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REVIEW OF PORT INFRASTRUCTURE RESILIENCE WITH MATHEMATICAL MODELLING AND A BIBLIOMETRIC APPROACH

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ABSTRACT: This study reviews the resilience of port infrastructure using a mathematical modeling approach and bibliometric analysis. With the increasing threats of climate change and natural disasters, enhancing port infrastructure resilience is crucial for maintaining operational continuity. The bibliometric analysis, focusing on the keyword "Port Infrastructure Resilience," identifies trending and novel keywords for future research, including climate change, risk analysis, resilience, and port facilities. Data from the Scopus database (2014-2024) were analyzed using VOSviewer to map key research trends. Findings indicate that improving port infrastructure resilience to climate change and disasters requires a multidimensional approach, such as structural optimization, drainage improvements, and risk mitigation strategies. Current research trends emphasize sustainability and disaster impact reduction through advanced technology. Investing in monitoring technology and cross-sector strategic planning is essential to enhance port resilience. This study highlights the importance of technological innovation and stakeholder collaboration, recommending further exploration of digital technology adoption for optimizing port resilience. Relevant case studies for mathematical modeling, which can serve as references in future analyses, include multidimensional modeling for coastal flood simulations, optimization models for climate change strategies in ports, seismic design optimization based on building resilience, evaluation of solutions for multi-objective problems, and improved water network distribution optimization methods. These case studies illustrate the diverse and comprehensive approaches necessary to address the complex challenges faced by ports in the context of a changing climate.

Keywords: Climate, Drainage, Resilience, Risk, Seismic

1. INTRODUCTION

The increasing relevance of ports in supporting international trade and global economic growth underscores their integral role within the broader maritime supply chain network [1]. As globalization accelerates and the reliance on maritime logistics expands, ports become not only essential nodes of commerce but also potential points of vulnerability. The susceptibility of port infrastructure to climate change impacts, such as rising sea levels and intensifying storm events, poses significant challenges [2]. This vulnerability can lead to substantial physical damage, operational disruptions, and extensive economic repercussions, adversely affecting supply chain efficiency and long-term sustainability [3]. Climate change has emerged as a pivotal concern in port operations due to its direct impact on infrastructure resilience. The resilience of a port is defined as its capability to withstand, adapt to, and recover from external stresses and disturbances [4]. Ports with insufficient resilience face amplified risks of operational failure, leading to costly interruptions and potential cascading effects throughout global trade networks [5]. The need for adaptive strategies in design, construction, and risk mitigation is critical to safeguarding these maritime hubs [6].

A substantial body of research emphasizes the necessity for ports to incorporate innovative resilience measures that address current and projected climatic risks [7]. This includes optimizing port infrastructure through the reinforcement of building materials, applying advanced structural engineering techniques, and implementing robust drainage systems, especially in flood-prone regions [8]. Effective drainage and hydrosedimentological management not only mitigate flood risks but also support long-term operational efficiency [9]. Strategic investment in port infrastructure resilience must be informed by comprehensive risk assessment tools and methodologies. Recent advancements in resilience assessment frameworks and risk management strategies provide critical insights into enhancing the adaptive capacity of ports [4]. Studies conducted on the operational resilience of various ports underscore the effectiveness of tailored resilience planning [10]. For instance, integrated modeling approaches can provide stakeholders with data-driven insights for improved decision-making [9].

Several challenges remain in advancing the resilience of port infrastructure. One of the primary obstacles is the economic burden associated with retrofitting existing structures to meet resilience standards [11]. Investments in infrastructure are often constrained by limited financial resources, necessitating a balance between cost-effectiveness and resilience efficacy [11]. Additionally, the development and implementation of resilience-enhancing technologies, such as digital monitoring and early warning systems, are critical for preemptive action against climate-related disruptions [12]. Research has highlighted the potential benefits of employing green infrastructure within port ecosystems. Green zones, for instance, can serve as natural buffers that absorb floodwaters and mitigate the impacts of storm surges [13]. Such sustainable practices align with global efforts to enhance port sustainability and operational resilience. However, the adoption of environmentally friendly solutions must be evaluated within the context of their feasibility and compatibility with existing infrastructure [14].

Bibliometric analyses and systematic literature reviews are valuable tools in synthesizing the breadth of research on port resilience. Through bibliometric mapping, key trends, influential studies, and knowledge gaps can be identified [15]. The use of tools like VOSviewer allows researchers to visualize networks of scholarly work and detect patterns that inform future research directions [7]. By analyzing data from reputable sources such as Scopus, insights into the evolution of port resilience research can be gleaned, highlighting emerging themes and innovative approaches [16]. A recurring theme in the literature is the importance of collaborative approaches involving stakeholders across public and private sectors [17]. Effective governance models that support integrated flood management and resilience planning contribute significantly to the long-term sustainability of ports [18]. For instance, the Port of Rotterdam has exemplified this approach by employing comprehensive flood resilience strategies that extend beyond traditional dike systems [18]. Such cases provide valuable lessons for ports worldwide that seek to strengthen their infrastructure in response to climate variability.

The development of strategic frameworks that incorporate resilience assessment tools is also critical for operational readiness and post-event recovery. The study by [4] emphasizes the utility of resilience tools that integrate urban analytics with port planning. By assessing vulnerabilities through a combination of environmental and infrastructural data, ports can anticipate and mitigate potential disruptions more effectively [19]. The implementation of such frameworks in Korean ports, for instance, illustrates their potential to enhance resilience through data-informed decision-making [19]. Ports situated in regions susceptible to extreme weather, such as those in coastal and delta areas, require specialized resilience measures. Studies on ports like Aveiro in Portugal underscore the complex interplay between environmental conditions and port operations [8]. Strategies tailored to local climatic and geographic factors are essential to reduce exposure and adapt to changing conditions. Comprehensive hydrosedimentological modeling, as explored [9], provides actionable insights that inform the design and operational protocols of ports.

Despite advancements in resilience research, gaps remain, particularly in the integration of innovative digital tools and automated systems for real-time monitoring [10]. Emerging technologies, such as remote sensing and digital twin models, offer new opportunities for enhancing the responsiveness of port infrastructure [12]. The application of these technologies requires a strategic alignment with port-specific operational frameworks and existing infrastructure capabilities [20]. In conclusion, port resilience in the face of climate change is a multi-faceted challenge that requires coordinated efforts across engineering, policy-making, and technological innovation. The literature underscores the need for adaptive design approaches that incorporate both structural and non-structural measures, including optimized material usage, advanced drainage systems, and comprehensive risk mitigation strategies [2, 21]. Furthermore, future research should prioritize cross-disciplinary collaborations and integrate technological advancements to enhance the predictive capabilities and overall resilience of port infrastructure [22]. Addressing the economic and logistical challenges associated with these advancements will be crucial to ensuring sustainable and efficient port operations in an era defined by climatic uncertainty.

Measuring the resilience of port infrastructure involves evaluating various indicators that reflect the port's ability to survive, adapt, and recover from disruptions. Key indicators include the Port Resilience Index, which assesses infrastructure condition, operational continuity, emergency preparedness, and recovery planning. The Marine Transportation System Resilience Assessment Guide emphasizes stakeholder engagement, system vulnerability analysis, and risk mitigation practices [23]. Additionally, the Resilience Assessment Resource Matrix provides a web-based library of tools, methods, and data sources for conducting resilience assessments. These indicators collectively address the dimensions of survivability, adaptability, and recoverability, ensuring that ports can effectively manage and recover from various challenges. By using these structured approaches, port authorities can enhance their infrastructure's resilience and maintain operational stability in the face of disruptions [24].

Emerging threats such as cybersecurity and technological disruptions pose significant challenges to the resilience of port infrastructure. As ports increasingly rely on digital systems for operations, these threats become more pronounced. Cybersecurity threats can disrupt port operations by compromising critical systems, leading to significant economic and operational impacts [25]. Technological disruptions, such as the rapid advancement of digital technologies, can also introduce new vulnerabilities and require significant adjustments in existing processes. Given the increasing digitalization of port operations, digital optimization is highly relevant. Leveraging advanced technologies like AI, IoT, and blockchain can enhance operational efficiency and resilience, enabling ports to quickly adapt and recover from disruptions. Addressing these emerging threats is essential for maintaining port resilience and ensuring the continuity of operations [26]

Several review papers have been written by researchers on port resilience. In 2020, [27] reviewed the impact of port disruptions on the maritime supply chain. In 2021, [28] published a review focusing on critical infrastructure resilience. In 2022, [29] provided a comprehensive review of infrastructure system resilience. In 2023, [30] examined the processes involved in maritime transportation resilience. Most recently, in 2024, [31] conducted a systematic review on the future of maritime transportation resilience. Several bibliometric review studies have examined different aspects of maritime transport. For example, [32] in 2023 reviewed the resilience of maritime transport and its impact on trade. In 2023, [33] explored research directions related to the maritime transport supply chain. In 2024, [34] analyzed the global vulnerability of port infrastructure to climate change. Additionally, In 2024, [35] conducted a review on the resilience of maritime transport in relation to trade. Although there has been a significant number of review papers related to bibliometric and port infrastructure resilience, the combination of bibliometric and mathematical modeling approaches remains rare.

The main purpose of this review research is ~~first~~ to explore and examine the port infrastructure resilience system related to safety and potential hazards to port infrastructure resilience for both the community and policymakers and all those involved in this issue. Thus, this review is very important to do because it concerns the safety of many people or many parties. The first important thing is the factors that influence port infrastructure resilience, including structural optimization, drainage system improvements to reduce flood risk, and risk mitigation strategies to strengthen resilience to natural disasters. Second, bibliometric analysis to help researchers, lecturers, and readers in seeing the latest research trends related to current research gaps and finding ideas and concepts in developing this port infrastructure resilience. Third, reviewing mathematical modelling is the most important aspect of this review because it is still rarely done. This mathematical modelling is very helpful in calculating parameters or variables related to the performance of the port resilience system, especially the current case. The help of this mathematical model can help researchers see parameters or variables that are relevant to their future research and can design better. Therefore, the combination of mathematical and bibliometric models is very valuable for researchers in planning, designing, and constructing a safe and sustainable port infrastructure resilience system.

To guide the structure of this article, the subsequent sections are organised as follows: Section 2 outlines the methodological framework, including the literature selection protocol and the analytical model used to evaluate infrastructure resilience. Section 3 presents the results of the bibliometric synthesis and the initial validation of the proposed model. Section 4 discusses the implications of the findings in relation to regional policy, technical feasibility, and adaptive strategies for port infrastructure. Finally, Section 5 concludes the study by summarising key insights and proposing directions for future research and regional calibration.

2. RESEARCH SIGNIFICANCE

The significance of the research is combination of bibliometric and mathematical modeling approaches, which are still rarely applied in port infrastructure resilience studies. It is crucial for identifying factors affecting port resilience against natural disasters, such as structural optimization and drainage system improvements. Bibliometric analysis reveals current research trends and gaps, while mathematical modeling enables quantitative evaluation of port resilience system performance. The integration of both approaches offers strategic value for researchers and policymakers in planning, designing, and constructing safe and sustainable port infrastructure resilience systems.

3. BIBLIOMETRIC ANALYSIS

The materials for this study consist of data extracted from the Scopus database, covering publications from 2014 to 2024. Boolean Search Logic is ("port infrastructure" OR "seaport infrastructure" OR "harbor infrastructure") AND (resilien* OR "climate resilience" OR "disaster resilience" OR "infrastructure resilience" OR "resilient design") AND ("climate change" OR "natural disaster" OR "extreme weather" OR "sea level rise" OR "disruption" OR "risk management") with associated factors such as climate change, disaster risk, and infrastructure adaptation. The review focused on identifying key strategies, technological innovations, and policy frameworks that enhance the resilience of seaport infrastructure.

The inclusion criteria for this systematic review were established to ensure relevance and quality of the selected studies. Articles were included if they primarily focused on the resilience of port infrastructure in the context of disasters, climate change, or operational disruptions. Eligible studies comprised empirical research, case studies, policy reviews, or risk evaluation models that directly relate to port systems. Only documents published in peer-reviewed journals, reputable conference proceedings, or technical reports were considered. To ensure language accessibility and scholarly rigor, only articles written in English or Indonesian were included. The review also applied a publication time frame from 2014 to 2024, capturing the most recent developments in the field.

Conversely, the exclusion criteria were applied to eliminate studies with limited relevance. Articles were excluded if they did not specifically address port infrastructure, or if they focused solely on general logistics resilience without port-specific elements. Studies that emphasized non-infrastructure aspects, such as human resources or financial management in ports, were also excluded. In addition, papers that discussed commercial operations without linking them to resilience or disruption scenarios were omitted. Editorials, opinion pieces, non-academic summaries, or articles not peer-reviewed were disregarded, as were those without full-text access for comprehensive evaluation.

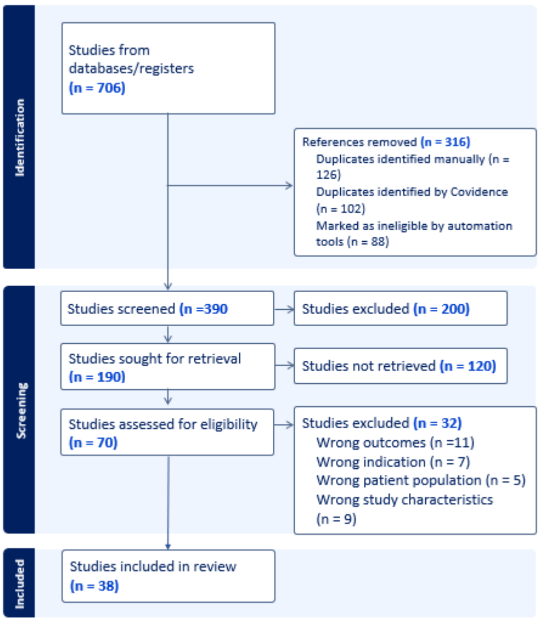

Fig. 1. PRISMA Diagram

The PRISMA flow diagram is shown in Fig. 1. visually documents the systematic process of literature identification, screening, and inclusion, resulting in a curated dataset of 38 studies relevant to the research scope. Following data collection, duplicates and irrelevant publications were removed during the data cleaning process, resulting in a final dataset that was analyzed using VOSviewer to visualize research clusters and major themes. The network analysis encompassed a co-occurrence network to analyze keyword frequency and topic connections, a co-authorship network to map international collaboration between countries and institutions, and a citation network to highlight influential papers in the field. Quantitative analysis measured publication growth, citation impact, and collaborative trends over the decade.

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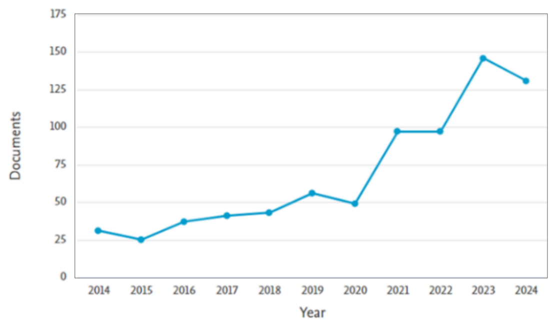

Fig. 2. Documents by year

The number of documents produced annually from 2014 to 2024 is shown in Fig. 2. At the beginning of the period, the number of documents gradually increases, reflecting a steady rise in production and publication. In 2020, the number of documents produced is approximately 50. This number increases to around 75 in 2021 and continues to grow to about 100 in 2022. The number of documents peaks in 2023 with around 150 documents. In 2024, the number slightly decreases to approximately 125 documents, though it still shows an overall increase from the previous years. The graph highlights two significant periods of increased research activity in 2021 and 2023, with the highest number of documents produced in 2023, marking the peak of scientific output in this decade.

The number of documents per years by sources with the keyword "Port Infrastructure Resilience" reveals a growing academic interest over the past decade, with a notable concentration of publications in five key journals. Sustainability Switzerland leads with 24 documents, reflecting its broad focus on sustainable development and infrastructure resilience is shown in Fig. 3. It is followed by Maritime Policy and Management (18 documents) and Maritime Economics and Logistics (15 documents), both of which emphasize policy and economic aspects of maritime infrastructure. The Journal of Marine Science and Engineering (14 documents) and Transportation Research Part A: Policy and Practice (12 documents) also contribute significantly, highlighting the interdisciplinary nature of the topic. From 2014 to 2024, the number of publications has generally increased across these sources, indicating a rising awareness and scholarly engagement with the resilience of port infrastructure in the face of global challenges such as climate change, supply chain disruptions, and geopolitical tensions.

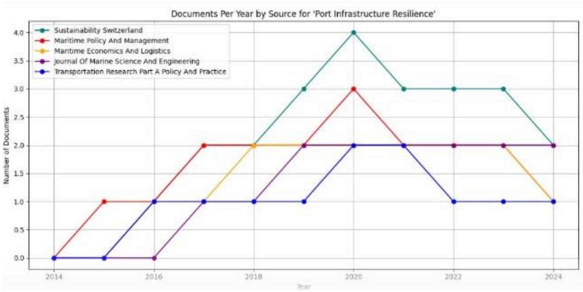

Fig. 3. Documents per years by sources

The network visualization of keywords associated with "Port Infrastructure Resilience" illustrates a rich

and interconnected thematic landscape is illustrated in Fig. 5 . At the core of the network is the term "port infrastructure", which branches out to closely related concepts such as port development, sustainable development, decision making, environmental impact, port logistics, and port facilities. These connections highlight the multifaceted nature of port infrastructure, encompassing operational, environmental, and emphasizing policy and economic implications; the climate change cluster connects to sustainability and disasters, reflecting environmental challenges; and the strategic dimensions. Surrounding clusters further enrich the analysis: the maritime transportation cluster links to transportation policy and economic growth, risk assessment cluster ties into risk management and risk analysis, underscoring the importance of resilience planning. This visualization underscores the interdisciplinary scope of research in port infrastructure resilience, bridging engineering, policy, environmental science, and risk management.

The latest keywords and research trends in 2021 and beyond are climate change is shown in Fig. 4. The urgency for adaptation strategies is underscored by the projected increase in extreme weather events, including rising sea levels and more frequent storms, which pose substantial risks to port operability and infrastructure integrity [9, 37]. Adaptation measures for ports must encompass a multifaceted approach that includes enhancing physical infrastructure, improving hydrological forecasting, and integrating climate resilience into planning processes. Emphasizes the necessity of integrated modeling of hydrosedimentological processes to bolster port resilience and facilitate informed decision-making in the face of climate change [9]. Similarly, [38] highlights that while port managers recognize the importance of climate change, many have resorted to fragmented adaptation strategies, underscoring the need for cohesive management practices that prioritize infrastructure improvements. This sentiment is echoed who advocate for a systematic evaluation of operational vulnerabilities in port docks under climate scenarios, emphasizing the importance of identifying potential impacts and metocean agents [39].

The economic implications of climate adaptation in ports are profound. Hanson and Nicholls project that

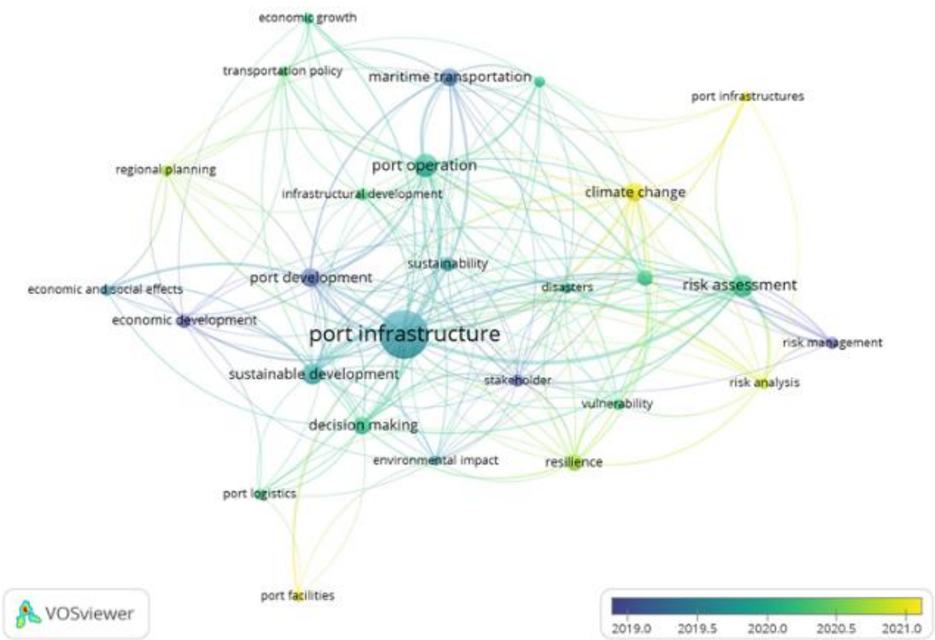

Fig. 4. Overlay map with the main keyword theme "Port Infrastructure Resilience"

the demand for port services will significantly increase by 2050, necessitating substantial investments not only for expansion but also for adaptation to sea-level rise [40]. [41] argue that the economic importance of ports, coupled with their vulnerability, requires targeted adaptation strategies that consider both immediate and long-term climate impacts. Additionally, [13] discusses the benefits of incorporating green zones within city-port systems, which can mitigate climate impacts and improve overall port metabolism. Advocate for sustainability performance assessments in port infrastructure to ensure compliance with global sustainability goals [42]. However, barriers persist in identifying the challenges decision-makers face when implementing proactive adaptation measures. This often results in a reliance on reactive strategies that do not fully address the complexities of climate change [43]. This underscores the need for a paradigm shift toward comprehensive, integrated strategies encompassing all aspects of port management and operation.

The second keyword that is the latest research trend and opportunity for future research is risk analysis as shown in Fig. 4. Seismic risk assessment is a critical aspect of port infrastructure analysis, particularly in earthquake-prone regions. In 2022, [44] emphasize that seismic events impact ports beyond immediate repair costs, significantly affecting operational continuity and shipping activities. This claim is supported by [45] who apply stress test concepts to evaluate port infrastructure resilience against natural hazards, highlighting the necessity for robust assessment methodologies to mitigate risks. The interconnected nature of various infrastructural components, such as cargo handling and utility systems, further complicates the risk landscape, underscoring the need for a comprehensive evaluation approach [44].

In addition to natural hazards, cybersecurity has become a paramount concern for port infrastructures. The growing reliance on digital technologies in maritime operations exposes ports to diverse cyber threats. The Cyber-MAR project exemplifies the significance of hybrid cyber ranges for assessing cybersecurity risks in port operations, offering a framework for simulating potential incidents and enhancing preparedness [46]. [47] highlight vulnerabilities in cyber-physical systems within maritime environments and advocate for comprehensive security risk assessment tools to address these challenges. Integrating cybersecurity into overall risk management strategies is essential, as emphasized [48]. whose systematic survey identifies key vulnerabilities in maritime infrastructure [49]. Additionally, operational safety remains a focal point, noting the rarity of significant accidents complicates the development of effective risk assessment methods

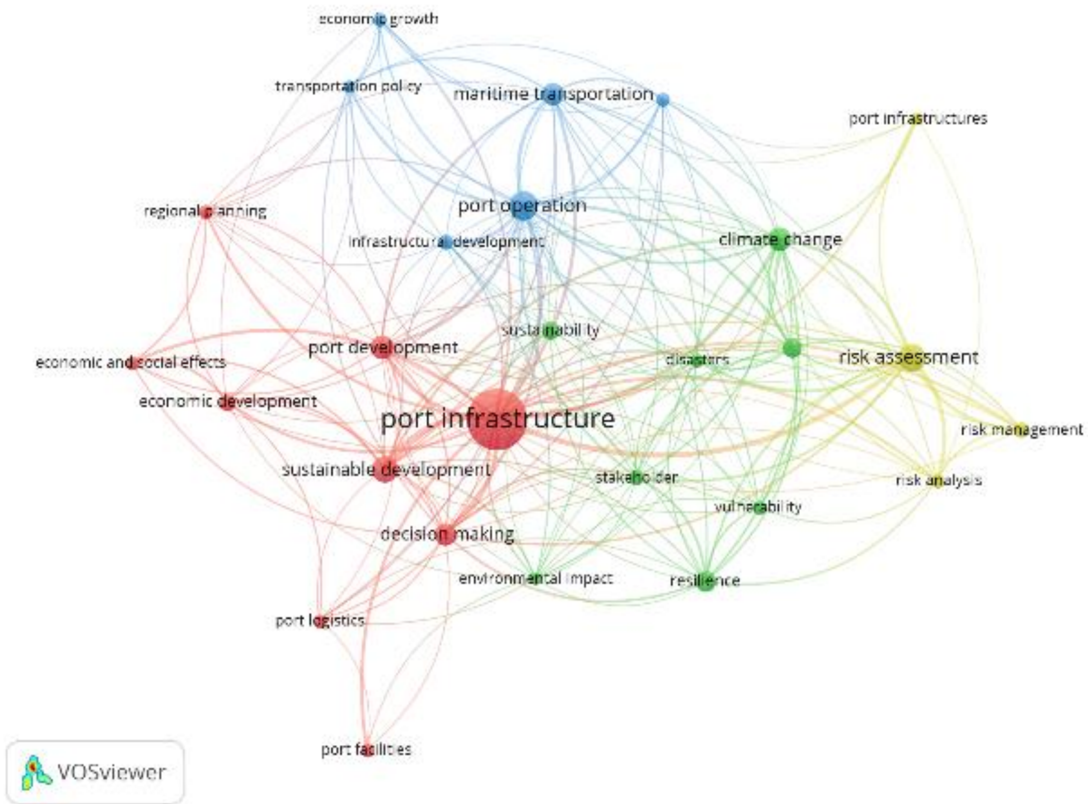

Fig. 5. The network visualization of keywords "Port Infrastructure Resilience"

[50]. Their analysis calls for thorough hazard evaluation, including ship maneuver-related risks, to inform port planning and regulation. The necessity of aligning protective measures with international security standards is further reinforced [51], enhancing the safety and resilience of port operations. The COVID-19 pandemic has also highlighted the importance of adaptive safety assessments [52]. [53] discuss, revealing the need for resilience strategies to ensure continuous port functionality during unprecedented challenges.

The third keyword that emerged for future research is related to resilience as in Fig. 3. Ports are vital nodes in global supply chains, and their capacity to withstand and recover from disturbances is crucial for economic stability and facilitating trade. Recent studies emphasize the need for comprehensive resilience strategies that integrate engineering, management practices, and stakeholder collaboration. Research indicates that many port managers recognize the importance of addressing climate change but often resort to fragmented adaptation strategies, underscoring the need for a more cohesive approach that enhances physical infrastructure and management practices [38]. The proposed development of a Port Resilience Index is one example of systematic efforts to evaluate and strengthen port resilience against climate-related threats [24]. Such frameworks can guide policymakers in making informed decisions that bolster port infrastructure against a range of risks, including natural disasters and operational disruptions.

Innovative methodologies, such as fuzzy Bayesian networks, have advanced the assessment of port resilience, offering nuanced insights into how ports can respond to storm disturbances [54]. These approaches complement traditional engineering assessments, which focus on stress testing critical infrastructure against extreme events like tsunamis and earthquakes [15]. The role of technology in improving resilience is also paramount, with non-destructive testing (NDT) methods enhancing the ability for timely maintenance and repairs [55]. Additionally, unmanned aerial vehicles (UAVs) used for structural health monitoring provide a modern tool for vulnerability assessment and maintenance optimization [56]. The interconnectedness of global supply chains further complicates the resilience landscape, as disruptions in one port can cascade through the entire system, emphasizing the importance of collaborative planning among stakeholders [2].

The fourth trending keyword is related to port facilities as shown in Fig. 4. The evolution of port facilities is vital for improving operational efficiency, supporting larger vessels, and ensuring competitiveness in the global supply chain. One of the primary factors influencing port infrastructure is the need for adequate facilities to accommodate modern shipping demands. In 2024, [57] emphasizes that successful port development relies on having sufficient infrastructure, including deep wharves and modern loading and unloading facilities, which are essential for handling large vessels and improving operational efficiency. Similarly, [58] highlight that port transport conditions and infrastructure are critical indicators of a port's production and operational capacity, directly affecting its logistics competitiveness. This underscores the necessity of investing in robust infrastructure to bolster port capabilities and maintain a competitive edge.

The integration of digital technologies and the smart port concept has become increasingly important for modern ports. In 2023, [59] discusses how digitalization supports supply chain activities, streamlining processes within port operations for greater efficiency. The shift toward smart ports is not just a trend but a necessity to remain competitive in a rapidly evolving logistics landscape. Further note that coordinating logistics services and infrastructure is crucial for enhancing integration between maritime and inland logistics, which is vital for overall port competitiveness [60]. Additionally, the resilience of port logistics systems has come into focus due to vulnerabilities exposed by natural disasters and global disruptions like the COVID-19 pandemic. [61] emphasizes the importance of strengthening disaster detection and management to minimize logistics system vulnerabilities. The pandemic underscored the value of operational flexibility and the capacity to adapt to unforeseen challenges [52]. [62]. Moreover, the sustainability of port operations is increasingly recognized as essential for reducing resource loss and carbon emissions, aligning with the push for environmental responsibility in port planning [63]. Port authorities play a crucial role in facilitating logistics integration and enhancing service delivery [64] noting that infrastructure and connectivity significantly impact port performance, underscoring the need for strategic investments and planning.

The network visualization with country collaboration network is illustrated in Fig. 7. The country collaboration network for the keyword "Port Infrastructure Resilience" reveals a dynamic and interconnected global research landscape. China and the United States emerge as central players, exhibiting strong bilateral collaboration and multiple links to other nations such as the Netherlands, Italy, and South Korea. Within Europe, Italy, Spain, Germany, France, and the United Kingdom form a dense cluster of cooperation, indicating robust regional partnerships in port infrastructure research. Notably, Germany and France serve as key bridges, connecting various European countries and facilitating broader collaboration. South Korea and Greece also participate in the network, though with fewer connections, suggesting emerging or specialized contributions. The varying thickness of the connecting lines reflects the intensity of collaborative efforts, with thicker lines denoting more frequent or impactful joint research.

This visualization underscores the international nature of research on port infrastructure resilience, driven by shared challenges and the need for coordinated solutions across borders.

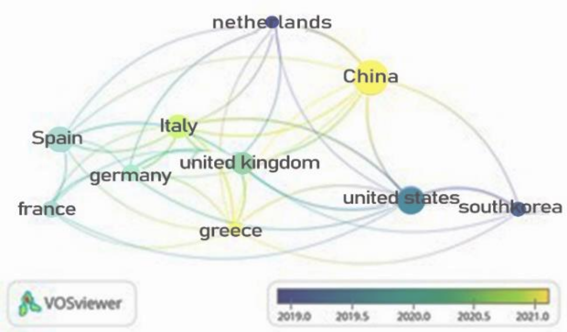

Fig. 6. Visualization of Research Collaboration Network Map

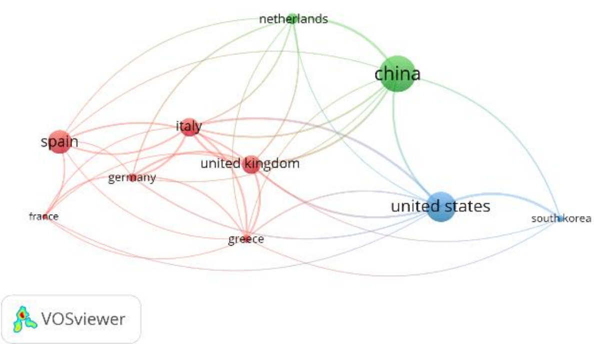

Fig. 7. Network visualization with country collaboration network

A map of the international research collaboration network generated by VOSviewer, depicting the relationships between countries in the period 2019 to 2021, represented by different colors is illustrated in Fig. 6. The main countries in this collaboration include China, the United States, Italy, Spain, the United Kingdom, and Germany, where the size of the circles indicates the level of contribution, with China and the United States being the main contributors. The connecting lines indicate the collaborative relationships, and their thickness indicates the strength of the collaboration. This map provides a clear visualization of global collaboration in scientific research, helping to understand the dynamics and identify the most active countries and the development of their relationships over time. The chosen period of 2019 to 2021 is particularly significant as it captures recent trends and developments in research collaborations, allowing for a focused and contemporary analysis of the most active and influential contributors in this field.

Bar graph comparing the number of documents and citations from different countries, namely Morocco, Indonesia, Japan, Brazil, Poland, Australia, Singapore, Germany, Italy, the United Kingdom, and the United States is demonstrated in Fig. 8.

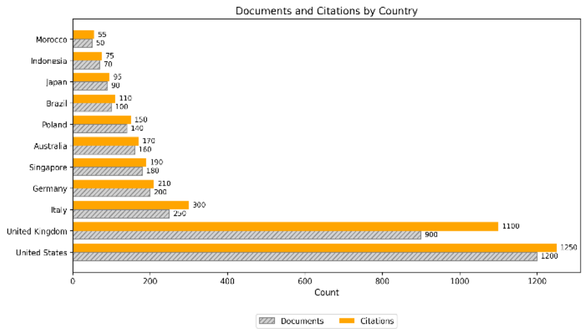

Fig. 8. Comparison of Number of Documents and Citations

The horizontal axis shows the number of documents and citations, while the vertical axis shows the country name. Each country has two bars: blue for the number of documents and orange for the number of citations. The graph shows that the United States has the highest number of documents and citations, with more than 1200 citations and around 200 documents, followed by the United Kingdom, Italy, Germany, and Singapore. In contrast, Morocco and Indonesia have lower numbers of documents and citations. This graph provides an overview of the scientific contributions of different countries in the form of documents and citations, reflecting the level of research activity and scientific influence of each country.

4. THE PORT INFRASTRUCTURE RESILIENCE

The integration of structural optimization, enhanced drainage systems, and comprehensive risk mitigation strategies is crucial for bolstering the resilience of port infrastructure amidst climate change and frequent natural disasters. As depicted in Fig. 9, these interconnected elements collectively enhance port sustainability and operational stability. Structural optimization, as outlined [65] in 2024 focuses on innovative design approaches and the use of durable materials that minimize damage during extreme weather events. These strategies not only mitigate the immediate impacts of environmental stresses but also contribute to long-term cost savings by reducing repair expenses and minimizing operational disruptions. The importance of improved drainage systems is highlighted in the context of mitigating flooding impacts. [66] assert that the configuration and efficiency of sewer networks significantly affect the frequency and severity of combined sewer overflows (CSOs). In the context of ports, robust drainage infrastructure can swiftly channel excess water during heavy rainfall or elevated sea levels, thereby protecting critical assets and ensuring continuous port operations.

This aspect is vital as ports are often located in vulnerable coastal areas where rapid response to changing water levels is necessary. Effective implementation of these technical measures requires coordinated policy support and integration with ecohydraulic practices to address environmental and infrastructural challenges holistically. to ensure long-term flood mitigation, the government should adopt a comprehensive strategy that integrates structural solutions with ecohydraulic approaches [67]. Integrating advanced technologies such as deep learning-based predictive models can further enhance these strategies by providing accurate and timely flood forecasts to support decision-making. The application of deep learning models particularly Gated Recurrent Units (GRU), Long Short Term Memory (LSTM) networks, and Convolutional Neural Networks (CNNs) has demonstrated significant potential in improving the accuracy of flood prediction [68]. Accurate assessment of coastal vulnerability through analysis of geomorphological and hydrodynamic parameters is essential to tailor these mitigation strategies effectively. Key factors shaping coastal vulnerability include geomorphology, rate of shoreline change, coastal elevation, and wave height. Sea level fluctuations and tidal range are considered equally critical along the coastline. Refining parameter significance can be achieved through weighted analytical approaches [69].

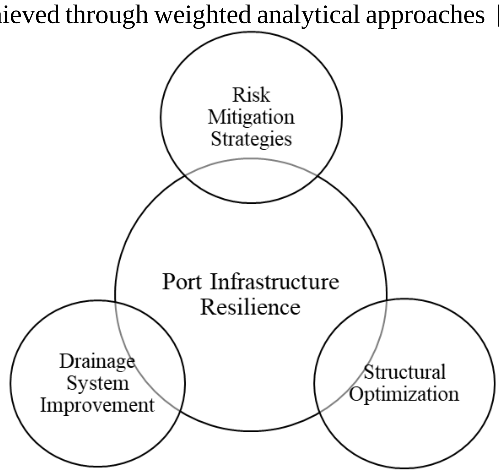

Fig. 9. The Port Infrastructure Resilience Intersection

Risk mitigation strategies encompass a range of proactive measures, including early warning systems, comprehensive emergency response plans, and sustainable design principles. [38] emphasizes that tailored disaster preparedness measures can enhance the adaptive capacity of ports, facilitating quicker recovery post-disaster. The deployment of advanced technologies such as AI and IoT, as discussed [70]. [71] enables real-time monitoring and enhances decision-making processes, ensuring that responses are timely and effective. The synergy between structural optimization, drainage enhancement, and risk mitigation creates a multi-layered defense system that reinforces port resilience. This integrated approach supports continuous operations, limits economic losses, and safeguards against potential disruptions caused by natural disasters. Further illustrate that scenario analysis and comprehensive risk management protocols are pivotal in preparing for and mitigating risks associated with port logistics [72]. Moving forward, research on the integration of emerging technologies and international collaboration, as suggested [73] can further augment the resilience of global port infrastructure, ensuring their sustainability and robustness in an era of increased climatic uncertainties.

4.1 The Structural Optimization of Port Infrastructure

The structural optimization of port infrastructure plays a pivotal role in ensuring resilience and sustainability in response to multifaceted environmental and operational challenges. Ports, being critical nodes in global trade and logistics, are frequently exposed to harsh conditions such as large sea waves, strong winds, and seismic activities [74]. Consequently, robust and cost-effective design strategies are paramount for enhancing port durability while optimizing resource allocation. Structural optimization not only reduces material usage but also improves the precision of load distribution across structural elements [64]. This approach ensures that critical components receive adequate reinforcement, such as corrosion-resistant materials at points of continuous water contact, thereby extending the infrastructure's lifespan and minimizing long-term maintenance costs [75].

Adopting advanced structural health monitoring (SHM) techniques has been shown to be effective in tracking the condition of port facilities, facilitating timely interventions before significant degradation occurs [55, 56]. The use of SHM combined with optimization methods can particularly enhance the detection and mitigation of vulnerabilities, such as those posed by seismic threats or flooding in high-risk areas [76]. Additionally, integrating resilience frameworks that account for climate change-induced sea level rise is crucial for future-proofing port infrastructure. [77] highlighted that adaptive designs incorporating anticipatory measures for future sea level fluctuations are essential for sustaining operations under evolving environmental pressures.

Moreover, optimization supports the strategic allocation of resources to reinforce ports against catastrophic events like storms and earthquakes. Utilizing advanced simulation tools can inform design choices that align with best practices for resilience, as demonstrated in recent research employing Bayesian networks for risk assessment [54]. These methodologies, paired with structural optimizations, allow ports to maintain operational integrity and swiftly recover post-disturbance, preserving economic and logistical stability. In conclusion, structural optimization is a critical component of strategic port management, enabling the construction of resilient infrastructures that meet present and future demands. This approach, grounded in engineering precision and supported by innovative monitoring and predictive maintenance systems, ensures long-term efficiency and reliability [74]. The collective application of these strategies not only mitigates risks but also strengthens the competitive advantage of ports in the face of global challenges [56].

4.2 The Importance of Improving Drainage Systems to Reduce Flood Risks

Enhancing the drainage systems in ports is a crucial strategy for mitigating flood risks, particularly in coastal areas frequently subjected to extreme weather conditions [78]. Ports located near seas or river estuaries are especially susceptible to water accumulation due to high rainfall or tidal surges. Without optimal drainage infrastructure, water fails to evacuate swiftly, potentially leading to flooding that can damage port infrastructure, including dock foundations, access roads, and operational zones. The economic repercussions are significant, as disruptions in loading and unloading activities may result in delays in shipments and substantial financial losses [79]. Improved drainage management ensures that ports maintain uninterrupted operations during heavy rainfall or tidal flooding, fostering economic stability and reliability [80].

Research underscores that efficient drainage systems contribute to rapid water discharge, minimizing the risk of prolonged inundation and shielding port infrastructure from water-related deterioration. This proactive measure not only supports the operational integrity of ports but also promotes environmental sustainability by preventing soil erosion and enhancing the durability of port structures [81]. Furthermore, incorporating advanced drainage solutions aligns with broader flood risk management practices that integrate participatory approaches, which can enrich decision-making and increase the resilience of flood response strategies [82].

Ports equipped with robust drainage frameworks are better prepared to withstand climate-induced challenges, including rising sea levels and more frequent extreme weather events [8]. Such infrastructure investments are essential not only for immediate operational benefits but as part of long-term risk mitigation and adaptation strategies. High-quality data and precision modelling, as demonstrated in studies on natural flood protection services, can optimize the placement and functionality of drainage systems [83]. These measures represent a comprehensive approach to safeguarding port operations against floods, contributing to sustained infrastructure functionality and economic resilience. Improved drainage, therefore, is not only a short-term solution but a strategic long-term investment for port sustainability and disaster preparedness.

4.3 Risk Mitigation Strategies to Strengthen Port Resilience to Natural Disasters

Risk mitigation strategies play a crucial role in enhancing the resilience of ports against natural disasters, particularly given the high susceptibility of ports to threats such as earthquakes, floods, and storms. Effective implementation of mitigation measures significantly contributes to the ability of ports to withstand and respond to disaster impacts. For instance, designing infrastructure with earthquake-resistant features and incorporating protective systems against large waves can markedly reduce structural damage and ensure continuity in port operations [5]. In addition to physical reinforcements, comprehensive emergency response plans that are well-documented and regularly practiced are essential. These plans ensure that all stakeholders are prepared and coordinated, which is vital during actual disaster events [84]. Regular simulations and drills enhance readiness and improve response efficiency among emergency teams, bolstering the overall disaster response framework [85].

Modern technology, including early warning systems and weather monitoring tools, further strengthens risk mitigation by enabling ports to detect potential hazards early and activate response protocols proactively [22]. This integration of technology into risk management frameworks helps minimize operational disruptions and safeguards both infrastructure and personnel [86]. Liu and Chen [87] emphasized that resilience assessments incorporating both physical and operational aspects are essential for comprehensive risk management. The investment in robust risk mitigation measures has far-reaching implications beyond immediate disaster response. Such efforts contribute to sustained operational continuity, thereby reinforcing the port’s role in local and global economic stability [61]. These strategies represent a long-term commitment to safety and efficiency, protecting assets and ensuring that ports remain reliable hubs even in the face of extreme weather and other natural events [88]. The proactive adoption of these measures aligns with global disaster risk reduction frameworks and underscores the importance of continuous adaptation to evolving environmental challenges. This holistic approach not only secures physical infrastructure but also promotes operational resilience, fostering an environment where ports can maintain their essential functions despite external adversities.

Recent findings in port infrastructure resilience have significantly impacted current understanding and practices. Reports from organizations like the International Association of Ports & Harbors (IAPH) have highlighted critical gaps in global port infrastructure, particularly in resilience, digitalization, and decarbonization. This has led to more focused approaches in addressing these gaps through targeted action plans and collaborations. Comprehensive frameworks for port resilience emphasize the need for preparedness against a wide range of disruptions, integrating economic, social, and environmental dimensions. Effective governance structures and risk management practices are now recognized as essential, encouraging ports to adopt proactive stances in identifying and mitigating risks. The increasing reliance on automated and cyber-dependent systems has introduced new vulnerabilities, prompting measures to bolster cybersecurity and improve supply chain resilience. Additionally, the impact of climate change on port infrastructure has become a critical consideration, with adaptive pathways and best practices being integrated into management strategies to ensure operational sustainability. These findings are helping ports worldwide become more resilient, ensuring they can continue to serve as vital links in global supply chains despite the increasing frequency and severity of disruptions.

5. MATHEMATICAL MODELLING

5.1 Multidimensional modeling for multiple coastal flood simulation

A multidimensional model for simulating multiple floods on the coast was developed by [89]. The model introduced an advanced MH3 (Multidimensional Hydraulics, Hydrodynamics, and Hydrologic) modeling system using the Interconnected Channel and Pond Routing (ICPR) model to simulate compound coastal floods (CCF) driven by heavy rainfall, storm surge, and tides. Applied to the Charleston Peninsula, South Carolina, with high-resolution LiDAR DEM and DSM data, the study demonstrated that using a momentum balance method and DSM significantly enhanced model accuracy, achieving a correlation coefficient of 0.86 and an accuracy of 98.35% in detecting street-level flooding. The DSM improved simulation accuracy by 15-33% over DEM, and validation against USGS data and road closure reports confirmed the model's effectiveness. This research underscores the need for detailed urban features and diverse data integration for reliable flood risk assessment in coastal areas.

For the level change equation in the ICPR model is as follows:

$$\frac{\mathbf{dz}}{\mathbf{dt}} = \frac{\mathbf{Q_{in} - Q_{out}}}{\mathbf{A_{surface}}} \tag{1}$$

Where, the incremental change in stage is $\boldsymbol{dz}$, for the total inflow rate to the node is $\boldsymbol{Q_{in}}$, for the total outflow rate from the node is $\boldsymbol{Q_{out}}$, for the wetted surface area at the node is $\boldsymbol{A_{surface}}$ and the computational time step is $\boldsymbol{dt}$.

For the equation to calculate the water level at the node :

$$\boldsymbol{Z_{t+dt} = Z_t + d_z} \tag{2}$$

Where, for the water level elevation at time t+dt is $\boldsymbol{Z_{t+dt}}$, for the water level elevation at time t is $\boldsymbol{Z_t}$ and for the incremental stage change is $\boldsymbol{d_z}$.

For the inflow equation to the node is:

$$\boldsymbol{Q_{in} = \sum Q_{link\_in} + \sum Q_{excess} + \sum Q_{external} + \sum Q_s} \tag{3}$$

Where, for the amount of inflow to the control volume is Q_{in}, for the direct flow due to excess rainfall is Q_{excess}, for the flow contribution from external sources is $Q_{external}$ and for the seepage flow contribution from groundwater Q_s.

5.2 The Optimization model of climate change strategy in ports

Optimization modeling of climate change strategies in ports has been conducted. This paper [90] discussed the Climate Change Mitigation (CCM) and Climate Change Adaptation (CCA) strategies used by ports to deal with climate change, where CCM focuses on reducing greenhouse gas emissions, while CCA adjusts facilities to mitigate climate change impacts. The economic model constructed shows that both strategies increase port operational output, with CCM having a greater impact than CCA. CCA strategy may decrease the output of other ports if it is independent or substitutive, but may increase output if it is complementary, while CCM may have a positive or negative impact depending on its market relationship. This study highlights that CCA may be more effective in situations with difficult coordination, as it has smaller external effects than CCM.

The economic model with short-term profit function of port i is as follows:

$$\mathbf{max_{qi} \prod i = q_i p_i(q_i, q_j) - c_i(q_i)} \tag{4}$$

Where, for the operational output of port *i* is $\boldsymbol{q_i}$, for the operational output of other ports is $\boldsymbol{q_i}$, for the inverse demand function that depends on the output of port *i* and other ports *j* is $\boldsymbol{p_i(q_i, q_j)}$, and for the operational cost function of port *i* is $\boldsymbol{c_i(q_i)}$.

For the maximum condition equation can be derived with respect to $\boldsymbol{q_i}$

$$\boldsymbol{\frac{\partial \prod i}{\partial q_i} = p_i(q_i, q_j) + q_i \frac{\partial p_i}{\partial q_i} - \frac{\partial c_i}{\partial q_i}} \tag{5}$$

For the equilibrium condition equation can be calculated

$$\boldsymbol{p_i(q_i, q_j) + q_i \frac{\partial p_i}{\partial q_i} - \frac{\partial c_i}{\partial q_i} = 0} \tag{6}$$

Where for marginal revenue MR is $\frac{\partial \prod i}{\partial q_i} = \boldsymbol{MR}$, for marginal cost MC is $\frac{\partial c_i}{\partial q_i} = \boldsymbol{MC}$.

5.3 The Seismic design optimization based on building resilience

A multi-objective optimization process on seismic design based on building resilience has been conducted by [91]. This paper discusses the use of genetic algorithms (NSGA-II) to optimize earthquake-resistant building design with a multi-objective approach. The evaluation was conducted on 4, 7, 10, and 15 story reinforced concrete buildings (Risk Category II) by adjusting stiffness, strength, and deformation capacity to improve resilience. This study measures the balance between cost and resilience metrics, such as loss of function and repair costs. The results show that code-based building design (Risk Category IV) is quite effective, but not always optimal in terms of cost efficiency. An increase in initial cost of 2% can significantly reduce loss of function and improve long-term cost efficiency. This finding emphasizes the importance of optimization in building design and the need to adjust building code criteria to be more adaptive. The first stage with Solution Representation with the NSGA Algorithm in optimizing earthquake-resistant building design is as follows:

$$\boldsymbol{DV} = \left\{\frac{K}{K_0}, \frac{V_y}{V_{y0}}, \frac{D}{D_0}\right\} \tag{7}$$

Where, for the stiffness ratio is $\frac{K}{K_0}$, for the base shear strength ratio is $\frac{V_y}{V_{y0}}$ and for the deformation capacity ratio is $\frac{D}{D_0}$.

The second stage is the population initialization process with N individuals being the initial population generated randomly in the design space. The third stage is the evaluation of the objective function. The equation of the objective function is

$$\boldsymbol{O}(\boldsymbol{DV}) = \{\boldsymbol{TC}, \boldsymbol{LF}\} \tag{8}$$

Where, the total cost including the initial construction cost and the repair cost is TC and for the loss of function (LF) is the product of the unusable floor area and the repair duration. The equation for the consequence (Co) and the probability of occurrence (Po) is with the following damage consequence expectation equation

$$OCDSi = \int CoPo \left|\frac{dH}{dSa}\right| dSa. \tag{9}$$

5.4 The Evaluation of solutions in multiobjective problems

The robustness of solutions to multi-objective problems using Pareto solutions has been evaluated by [92]. Traditional approaches often overlook how theoretical solutions may not replicate well in practical production due to variability, rounding, or errors in variable implementation. This research proposes using the gradient norm as a measure of resilience, aiding decision-makers in selecting solutions that remain robust under slight perturbations in input settings. The method's application is illustrated through a case study, emphasizing its utility in ensuring more reliable outcomes when implementing solutions in real-world processes

The objective function equation for the multiresponse problem for the case of maximization of k objectives is $\boldsymbol{maximize}\{\boldsymbol{f_1}(\boldsymbol{x}), \boldsymbol{f_2}(\boldsymbol{x}), \dots\dots, \boldsymbol{f_k}(\boldsymbol{x})\}$ with $\boldsymbol{x} \in \boldsymbol{X}$

Where, $\boldsymbol{f_1}(\boldsymbol{x}), \boldsymbol{f_2}(\boldsymbol{x}), \dots\dots, \boldsymbol{f_k}(\boldsymbol{x})$ is the objective function to be maximized, for the decision vector is x and for the set of solutions that satisfy the conditions is $\boldsymbol{X}$

The gradient method equation is as follows

$$\boldsymbol{\nabla f}(\boldsymbol{x}) = \left[\frac{\partial f(x)}{\partial x_1}, \frac{\partial f(x)}{\partial x_2}, \frac{\partial f(x)}{\partial x_3}, \dots\dots, \frac{\partial f(x)}{\partial x_n}\right] \tag{10}$$

Where, $\frac{\partial f(x)}{\partial x_i}$ is the partial function derivative of $\boldsymbol{f}(\boldsymbol{x})$ with respect to variable $\boldsymbol{x_i}$

$$\|\boldsymbol{\nabla f}(\boldsymbol{x})\| = \sqrt{\left(\frac{\partial f(x)}{\partial x_1}\right)^2 + \left(\frac{\partial f(x)}{\partial x_2}\right)^2 + \cdots . +}\left(\frac{\partial f(x)}{\partial x_n}\right)^2 \tag{11}$$

The equation for the optimal solution based on Pareto solution robustness is :

$$\boldsymbol{rGN} = \boldsymbol{min}\left(\sum_i \boldsymbol{w_i}\left(\frac{\|\nabla f_i(x_m^*)\|}{max\|\nabla f_i(x)\|}\right)\right) \tag{12}$$

Where, for the relative gradient norm is rGN, for the weight or priority on the i response with the provision $\sum_i w_i = 1$, the gradient norm on the m-th Pareto solution is $\|\nabla f_i(x_m^*)\|$ and to normalize the gradient so that the comparison between responses remains consistent is $max\|\nabla f_i(x)\|$.

5.5 The improvement of water network distribution optimization methods

The improvement of multi-objective optimization methods for water distribution network (WDN) design, by developing a new, more effective version of NSGA-II was studied by [93]. This version overcomes the limitations of classical NSGA-II in reaching diverse solutions, especially in large networks, through four generation methods (G1-G4) covering the Pareto front area, including the “knee” area. Tests on five benchmark networks show that this algorithm outperforms the original NSGA-II and other MOEAs, with more non-dominated solutions and a wider Pareto front without increasing the computational burden, thus contributing to more efficient water distribution network optimization.

The equation of the objective cost function is

$$\boldsymbol{Minimize\ Cost} = \sum_{i=0}^{N} \boldsymbol{C_{ij}} \times \boldsymbol{L_{ij}} + \sum \boldsymbol{C_p} \tag{13}$$

Where, the unit cost of the *j*^th^ pipe diameter is $\boldsymbol{C_{ij}}$, for the pipe length is $\boldsymbol{L_{ij}}$ and for the cost of additional components is $\boldsymbol{C_p}$.

The equation of the durability objective function or durability index is

$$\boldsymbol{Maximize\ I_r} = \frac{\sum_{j=1}^{nn} C_j Q_j (H_j - H_j^{req})}{\sum_{k=1}^{nr} Q_k H_k + \sum_{i=1}^{npu} \frac{P_i}{\gamma} - \sum_{j=1}^{nn} Q_j H_j^{req}} \tag{14}$$

Where the network resilience index is I_r, for the number of demand nodes is nn, the coefficient at node *j* is C_j, for the flow rate is Q_j, for the actual heat is H_j.

6. CONCLUSIONS

This study reviews the resilience of port infrastructure using a mathematical modeling approach and bibliometric analysis. The bibliometric analysis with the main keyword "Port Infrastructure Resilience" reveals that trending and novel keywords for future research include climate change, risk analysis, resilience, and port facilities. Findings indicate that enhancing port infrastructure resilience to climate change and disasters requires a multidimensional approach, such as structural optimization, drainage improvements, and risk mitigation strategies. Current research trends emphasize sustainability and disaster impact reduction through advanced technology. Investment in monitoring technology and cross-sector strategic planning is crucial to bolster port resilience. This study highlights the importance of technological innovation and stakeholder collaboration, recommending further exploration of digital technology adoption for optimizing port resilience. Relevant case studies for mathematical modeling as references in future analyses include multidimensional modeling for multiple coastal flood simulations, optimization models for climate change strategies in ports, seismic design optimization based on building resilience, evaluation of solutions for multi-objective problems, and improved water network distribution optimization methods.

7. RECOMMENDATIONS AND LIMITATIONS

To enhance the resilience of port infrastructure, it is recommended to adopt advanced technologies such as IoT sensors, AI, and machine learning for real-time monitoring and predictive maintenance. Implementing structural optimization techniques can fortify port facilities against climate change and natural disasters. Upgrading drainage systems is crucial to mitigate flood risks and ensure efficient water management during extreme weather events. Comprehensive risk mitigation strategies, including emergency response plans and resilience-building measures, are essential. Cross-sector strategic planning should be fostered, encouraging collaboration between government agencies, the private sector, and local communities to create integrated and effective resilience plans. Emphasizing sustainability in all resilience-building efforts ensures that port infrastructure developments are environmentally friendly and resource-efficient. Using relevant case studies, such as multidimensional modeling for coastal flood simulations and optimization models for climate change strategies, can greatly benefit future research and practical applications.

However, there are limitations to consider. The study uses information from the Scopus database, which might not include all relevant research. This could make the bibliometric analysis less complete. The recommendation to adopt advanced technologies may face challenges due to high initial costs, lack of technical expertise, and resistance to change among stakeholders. The findings and recommendations may not be universally applicable to all ports, as local conditions and specific vulnerabilities can vary significantly. Practical implementation of structural optimization, drainage improvements, and risk mitigation strategies may encounter logistical, financial, and regulatory hurdles. Effective cross-sector strategic planning requires seamless coordination among diverse stakeholders, which can be difficult to achieve in practice. The study also points out some new research trends, but it might not fully capture how quickly research into port infrastructure resilience is changing, so it needs to be updated and looked over all the time.

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