established and frequently used methods which in conjunction with optimization techniques, are usually employed to optimize the resilience for achieving the maximum effectiveness. Zhen, Lin, and Zhou (2022) sought to evaluate the resilience of a seaport by quantifying the resilience of its traffic-electric power coupled system. They developed a two-stage stochastic mixed-integer nonlinear mathematical model within the constraints of a predetermined budget. The two-stage entail making a decision regarding the implementation of preparedness measures in the initial stage, and the implementation of appropriate recovery measures for the power system in the second stage. The result indicated that simultaneous implementation of the pre-event preparedness measures and post-event recovery measures yields greater advantages in enhancing and sustaining port resilience. León-Mateos et al. (2021) introduced a Port Resilience Index (PRI) to evaluate seaport resilience by associating it with perceived indicators. Using a multi-stage approach, they identified climatic risks, analyzed resilience factors, and incorporated expert opinions to derive normalized scores. A case study at the port of Galicia, Spain, revealed a PRI of 52%, highlighting the port's vulnerability to climate change impacts, especially concerning its infrastructure, facilities, and operations.

Mathematical modeling and optimization approaches provide a powerful framework for assessing and enhancing seaport resilience by enabling the quantification and optimization of relevant strategies such as preparedness and recovery. These models are particularly useful for handling complex, coupled systems and allow for structured, scenario-based decision-making. However, their effectiveness can be compromised by data scarceness, simplifying assumptions, and the potential subjectivity involved in indicator-based models. To maximize their usefulness, mathematical models should be continuously refined with updated data, and efforts should be made to reduce bias in indicator selection and weighting.

4.3.5. Miscellaneous methodologies

In addition to the aforementioned methodologies, several other approaches that do not fit into the previously discussed categories have been utilized in the literature. For instance, Galbusera et al. (2018) put out a theoretical framework based on Boolean networks to analyze the complex interdependencies and dynamic nature of a multidomain port infrastructure network. The construction of the model is grounded in the use of directed functionality graphs, whereby the nodes symbolize infrastructure components and the edges symbolize the interdependencies between them. This study aims to examine the performance of a seaport under stressful conditions and analyze its recovery profile using resilience metrics. These metrics include functionality measurements, systemic impact, total recovery effort, and departure from desired system performance levels. Cho and Park (2017) developed a framework for port infrastructure resilience assessment using system dynamics. Their framework evaluates the resilience of port systems by considering various factors such as disruption, recovery actions, and long-term effects. In addition, the model further integrates socioeconomic aspects, such as fluctuations in freight demand and financial conditions. Table 3 provides an overview of relevant research along with their outputs.

5. Network resilience assessment of seaports

In the previous sections, the papers were examined on the resilience of ports within their physical boundaries and their individual capacity to withstand various disruptions. However, it is important to note that seaports are not confined to their physical boundaries, but are part of various interconnected networks, collectively known as port networks. From this perspective, a port's overall performance, despite all preventative, mitigative and recovery measures implemented within its operational zone, is contingent upon the efficacy of other ports within the network. This is because an individual port with suboptimal functionality may significantly impair the overall system performance. To illustrate this point, consider a hypothetical incident occurring at an arbitrary port, which impacts its capacity to efficiently manage and execute a certain volume of goods or services within a given time frame. A lack of berth capacity for incoming vessels will lead to delays in the movement of vessels to subsequent locations, resulting in queues and increased congestion both upstream and downstream. The presence of a disruption is clearly linked with subsequent disruptions that spread throughout the network, causing negative consequences for the functioning of other ports and the overall performance of the network system. Given this situation,

Table 3. Seaport resilience assessment methodologies.

Approach	Methodology	Remarks	Representative Studies
Qualitative	Conceptual framework	Conceptual frameworks are concerned with describing the resilience elements and identification of their causal links. They benefit the stakeholders and managers with a general framework as a guiding principle.	Almutairi et al. (2019); Mansouri, Nilchiani, and Mostashari (2010); Mostashari et al. (2011)
	Empirical studies	Empirical studies in resilience assessment entail collecting real-world data via observation or experimentation to comprehend and assess the resilience of a given system.	Loh and Thai (2015); Rice and Trepte (2012); Trepte and James (2014)
Semi-quantitative	Scoring systems, Ranking methods	The semi-quantitative approaches focus on constructing resilience elements and assessing their characteristics based on expert elicitation on a number or percentage scale.	Kim, Choi, and Kim (2021); Mutombo, Ölçer, and Kuroshi (2017)
Quantitative	Bayesian network	BN has the ability to accurately represent the cause-and-effect connections among different variables, handle both objective and subjective data and allow for probabilistic resilience analysis.	Hosseini and Barker (2016); Panahi et al. (2022); Wang, Wu, and Yuen (2023)
	Multiple criteria decision-making	MCDM is concerned with the consideration of both qualitative and quantitative elements simultaneously to address the complexity of port resilience assessment. A combination of fuzzy techniques such as FAHP and TOPSIS could be a good example of the MCDM approach.	Cao and Lam (2019); John et al. (2014); Wan et al. (2024)
	Simulation	The simulation approach enables the evaluation of the performance of ports in different scenarios and investigates their behavior under specified conditions.	Folkman et al. (2021); Shafieezadeh and Burden (2014); Zhou et al. (2021)
	Mathematical modeling	This methodology relies on mathematical models and ideas for the definition of resilience elements and quantification of relevant items.	León-Mateos et al. (2021); Zhen, Lin, and Zhou (2022)
	Miscellaneous	There are other resilience analysis procedures that do not align with the aforementioned particular categories, while providing innovative ways to quantitatively address the concept of seaport resilience.	Cho and Park (2017); Galbusera et al. (2018)

it is crucial to examine, measure, and improve the resilience of port networks in relation to the systemic risk concept. This analysis should take a broader perspective, considering the repercussions of any disturbances that may impact the interconnectedness of port networks.

In this regard, a modest number of studies conducted over the past decade have focused on investigating the impacts of disruptions on the operation of seaport networks. In the work conducted by Mansouri, Sauser, and Boardman (2009), they aimed to conceptualize and analyze maritime transportation systems as a 'System of Systems' (SoS). 'Systems Thinking' is employed to examine key attributes of a SoS, including resilience and security, in response to disruptions within a complex network of ships, seaports, intermodal links, waterways, and users. Rose and Wei (2013) proposed a systematic approach that integrates demand-driven and supply-driven input-output (I-O) analyses for assessing the overall financial ramifications due to a port service interruption, taking into account various key dimensions of resilience. Olalla (2012) constructed and applied attacker-defender network interdiction-optimization models to assess the global maritime network resiliency against manmade disruption caused by either piracy or political issues at critical chokepoints of maritime routes. From the perspective of seaport network resiliency, numerous studies have proposed approaches for modeling resilience in the broader maritime network. These approaches can be categorized into two main groups: centralised and decentralised approaches. The former assumes that investment decisions for network resilience improvement can be centrally determined with the full cooperation of all ports for the collective benefit, disregarding business competition among ports. In contrast, decentralised approaches align more closely with real-world scenarios. They assume that ports operate in a competitive and cooperative manner, striving to enhance their individual market shares. The predominant focus in the existing literature on the subject of seaport network resilience, revolves around centralised approaches, which have employed a range of methodologies, including graph theory (Cui and Notteboom 2018), mathematical optimization (Peng et al. 2016), empirical analysis (Poo et al. 2024), and system dynamics (Omer et al. 2012), among others.

However, in recent years, a few studies have put forth a co-opetitive optimization scheme, which combines competition and collaboration, as an alternative to centralised decision-making for improving the port networks resilience. Their argument is predicated on the belief that pooling substantial capital investment and exchanging crucial information among diverse entities or nations that own port facilities is considered impractical and unattainable. The idea of co-opetition was first presented by Nalebuff, Brandenburger, and Maulana (1996) within the realm of business management. Drawing on this concept, Asadabadi and Miller-Hooks (2018) put up a conceptual framework in which individuals involved with the port, assuming the roles of participants in a game, engage in collaborative efforts through cross-port investment. The aim of this collaboration is to enhance throughput during a disaster event, while simultaneously engaging in competitive activities to secure business opportunities. The dynamics of co-opetition observed among ports are addressed by employing a bi-level multiplayer game theoretic framework, in which, each individual port makes strategic investment decisions aimed at protecting its interests, while also considering the potential reaction of the typical market-balancing shipping mission problem within the affected network. Games were modeled to simulate a range of cross-port investment plans, including unrestricted (where ports may invest arbitrarily), limited (where ports only invest in themselves), and semi-restricted (where certain ports can invest across borders while others will only self-invest). Asadabadi and Miller-Hooks (2020) further expanded their analytical approach to evaluate the resilience of a port network in the face of various natural hazard events. Similarly, using the concept of Equilibrium Problems with Equilibrium Constraints (EPECs), Li, Asadabadi, and Miller-Hooks (2022) conceptualized a framework to investigate the potential benefits in terms of resilience, return on investment and demand fulfillment rates that can be achieved through port coalitions. In these coalitions, individual ports have the opportunity to invest in the protection of coalition member ports, and the members can also pool their resources during times of catastrophic occurrences. Based on the results, it is indicated that the overall resilience of the network is enhanced through mutual investment and capacity sharing in the face of significant disruptions. Although there might be a slight drop in the level of resilience of individual ports, particularly those that engage in capacity investment or collaboration with other ports. Table 4 provides a modest compilation of relevant studies on the resilience of port networks. They have been organized according to their classification and the different types of disruptive scenarios they analyzed.

6. Discussion and future research directions

This section provides a concise, evaluative examination of the previously discussed topics, exploring their shortcomings and challenges, as well as potential avenues for future research.

6.1. The concept of seaport resilience analysis

The primary focus on resilience in the context of seaports is attributed to their capacity to withstand and recover from a disruptive scenario. In terms of measuring seaport resilience, numerous research investigations have addressed the concept of resilience by examining the fluctuations in functionality over a period of time. Some studies consider the ratio of the degraded system functionality to its original state, while others express it as the ratio of recovery to loss of functionality. However, resilience is a comprehensive concept that encompasses various scales and dimensions, requiring evaluation from diverse perspectives and throughout different time periods, including pre-disruption, during disruption, and post-disruption.

Table 4. List of studies on port network resilience assessment.

Approach	Methodology	Disruption scenario	Research output	Literature
Centralized	conceptualized qualitative framework	Natural hazards	Developing a novel risk framework to analyze the impacts of weather and climatic related events on three layers of port networks, including critical infrastructure, hinterland, and maritime networks and to provide different resilience strategies against identified systemic risks.	Verschuur et al. (2022)
	Network optimization problem, System dynamics	Natural and anthropogenic hazards	Proposing a framework called Networked Infrastructure Resiliency Assessment (NIRA) to optimize maritime network performance. The proposed framework treats the problem as a network optimization task, with the objective of maximizing the overall flow on the network links. In this respect, three MTS resiliency metrics (tonnage resiliency, time resiliency and cost resiliency) are suggested.	Omer et al. (2012)
	Complex networks, Graph theory	Climate disasters	Developing a multi-stage framework based on the integration of climatic risk variables, centrality evaluation, and an optimized model of shipping routes to address the related vulnerabilities and to analyze the resilience of the global shipping networks.	Poo and Yang (2022)
	Empirical study, Graph theory	Earthquake, malicious attack, hurricane	Studying and analyzing the local ports' resilience against the impacts of the selected shocks based on a spatiotemporal scale.	Rousset and Ducruet (2020)
	Fuzzy logic, Bayesian networks, Evidential reasoning	Operational risks	Establishing a comprehensive methodology for evaluating the resilience of maritime container transport networks (MCTNs), assessing the hazards associated with container shipping activities as well as the significance of individual shipping routes across MCTNs. Network centrality measures are employed to assess the susceptibility of individual shipping routes across the network.	Wan et al. (2019)
	Graph theory	Seismic hazards, political conflicts	Modeling the impacts of both natural and anthropogenic disruptive scenarios on a multi-port system and liner shipping networks through quantification of port and route capacity reduction. A cost-based container assignment model is also implemented to minimize the total system-wide cost.	Achurra-Gonzalez et al. (2019)
	Complex network theory	Intentional attacks, random failure	Developing a framework to assess the robustness of the global shipping networks against failure of nodes (ports).	Angeloudis, Bichou, and Bell (2013)
	Mathematical model	Unpredictable disasters	Developing a two-stage stochastic program to allocate optimized limited resources to seaports against undesired events for minimization of total loss.	Peng et al. (2016)

(*Continued*)

Table 4. (Continued).

Approach	Methodology	Disruption scenario	Research output	Literature
De-centralized	Game theory, Mathematical model	Earthquake, Flooding	Developing a co-opetitive protective investment problem for port network protection against natural disasters and improving their resilience.	Asadabadi and Miller-Hooks (2018)
	Game theory, Mathematical model, optimization technique	Tsunami, Earthquake, Flooding	Modeling a stochastic optimization program for finding optimal investment strategies to improve the reliability and enhance the resilience of ports in a network against natural disasters.	Asadabadi and Miller-Hooks (2020)
	Game theory, mathematical model,	Hurricane, Tsunami, Earthquake, Flooding	Developing an equilibrium problem with equilibrium constraints (EPEC) for improving the resilience of individual ports and the network they are in, based on resource pooling in protective plans of actions through coalition idea.	Li, Asadabadi, and Miller-Hooks (2022)
	Conceptual qualitative framework	Climate disasters	Developing a standard set of guidelines based on a multi-stage methodology to enhance the resilience of individual ports and the larger network they represent.	Python and Wakeman (2016)
	Dynamic spatial Markov Chain (DSMC)	Financial crises, Epidemics, Environmental and ecological risks, Traffic congestion, Trade disputes and conflicts	The resilience analysis of regional container port networks, identifying key factors influencing resilience and proposing strategies to enhance network adaptability amid external shocks and internal risks.	Chang, Li, and Zhao (2024)

A partial assessment of capabilities or phases would not deliver a thorough evaluation of seaport resilience, as most of the articles reviewed in this study fail to fulfill this requirement. In this regard, it is strongly recommended that resilience metrics designed for seaports should extend beyond a partial temporal stage and should also encompass various dimensions of resilience, including reliability, vulnerability, resourcefulness, cost-effectiveness, and even safety culture. An additional significant aspect that has been overlooked by the majority of research studies is the assessment of the vulnerability of main components which contribute significantly to maintaining the seaport functionality. Unlike the reliability assessment of engineering systems, which includes the identification of critical components as an essential aspect, little research has been conducted to identify the vulnerable components and measure their criticality level based on the resilience of the whole seaport. A holistic approach not only helps in addressing the vulnerabilities of a seaport but also contributes to a deeper understanding of the trade-offs involved in achieving both efficient resource allocation and increased resilience. With the use of quantitative metrics, it enables the comparison and evaluation of various resilience strategies to determine the optimal outcomes. Therefore, the formulation of a systematic framework to evaluate the resilience of seaports, factoring in the aforementioned items, presents a significant area for future investigation.

6.2. Disruptive scenarios and resilience strategies

Figure 6 shows the distribution of the disruptive scenarios in 142 seaport resilience papers that we have analysed. 32% of them deal with environmental-related disruptions, and 27% of them are related to human-induced ones. This is unsurprising, as the majority of disruptive events are linked to the geographical locations of seaports and the significant engagement of human activities. However, it is important to acknowledge that some sub-factors within the realm of the aforementioned factors, such as climate change and cyber-attacks, continue to be sources of concern and require more scrutiny from academics. In contrast, there is a significant lack of analytical frameworks that specifically examine the concept of seaport resilience in relation to access and network factors.

One notable aspect of the disruptive scenarios is the presence of interdependent multi-hazards. This term refers to a situation where multiple disruptive events, whether natural or anthropogenic, occur simultaneously, consecutively, or partially overlap. As a result, this situation introduces greater potential for adverse effects on seaport functionality and

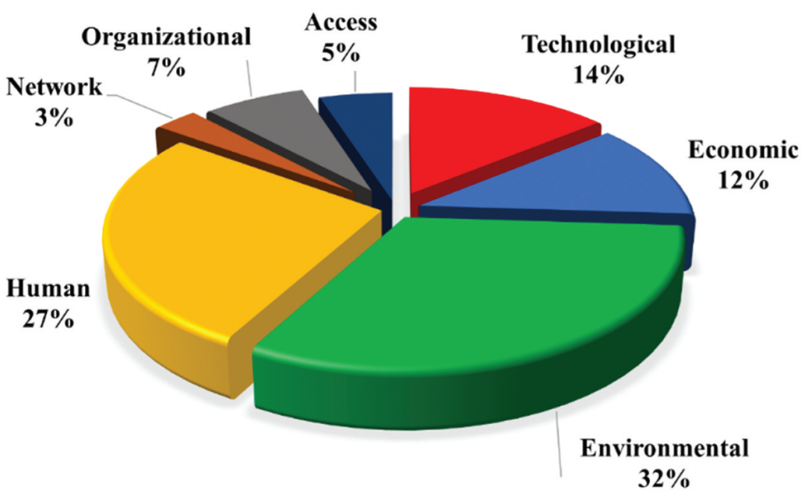

Figure 6. Percentage distribution of disruptive scenarios in seaport resilience studies.

increases the complexity of response and recovery operations. A historical example that exemplifies the concept of interdependent multi-hazards and their repercussions on seaports is the case of Sendai port in Japan (Kazama and Noda 2012). In 2011, a massive earthquake followed by a subsequent tsunami led to substantial structural damage to port infrastructure, such as cranes, quays, piers, and storage facilities, as well as the inundation of the port zone by the resulting tsunami waves. An additional layer of complexity was also added to the disaster by the release of radioactive materials from the damaged Fukushima Daiichi Nuclear Power Plant, located relatively close to the port. This practically hampered the response and recovery efforts due to radiation concerns. In light of this matter, which has been overlooked by the existing studies, it is imperative to explore interdependent multi-hazards within the seaport environment and advance corresponding resilience models in future research investigations.

Concerning resilience strategies, as discussed in section 3.4, effective approaches typically involve a blend of proactive risk reduction, adaptive capacity-building, and flexible response methods. However, the existing literature lacks extensive exploration of diverse resilience strategies and their impact on seaport resilience. Hence, future research should prioritize understanding various resilience strategies, their influence on resilience components, and the development of innovative quantitative evaluation methods. To facilitate this, a comprehensive list of applicable resilience strategies for seaports, along with detailed descriptions and applications, is provided in Table A1 in the Appendix.

6.3. *Methodologies developed for seaport resilience assessment*

The prevailing methodologies used for assessing resilience in the context of seaports include conceptual frameworks, semi-quantitative approaches, BN, simulation, MCDM, mathematical modeling and optimization techniques. Figure 7 shows the distribution of the methodologies utilized by the studies reviewed in this article. As can be seen, simulation approaches constitute the majority of approaches, accounting for 31%, followed by conceptual frameworks (23% of the reviewed studies).

To get a deeper insight into the capabilities of these methodologies, Table 5 presents a detailed overview of their advantages and disadvantages.

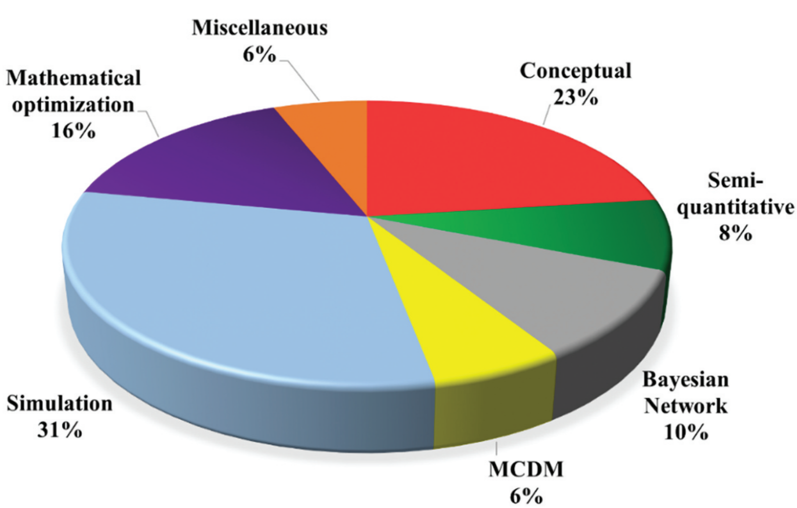

Figure 7. Percentage distribution of different methodologies adopted for seaport resilience assessment.

Table 5. Strengths and limitations of different resilience assessment methodologies.

Methodology	Strengths	Limitations
Conceptual framework	Provides a structured and organized methodology that facilitates an overall understanding of seaport resilience, outlines the key components and essential elements that contribute to a port's resilience, and finally assists researchers and practitioners in conducting a systematic evaluation of various dimensions of resilience.	Because of the theoretical foundation of conceptual frameworks and due to their limited reliance on quantitative data, the conclusion may lack persuasiveness, thereby failing to provide a comprehensive representation of the whole picture.
Semi-quantitative	Leverages both quantitative data and qualitative insights and allows for the incorporation of qualitative input from experts and stakeholders when quantitative data is unavailable.	The presence of biases has the potential to exert an influence on one's judgment. The utilization of expert judgments is hindered by the insufficient comprehension and management of biases, giving rise to various challenges.
Bayesian Network	Being able to model uncertainties, dependencies and inter-dependencies between various factors in complex systems, to integrate different types of data, including quantitative data from historical records, expert elicitations, and qualitative insights, to simulate different scenarios and to conduct sensitivity analysis.	The utilization of Bayesian Networks necessitates a substantial volume of data, and its analysis and computation entail intricate processes. Moreover, developing Bayesian Networks is a challenging task that requires substantial effort and expertise. Therefore, only the network's designer may utilize causal effects.
MCDM	Capable of handling both quantitative data and qualitative insights, where a combination of quantifiable measures and expert judgments is necessary; mitigating biases and promoting judgments by assigning weights to criteria.	The effectiveness of the methodology could be contingent upon the precision and comprehensiveness of the employed data. Moreover, the inclusion of subjective criteria and the utilization of fuzzy logic may introduce a certain degree of uncertainty into the decision-making process.
Simulation	Provides a dynamic and quantitative approach for examining various disruptive scenarios; effectively capturing the dynamic behaviors of a system and offering valuable insights into the propagation of disruptions; tests different resilience strategies and assists in optimizing resource allocation to boost seaport resilience.	Despite its utility, this evaluation methodology demands a significant investment of time and resources, as well as a limited scope of testing that only encompasses specific case scenarios.
Mathematical modeling and optimization	Facilitates a more evidence-based and data-driven decision-making by evaluating the decisions and strategies based on measurable criteria; assists the decision-makers to quickly evaluate the potential consequences of different strategies by integrating mathematical models and real-time data; helps to understand the system's behavior by representing interactions and dependencies mathematically; optimises the resource allocation by considering various constraints and objectives.	The mathematical models are usually based on specific assumptions and scenarios, and there exist certain factors that are not accounted for. Therefore, their applicability in real-world contexts may be limited.

Considering the strengths and limitations of the aforementioned methodologies, as presented in Table 5, the following innovative avenues for future study are proposed:

(a) Integration of stochastic optimization techniques with Simulation models: Genetic Algorithms (GA) or Particle Swarm Optimization (PSO) could be employed as effective methods for optimising resource allocation tactics to achieve the highest possible level of resilience. The validation of the optimal techniques could be conducted via the use of simulation models that include both uncertainty and dynamic behavior.

(b) The use of MCDM in combination with BN: This could enable the generation of trade-off solutions that effectively account for the inherent uncertainty and probabilistic characteristics of disruptions. BN have the capability to represent the probabilistic relationships and dependencies among different components and factors within the seaport system, while by employing MCDM, it is possible to establish a set of criteria that represent seaport performance. These criteria may include economic impact, operational efficiency, environmental sustainability, and so on.

(c) Developing digital twin models of seaports: The integration of real-time data with simulation components is an innovative tool for assessing the effectiveness of resilience strategies in various disruption scenarios. This tool allows stakeholders to experiment with alternative methods in a controlled environment, thereby enhancing their ability to react to and recover from disruptive events.

(d) The incorporation of human behavior and decision-making into established methodologies: The utilisation of agent-based modeling to analyse personnel responses during disruptions or the application of cognitive science principles has the potential to yield more efficient strategies for bolstering seaport resilience in the face of disruptions.

While the implementation of the proposed integrated methods may have the potential for improved outcomes, it is essential to validate these approaches using real-world data. The process of validation is essential in ensuring that the integrated models effectively and properly depict the behavior of port systems in the event of disturbances.

6.4. Seaport network resilience

As mentioned earlier, a considerable number of studies primarily concentrate on resilience analysis of individual seaports, rather than adopting a holistic approach that encompasses the whole seaport network. There still exists a deficiency in the development of comprehensive models that effectively include the interconnections, interdependence, and cascading effects occurring within and among seaport networks. Furthermore, it is apparent that the prevalence of decentralized approaches is much lower in comparison to centralized ones. Hence, there is a need for increased emphasis on the development of methodologies that are based on a decentralized approach. In this regard, the following insights might provide valuable guidance for future research directions:

(a) There exists a research gap pertaining to the successful integration of micro-level analysis, which focuses on individual port components, and macro-level analysis, which encompasses network-wide resilience assessment. In this respect, the understanding of how disruptions occurring at a specific seaport might have repercussions on other seaports, as well as the analysis of the complex interdependencies within the network, should receive more attention.

(b) Further investigation is needed to address the existing deficiencies in data. The construction of precise and comprehensive models of seaport networks requires the acquisition of substantial data, a task that is hindered by privacy considerations, challenges in data sharing, and the diverse range of data sources. Therefore, devising effective strategies for managing data and methodologies to handle the diversity and dynamicity of these data should be addressed in future studies.

(c) Developing a hybrid approach that combines the components from both centralised and decentralised tactics appears to be a commendable strategy to utilise the advantages offered by both paradigms. For instance, establishing overarching rules and promoting cooperation through the centralised approaches, as well as letting individual ports maintain independence in executing customized plans based on their specific conditions through decentralised approaches, could create a promising framework to serve this need.

7. Conclusion

This study represents an inaugural, critical and comprehensive assessment of current studies on seaport resilience using the Web of Science database. Through this study, the approaches, models, and techniques that have been developed for the resilience analysis of seaports were identified, categorised and analysed. Furthermore, an extensive inventory of disruptive scenarios, as well as the relevant resilience strategies pertaining to these scenarios, were compiled. The findings of this paper reveal a limited body of research on the topic of seaport resilience, despite the high degree of importance associated with this important infrastructure. Moreover, the methodologies that have been established in this context are still in their infancy and possess significant potential for improvement. It is believed that the incorporation of additional quantitative techniques would enhance the robustness and perception of the methodologies developed for the investigation of seaport resilience. This study also contributes significantly to identifying research gaps in enhancing seaport resilience and exploring potential avenues for future investigation. The outcomes established in this review serve as a critical cornerstone for further research, offering valuable insights for both academic scholars and industry practitioners. Moreover, this review article not only provides practical approaches for implementation but also furnishes essential references for managing seaport disruptions, whether at the individual or network level.

While this study endeavors to shed light on methodologies pertinent to the analysis of seaport resilience, it is imperative to recognize some limitations that warrant discussion. Foremost among these limitations is the omission of research pertaining to seaports within the broader intermodal transportation network, known as maritime supply chain resilience. The complex dynamics of the maritime supply chain, which involves the interplay of various transportation modes such as railways and roads is required to be addressed for the sake of a holistic resilience analysis. However, it is noted that this absence stems from the primary focus of this study, which prioritizes methodologies directly relevant to the examination of seaport resilience. Secondly, this review paper draws upon papers from reputable journals as its main source for identifying relevant literature. While this is a standard practice for conducting a critical review paper, the decision to exclusively rely on it for literature selection means that potentially valuable studies, including conference papers, white papers, technical notes, and relevant reports, are neglected. Consequently, there may be some degree of literature omission, which could have influenced the comprehensiveness of the findings and the overall scope of the review.

In summary, seaport infrastructures are vulnerable to a diverse array of disruptions, necessitating further efforts in the development of innovative approaches to assess and enhance their resilience against these threats.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the European Research Council under Grant [Number TRUST CoG 2019 864724].

ORCID

Massoud Mohsendokht http://orcid.org/0000-0003-2271-6838
Christos Kontovas http://orcid.org/0000-0001-9461-6436
Chia-Hsun Chang http://orcid.org/0000-0002-7351-8471
Zhuohua Qu http://orcid.org/0000-0001-9241-9332
Huanhuan Li http://orcid.org/0000-0002-4293-4763
Zaili Yang http://orcid.org/0000-0003-1385-493X

References

Achurra-Gonzalez, P. E., M. Novati, R. Foulser-Piggott, D. J. Graham, G. Bowman, M. G. H. Bell, and P. Angeloudis. 2019. "Modelling the Impact of Liner Shipping Network Perturbations on Container Cargo Routing: Southeast Asia to Europe Application." *Accident Analysis and Prevention* 123 (February): 399–410. https://doi.org/10.1016/j.aap.2016.04.030.

Adam, E. F., S. Brown, R. J. Nicholls, and M. Tsimplis. 2016. "A Systematic Assessment of Maritime Disruptions Affecting UK Ports, Coastal Areas and Surrounding Seas from 1950 to 2014." *Natural Hazards* 83 (1): 691–713. https://doi.org/10.1007/s11069-016-2347-4.

Almutairi, A., Z. A. Collier, D. Hendrickson, J. M. Palma-Oliveira, T. L. Polmateer, and J. H. Lambert. 2019. "Stakeholder Mapping and Disruption Scenarios with Application to Resilience of a Container Port." *Reliability Engineering and System Safety* 182 (February): 219–232. https://doi.org/10.1016/j.ress.2018.10.010.

Angeloudis, P., K. Bichou, and M. Bell. 2013. "Security and Reliability of the Liner Container-Shipping Network: Analysis of Robustness Using a Complex Network Framework." *Risk Management in Port Operations, Logistics and Supply Chain Security*. https://doi.org/10.4324/9781315850504-17.

Asadabadi, A., and E. Miller-Hooks. 2018. "Co-Opetition in Enhancing Global Port Network Resiliency: A Multi-Leader, Common-Follower Game Theoretic Approach." *Transportation Research Part B: Methodological* 108 (February): 281–298. https://doi.org/10.1016/j.trb.2018.01.004.

Asadabadi, A., and E. Miller-Hooks. 2020. "Maritime Port Network Resiliency and Reliability Through Co-Opetition." *Transportation Research Part E: Logistics & Transportation Review* 137 (May): 101916. https://doi.org/10.1016/j.tre.2020.101916.

Baroud, H., K. Barker, J. E. Ramirez-Marquez, M. Claudio, and S. Rocco. 2014. "Importance Measures for Inland Waterway Network Resilience." *Transportation Research Part E: Logistics & Transportation Review* 62 (February): 55–67. https://doi.org/10.1016/j.tre.2013.11.010.

Biringer, B., E. Vugrin, and D. Warren. 2013. *Critical Infrastructure System Security and Resilience*. 1st ed. FL: CRC Press, Taylor & Francis Group.

Cao, X., and J. S. L. Lam. 2018. "Simulation-Based Catastrophe-Induced Port Loss Estimation." *Reliability Engineering and System Safety* 175 (July): 1–12. https://doi.org/10.1016/j.ress.2018.02.008.

Cao, X., and J. S. L. Lam. 2019. "A Fast Reaction-Based Port Vulnerability Assessment: Case of Tianjin Port Explosion." *Transportation Research Part A: Policy and Practice* 128 (October): 11–33. https://doi.org/10.1016/j.tra.2019.05.019.

Chang, W., N. Li, and Y. Zhao. 2024. "Resilience of Regional Container Port Network: Based on Projection Correlation and Dynamic Spatial Markov Chain." *Maritime Policy & Management*: 1–17. July. https://doi.org/10.1080/03088839.2024.2385846.

Cho, H., and H. Park. 2017. "Constructing Resilience Model of Port Infrastructure Based on System Dynamics." *International Journal of Safety and Security Engineering* 7 (3): 352–360. https://doi.org/10.2495/SAFE-V7-N3-352-360.

Critical Infrastructure Resilience: Final Report and Recommendations. 2009. "National Infrastructure Advisory Council (NIAC)."

Cui, H., and T. Notteboom. 2018. "A Game Theoretical Approach to the Effects of Port Objective Orientation and Service Differentiation on Port Authorities' Willingness to Cooperate." *Research in Transportation Business & Management* 26 (March): 76–86. https://doi.org/10.1016/j.rtbm.2018.03.007.

Fan, H., J. Lyu, S. Wang, and X. Gong. 2024. "Leverage Rule-Based Bayesian Network on Assessing Straits/Canals Resilience Performance on a Risk Coupling Analysis Perspective." *Maritime Policy & Management* 52 (2): 250–268. January. https://doi.org/10.1080/03088839.2024.2306952.

Faturechi, R., and E. Miller-Hooks. 2015. "Measuring the Performance of Transportation Infrastructure Systems in Disasters: A Comprehensive Review." *Journal of Infrastructure Systems* 21 (1): 04014025. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000212.

Folkman, D., A. Gharehgozli, J. Mileski, and C. B. Galvao. 2021. "Port Resiliency and the Effects of Hurricanes on Port Operations." *International Journal of Advanced Operations Management* 13 (4): 409. https://doi.org/10.1504/IJAOM.2021.120779.

Galbusera, L., G. Giannopoulos, S. Argyroudis, and K. Kakderi. 2018. "A Boolean Networks Approach to Modeling and Resilience Analysis of Interdependent Critical Infrastructures." *Computer-Aided Civil and Infrastructure Engineering* 33 (12): 1041–1055. https://doi.org/10.1111/mice.12371.

Grainger, A., and K. Achuthan. 2014. "Port Resilience: A Primer." https://nottingham-repository.worktribe.com/output/723651.

Gu, B., and J. Liu. 2023. "A Systematic Review of Resilience in the Maritime Transport." *International Journal of Logistics: Research & Applications*: 1–22. January. https://doi.org/10.1080/13675567.2023.2165051.

Hossain, N. U. I., S. El Amrani, R. Jaradat, M. Marufuzzaman, R. Buchanan, C. Rinaudo, and M. Hamilton. 2020. "Modeling and Assessing Interdependencies Between Critical Infrastructures Using Bayesian Network: A Case Study of Inland Waterway Port and Surrounding Supply Chain Network." *Reliability Engineering and System Safety* 198 (June): 106898. https://doi.org/10.1016/j.ress.2020.106898.

Hossain, N. U. I., F. Nur, S. Hosseini, R. Jaradat, M. Marufuzzaman, and S. M. Puryear. 2019. "A Bayesian Network Based Approach for Modeling and Assessing Resilience: A Case Study of a Full Service Deep Water Port." *Reliability Engineering and System Safety* 189 (September): 378–396. https://doi.org/10.1016/j.ress.2019.04.037.

Hosseini, S., and K. Barker. 2016. "Modeling Infrastructure Resilience Using Bayesian Networks: A Case Study of Inland Waterway Ports." *Computers & Industrial Engineering* 93 (March): 252–266. https://doi.org/10.1016/j.cie.2016.01.007.

Hosseini, S., K. Barker, and J. E. Ramirez-Marquez. 2016. "A Review of Definitions and Measures of System Resilience." *Reliability Engineering and System Safety* 145 (January): 47–61. https://doi.org/10.1016/j.ress.2015.08.006.

John, A., Z. Yang, R. Riahi, and J. Wang. 2014. "Application of a Collaborative Modelling and Strategic Fuzzy Decision Support System for Selecting Appropriate Resilience Strategies for Seaport Operations." *Journal of Traffic & Transportation Engineering* 1 (3): 159–179. https://doi.org/10.1016/S2095-7564(15)30101-X.

Kazama, M., and T. Noda. 2012. "Damage Statistics (Summary of the 2011 off the Pacific Coast of Tohoku Earthquake Damage)." *Soils & Foundations* 52 (5): 780–792. https://doi.org/10.1016/j.sandf.2012.11.003.

Kim, S., S. Choi, and C. Kim. 2021. "The Framework for Measuring Port Resilience in Korean Port Case." *Sustainability* 13 (21): 11883. https://doi.org/10.3390/su132111883.

Kwesi-Buor, J., D. A. Menachof, and R. Talas. 2019. "Scenario Analysis and Disaster Preparedness for Port and Maritime Logistics Risk Management." *Accident Analysis and Prevention* 123 (February): 433–447. https://doi.org/10.1016/j.aap.2016.07.013.

Lagoudis, I. N., M. M. Naim, and A. T. Potter. 2010. "Strategic Flexibility Choices in the Ocean Transportation Industry." *International Journal of Shipping and Transport Logistics* 2 (2): 187. https://doi.org/10.1504/IJSTL.2010.030866.

Lam, J. S. L., and S. Su. 2015. "Disruption Risks and Mitigation Strategies: An Analysis of Asian Ports." *Maritime Policy & Management* 42 (5): 415–435. https://doi.org/10.1080/03088839.2015.1016560.

Lau, Y.-Y., Q. Chen, M. C.-P. Poo, A. K. Y. Ng, and C. C. Ying. 2024. "Maritime Transport Resilience: A Systematic Literature Review on the Current State of the Art, Research Agenda and Future Research Directions." *Ocean & Coastal Management* 251 (May): 107086. https://doi.org/10.1016/j.ocecoaman.2024.107086.

León-Mateos, F., A. Sartal, L. López-Manuel, and M. A. Quintás. 2021. "Adapting Our Sea Ports to the Challenges of Climate Change: Development and Validation of a Port Resilience Index." *Marine Policy* 130 (August): 104573. https://doi.org/10.1016/j.marpol.2021.104573.

Li, W., A. Asadabadi, and E. Miller-Hooks. 2022. "Enhancing Resilience Through Port Coalitions in Maritime Freight Networks." *Transportation Research Part A: Policy and Practice* 157 (March): 1–23. https://doi.org/10.1016/j.tra.2022.01.015.

Liu, Y., X. Fu, K. Wang, S. Zheng, and Y. Xiao. 2024. "Bibliometric Analysis and Literature Review on Maritime Transport Resilience and Its Associated Impacts on Trade." *Maritime Policy & Management*: 1–38. June. https://doi.org/10.1080/03088839.2024.2367971.

Loh, H. S., and V. V. Thai. 2015. "Management of Disruptions by Seaports: Preliminary Findings." *Asia Pacific Journal of Marketing & Logistics* 27 (1): 146–162. https://doi.org/10.1108/APJML-04-2014-0053.

Loh, H. S., and V. Van Thai. 2015. "Cost Consequences of a Port-Related Supply Chain Disruption." *The Asian Journal of Shipping and Logistics* 31 (3): 319–340. https://doi.org/10.1016/j.ajsl.2015.09.001.

Madhusudan, C., and G. P. Ganapathy. 2011. "Disaster Resilience of Transportation Infrastructure and Ports – an Overview." *International Journal of Geomatics & Geosciences* 2 (2). https://www.indianjournals.com/ijor.aspx?target=ijor:ijggs&volume=2&issue=2&article=009.

Mansouri, M., R. Nilchiani, and A. Mostashari. 2010. "A Policy Making Framework for Resilient Port Infrastructure Systems." *Marine Policy* 34 (6): 1125–1134. https://doi.org/10.1016/j.marpol.2010.03.012.

Mansouri, M., B. Sauser, and J. Boardman. 2009. "Applications of Systems Thinking for Resilience Study in Maritime Transportation System of Systems." *2009 3rd Annual IEEE Systems Conference*, 211–217. Vancouver, BC, Canada: IEEE. https://doi.org/10.1109/SYSTEMS.2009.4815800.

Modarres, M., M. Kaminskiy, and V. Krivtsov. 2016. *Reliability Engineering and Risk Analysis: A Practical Guide*. 3rd ed. CRC Press. https://doi.org/10.1201/9781315382425.

Mohsendokht, M., H. Li, C. Kontovas, C.-H. Chang, Z. Qu, and Z. Yang. 2024. "Decoding Dependencies Among the Risk Factors Influencing Maritime Cybersecurity: Lessons Learned from Historical Incidents in the Past Two Decades." *Ocean Engineering* 312 (November): 119078. https://doi.org/10.1016/j.oceaneng.2024.119078.

Mohsendokht, M., H. Li, C. Kontovas, C. Chang, Z. Qu, and Z. Yang. 2024. "Enhancing Maritime Transportation Security: A Data-Driven Bayesian Network Analysis of Terrorist Attack Risks." *Risk Analysis* 45 (2): 283–306. July. https://doi.org/10.1111/risa.15750.

Mostashari, A., R. Nilchiani, M. Omer, N. Andalibi, and B. Heydari. 2011. "A Cognitive Process Architecture Framework for Secure and Resilient Seaport Operations." *Marine Technology Society Journal* 45 (3): 120–127. https://doi.org/10.4031/MTSJ.45.3.13.

Mutombo, K., A. I. Ölçer, and L. Kuroshi. 2017. "A New Approach to Assessing Port Infrastructure Resilience to Climate Risks and Adaptive Solutions Prioritization." *Journal of Maritime Research* 14 :56–67. http://refhub.elsevier.com/S0964-5691(24)00450-2/sref101.

Nalebuff, B., A. Brandenburger, and A. Maulana. 1996. *Co-Opetition*. London: HarperCollins Business.

Olalla, O. R. 2012. *Assessing the Resilience of Global Sea Routes*. Montery, CA: Naval Postgraduate School. https://apps.dtic.mil/sti/citations/ADA562745.

Omer, M., A. Mostashari, R. Nilchiani, and M. Mansouri. 2012. "A Framework for Assessing Resiliency of Maritime Transportation Systems." *Maritime Policy & Management* 39 (7): 685–703. https://doi.org/10.1080/03088839.2012.689878.

Pan, S., H. Yan, J. He, and Z. He. 2021. "Vulnerability and Resilience of Transportation Systems: A Recent Literature Review." *Physica A: Statistical Mechanics and Its Applications* 581 (November): 126235. https://doi.org/10.1016/j.physa.2021.126235.

Panahi, R., N. S. Gargari, Y.-Y. Lau, and A. K. Y. Ng. 2022. "Developing a Resilience Assessment Model for Critical Infrastructures: The Case of Port in Tackling the Impacts Posed by the COVID-19 Pandemic." *Ocean & Coastal Management* 226 (July): 106240. https://doi.org/10.1016/j.ocecoaman.2022.106240.

Peng, Y., W. Wang, Z. Guo, X. Song, and Q. Zhang. 2016. "A Stochastic Seaport Network Retrofit Management Problem Considering Shipping Routing Design." *Ocean & Coastal Management* 119 (January): 169–176. https://doi.org/10.1016/j.ocecoaman.2015.10.013.

Poo, M. C.-P., and Z. Yang. 2022. "Optimising the Resilience of Shipping Networks to Climate Vulnerability." *Maritime Policy & Management* 51 (1): 15–34. July. https://doi.org/10.1080/03088839.2022.2094488.

Poo, M. C.-P., W. Zhang, L. Kamalian, T. Wang, Y.-Y. Lau, and T. Z. Xu. 2024. "Resilience of Chinese Ports to Tropical Cyclones: Operational Efficiency and Strategic Importance." *Climate* 12 (12): 214. https://doi.org/10.3390/cli12120214.

Python, G. C., and T. H. Wakeman. 2016. "Collaboration of Port Members for Supply Chain Resilience." In *Ports 2016*, 371–380. New Orleans, LA: American Society of Civil Engineers. https://doi.org/10.1061/9780784479902.038.

Reggiani, A. 2013. "Network Resilience for Transport Security: Some Methodological Considerations." *Transport Policy* 28 (July): 63–68. https://doi.org/10.1016/j.tranpol.2012.09.007.

Rice, J., and K. Trepte. 2012. *The MIT CTL Port Resilience Survey Report*. Cambridge, MA: MIT Center for Transportation & Logistics. http://ctl.mit.edu/sites/default/files/Port%20resilience%20survey%20report%20v27%20sans%20SEM.pdf.

Rose, A., and D. Wei. 2013. "Estimating the Economic Consequences of a Port Shutdown: The Special Role of Resilience." *Economic Systems Research* 25 (2): 212–232. https://doi.org/10.1080/09535314.2012.731379.

Rousset, L., and C. Ducruet. 2020. "Disruptions in Spatial Networks: A Comparative Study of Major Shocks Affecting Ports and Shipping Patterns." *Networks and Spatial Economics* 20 (2): 423–447. https://doi.org/10.1007/s11067-019-09482-5.

Shafieezadeh, A., and L. I. Burden. 2014. "Scenario-Based Resilience Assessment Framework for Critical Infrastructure Systems: Case Study for Seismic Resilience of Seaports." *Reliability Engineering and System Safety* 132 (December): 207–219. https://doi.org/10.1016/j.ress.2014.07.021.

Shaw, D. R., A. Grainger, and K. Achuthan. 2017. "Multi-Level Port Resilience Planning in the UK: How Can Information Sharing Be Made Easier?" *Technological Forecasting & Social Change* 121 (August): 126–138. https://doi.org/10.1016/j.techfore.2016.10.065.

Trepte, K., and B. R. James. 2014. "An Initial Exploration of Port Capacity Bottlenecks in the USA Port System and the Implications on Resilience." *International Journal of Shipping and Transport Logistics* 6 (3): 339. https://doi.org/10.1504/IJSTL.2014.060800.

UNCTAD. 2023. "Review of Maritime Transport." *United Nations Conference on Trade and Development (UNCTAD)*. https://unctad.org/publication/review-maritime-transport-2023.

Vanlaer, N., S. Albers, A. Guiette, S. Van Den Oord, and H. Marynissen. 2022. "100% Operational! An Organizational Resilience Perspective on Ports as Critical Infrastructures." *Case Studies on Transport Policy* 10 (1): 57–65. https://doi.org/10.1016/j.cstp.2021.11.002.

Verschuur, J., R. Pant, E. Koks, and J. Hall. 2022. "A Systemic Risk Framework to Improve the Resilience of Port and Supply-Chain Networks to Natural Hazards." *Maritime Economics & Logistics* 24 (3): 489–506. https://doi.org/10.1057/s41278-021-00204-8.

Wan, C., Z. Yang, X. Yan, D. Zhang, E. Blanco-Davis, and J. Ren. 2019. "Risk-Based Resilience Analysis of Maritime Container Transport Networks." *Proceedings of the 29th European Safety and Reliability Conference (ESREL)*, 3667–3674. Research Publishing Services. https://doi.org/10.3850/978-981-11-2724-3_0213-cd.

Wan, C., Z. Yang, D. Zhang, X. Yan, and S. Fan. 2018. "Resilience in Transportation Systems: A Systematic Review and Future Directions." *Transport Reviews* 38 (4): 479–498. https://doi.org/10.1080/01441647.2017.1383532.

Wan, C., J. Yuan, D. Cao, T. Wang, and A. K. Ng. 2024. "A Fuzzy Evidential Reasoning-Based Model for Evaluating Resilience of Ports to Typhoons." *Transportation Research Part D: Transport & Environment* 133 (August): 104228. https://doi.org/10.1016/j.trd.2024.104228.

Wang, N., M. Wu, and K. F. Yuen. 2023. "Assessment of Port Resilience Using Bayesian Network: A Study of Strategies to Enhance Readiness and Response Capacities." *Reliability Engineering and System Safety* 237 (September): 109394. https://doi.org/10.1016/j.ress.2023.109394.

Wendler-Bosco, V., and C. Nicholson. 2020. "Port Disruption Impact on the Maritime Supply Chain: A Literature Review." *Sustainable and Resilient Infrastructure* 5 (6): 378–394. https://doi.org/10.1080/23789689.2019.1600961 .

Zhen, L., S. Lin, and C. Zhou. 2022. "Green Port Oriented Resilience Improvement for Traffic-Power Coupled Networks." *Reliability Engineering and System Safety* 225 (September): 108569. https://doi.org/10.1016/j.ress.2022.108569.

Zhou, C., J. Xu, E. Miller-Hooks, W. Zhou, C.-H. Chen, L. H. Lee, E. P. Chew, and H. Li. 2021. "Analytics with Digital-Twinning: A Decision Support System for Maintaining a Resilient Port." *Decision Support Systems* 143 (April): 113496. https://doi.org/10.1016/j.dss.2021.113496.

Appendix

Table A1. Description of resilience strategies in the context of seaports.

Resilience Strategies	Description	Sources
Regular maintenance	Regular preventative and corrective maintenance activities of a) structures: berths, quays, jetties, and piers, seawalls, revetments, breakwaters, b): machineries: cranes, hoists, forklifts, conveyors. and other cargo-handling equipment, c) electrical systems: lighting, power distribution, and backup generators, d) dockside infrastructure for vessel mooring, such as bollards, fenders, and mooring lines, e) dredging of channels, basins, and berths to maintain required depths, to name but a few.	Tsinker, G. P. (2004). Port Engineering: Planning, Construction, Maintenance, and Security. John Wiley & Sons.
Strong coastal protection	Consideration of the measures to effectively reduce the potential risks associated with coastal erosion, floods, sea level rise, etc., that have the potential to adversely affect the port infrastructure, vessels, cargo, and employees, including seawalls, breakwaters, Groynes, Revettments, Gabions, Dunes and Sand Dikes, Vegetation and Salt Marshes, and the relevant protective structures.	Tripak S., Willey S., Stokes J. Coastal Texas protection and restoration project; (2014). Available from: https://pdfs.semanticscholar.org/presentation/215d/b6290470d28f6656e57629a3866823e26357.pdf.
Strong cyber-secure infrastructure	Given the heavy reliance of seaports on digital technology for their operations, it is essential to implement the cybersecurity measures for mitigation of any interruptions and data breaches. The measures are as follows: Identification of cyber threats and vulnerabilities, isolating critical systems from non-critical ones by network segmentation, implementing strong authentication methods such as multi-factor authentication, deploying the Intrusion Detection and Prevention Systems (IDPS), cybersecurity training for personnel, among others.	ENISA (European Union Agency for Cybersecurity), (2019). Port Cybersecurity: Good Practices for Cybersecurity in the Maritime Sector. ISBN 978-92-9204-314-8.
Safety management	Including a range of strategies, processes, and activities that are performed to ensure the well-being of personnel, safeguard assets, avoid accidents, and environmental damage. The essential safety management practices can be succinctly outlined as follows: a) meticulous planning and comprehensive training of personnel, b) establishment of clear safety policies and procedures encompassing personnel safety, cargo handling, equipment maintenance, and emergency response, c) enforcement of the use of suitable personal protective equipment, including helmets, safety vests, gloves, and respiratory protection, d) Proper handling and disposal of hazardous materials, compliance with environmental regulations, e) staying abreast of pertinent safety regulations and guidelines.	Maritime and coastguard agency, (2017). A Guide to Good Practice on Port Marine Operations. https://www.southamptonvts.co.uk/admin/content/files/PDF_Downloads/170508_Port_Marine_Guide_To. _Good_Practice__Rev_Sept_2017.pdf
Security management	Including measures that are adopted to protect port superstructures, personnel, assets, and cargo from various security threats, including terrorism, smuggling, theft, and unauthorized access. some key security measures applied in seaports are: a) Implementing access control systems such as identification badges and biometric verification, b) Securing the port with physical barriers such as walls, fences, gates, c) Monitoring the critical areas with CCTVs and motion sensors along with video analytics techniques, d) Employing trained security personnel to guard the port facilities, e) Identification of hidden threats within containers using advanced scanning technologies, such as X-ray machines and radiation detectors, f) Proper implementation of ISPS code to enhance the security of vessels entering and leaving the port, g) Providing security awareness and training programs for port personnel.	Christopher, K. (2014). Port Security Management. In CRC Press eBooks. https://doi.org/10.1201/b17142.

(*Continued*)

Table A1. (Continued).

Resilience Strategies	Description	Sources
Resource conservation	Resource conservation practices bolster the resilience of seaports against the disruptions through minimization of environmental impacts, improving cost efficiency and mitigating the potential for further financial losses. Some key practices are: a) Conserving resources such as energy and water to maintain essential operations during crises, b) Allocating the saved funds to invest in disaster preparedness and infrastructure upgrades, c) Reducing emissions and waste to contribute to protecting the environment, d) Gaining positive reputation through demonstrating a commitment to resource conservation and sustainability.	Hossain, T., Adams, M., & Walker, T. R. (2021). Role of sustainability in global seaports. Ocean & Coastal Management, 202, 105435. https://doi.org/10.1016/j.ocecoaman.2020.105435.
Redundant energy infrastructure	Equipped with redundant or backup systems to guarantee the continuous and reliable energy supply during the failures or disruptions. Some examples of redundant energy infrastructures in seaports are: a) Emergency diesel generators, b) Uninterruptible Power Supply Systems, c) Emergency Battery Systems, d) Parallel power feeders from different sub-stations, e) redundant fuel storage tanks.	Berle, Ø., Rice, J. D., & Asbjørnslett, B. E. (2011). Failure modes in the maritime transportation system: a functional approach to throughput vulnerability. Maritime Policy & Management, 38(6), 605–632. https://doi.org/10.1080/03088839.2011.615870.
Redundant facility	Equipped with redundant or backup facilities to ensure the continued operation of essential functions during disruptions. The examples of redundant facilities in a seaport are: Backup terminal operations, backup berths, backup storage areas, backup IT infrastructures, backup communication systems including radio, satellite and internet connections.	J. Rice and K. Trepte, 'The MIT CTL port resilience survey report.' MIT Center for Transportation & Logistics, Cambridge, MA, 2012. [Online]. Available: http://ctl. mit. edu/sites/default/files/Port% 20resilience% 20survey% 20report% 20v27% 20sans% 20SEM. p df.
Backup main equipment	Equipped with redundant or spare machinery, vehicles, and tools including backup cranes, forklifts, loaders, additional trucks and trailers, spare tugboats, backup cargo handlers, such as reach stackers and straddle carriers.	J. Rice and K. Trepte, 'The MIT CTL port resilience survey report.' MIT Center for Transportation & Logistics, Cambridge, MA, 2012. [Online]. Available: http://ctl. mit. edu/sites/default/files/Port% 20resilience% 20survey% 20report% 20v27% 20sans% 20SEM. p df.
Reserved space	The allocation of additional specified areas inside a port, referred to as reserved spaces, is typically carried out by port authorities with the aim of mitigating congestion, maximizing the usage of resources, and improving the overall performance of the port. Within a container port, providing specialized sections for the storage of additional containers is advisable. Alternatively, designated zones may be allocated for the purpose of accommodating vehicles that are awaiting access to the terminal for cargo collection or distribution, hence mitigating the occurrence of congestion at entry gates. From a security perspective, it is recommended that designated areas be developed for the purpose of screening and inspecting potentially suspect cargoes in order to enhance port security.	Christopher, K. (2014). Port Security Management. In CRC Press eBooks. https://doi.org/10.1201/b17142.
Diverse energy systems	The use of renewable energy sources, such as solar, wind, hydro, tidal and wave power serves to enhance the energy supply diversification of a port. In the case of potential interruptions to conventional energy supplies, the use of alternative energy sources may provide a more reliable and consistent energy supply, hence guaranteeing uninterrupted operations.	Berle, Ø., Rice, J. D., & Asbjørnslett, B. E. (2011). Failure modes in the maritime transportation system: a functional approach to throughput vulnerability. Maritime Policy & Management, 38(6), 605–632. https://doi.org/10.1080/03088839.2011.615870.

(*Continued*)

Table A1. (Continued).

Resilience Strategies	Description	Sources
Diverse equipment	The complex and multifaceted nature of port operations necessitates the use of a varied array of equipment in order to effectively and efficiently handle a broad spectrum of tasks. In the case of an emergency and the malfunction of a system components, it may be possible to use alternative equipment that has been developed or built for a different purpose to perform the function of the failed system. For some kinds of cargo and certain circumstances, mobile cranes or Automated Guided Vehicle (AGVs) may serve as a viable alternative to main equipment.	J. Rice and K. Trepte, 'The MIT CTL port resilience survey report.' MIT Center for Transportation & Logistics, Cambridge, MA, 2012. [Online]. Available: http://ctl. mit. edu/sites/default/files/Port% 20resilience% 20survey% 20report% 20v27% 20sans% 20SEM. p df.
Equipment/cargo tracking systems	Seaport equipment/cargo tracking systems which are based on various technologies such as RFID, GPS, sensors, and data analytics, are deployed for the purpose of providing real-time information and monitoring the movement, location, status, and condition of equipment, containers, and cargos.	Yau, K. A., Peng, S., Qadir, J., Low, Y. C., & Ling, M. H. (2020). Towards smart port infrastructures: Enhancing port activities using information and communications technology. IEEE Access, 8, 83387–83404. https://doi.org/10.1109/access.2020.2990961.
Real-time data management systems	A real-time data management system implemented at a seaport is a technologically advanced solution that collects, processes, evaluates, and demonstrates data pertaining to diverse port operations and activities in real-time. These systems use cutting-edge technology, including sensors, IoT devices, data analytics, and communication networks.	Yang, Y., Zhong, M., Yao, H., Yu, F., Fu, X., & Postolache, O. (2018). Internet of things for smart ports: Technologies and challenges. IEEE Instrumentation & Measurement Magazine, 21(1), 34–43. https://doi.org/10.1109/mim.2018.8278808.
Data analysis program	Data analysis programs used in seaports refer to data analysis software tools or systems that are employed for the purpose of processing, interpreting, and comprehending the extensive volumes of data that are created within the operations of seaports. They deploy high-performance processing engines and advanced analytics algorithms, including machine learning and AI, to provide real-time insights into many facets of port operations. These programs are of utmost importance in the optimization of port efficiency, the enhancement of security measures, and the facilitation of informed decision-making for the managers via the use of data-driven insights.	Yang, Y., Zhong, M., Yao, H., Yu, F., Fu, X., & Postolache, O. (2018). Internet of things for smart ports: Technologies and challenges. IEEE Instrumentation & Measurement Magazine, 21(1), 34–43. https://doi.org/10.1109/mim.2018.8278808.
Preparedness Management	Preparedness management within a seaport context is the systematic and thorough process of strategizing, coordinating, and executing a range of initiatives with the objective of assuring the port's capacity to promptly and efficiently address and alleviate diverse emergency situations and critical events. The multifaceted nature of preparedness management in seaports could be represented by following examples: a) the effective preparedness management may serve as a deterrent to worker strikes occurring inside the port, b) The establishment of collaborative partnerships with local emergency services, police enforcement agencies, fire departments, and other pertinent entities guarantees seamless coordination and reciprocal assistance in times of disaster, c) the implementation of methods aimed at expeditiously mobilizing supplementary resources during emergencies, such as the establishment of contractual agreements with external organizations or corporations to acquire specialist equipment or employees, has the potential to ease the burden on port workers and enhance the effectiveness of emergency response efforts.	Çetin, Ç. K., & Cerit, A. G. (2010). Organizational effectiveness at seaports: a systems approach. Maritime Policy & Management, 37(3), 195–219. https://doi.org/10.1080/03088831003700611.

(*Continued*)

Table A1. (Continued).

Resilience Strategies	Description	Sources
Communication	During emergency situations, it is essential to establish efficient communication and coordination among many stakeholders, including port authorities, terminal operators, government agencies, emergency services, shipping agents, weather service, and community partners. Establishing effective channels of communication and clearly delineating roles and responsibilities are crucial factors in ensuring a prompt and efficient response. An illustrative case in history is the dynamic communication that took place between port officials in New York and New Jersey within the occurrence of Hurricane Sandy. This particular instance highlighted the pivotal significance of coordination and the interchange of information in the realms of disaster planning, response, and recovery. The implementation of this measure had a significant role in mitigating the adverse effects of the storm on port operations and bolstering the capacity to recover swiftly in the aftermath of the calamity.	Sturgis L.A., Smythe T.C., Tucci A.E. (2013). Port recovery in the aftermath of hurricane sandy: improving port resiliency in the era of climate change; Available from: https://s3.amazonaws.com/files.cnas.org/documents/CNAS_HurricaneSandy_VoicesFromTheField.pdf.?mtime = 20160906081313.
Alternative means of transportation	Alternative modes of transportation refer to diverse ways of conveyance that extend beyond conventional approaches for transporting commodities inside or in relation to the port setting. These alternate solutions are designed to improve efficiency and tackle the difficulties related to congestion and restricted transportation choices. For instance, in the event of a disruption at a destination port, railroads and trucks may serve as viable alternate modes of transit. In alternative scenarios, barges and other marine vessels possess the capability to convey substantial amounts of goods, therefore alleviating congestion on roadways and railroads.	MacKenzie, C. A., Barker, K., & Grant, F. H. (2012). Evaluating the consequences of an inland waterway port closure with a dynamic multiregional interdependence model. IEEE Transactions on Systems, Man, and Cybernetics, 42(2), 359–370. https://doi.org/10.1109/tsmca.2011.2164065.
Container repositioning	Container repositioning during a disastrous scenario is the deliberate and tactical relocation of containers within a port to effectively respond to and mitigate the unique problems and demands that arise as a result of the disaster. For example, during severe weather conditions such as storms or hurricanes, it is advisable to relocate containers to a lower location on the ground, preventing them from toppling over. Conversely, in the event of a flood, it is recommended to reposition objects at an elevated height that is beyond the reach of the floodwaters. Additional instances may be cited in scenarios such as fire, seismic events, and similar circumstances. In a quite different situation, such as explosions or chemical spills, the strategic relocation of containers may be used to establish protective barriers or buffer zones, so safeguarding adjacent regions of the port from possible damage.	S. Hosseini and K. Barker, "Modeling infrastructure resilience using Bayesian networks: A case study of inland waterway ports," Comput. Ind. Eng., vol. 93, pp. 252–266, Mar. 2016, doi: 10.1016/j.cie.2016.01.007.
Alternate functioning manner	When a seaport faced with a disruptive event, alternate functioning manner is attributed to the operational strategies and adaptations that seaports can implement to continue or modify their operations. For instance, seaports have the ability to curtail their operations to a limited capacity, prioritizing the processing of essential cargo or urgent provisions such as medical supplies, food, water, and emergency equipment to facilitate reaction and recovery actions. Or, in the case of an outbreak of a highly contagious disease, with utilization of advanced technologies, the remote management of some port services, including the remote operation of cranes and monitoring systems are possible.	N. Wang, M. Wu, and K. F. Yuen, "Assessment of port resilience using Bayesian network: A study of strategies to enhance readiness and response capacities," Reliab. Eng. Syst. Saf., vol. 237, p. 109394, Sep. 2023, doi: 10.1016/j.ress.2023.109394.

(*Continued*)

Table A1. (Continued).

Resilience Strategies	Description	Sources
Timely evacuation	The concept of timely evacuation entails the quick relocation of personnel, goods, cargos and facilities from a disrupted port to an alternative port or secure area, with the aim of minimizing possible losses and damages. For instance, a port situated in a region prone to floods has identified an impending hazard of river inundation as a result of intense precipitation. In order to mitigate potential losses, perishable commodities, equipment, and other critical cargo are promptly transferred to a more secure port in close proximity. Or, a seaport situated in an area characterized by political instability has received information suggesting the possibility of forthcoming disturbances. As a proactive measure, valuable cargoes and sensitive commodities are expeditiously redirected to a secure off-site storage facility until the situation attains stability.	Lee, P. T., & Flynn, M. (2011). Charting a new paradigm of container hub port Development Policy: The Asian Doctrine. Transport Reviews, 31(6), 791806. https://doi.org/10.1080/01441647.2011.597005.
Emergency unit	The establishment of an emergency unit inside a seaport serves the objective of facilitating a prompt and efficient reaction to a diverse range of emergencies, events, and crises that may arise within the port area or have an influence on port functionality. An emergency unit refers to a specialized group that has the requisite expertise, training, and resources to effectively handle, alleviate, and organize reactions to critical situations, with the ultimate goal of reducing potential damage to individuals, superstructures and assets.	N. Wang, M. Wu, and K. F. Yuen, "Assessment of port resilience using Bayesian network: A study of strategies to enhance readiness and response capacities," Reliab. Eng. Syst. Saf., vol. 237, p. 109394, Sep. 2023, doi: 10.1016/j.ress.2023.109394.
Rerouting	The establishment of a strategic alliance among proximate ports is an initiative of collaboration with the objective of mitigating possible economic setbacks and operational disturbances in the case of emergencies. Through collaboration, ports have the ability to collectively use resources, capabilities, and infrastructure to ensure the continuity of maritime commerce, particularly in situations when one of the ports is facing a disruption. For instance, let's consider two ports A and B have a strategic alliance. In instances involving natural disasters, labor strikes, capacity overload, port infrastructure maintenance, geopolitical instability, and similar factors, cargo ships intended for disrupted port A are rerouted to port B for the purposes of unloading and processing.	Lee, P. T., & Flynn, M. (2011). Charting a new paradigm of container hub port Development Policy: The Asian Doctrine. Transport Reviews, 31(6), 791806. https://doi.org/10.1080/01441647.2011.597005.
Effective information sharing	The utilization of effective information sharing mechanism enables the effective synchronization of activities, well-informed decision-making, and preemptive measures to address disruptive scenarios. For instance, the prompt dissemination of information on meteorological forecasts, the occurrences of natural disasters, or security risks enables seaport authorities and relevant parties to make necessary preparations and execute steps aimed at minimizing adverse impacts. This may include activities such as ensuring the safety of goods, facilitating the evacuation of workers, and fortifying infrastructure in order to mitigate potential harm and minimize any resulting disturbances. Or from an optimized resource allocation perspective, it is possible to improve the allocation of berths, distribution of manpower, and use of equipment, therefore mitigating bottlenecks and improving the overall efficiency of port operations.	Sturgis L.A., Smythe T.C., Tucci A.E. (2013). Port recovery in the aftermath of hurricane sandy: improving port resiliency in the era of climate change; Available from: https://s3.amazonaws.com/files.cnas.org/documents/CNAS_HurricaneSandy_VoicesFromTheField.pdf.?mtime = 20160906081313.
Budget restoration	The objective of budget restoration during the recovery phase of a seaport is to guarantee the availability of essential financial resources for the purpose of restoring the port to its regular operational state. The process of restoring the budget of a seaport is contingent upon its financial structure, and may need the use of many sources, including reserves, insurance claims, government help, or emergency money that have been specifically allocated for such circumstances.	Haimes, Y. Y. (2009). On the Definition of Resilience in Systems. Risk Analysis, 29(4), 498–501. https://doi.org/10.1111/j.1539-6924.2009.01216.x.

(*Continued*)

Table A1. (Continued).

Resilience Strategies	Description	Sources
Service restoration	Refers to the systematic recovery of critical services and activities necessary for the continued operation of the port after a disruptive event. These services cover a diverse array of activities that together facilitate the efficient functioning of the port, including cargo handling, vessel operations, customs clearance, security measures, logistics management, among others. The service restoration relies heavily on a resumption of the human workforce, including engineers, technical teams, operators, and workers.	Burns, M. G. (2018). Port Management and Operations. In CRC Press eBooks. https://doi.org/10.4324/9781315275215.
Facility recovery	Refers to the process of restoring and bringing back to operational status the affected and damaged seaport facilities such as cranes, docks, berths, container yards, warehouses, machineries, etc. The restoration of port operations at a seaport necessitates a synchronized and cooperative endeavor that engages many stakeholders, aiming to guarantee the effective and prompt recovery of facility functions.	S. Hosseini and K. Barker, "Modeling infrastructure resilience using Bayesian networks: A case study of inland waterway ports," Comput. Ind. Eng., vol. 93, pp. 252–266, Mar. 2016, doi: 10.1016/j.cie.2016.01.007.
Technology recovery	Seaports heavily rely on technologies such as TOS (terminal operating systems), EDI (electronic data interchange), RTU (remote terminal unit), PLC (programmable logic control), AGV (automated guided vehicles), VTMS (Vessel Traffic Management Systems), Cargo Inspection and Scanning to facilitate cargo handling, vessel operations, security, communication, and various administrative functions. Technology restoration ensures that these systems are functional and operational, allowing the port to resume its activities efficiently and effectively.	Agatić, A., & Kolanović, I. (2020). Improving the seaport service quality by implementing digital technologies. Pomorstvo, 34(1), 93–101. https://doi.org/10.31217/p.34.1.11.