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# The Impact of Industry 4.0 Technologies on Port Resilience: A Review

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## ABSTRACT

The consequences of port disruptions on the total supply chain make it imperative for ports to focus more on resilience measures. The current dimensions of port disruptions and the prevailing resilience mechanisms foster more innovative solutions for resilience management. On this ground, the industry 4.0 technologies in ports may play a vital role. This paper aims to conceptualize the impact of industry 4.0 technologies on port resilience. Even though the literature on industry 4.0 technologies in ports or smart ports as well as port disruptions and resilience are very extensive, acknowledgement of the impact of industry 4.0 technologies on port resilience is negligible. A systematic literature search found very little research on some aspects of smart ports and resilience. Based on an initial search review, this paper examines all the domains, for example, port resilience, port disruptions, resilience measures, and smart ports. Based on a snowball approach, it later discusses these domains and conceptualizes the possible impact of smart port technologies on port resilience. This paper aims to provide a holistic view of the interrelationship of all these domains. Furthermore, it discusses the various characteristics of smart ports and how each of these characteristics can impact resilience in ports. A specific focus on cyber resilience is addressed indicating the mutual interdependency of port resilience, smart ports, and cyber resilience. The paper also provides a reference for ports to implement industry 4.0 port technologies and improve their resilience. It also identifies future research needs and potential areas of research.

**Keywords:** port resilience, port disruption, industry 4.0 technologies, smart ports, cyber resilience.

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# 1 INTRODUCTION

Global supply chains are very much dependent on maritime transport, which handles about 90% of the world's merchandise trade volume. More than 11 billion tons of international cargo trade in 2022 got moved using maritime transport (United Nations Conference on Trade and Development [UNCTAD], 2022). As nerve centers within the global maritime transport supply chain, ports facilitate the seamless transfer of cargo (from bulky raw materials or finished goods to high-value manufactured goods) between maritime and non-maritime landside logistics interfaces. This conventional role of ports coupled with several burgeoning industry changes highlights the need for them to build resilience into their operations. Ports must therefore evolve to cater for the growing complexities confronting them on the operational front to avoid supply chain disruptions. Another factor stressing the need for ports to become highly adaptive is their susceptibility, such as locational vulnerability due to their proximity to coastlines, to varying climatic disruptions (León-Mateos et al., 2021). Other disruptions could emanate from organizational crises, technological crises, economic crises, political events, natural disasters, cyber security incidents, and events like the Covid 19 pandemic (Afenyo & Caesar, 2023; Hossain et al., 2019; UNCTAD, 2022).

The disruptive effect of weather and climate-related events on ports was evident in the findings of an online survey by the UNCTAD in 2017. The survey found that many of the participating ports had experienced some significant impact from climatic conditions. These include operational disturbances in 76% of cases, delays in 60% of cases, and disruptions to service/operations in 78% of cases; in addition, around 45% of ports faced some significant physical damage (Asariotis et al., 2017). In the United States for instance, extreme weather-related conditions such as hurricanes, storm surges, heat waves, cyclones, etc., caused logistical disruptions at several ports. Most East Coast and Gulf ports directly lie in the path of tropical storms and are sometimes closed during the hurricane season. More than 60 port closure days were recorded in 2020 due to hurricane-related disruptions (Bureau of Transportation Statistics [BTS], 2021). After an analysis of 141 disruption incidents at 74 U.S. ports, Verschuur et al. (2020) found that climate-related disruptions lasted between 6-22 days. This data explains the importance of resilient port management systems, given the significant role ports play in the global supply chain. Furthermore, disruptions in ports can shock regional and global economies (Rose & Wei, 2013). Since ports are highly interconnected to critical supply chains, the rippling effect of any disruption they experience can result in massive economic losses.

Given that maritime business happens in a highly volatile and erratic global economic space, the many efforts designed to build resilience in seaport systems has not yielded the desired results. This has been further complicated by the constant interfacing between ports and the adjoining supply chains they serve. Given the high dependence of these supply chains on ports, any disruption at either end undermines the ability of these ports to quickly recover and adapt during or in the aftermath of disruptive incidents. As a result, disruptions in ports are influenced by both internal and external factors (John et al., 2016; UNCTAD, 2022). Internal factors cover the aspects over which ports and shipping firms have some degree of control, whereas external factors cover the aspects that influence the demand for port and shipping services over which ports have little control (UNCTAD, 2022). Therefore, a mechanism of integrated communication throughout the supply chain, including both the internal and external factors of port disruptions, could help implement a better port resilience system. In this regard, introducing industry 4.0 technologies such as internet of things and sensing solutions, system integration, 3D printing and additive manufacturing, cloud computing, big data, business analytics, block chain, simulated and augmented reality and modelling, and cyber security into the supply chain can help facilitate an




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autonomous connection among the machines, digital processes, and systems. This would create an intelligent network throughout the value chain to facilitate prompt and timely interaction among firms to proactively mitigate the effect of any disruption (Ralston & Blackhurst, 2020). Since port disruptions are growing increasingly complex, the use of old mitigation strategies such as port substitution during incidents appear to be limited (Verschuur et al., 2020). Concurrent disruptions now happen at multiple ports and the ability of cyber attackers to simultaneously target several establishments within a supply chain (Afenyo & Caesar, 2023), suggests that ports will need industry 4.0 technologies to increase their adaptive capabilities.

The introduction and application of industry 4.0 technologies in the port sector is not new. If anything, there has been a rapid increase in the digitalisation of port business operations (de la Peña Zarzuelo et al., 2020). This is understandably so as the clamour for smart ports whose activities promote operational, social, and environmental sustainability underscores the need for industry 4.0 technologies, which are critical for producing seismic levels of supply chain connectivity for port users. However, there appears to be a dearth of research on the specific impact of these technologies on the resilience of ports as it is less emphasised. This paper attempts to highlight the important yet under-researched role of industry 4.0 technologies and port resilience, and conceptualize the impact of industry 4.0 technologies on port resilience. In order to address this issue, this paper examined the relevant literature following a systematic approach and found a scarcity of literature in this cross-disciplinary area. This limited body of literature underscores the importance of a thorough examination of these interlinked areas to address the subject matter. Therefore, this paper used a snowball process to review the relevant literature on port resilience, port disruptions, port resilience mitigation mechanisms or measures, and industry 4.0 technologies in ports (smart ports or port 4.0).

This paper first defines port resilience followed by the factors impacting port disruptions. Then it covers the different tools and technologies implemented for port resilience followed by the implementation of industry 4.0 technologies in ports. Finally, it integrates both the resilience and industry 4.0 technologies in case of port disruption followed by the conclusion. Although the discussion indicates the coverage of a wider domain of resilience, disruptions, and industry 4.0 technologies in ports, the scope of this paper is limited to identifying and conceptualizing the possible impact of industry 4.0 technologies on port resilience. The paper is structured as follows: Section 2 explains the methodology, Section 3 presents the literature review, Section 4 details the research findings, specifically the conceptualisation of the impact of industry 4.0 technologies on port resilience, and Section 5 provides the conclusion.

## 2 LITERATURE REVIEW METHODOLOGY

This section discusses the methodology of this paper. As mentioned, the objective of this paper is to conceptualise the impact of smart port technologies on port resilience; therefore, the primary focus was to identify and discuss all the relevant subject areas. This started with a systematic approach; however, considering the search findings and realising the large and emerging body of research in some of the relevant areas of interest, a snowball approach was adopted in the later part. The systematic search started by primarily using three search queries through Google Scholar on August 27, 2023. The search results are listed in Table 1 as well as the total number of articles.

**Table 1. Number of articles found by keywords. (By authors)**

| Category of key words | Number of articles | Remarks |
|---|---|---|
| "industry 4.0" and "port technology" or "smart port" and "port resilience" | 2 | 2 |
| "smart port" and "port resilience"/ "smart port" or "port resilience" | 20 | 18 excluding the 2 articles found in the first search |
| "smart port" and "port disruption"/ "smart port" or "port disruption" | 8 | 5 excluding 3 articles found in the second search |
| Total | 30 | 25 excluding 5 articles those are common in all searches |

After examining the title of the two articles under the first category of keywords, both of them were selected for further review, whereas six papers from the second category of keywords and one from the third category of keywords were primarily selected for further review. After reading these (2 + 6 + 1 = 9) articles, the two articles from the first category, three articles from the second category, and one article from the third category (i.e., 6 in total [2+3+1)] showed some interrelation between smart ports and port resilience.

After reviewing these papers, it was observed that, the two articles found in the first search addressed some direct interrelationship or impact of smart ports or port digitalisation on port resilience. Whereas the rest four articles addressed the issue by partially discussing some indirect interdependency among them. He et al. (2023) conducted a quantitative analysis on the influence of digital technologies on operational resilience. Through a regression modelling they concluded that the digital transformation of the port introduced as port digital grade had a positive impact on the port operational resilience. Port operational resilience is defined as the capability of a port to cope with risk and predict, respond, and adapt to disruptions due to changes in the external environment. To calculate the port operational resilience, this paper used the DEA method, where port investment, infrastructure, equipment, operating expenses, digital infrastructure investment, and employee quality were considered as input. Whereas operating revenue, non-operating income, growth rate, accident rate, and average vessel waiting time were considered as output. On the other hand, through a cross-domain literature review Klar et al. (2023) defined a concept named digital twins of ports. According to this study, a digital twin means the "grouping of models and algorithmic components that jointly describe the complex interplay of port processes and operations allowing the characterization, estimation, and prediction of the most efficient operations at the process level, but also for the port as a whole." It discussed evidence that the implementation of digital twins for ports among other measures can contribute towards port resilience.

Among the rest four papers, the study by Liu et al. (2023) developed a port resilience index and examined its impact on port governance performance. In calculating the port resilience index, this study considered several indicators for ports where smart port technology, the ICT infrastructure, and the digital industrial convergence of the hinterland were included. This highlighted the importance of ports becoming smart in order to be resilient. This study also discussed practical examples of how a lack of smart technology has reduced the resilience index



Marine Research of the National Academy of Marine Research
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of some ports. León-Mateos et al. (2021) also significantly considered the role of digitalisation in ports for information flow throughout the supply chain while developing their port resilience index by using different factors, including port governance, infrastructure, operation, society, and risk management. Implementing the maturity model development methodology, Boullauazan et al. (2022) examined smart ports and discussed the different domains of the smart ports' maturity model. This study suggests that the safety and security domain of smart ports can contribute to their resilience. The final article selected from the literature search, by Punt et al. (2023), is on the cyber resilience of ports. Through a literature review, semi-structured interviews, and case studies, this article concluded that while there is much discussion on the vulnerability of ports and related infrastructure to cyberattacks, preparedness strategies are incremental, informal, and non-institutionalised. The article also suggests investing in procedural standards, cyber security, and the development of comprehensive regulatory framework. It also suggested the importance of examining the digitalization in ports and its role in cyber security.

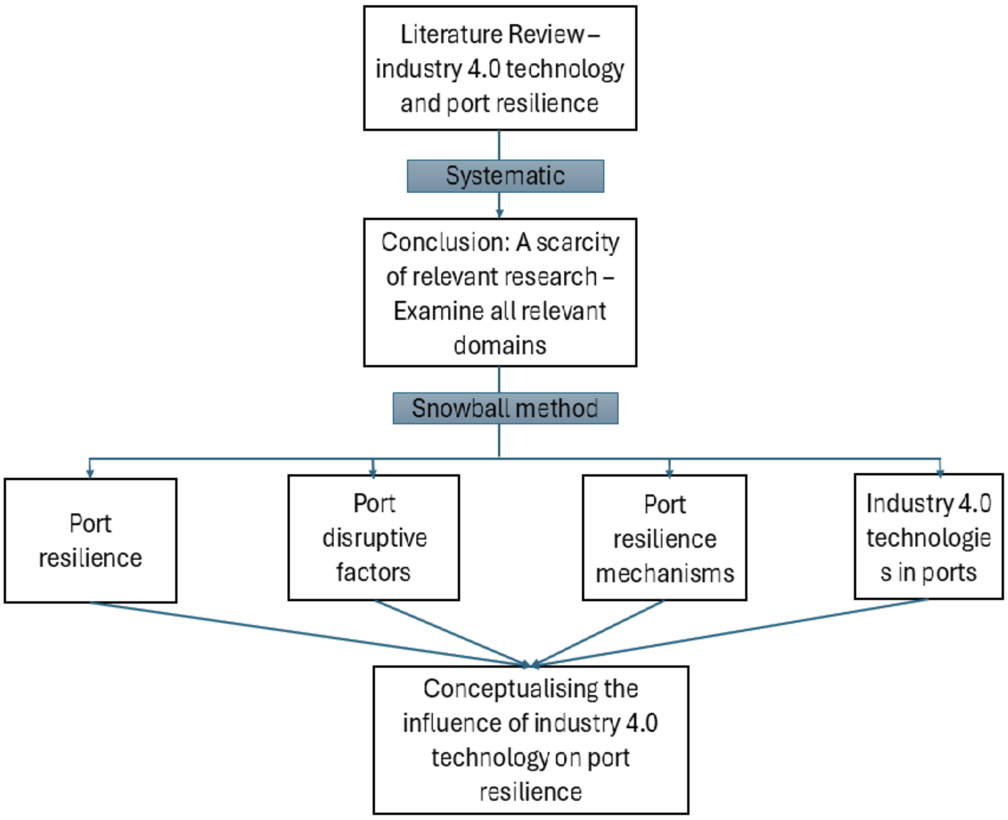


**Figure 1. Research methodology.**

From the above discussion it can be concluded that the impact of smart ports, port digitalization, industry 4.0 technologies in ports, or ports 4.0 technologies on port resilience is evident, but very little research has been conducted in this area. Moreover, among these articles, none of them have comprehensively addressed not only port resilience but also smart ports considering all the different dimensions and perspectives when discussing any impact of smart ports on port resilience. Therefore, it was necessary to examine each of these port management literature domains and identify the possible links among them. As a result, a second phase of the literature search was conducted. Considering the large and emerging body of research on port resilience, port disruptions, smart ports, and cyber resilience, a snowball approach was chosen to define the interrelationship and conceptualize the impact of smart ports on port resilience. Figure 1 portrays the research methodology explaining how the literature review was designed to conceptualise the influence of industry 4.0 technologies on port resilience.




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# 3 LITERATURE REVIEW

## 3.1 Port Resilience

This section provides an extensive description of port resilience and resilience activities/actions, to better grasp how smart ports can contribute. Port resilience is usually described as the capacity of ports to anticipate and respond to changing situations, survive and/or quickly recover from disruptions, and return to normal operations and flow of cargo to, from, and through ports (Notteboom et al., 2022). According to the UNCTAD (2022), it is the ability to remain operational and maintain an acceptable level of service and infrastructure to ships, cargoes, and other stakeholders in the face of disruptions. It is expected that a resilient port is able to act in three areas as depicted in Figure 2. To be resilient, ports must be absorptive, restorative, and adaptive.

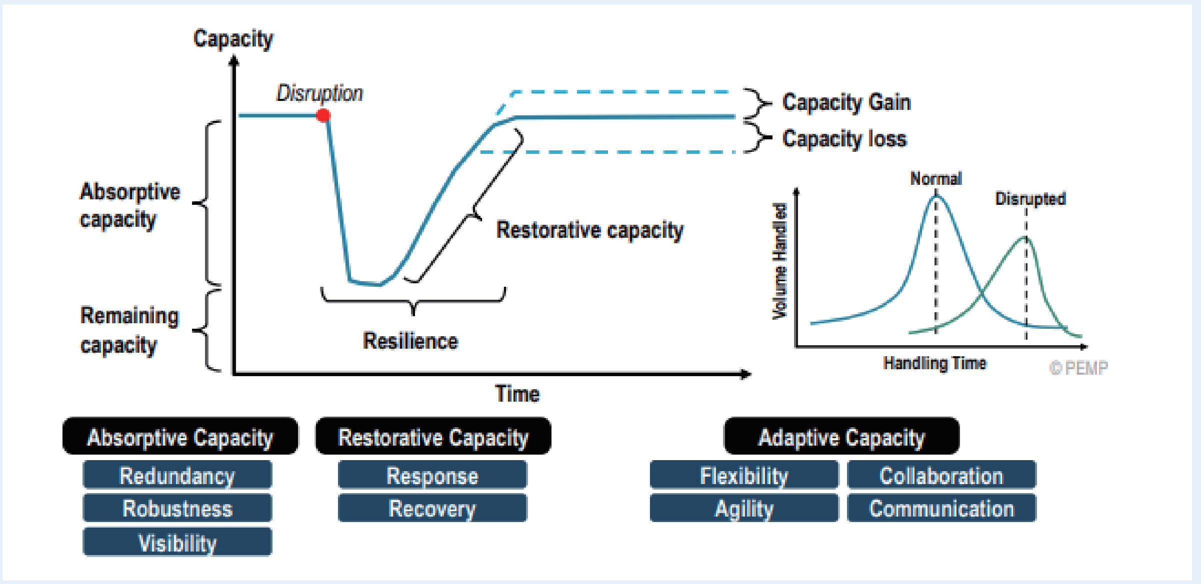


**Figure 2. Concept of resilience. (Linkov & Palma-Oliveira, 2017 as cited in UNCTAD, 2022, p. 4)**

It can be observed from Figure 2 that each of these three dimensions of port resilience is subdivided into secondary dimensions. A discussion of all these dimensions is required to get a clear understanding of the concept of port resilience. Table 2 includes the definition of all these primary and secondary dimensions of port resilience. In discussing all these different dimensions of port resilience, the guidebook on "Building Capacity to Manage Risks and Enhance Resilience" developed by the UNCTAD (2022) and two research articles by Kim et al. (2021) and Gu and Liu (2023) were considered as the main source of discussion. The report by the UNCTAD (2022) provides an extensive understanding on resilience and a reference for the implementation of resilience in ports. Whereas the article by Kim et al. (2021), in discussing a framework for measuring port resilience in ports, discusses all the relevant definitions based on different literature. Moreover, the article by Gu and Liu (2023) is a systematic literature review on the port resilience defining all these dimensions.



Marine Research of the National Academy of Marine Research
DOI: 10.29677/MR.202512_5(2).0001

**Table 2. Various dimensions of port resilience. (By authors)**

| Dimensions | Definition | Sources |
|---|---|---|
| 1.0 Absorptive | The capacity of absorbing a disruption with the existing infrastructure and services and maintain a desired level or same level of services. | Notteboom et al. (2022) and UNCTAD (2022) |
| 1.1 Redundancy | Ports have the additional (reserve) capacity to combat any (unexpected) disruptive situation by accelerating operations and maintaining their overall performance. | Gu and Liu (2023), UNCTAD (2022), Kim et al. (2021), and Wan et al. (2018) |
| 1.2 Robustness | The ability of ports to survive (maintain the regular or target performance) in a disruptive situation by encapsulating their technical and engineering design characteristics. | Kim et al. (2021), UNCTAD (2022), and Wan et al. (2018) |
| 1.3 Visibility | The capability of the ports' information system to track all operations, manage, and program real-time data and information sharing with partners and stakeholders to take restrictive measures during a disruption. | Kim et al. (2021), Pettit et al. (2013), and UNCTAD (2022) |
| 2.0 Restorative | The ability of ports to recover services to a similar level or even above in the face of a disruptive situation. | Notteboom et al. (2022) and UNCTAD (2022) |
| 2.1 Responsive | The preparedness (contingency plan) of ports for a disruption with the adequate and quick deployment of all resources to mitigate the impact. | Gu and Liu (2023), Kim et al. (2021), UNCTAD (2022), and Wan et al. (2018) |
| 2.2 Recover | Ports respond to a disruption and return to their normal level of operation quickly, cost efficiently, and with the least damages. | Gu and Liu (2023), Kim et al. (2021), UNCTAD (2022), and Wan et al. (2018) |
| 3.0 Adaptive | The ability to change the operations and even the management either in anticipation or as a response to a disruption. | Gu and Liu (2023), Notteboom et al. (2022), UNCTAD (2022) and Wan et al. (2018) |
| 3.1 Flexibility | The adjustability of ports operations and other activities by changing the schedule and workflows. | Kim et al. (2021), UNCTAD (2022), and Wan et al. (2018) |
| 3.2 Agility | The quickness of responding to a disruption, which may cover responding to quick changes in workflows, performing multiple works, quickly switching between works, and even some unexpected requests by partners or stakeholders. | Kim et al. (2021) and UNCTAD (2022) |
| 3.3 Collaborative | Joint work among key partners and formulation and works on the mutual managerial goals and strategies among key partners to share resources and other tools and techniques to utilize on a disruptive situation. | Kim et al. (2021) and UNCTAD (2022) |
| 3.4 Information sharing | The exchange of relevant, timely, and accurate information with partners and stakeholders on every aspect of changes and adjustment. | Kim et al. (2021) and UNCTAD (2022) |



Marine Research of the National Academy of Marine Research
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A close examination of Figure 2 and Table 2 depicts that, when a disruption appears, ports with all of their capacity from different dimensions try to manage and mitigate it. Ports with absorptive capacity try to manage and maintain a desired level of service through redundancy, robustness, and visibility. Parallelly, ports with restorative capacity subsequently try to return to their normal or an expected level of service through responsiveness and recovery measures. The adaptive capacity helps ports in every aspect while ports are in the absorptive and restorative stage. By leveraging flexibility, agility, collaboration, and communication, ports can impact both their absorptive and restorative measures to anticipate and mitigate a potential disruption. Taking into account all the different dimensions of port resilience, this paper concluded that port resilience is the capacity and capability of ports to anticipate and withstand the disruptive effect of either natural or man-made events, and return to normal operations in the aftermath of incidents without descending into a system meltdown (where the capacity and capability of ports indicates ports' redundancy, robustness, visibility, responsiveness, recovery, flexibility, agility, collaboration, and communication dimensions).

### 3.2 Factors Impacting Port Disruptions

The need to build resilience into port systems is urgent and obvious. This is particularly so when the inimical effect of disruptions happens on critical supply chains. Given that port disruptions are caused by a multiplicity of factors, which are becoming increasingly complex, a thorough understanding of the nature of these causative factors is needed. Such insight will help establish disruption-proof port systems, endowed with adequate adaptive capabilities. As León-Mateos et al. (2021) emphasize, identifying factors that affect port resilience is parallelly important to developing port adaptability. According to Notteboom et al. (2022), the sources of port disruptions are multiple; some predictable, others random, and a few falling in the unexpected category. A more generic nomenclature classifies the sources of disruptions as emanating from internal sources and external sources. Internal sources include factors under the control of port authorities or operators such as breakage of equipment resulting from improper maintenance, security breaches or weak security. External factors can include natural disasters such as hurricanes, earthquakes, and tsunamis, economic turmoil due to regional war or closing of trade etc. Notteboom et al. (2022) broadly classified the sources of disruptions as natural and anthropogenic events. Natural events include extreme weather events, geophysical events, and climate change. On the other hand, anthropogenic disruptions cover accidents, labor disputes, economic and geopolitical events, information technologies, and pandemics. In addition to the above factors, the UNCTAD (2022) added another factor—sanitary threats—resulting from pandemic situations such as the spread of communicable diseases. In the U.S. and other developed economies (Australia, New Zealand, and Canada), port sector workers are notorious for industrial strike actions. This is one of the major sources of port disruptions within the U.S., with devasting effects. For instance, a 2022 National Association of Manufacturers (NAM) report estimated that ports in the U.S. West Coast could lose US$500 million each day and 41,000 jobs in a three-week period of industrial strike (Murray, 2023). A 2002 ten-day strike by dockworkers disrupted 40% of containerized shipments at U.S. ports and resulted in a loss of US$19.4 billion (Thekdi & Santos, 2016). Analyzing the typhoon induced wind disaster data for a period of ten years from 2007 to 2017, Zhang et al. (2020) estimated that the ports of Shanghai, Ningbo, Shenzhen, and Guangzhou, respectively, face an average loss of 0.31 billion, 0.26 billion, 0.89 billion, and 0.39 billion RMB during the summer period (August/September). However, it is important to carefully consider the human influence on natural events. A study from the UN University highlighted the connection of human activity to disasters such as cyclones, floods, and droughts, and identified that the root causes are human induced greenhouse gas emissions, inadequate risk management of disasters, and underestimating the cost of environmental impacts during decision making (United Nations, 2021). On the other hand, the threat of cyberattacks is another important area to focus, as the use of digital technologies is increasing daily. In 2017, ransomware attacked the Maersk terminal operating system, forcing it to reinstall the system in 4,000 servers and 40,000 PCs, costing around US$200 million (Weaver et al., 2022).



Marine Research of the National Academy of Marine Research
DOI: 10.29677/MR.202512_5(2).0001

Shaw et al. (2017) provide a wider analysis of the disruptive factors, where they identified seven groups of factors that could contribute to port disruptions. These include economic, environmental, human, access to ports, network or supply chain capabilities, information, and communication technology (ICT), and other enabling technologies and organizational factors. The economic factors consist of an adverse economic climate, bankruptcy of a major port user, competition from other ports, and seasonality. Environmental factors cover hydrological hazards, pollution, seismic events, adverse weather, and unexploded World War II ordinances. Human factors incorporate human errors, industrial actions, epidemics, terrorism and crime, and other human mobilization events. Access factors cover the marine access, land access, and official inspection of people and goods. Network factors cover disruptions up or down the supply chain and disruptions in other major ports. Technological factors comprise accidents, system failures, and loss of key utilities. Finally, organizational factors involve insufficient resources, lack of planning, poor planning, ineffective communication, bureaucracy, conflicting priorities among port stakeholders, and conflicts with contractual and statutory obligations. Figure 3 shows the Ishikawa diagram developed by Shaw et al. (2017), describing all the factors with some examples. The figure appears to suggest that singularly or in a convergent manner, these factors may culminate in disruption or the closure of a port.

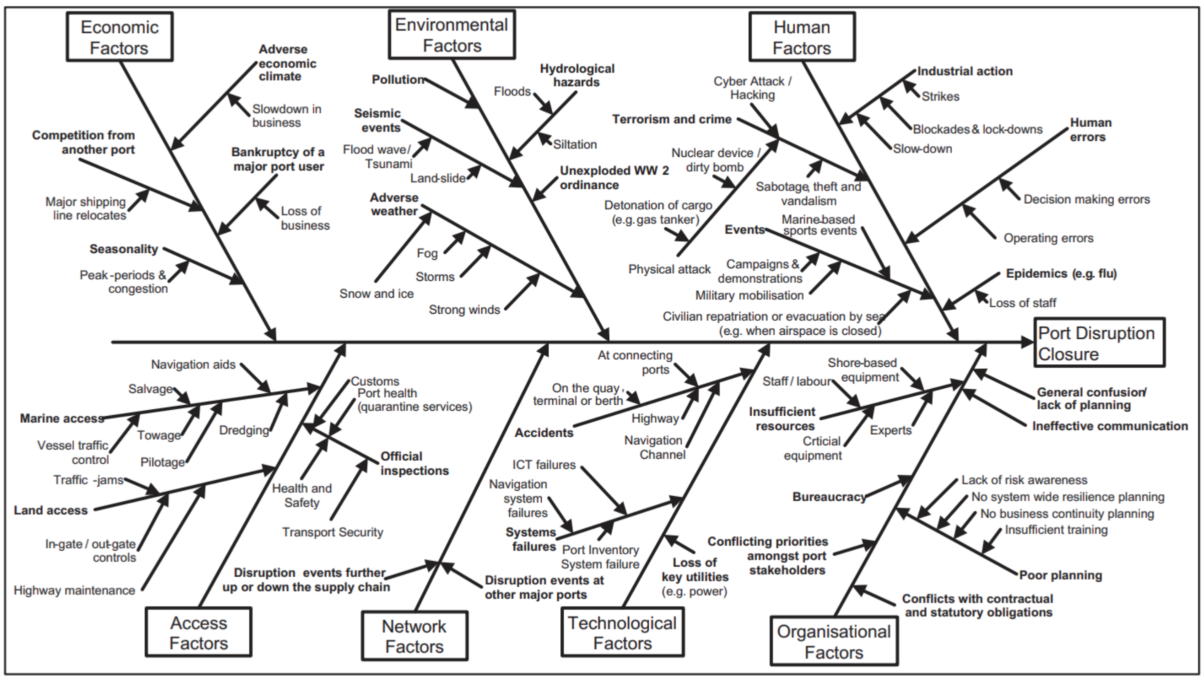


**Figure 3. Ishikawa diagram showing the seven groups of factors and sub-factors. (Shaw et al., 2017)**

In modelling and assessing resilience, Hossain et al. (2019) also agree that natural disasters, malicious cyberattacks, technological factors, organizational factors, economic factors, and human error are some of the key sources of port disruption. A list of factors that cause port disruptions by John et al. (2016) includes operational factors, security factors, technical factors, organizational factors, and natural factors. Operational factors consist of port equipment failures, vessel accident/grounding, cargo spillage, and human errors, whereas security factors entail sabotage, terrorism attacks, surveillance system failures, and arson. Technical factors include the lack of equipment and navigational aids maintenance, lack of ICT system maintenance and lack of dredging maintenance,




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whereas organizational factors consist of labor unrest, disputes with regulatory bodies, berth congestion, gate congestion, and storage area congestion. Finally, natural factors cover geologic/seismic, hydrologic, and atmospheric factors. A wider analysis on the impact of climatic change on ports by Asariotis et al. (2017) indicates that climatic factors such as rising sea levels can damage port infrastructure. In addition, changes in tides can cause sedimentation in channels affecting operational timetables, impacting the coastal road/railway links, and resulting in the relocation of businesses and people. Rising temperatures can also impact infrastructure and staff health, cause higher energy consumption, delays in constructions, and changes in demand. Precipitation causes damages to land infrastructure and cargo/equipment; in addition, inland navigation restrictions and fog can delay terminal/ship operations. Finally, wind can create problems in seaport navigation, berthing, and operation disruptions. An analysis on the port decision-makers' perceptions on the impact of rising sea levels and high winds and storms by (Ng et al., 2018) concluded that due to climate change the future impact will be more severe and ports need to undertake further approaches to adapt to climate-related disruptions.

The types of port disruptions around the world may provide an understanding on any prevailing relationship between the size of ports in terms of productivity, management model, location or even economic situation of the region which it is serving. The research by Lam and Su (2015) examined historical data from 2000 to June 2011 in ports located in East and South Asia, covering multiple countries such as China, Hong Kong, Macau, Taiwan, North and South Korea, Japan, Philippines, Vietnam, Singapore, Malaysia, Thailand, Brunei Darussalam, Myanmar, Cambodia, Timor-Leste, Indonesia, India, and Bangladesh, and concluded that natural disasters (47%) and labor strikes (39.75%) are the two main causes of port disruptions. However, the severity of a natural disaster represents as high as 83% of cargo-related disruptions. In order to understand the nature of port disruptions in various part of the world, the 23 different port disruption cases presented in the "Building Capacity to Manage Risks and Enhances Resilience: A Guidebook for Ports" by the UNCTAD (2022) could be good source. A summarization of the 23 cases is presented in the table below:

**Table 3. Disruption in ports by nature and location. (By authors)**

| Sl. No. | Types/ Sources/ Nature of disruptions | Ports name and country of location |
|---|---|---|
| 1. | Covid-19 | i) Los Angeles and Long Beach, U.S. ii) Port of Djibouti |
| 2. | Operational accident/Canal obstruction | i) Port of Said, Egypt ii) Port of Ho Chi Minh, Vietnam |
| 3. | Safety accident/Explosion | i) Port of Tianjin, China |
| 4. | Labor strike | i) Port of Gothenburg, Sweden ii) Port of Valparaiso, Chile |
| 5. | Capacity constraints | i) Port of Rotterdam, Netherlands, and Port of Antwerp, Belgium ii) Port of Hamburg, Germany iii) Port of Chittagong, Bangladesh |
| 6. | Climate factors/Sea-level rise/ Hurricane Super storm/ Tsunami/Flood | i) Port of Seattle, U.S. ii) Port of Gulfport, U.S. iii) Port of New York, U.S. iv) Port of Huston, U.S. v) Port of Meulaboh, Indonesia vi) Port of Freeport, Bahamas vii) Port of Port-au-Prince, Haiti viii) Port of Vila, Vanuatu ix) Port of Male, Maldives x) Port of Laem Chabang, Thailand |
| 7. | Post-civil war | i) Port of Lagos, Nigeria |
| 8. | Cyberattack | i) Jawaharlal Nehru Port Trust (JNPT), India ii) Port of Durban, South Africa |



Marine Research of the National Academy of Marine Research
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An examination of Table 3 shows that the ports have faced almost all the different types of disruptions that are discussed in the literature. But among these 23 ports, the highest number of port disruptions are sourced from the climate-related disruptions, totaling 10 incidents. Among these, cyclones and super storms cover the highest numbers; moreover, six incidents occurred in the U.S. and Caribbean region. Four ports have faced disruptions due to capacity constraints. Interestingly, these sources of disruptions include three ports in Northern Europe and one in Bangladesh. The ports in Rotterdam and Antwerp are discussed as a single case, and between the 2014-17 period, the ports faced capacity constraints. The reason behind the capacity constraints is the increased vessel size and limited hinterland capacity to handle the sudden peak in containers. In the case of the Port of Hamburg, the reason for disruption in 2013-14 was also similar (increased ship size and number of calls). However, the capacity constraints were also influenced by a series of storms. On the other hand, the Port of Chittagong faces congestion periodically due to insufficient infrastructure and yard congestions. The findings from the UNCTAD (2022) align with Lam and Su (2015), as the later identified natural disasters as one of the main sources of port disruptions. But a smaller number of labor strikes in the UNCTAD (2022) report could be due to the selection of ports. A notable addition to this report is the inclusion of two cyberattack cases. The first case was previously discussed in the context of cyber-related risks. A clear observation from all 23 cases is that any type of disruption, even a capacity-related issue, can occur in any port, regardless of its infrastructure, operating capacity, or geographical location.

To summarize the discussion, port disruptions can be influenced by a range of factors: the regional economy, the climate and geophysical conditions, the policy and organizational structure, internal and external personnel, various operating systems (such as infrastructure, equipment, and ICT), stakeholders, and the environment surrounding the ports. It is important to highlight that some of the disruptive factors are being well addressed by the port operators and authorities around the world, whereas some are attaining new dimensions. The impact of climate change is one of the most important factors, as evidenced by the impact of natural disasters worldwide. Another crucial factor is cyber security. With the increasing digitalization of the port industry and the implementation of smart ports, cyber security needs to be given higher priority. The economic loss and the impact of cyber disruptions in the port sector has also been previously highlighted. Since this paper aims to conceptualize the impact of smart ports on port resilience, the resilience of the smart system itself must be carefully considered.

## 3.3 Resilience Mechanisms (Tools and Technologies)

There is extensive literature regarding disruption mitigation and adaptation mechanisms. Notteboom et al. (2022) indicate that ports can play a vital role in mitigating total supply chain disruptions. They emphasized the role that ports played during the Covid-19 pandemic, which helped develop the resilience capacities of ports and provided them with an adaptability mechanism. According to them, mitigation mechanisms should include port infrastructure and superstructure improvements, planning traffic diversion strategies, preparedness for every aspect of operation, relocation, repair and maintenance, hazmat reporting, and satellite or off-site facilities. The resilience capacity building report by the UNCTAD (2022) provides a comprehensive picture of mitigation and response measures. The report proposes nine general areas of engagement to improve port resilience: port risk and crisis management, contingency planning, improving infrastructure and superstructure, satellite facilities, traffic diversion, hazmat reporting, and cyber resilience. Each of these realms consists of several other elements, which are depicted in Figure 4.




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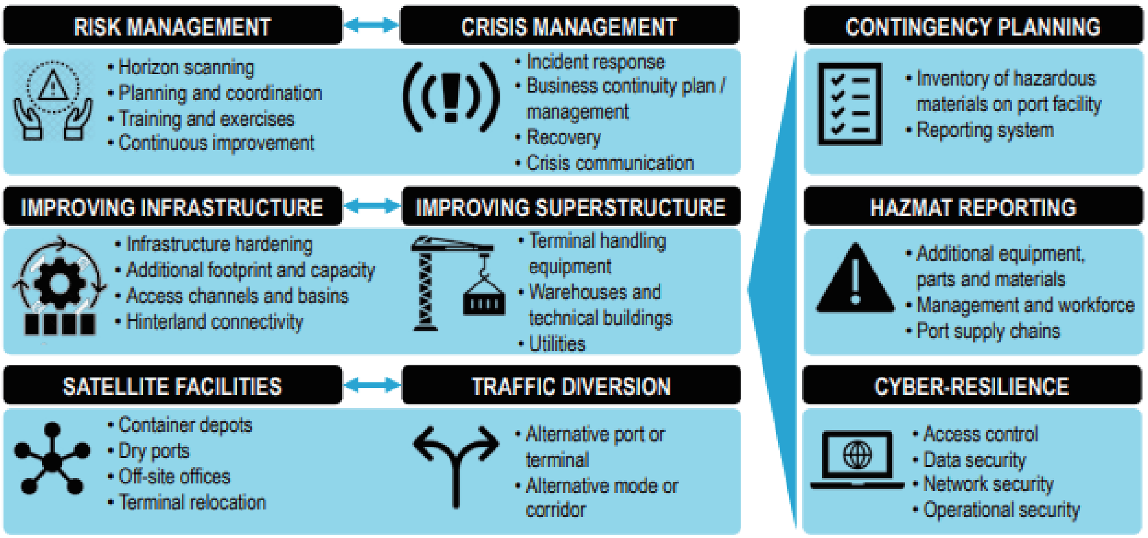


**Figure 4. Key mitigation and response measures for port disruptions. (UNCTAD, 2022, p. 22)**

Besides this wider analysis of mitigation measures for port disruptions contained in the UNCTAD (2022) report, other specific measures are found within the extant literature. For example, Shaw et al. (2017) analyzed the importance of information sharing among supply chain stakeholders for disruption mitigation in ports in the UK. According to this study, inadequate access to information, lack of accurate information, and outdated information were some of the drawbacks for resilience planning in ports. In this regard, port digitalization and other industry 4.0 innovations are critical to aid the timely sharing of response information between ports and other actors within their given network. Justice et al. (2016) discussed the importance of innovation and self-organization to facilitate quick adaptation to changing circumstances. Considering extreme weather as a key source of port disruptions, Repetto et al. (2017) emphasized the need for innovative forecasting systems, access to timely information for port authorities, and a high-level monitoring network to aid quick decision making during or in the aftermath of incidents. A port-hinterland container transportation network resilience analysis by Chen et al. (2018) considered only three port disruption factors: catastrophic accidental explosions, labor strikes, and terrorist attacks. They named these three port disruptive factors as man-made unconventional emergency events (MUEE) and proposed a number of mitigation measures (including investment in employee welfare), focusing on investment, training, and law reform. Taking the petroleum trade in the U.S. as an example, Rose et al. (2018) suggested some effective initiatives such as inventory use, tankers re-routing, production recapture, and export diversion. While they may not fully prevent port disruptions, these measures can alleviate pressure on the affected ports and provide them with valuable buffer time for recovery. In addition, this study recommends a discussion of specific port resilience measures identified in the literature, including: new port infrastructure development (Almutairi et al., 2019); maintenance, alternate routing, and manpower restoration (Hossain et al., 2019); communication and coordination in restoring lifelines, networks, and social relations (Kim & Bui, 2019); capacity enhancement (Gong et al., 2020); and production recapture and port substitution (Verschuur et al., 2020).



Marine Research of the National Academy of Marine Research
DOI: 10.29677/MR.202512_5(2).0001

After considering the port disruption mitigation measures, tools, and technologies discussed, the nine areas highlighted in the UNCTAD (2022) report represent the most comprehensive analysis of port resilience measures. But alongside these nine measures, access to proper information, communication and coordination among all the stakeholders, reducing the pressure from the supply chain by using the existing inventory or production alternatives and innovation are also important. In the case of information sharing, communication and coordination, and innovation, smart port technologies can contribute directly, since they could facilitate the smooth, proper, and effective implementation of the nine specific measures proposed by the UNCTAD (2022) as well. After addressing the industry 4.0 technologies in ports or smart ports technologies in the next section, the following section will try to address how industry 4.0 technologies in ports can impact their resilience.

### 3.4 Industry 4.0 Technologies in Ports

This section specifically discusses the industry 4.0 technologies that have been introduced in port operations, management, and planning systems to increase the performance of ports. Industry 4.0 consists of smart systems and autonomous processes that integrate business operations to perform tasks intellectually, automatically, efficiently, and effectively (Ralston & Blackhurst, 2020). Industry 4.0 is founded on the internet of things (IoT) and sensing solutions, horizontal and vertical system integration, cyber security, cloud computing, artificial intelligence (AI), machine learning (ML), big data and business analytics, block chain, 3D printing and additive manufacturing, augmented reality, simulations and modelling (de la Peña Zarzuelo et al., 2020). The same study classified these elements into three broader categories: advanced methods and tools, horizontal and vertical system integration and application through new standards, and open challenges. The study also emphasized that some of these technologies are already matured in the port industry. The implementation of these industry 4.0 technologies in ports is termed as smart ports or port 4.0 by de la Peña Zarzuelo (2021). Molavi et al. (2020) defines smart ports are those that utilize industry 4.0 technologies to solve the current problems in port operations, management, and planning. Considering the utilization of industry 4.0 technologies, Molavi et al. (2020) highlighted two categories of ports around the world. The first group is very much focusing on the long-term planning aspects and some of their common goals are to develop efficient operations and logistics through automation and technology. Whereas the other group is very much focused on the solution of specific problems in ports by adopting specific information technology solutions. Example of such initiatives include the use of ICT for knowledge sharing and information analysis to improve efficiency in operations and energy consumption. They further classified the activity domains of smart ports in operations, environment, energy, and safety and security. Heikkilä et al. (2022) define the ports using industry 4.0 technologies as ports 4.0, and highlighted that such ports focus on the automation, sustainability, and collaboration aspects. A very recent literature review by Belmoukari et al. (2023) provides a wider coverage of smart ports and defines 11 distinct characteristics of smart ports, which are grouped into seven different business domains. The following table shows the 11 characteristics and the corresponding seven business domains. The research by Heikkilä et al. (2022) shows that, the characteristics under the operations domains reflect mainly three characteristics such as stakeholder collaboration and involvement in port projects, efficiency of operation, and communication and data exchange between ports. The intelligent traffic management and real-time information sharing is reflecting the communication and data exchange characteristic. Moreover, under the human resource domain, the characteristics of skilled and creative workforce, and good governance and human resources management also reflect one characteristic.



Marine Research of the National Academy of Marine Research
DOI: 10.29677/MR.202512_5(2).0001

**Table 4. Business areas and associated smart port characteristics. (Copied from Belmoukari et al., 2023)**

| Business areas | Characteristics |
|---|---|
| Infrastructure, equipment, and innovative technologies | Connectivity<br>Intelligent and innovative infrastructure, equipment, and technologies<br>Automation |
| Operations | Stakeholder collaboration and involvement in port projects<br>Efficiency of operation<br>Communication and data exchange between ports<br>Intelligent traffic management and planning<br>Real time information sharing |
| Energy | Energy efficiency |
| Environment | Environmental sustainability |
| Safety and security | Safety and security |
| Social | Quality of life of the population |
| Human resources | Skilled and creative workforce<br>Good governance and human resources management |

Therefore, smart ports are those that utilize industry 4.0 technologies in every aspect of infrastructure and superstructure, operation, energy, automation, safety and security, environment, social, governance and human resource, collaboration and communication to solve day-to-day problems in port operations, management, and planning. Moreover, from Table 4 we can conclude that smart ports focus on communication, collaboration, automation and intelligence, real-time information exchange, energy efficiency, environmental sustainability, quality of life of people as well as the employees. All of these characteristics of smart ports can contribute to port resilience. Therefore, the following section will focus on the conceptualization of the impact of smart ports on port resilience, extracting all the findings from the previous sections.

# 4 INDUSTRY 4.0 TECHNOLOGIES TO IMPROVE THE RESILIENCE OF PORTS

The utilization of industry 4.0 technologies in solving the day-to-day problems in ports is discussed in Section 3.4. While industry 4.0 technologies are widely utilized in ports, there is limited focus on their specific role in enhancing port resilience. The implementation of industry 4.0 technologies in ports can help ports mitigate some of the port disruptive factors, such as those related to operations, infrastructure, networking, safety and security, and environment and climate as discussed in Section 3; however, these factors are not addressed from the perspective of resilience management. For example, Verschuur et al. (2020) utilize the vessel tracking AIS data in ports to analyze the vessel movements during and after a port disruption and evaluate disruptions' duration and the resilience of ports. The application of simulation and mathematical modelling for analyzing port resilience mechanisms and their effectiveness is well observed in the literature (John et al., 2014, 2016; Pant et al., 2014). Research on cyber security has also received attention in the literature (de la Peña Zarzuelo, 2021; Heikkilä et al., 2022). A recent study by Ren et al. (2024) indicates that, from a resilience perspective, the safety and security performance of ports can be improved by implementing industry 4.0 technologies in ports. However, none of these studies focus on the impact and role of industry 4.0 technologies on port resilience from a holistic approach.



Marine Research of the National Academy of Marine Research
DOI: 10.29677/MR.202512_5(2).0001

In order to focus the capability or capacity of industry 4.0 technologies to mitigate port disruptions and implement port resilience, it is necessary to look at port resilience from a holistic point of view, covering all areas such as the capabilities required for a port to be resilient, the factors that impact disruptions, as well as the mechanisms to mitigate disruptions and implement resilience in ports. This could provide a better look on port resilience and how the capacity or capability of industry 4.0 technologies could enhance ports' resilience. According to Molavi et al. (2020), smart ports are those that leverage technology-based solutions to mitigate issues such as congestion, delays, operating errors, lack of information sharing, construction and expansion activities, energy disruption impacting port activities, safety issues (including vessel collision and striking), and security. All these issues are directly related to the port disruption factors discussed in Section 3.2. Therefore, the following part of this section conceptualizes the impact of industry 4.0 technologies on port resilience.

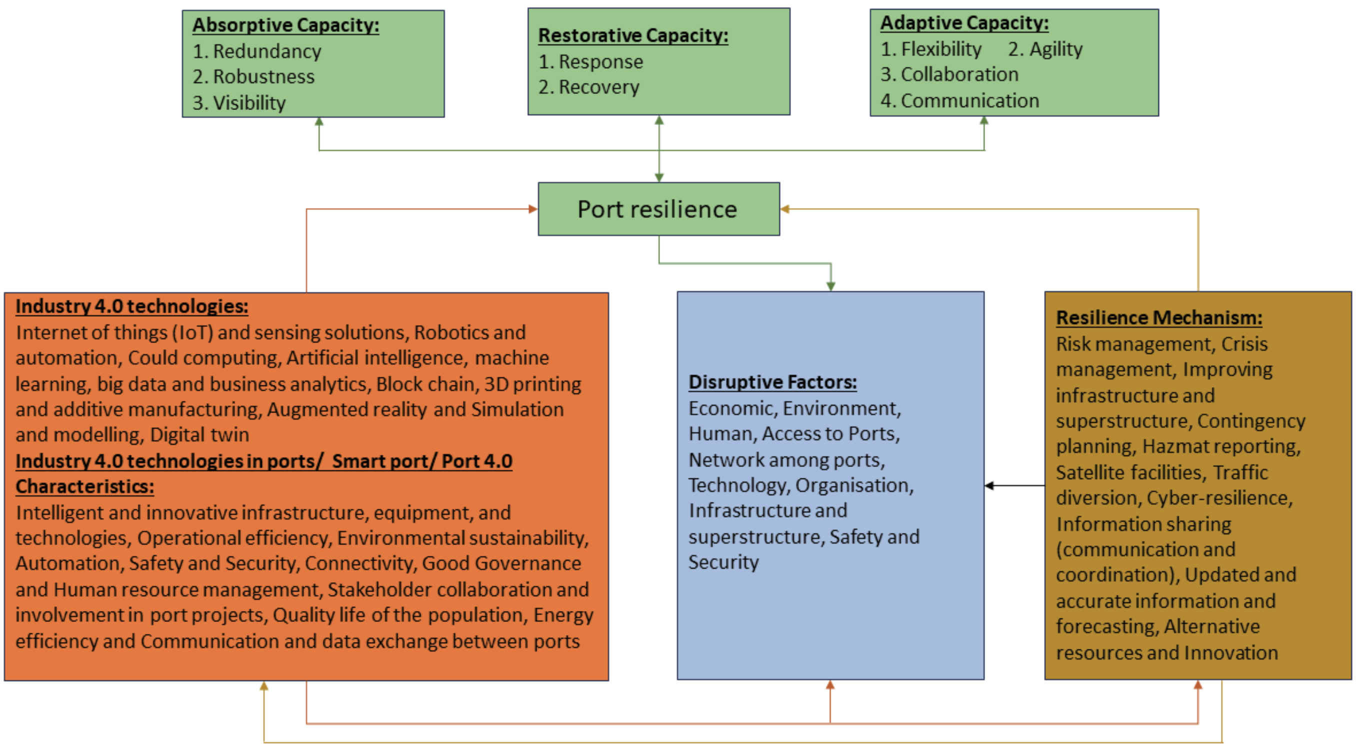


**Figure 5. A holistic view on the influence of smart ports/Ports 4.0 on port resilience. (Drawn by authors, based on Sections 3.1, 3.2, 3.3, and 3.4)**

Figure 5 provides a holistic view of port resilience systems and industry 4.0 technologies in ports. It depicts that smart port technologies and the characteristics of smart ports can impact the implementation of port resilience mechanisms and mitigate disruptive factors, thereby contributing to port resilience in terms of absorption, restoration, and adaptation. Port disruptions influenced by various disruptive factors presented in Figure 5 can be coped with port resilience systems. The port resilience systems are founded on three fundamental capacities of ports: absorptive, restorative, and adaptive. To achieve this capacity, ports need to implement various resilience mechanisms or tools. These tools play an important role to make ports resilient and mitigate or minimize the impact of various disruptions. Ports are adopting more and more industry 4.0 technologies to improve their performance in various areas such as operational efficiency, sustainability, integration, and communication. All these industry 4.0 technologies can improve the implementation of various port resilience mechanisms or tools by reducing the impact of various disruptive factors. The arrow from the industry 4.0 technologies leading to disruptive factors indicates that these technologies can reduce the impact of disruptions. Similarly, the arrow from the industry 4.0 technologies pointing to port resilience mechanism indicates how the technologies can improve the performance of the resilience mechanisms or tools placed in ports. On the other hand, the arrow from resilience mechanisms to industry 4.0 technologies indicates the resilience of the industry 4.0 technologies. Cyber resilience is crucial for every port to ensure the resilience of the industry 4.0 technologies, which improve port resilience in the areas such as operation, environment, safety and security. The arrows from both the industry 4.0 technologies and port resilience mechanisms to port resilience show that both can improve port resilience systems through achieving absorptivity, restorability, and adaptability. A detailed discussion on each of the characteristics of smart ports that have been adopted by Belmoukari et al. (2023) and their impact on port resilience is provided below. Furthermore, in Section 7, the importance of cyber security is described, which is part of the port resilience measures. Cyber security measures were independently addressed considering their role in maintaining the smooth working of smart ports and keeping them safe from the potential risks.

## 4.1 Intelligent and Innovative Infrastructure, Equipment, and Technologies

This characteristic includes the use of technologies (both hardware and software) to improve the operational efficiency of ports (Molavi et al., 2020; Yau et al., 2020). Industry 4.0 technologies in ports are developed based on reliable wireless connections, sensing technology, unmanned aerial vehicles, and location equipment. All these can facilitate the improvement of optimized operations and data extracted management decision in ports (Alzate et al., 2024; Nomikos et al., 2023; Li et al., 2022). This can directly impact resilience mechanisms such as risk management, crisis management, improving infrastructure and superstructure, contingency planning, satellite facilities, and traffic diversion. Intelligent and innovative infrastructure, equipment, and technology include a wide variety of smart technologies such as barcodes, radio frequency identification tags (RFID), face recognition systems, and other types of sensors and detectors, IoT and connectivity, container management and vessel management systems, and other similar technologies and systems. These technologies and systems can automatically detect and respond to the required services and improve the utilization of infrastructure, superstructure, equipment and other resources. These smart technologies and systems can respond to a risk and crisis through automatic detection and assist the port operators to implement contingency plans. Through these technologies, ports can also communicate with stakeholders and utilize satellite facilities, which can help ports enhance their absorption, restoration, and adaptation.



Marine Research of the National Academy of Marine Research
DOI: 10.29677/MR.202512_5(2).0001

### 4.2 Operational Efficiency

This is the most discussed topic in the smart ports literature: how industry 4.0 technologies can be used to improve port productivity and output. Technological interventions such as RFID, integrated systems, big data and data analytics, vessels management, container management and port management systems (for a detailed discussion, see Yau et al., 2020) can be utilized to better monitor the performance of infrastructure and equipment as well as every system and process operating in ports. Better output and productivity could be achieved by undertaking adequate measures such as efficient and agile utilization of resources (Belmoukari et al., 2023; Molavi et al., 2020). Furthermore, smart ports could achieve the ability to respond to various emergency and adaptability-related incidents (Yen et al., 2023). Therefore, this characteristic of smart ports can impact resilience measures such as risk management, crisis management, satellite facilities, and traffic diversion, and can help ports perform better in every feature of absorption, restoration, and adaptation. Any disruption at the first place will impact the operation performance of ports, where the various industry 4.0 technologies can create differences (Alzate et al., 2024; Gu et al., 2024). Efficient and agile resource utilization helps ports become more flexible, responsive, and adaptable. This allows them to quickly respond to situations, implement risk and crisis management measures, accommodate diverted traffic, and provide satellite services.

### 4.3 Environmental Sustainability

The use of technology for environmental management in ports (Molavi et al., 2020; Yau et al., 2020) can impact significantly port resilience management. Smart technologies such as sensing and detecting, data analytics, and other monitoring systems can optimize port operations from an environmental perspective. Data driven green and lean initiatives, which integrate data analytics and sustainable practices (Ahmed et al., 2023), can impact significantly port environmental management. An improved environmental management system ensures the optimal utilization of resources, better management and preparedness for the preservation of natural resources (such as water and air quality) as well as the waste generated in ports. This can contribute directly to enhance risk management, crisis management, and a contingency planning culture. On the other hand, by implementing a better environmental management plan, ports can indirectly impact the root cause of climate change and climate vulnerabilities to ports and coasts.

### 4.4 Automation

Automation means the reduction of human involvement from every system and process by using remote control systems (Molavi et al., 2020). Decisions are taken automatically based on the analysis of huge data and information, taking into account the uncertain business environment. Automation can develop an automatic handling system, automatic scanning system, remote control system, and even a full automation of the system in ports (Yen et al., 2023). Automation in ports can impact their productivity and operational efficiency by contributing to the better utilization of resources and establishing reliability in service delivery. Furthermore, it could automatically detect disruptive issues, such as a shortage of manpower and hazardous incidents. This allows for the automatic implementation of a wide range of functions, including risk and crisis management, infrastructure and superstructure utilization, contingency planning, hazmat reporting. Through these functions, along with satellite facilities, traffic diversion, cyber resilience, information sharing (communication and coordination), updated and accurate information and forecasting, alternative resources, and innovation, automation enables ports to absorb, restore, and adapt more effectively.



Marine Research of the National Academy of Marine Research
DOI: 10.29677/MR.202512_5(2).0001

### 4.5 Safety and Security

Safety management systems are comprehensive frameworks that administer all the safety principles for a particular port. Security management systems, on the other hand, identify and analyze all the potential threats to ports and implement the required measures to handle relevant risks (Molavi et al., 2020). These systems can identify risks and implement resilience measures, such as risk and crisis management, hazmat reporting, contingency planning, and information sharing. Characteristics such as innovative and intelligent infrastructure, equipment, technology, and automation can contribute parallelly in the safety and security of ports through the proactive prevention and management measures, thus enabling ports to become resilient (Boullauazan et al., 2022). The empirical analysis by Ren et al (2024) concludes that the utilization of various communication technologies, such as 5G, Wi-Fi 6, integrated information systems among ships, people, vehicles, goods and objects in ports, can improve port security and safety.

### 4.6 Connectivity

In terms of connectivity, a smart port utilizing intelligent technology and infrastructure (Molavi et al., 2020; Yau et al., 2020) can impact port resilience mechanisms. Ports traditionally consider the horizontal and vertical integration to increase their competitiveness. Smart port technologies enable ports to provide more efficient and effective ways of establishing such competitiveness (de la Peña Zarzuelo et al., 2020). Real-time data sharing and integrated terminal management systems can enable ports to implement integrated risk and crisis management, contingency planning, hazmat reporting, satellite facilities, traffic diversion, cyber resilience, information sharing (communication and coordination), accurate information and forecasting, alternative resources sharing, and innovation. Integrated connectivity among various stakeholders can facilitate real-time data exchange and enhance resilience measures (Alzate et al., 2024; Basulo-Ribeiro & Teixeira, 2024).

### 4.7 Good Governance and Human Resource Management

Port governance and human resource management systems and mechanisms under the purview of industry 4.0 technologies take into consideration the need for learning and training programs (Belmoukari et al., 2023; Kearney et al., 2018). The operation of smart infrastructure, equipment, and technology requires a well-educated and skilled workforce who possesses a better understanding of monitoring and quick responses (Yen et al., 2023). Such capabilities in ports can impact their resilience by assisting the implementation of risk and crisis management, hazmat reporting, cyber resilience, information sharing (communication and coordination), updated and accurate information and forecasting, alternative resources, and innovation, thereby enabling ports to absorb, restore, and adapt.

### 4.8 Stakeholder Collaboration and Involvement in Port Projects

The utilization of industry 4.0 technologies in the implementation of port community systems (Belmoukari et al., 2023; Keceli, 2011) can further contribute to port resilience mechanisms, including risk and crisis management, infrastructure and superstructure improvement, contingency planning, hazmat reporting, satellite facilities, traffic diversion, information sharing (communication and coordination), updated and accurate information and forecasting, alternative resources, and innovation, thereby enabling ports to absorb, restore, and adapt. Modern port community systems, through the utilization of technologies such as IoT, RFID, blockchain, AI, big data analytics, and other digital technologies, can establish an efficient communication system and enable cooperative efforts for resilience (Baaijen, 2023).




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## 4.9 Quality Life of Population

This characteristic of smart ports complies with other characteristics such as environmental sustainability, safety and security, good governance and human resource management, and stakeholder collaboration (Belmoukari et al., 2023). Smart technologies such as IoT, AI, big data analytics, MI, and block chain, among other technologies, and automation have contributed much to the betterment of human life from the perspective of comfort and work-related health and safety. The Covid-19 period is one of the best examples for explaining the role played by digital technologies (Liu et al., 2023). Therefore, smart technologies in ports that improve the quality of life can parallelly impact resilience measures such as risk and crisis management, contingency planning, hazmat reporting, satellite facilities, traffic diversion, cyber resilience, information sharing (communication and coordination), updated and accurate information and forecasting, alternative resources, and innovation, thereby enabling ports to absorb, restore, and adapt.

## 4.10 Energy Efficiency

Smart port technologies, through operational efficiency, automation, and innovation, can contribute to energy savings and the implementation of a proper energy management system (Molavi et al., 2020). Smart energy management systems, which include technologies like motion sensing lights and automatic switch-offs, can implement fixed and variable energy consumption based on port requirements. These systems, along with crane and route planning can help ports reduce their overall energy consumption (Munim et al., 2020; Yau et al., 2020). The various technologies in smart ports for reduction of energy consumption can increase resilience capabilities such as adaptability and restoration. Ports can be better equipped in implementing resilience measures such as risk and crisis management, contingency planning, hazmat reporting, satellite facilities, alternative resources, and innovation.

## 4.11 Communication and Data Exchange Between Ports

Integrated systems between ports and other stakeholders can implement optimized monitoring systems (Molavi et al., 2020) and impact port resilience mechanisms such as risk and crisis management, contingency planning, hazmat reporting, satellite facilities, traffic diversion, cyber resilience, information sharing (communication and coordination), updated and accurate information and forecasting, alternative resources, and innovation, thereby enabling ports to absorb, restore, and adapt. Networking and intelligent communication systems can establish uninterrupted connection among different stakeholders, facilitate the access to various data centers, and enable data analytics and automatic notifications for all stakeholders, facilitating the undertaking of resilience measures.

The above discussion shows that implementing industry 4.0 technologies helps ports become more resilient by enabling them to execute and expedite resilience measures. However, cyber security and cyber resilience will become the most significant areas of concern. Therefore, a specific discussion on cyber security and cyber resilience in ports is included in the next section.

### 4.12 Industry 4.0 Technologies, Cyber Security, and Cyber Resilience of Ports

As the objective of this paper is to conceptualize the impact of industry 4.0 technologies on port resilience, it focuses parallelly in the potential risks or disruptions to the resilience of smart ports. The potential risk of disruption is the cyber security as it is considered as one of the three top risks in ports along with piracy and terrorism by Deep Trekker, an underwater robotics manufacturer (de la Peña Zarzuelo, 2021). The increasing use of industry 4.0 technologies and the dependency of global supply chains on ports have growingly made ports a target of cybercrimes (Ben Farah et al., 2022). Not much research in port cyber security was found in the literature, as it is considered one of the least studied areas in the field of smart ports (Heikkilä et al., 2022). The studies by Ben Farah et al. (2022) and Polikarovskykh et al. (2023) list that the possible cyberattacks in ports will include spear-phishing created by links containing emails, distributed denial of service targeting the communication between different elements, port scanning to access the database, supply chain end-to-end network, social engineering based on human curiosity, and damages to information systems by malware/ransomware/trojans. According to Polikarovskykh et al. (2023), the vulnerability of ports to cyberattacks is higher than that of shipping, and the most frequent attacks include ransomware, phishing, malware, Petya ransomware, GPS spoofing, and navigation systems attacks. Highlighting the similar nature of cyberattacks, Simola et al. (2023) indicated that potential risk areas include ship systems, port systems, port logistics systems, control center systems, VTS systems, weather forecast systems, stakeholders' systems, and power supply systems. This list of potential areas for cyberattack explains that the consequences could be devastating for the total trade and transports. United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP, 2021) and Heikkilä et al. (2022), referencing the European Union Agency for Cyber Security (ENISA), highlighted some of the probable impacts of cyber security challenges on smart ports. These include operation shutdowns, port paralysis, sensitive and critical data theft, cargo theft, system damages or destruction, loss of competitiveness, and environmental disasters. The same study also covers some security measures, including enhancing cyber security governance within all business units, raising awareness and training, suggestions on cyber security implementation and related technical requirements, applying security in applications design, and enforcing detection and response capabilities. The UNCTAD (2022) identifies cyber resilience as a key measure for port resilience. Their report suggests that the integrity of information systems must be supported by implementing access control, data security, network security, and operational security. The importance of human factors in response to cyber security is highly regarded by de la Peña Zarzuelo (2021). Considering the importance of cyber security, some ports in the world are introducing designated roles for cyber security issues. For example, the Port Cyber Resilience Office has been introduced in the Port of Rotterdam (de la Peña Zarzuelo, 2021; Heikkilä et al., 2022). Therefore, the role of smart ports for port resilience needs to be secured by a cyber resilience system indicating that both areas can contribute mutually for the better implementation of smart ports, port resilience, and cyber resilience. As a result, Figure 5 shows the mutual impact of smart ports and port resilience measures on each other, indicated by arrows starting from each and ending at each, as explained in the beginning of Section 4.



Marine Research of the National Academy of Marine Research
DOI: 10.29677/MR.202512_5(2).0001

## 5 CONCLUSIONS

This paper conceptualizes the possible implications of industry 4.0 technologies on port resilience. To do so, first it discusses port resilience and ports' related capabilities in different areas. Later it tries to focus on port disruption factors and resilience mechanisms to mitigate these disruption factors. Finally, it highlights the industry 4.0 technologies in ports and the characteristics of smart ports, and discusses how these characteristics can impact port resilience mechanisms and increase the capability of ports to be resilient in different areas. Furthermore, it addresses the importance of cyber security in the context of smart ports' resilience, indicating a mutual role of both smart ports in port resilience and cyber resilience.

The imperative issue to highlight is that there is not much literature indicating the impact or utilization of industry 4.0 technologies on port resilience from a holistic point of view. This paper indicates that industry 4.0 technologies play a significant role in implementing port resilience management, but they must also address cyber security with greater importance.

The contribution of this paper is first to provide a holistic view of the various domains that encompass port resilience, port disruptions, port resilience mechanisms or measures, and smart ports technologies, and explains how smart port technologies or the characteristics of smart ports can impact the improvement of port resilience. The paper discusses how each characteristic of smart ports can contribute to port resilience. It attempts to match the functions of smart port characteristics with various resilience measures to mitigate disruptions.

This paper provides a reference for academia and the industry to acknowledge the possible contributions of smart technologies in ports resilience. However, it is important to examine whether the ports with smart technologies have improved resilience mechanisms. Therefore, the future research can empirically analyze the impact of industry 4.0 technologies on port resilience. This can be done by examining the industry 4.0 technologies in practice in ports, the various mechanisms and tools under port resilience plans, and the possible positive influence of industry 4.0 technologies on the implementation of existing plans for improving port resilience and mitigating disruptions. Both qualitative and quantitative analysis can be conducted to understand the most important industry 4.0 technologies and resilience mechanisms. Data can be collected using interviews and survey methods to extract both the qualitative and quantitative nature of data. Quantitative data can be collected through surveys using the Likert scale and analytical methods such as multi-criteria decision analysis can be used to draw a precise conclusion. As for the empirical analysis, future research could address the limitations of this paper at the same time. An empirical examination in the future could add further insights on the findings of this paper. Another important research direction could be conducting a bibliometric analysis of the literature to understand its evolution in this area.



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