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# Literature Review on Incorporating Climate Change Adaptation Measures in the Design of New Ports and Other Maritime Projects

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**Abstract:** Due to their nature and location, ports and other maritime projects are particularly sensitive to climate change actions. Thus, when designing these types of projects, it is important to follow a methodology that incorporates climate change adaptation measures throughout the design process. This paper aims to identify the most relevant work developed in this field, along with the main knowledge gaps, through a systematic literature review process. Through a careful selection and analysis of relevant articles associated with "climate change adaptation", "ports" and "design", it was possible to conclude that these focused on existing infrastructures and specific case studies, on individual design aspects, on policies and economic or legal frameworks, on the perceptions around climate change or on stakeholder management. The literature review process described in this paper is part of a larger project, dedicated to the development of a practical and robust framework focused on the implementation of climate change mitigation measures in the design of new ports and other maritime projects.

**Keywords:** adaptation measures; climate change; literature review; maritime projects; ports



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## 1. Introduction

The IPCC states, with a high level of confidence, that global ocean temperatures have risen since 1970, with a direct impact on the global sea level rise and they have increased the exposure of coastal areas to tropical cyclones, extreme sea levels, wind and wave actions, they have increased storm frequency and severity, sea ice loss and permafrost thaw [1–3], which affect ports and other maritime and coastal structures, given their location and exposure to climate conditions.

Various climate change scenarios usually lead to diverging projections with trends spanning beyond 2050 or 2060, which are often difficult to translate on a practical approach [3–5]. On coastal projects, the uncertainties associated with climate change scenarios are often distilled into a projection for sea level rise (SLR), which is insufficient to represent future conditions at any project site, where slow trends must be combined with the high-frequency variability associated with tides and storms (wave action, changes to local currents, wind and rainfall) [6–8]. Given the typically long life spans of these projects [5,9], it is important to develop design guidelines and standards for ports and maritime structures that define how to incorporate climate change actions during the different stages of development of a new port or other maritime projects. This literature review, which focused on peer-reviewed research articles published between 2001 and October 2022, is the first step in the development of such guidelines, as it allows for a detailed understanding of the existing literature on the subject and for the identification of the trends regarding the most cited research topics addressing climate change, new ports, maritime structures and mitigation measures.

This literature review shows that, although several papers and scientific publications have been published on different aspects of this subject, most focus on specific case

studies [10–14] and, therefore, lack in the definition of general guidelines that may be applicable to other projects, in different locations and subject to different conditions. Other articles focus on recommendations on the incorporation of climate change mitigation measures along the shoreline focus but on different areas (urban zones, beaches and estuaries, natural parks, etc.), on other aspects not related with design (financing and revenue, decision-making models, socio-economic impacts, etc.) or on policies and legal frameworks amongst others [15–17]. When proposing guidelines for the specific incorporation of climate change in the design of ports and waterways infrastructures—like those published by PIANC/EnviCom's WG178 [1]—these usually apply to existing facilities and are not immediately applicable to new (greenfield/bluefield) projects.

## 2. Systematic Literature Review

### *2.1. Methodology*

Systematic literature reviews provide an objective snapshot of the state of knowledge on a given subject. Given the diverse topics and perspectives associated with climate change, this task gains added importance due to the unbiased nature of the process, and it is frequently used [18–22].

A literature review was carried out, based on peer-reviewed research articles, published in the English language, during the period between 2001 and October 2022 and referenced on the Scopus database. This literature review did not include other sources, even if technical reports, governmental publications and other documents may be recognized as valuable sources of information.

To identify a representative sample of the work published by the scientific community on the topics most closely related with "Incorporating Climate Change Adaptation Measures in the Design of Ports and Maritime Projects", several broad searches were carried out. The corresponding results were then screened through increasingly detailed analysis processes, until a final selection of the most representative articles was identified. This literature review, illustrated in Figure 1, included the following steps:

1. Identification of relevant keywords through multiple searches: a sensitivity analysis was carried out using the following keywords in multiple combinations: "climate change", "climate change adaptation", "ports", "maritime project", "coastal facilities", "design", "adaptation measures", "adaptive design" and "coastal resiliency". From this sensitivity analysis, the following combination of keywords applied to all fields in the articles (title, abstract, keywords and main text) proved the most relevant: "climate change adaptation", "ports" and "design";
2. Identification of the articles matching the search criteria: the search on the Scopus database (November 2022) for peer-reviewed articles published in journals in the English language returned 704 results;
3. Preliminary screening: through a preliminary screening, the identified articles were compiled into a database and, from the analysis of their titles, keywords and abstracts, a significant portion was excluded as they did not relate to the theme of this literature review. This exclusion process allowed for the quick identification and exclusion of papers that clearly related with other scientific fields (biology, sociology and economics) and different types of projects (urban water, dams, cities and urban planning, sea transport and logistics chains). At the conclusion of this step, 159 articles remained;
4. Detailed screening: the pre-selected articles were accessed when available in open-source databases. The contents of these articles were checked to confirm their relevance. This process, which consisted in reviewing the contents of each article in sufficient detail to confirm its relevance to this literature review, led to a further refinement of the selection, resulting in a list of 77 articles for complete analysis;
5. Analysis of selected articles: each of the articles selected was read and analyzed to allow for a detailed understanding of the contents, their subject area and the number of publications per year. To better understand the interconnections between the selected articles and their authors, software VOSviewer v1.6.18 [23]) was used. Additionally, and based on

professional experience, these articles were also categorized in accordance with the scale of the study and the main themes and objectives of the articles.

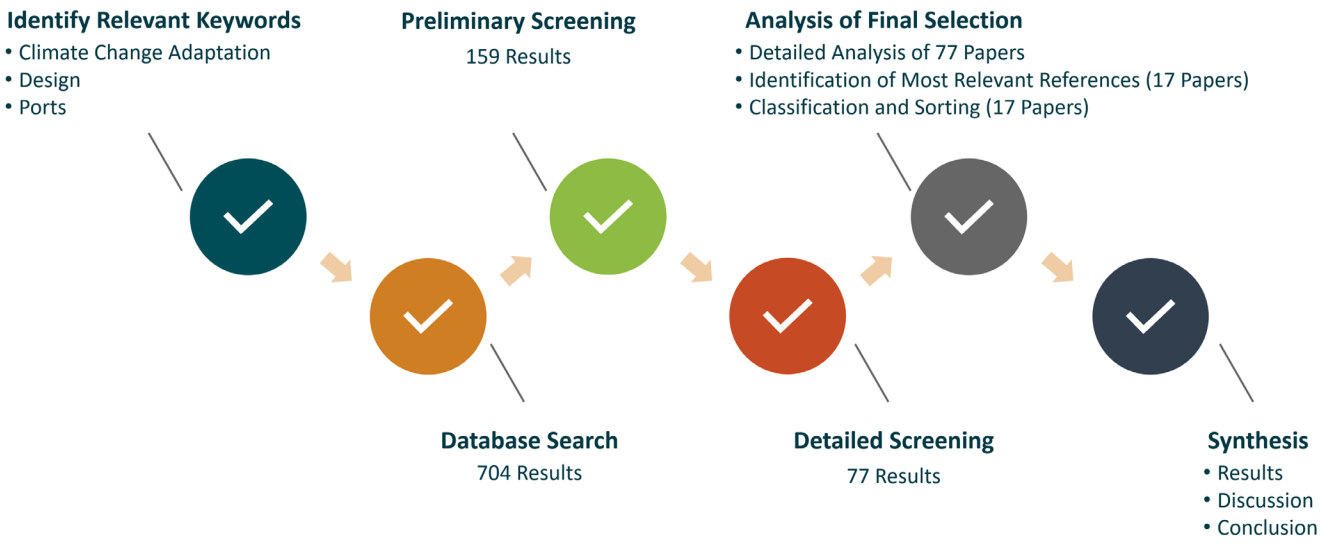


**Figure 1.** Literature review process (main steps).

*2.2. Results*

The detailed screening process resulted in 77 articles, selected from the 159 results of the preliminary screening.

A chronological analysis of these two datasets, shown in Figure 2, shows that all articles were published after 2010, with a clear upward trend.

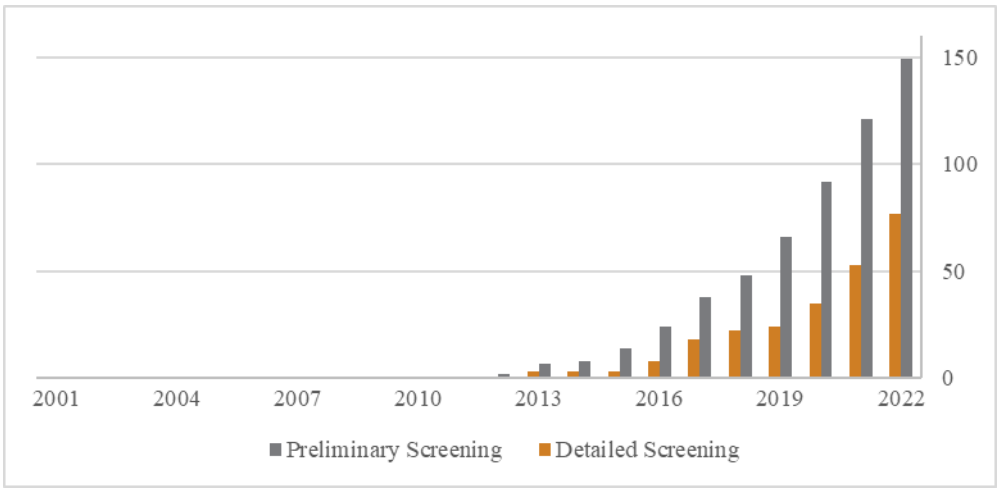


**Figure 2.** Cumulative plot of preliminary (159 results) and detailed screening (77 results).

The selected articles, resulting from the detailed screening, originated mainly from the United States of America (18), the United Kingdom (14) and Australia (13), followed by Canada (9) and China (9). The overall geographic distribution of the selected articles is depicted in the map shown in Figure 3.

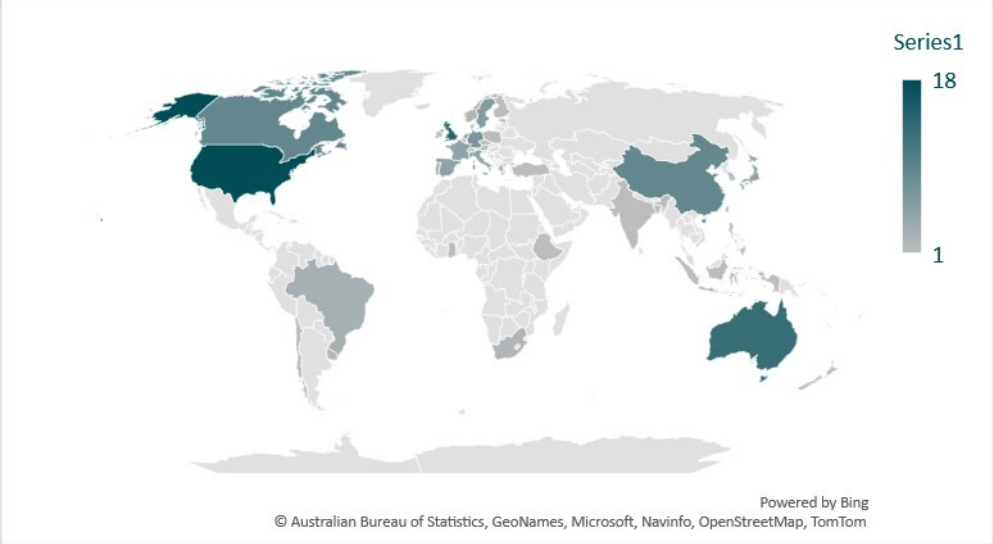


**Figure 3.** Geographic distribution of the selected articles (77 results).

Most of the selected articles were published in industrialized countries.

The 53 articles were issued across 36 different publications, which highlights the wide range of journals addressing different aspects of climate change adaptation in coastal areas.

The most cited articles are "A note on climate change adaptation for seaports: A challenge for global ports, a challenge for global society" [24], with 82 citations, "Risk and cost evaluation of port adaptation measures to climate change impacts" [25], which was cited 48 times and "Climate change and the adaptation strategies of ports: The Australian experiences" [26], with 46 citations.

An analysis of the co-citations between articles, shown in Figure 4, developed using the VOSviewer software package to process SCOPUS' bibliographic database, shows that the selected articles center around "Climate Change", "Adaptive Management" and "Risk Assessment". Figure 4 also shows that within the universe of climate change, the central themes of this literature review—port/ports and harbors/coastal protection—are located at the periphery of the diagram, at a significant distance from climate change.

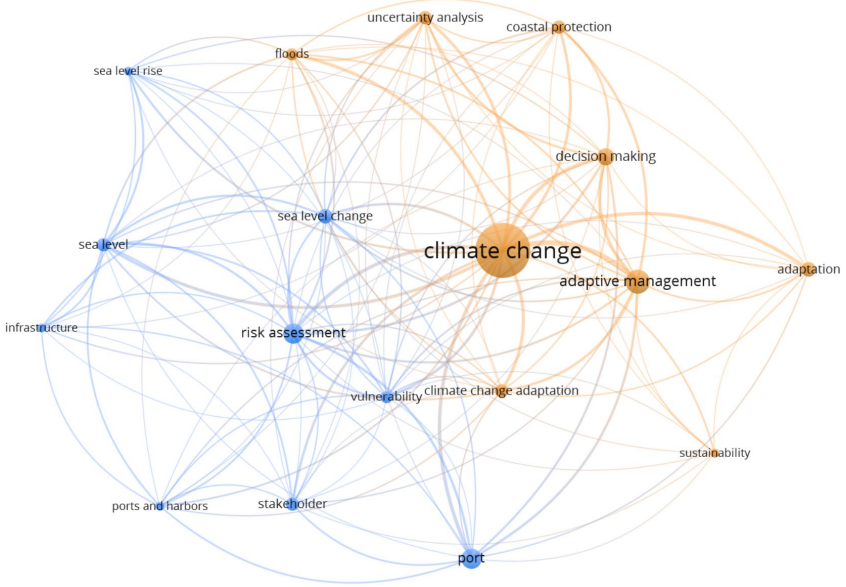


**Figure 4.** Plot of co-occurrence between the 77 selected articles (VOSviewer: clustering resolution of 1.0; min. cluster size of 1; normalization method—association strength).

The results of a separate analysis, depicted in Figure 5, also developed using VOSviewer, show the links between the authors of the selected articles, highlighting a clear cluster of authors, around Becker, A. and Ng, A.K.Y., with six smaller independent groups of authors.

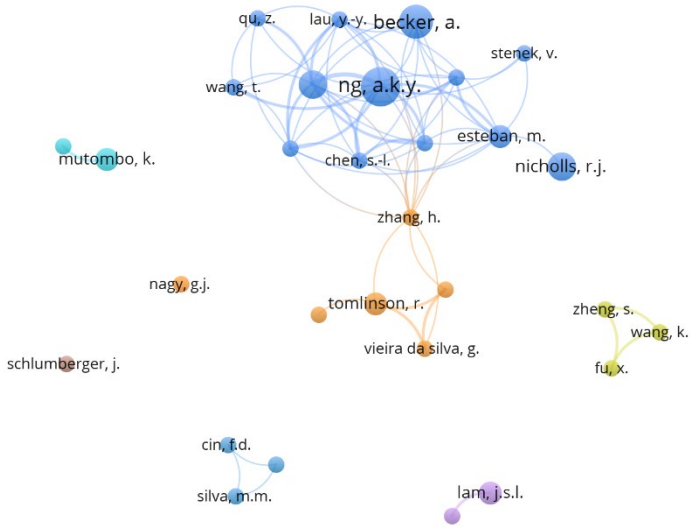


**Figure 5.** Plot of citations between authors of the 77 selected articles (VOSviewer: clustering resolution of 1.0; min. cluster size of 1; normalization method—association strength).

Multiple analysis confirmed that the article "A note on climate change adaptation for seaports: A challenge for global ports, a challenge for global society" [24] is not only the most quoted, but also a predecessor to several of the subsequent publications. This article presents seaports as critical infrastructure to world trade, which is very likely to be affected directly and indirectly by climatic changes. While acknowledging some uncertainty associated with the projected impact of climate change, the article outlies strategies for port resilience, recognizing the importance of stakeholder mobilization and the importance of mobilizing adequate financing and other resources to the implementation of these strategies. Figures 4 and 5 also highlight and confirm the continuous nature of the research community around these topics, as it emerged between 2005–2014 [27].

As part of the detailed screening, the 77 selected articles were catalogued as shown in Table 1. The criteria below were defined as part of Step 5 of the methodology, during the analysis process and were based on the relevance for the greater theme of "Climate Change Adaptation Measures in the Design of Ports and Maritime Projects".

**Table 1.** Characterization of the 77 selected articles.

| | Criteria | Number of Articles | % of Articles |
|---|---|---|---|
| Scale | Ports and Similar projects | 39 | 51% |
| | City/Regional/International | 30 | 39% |
| | No Scale | 8 | 10% |
| Subject | Case Study(ies) | 39 | 51% |
| | Policy/Strategy | 24 | 47% |
| | Framework/Guidelines | 42 | 55% |
| | Design/Specific Technical Subject | 28 | 36% |

The results in Table 1 have also been plotted in the graphic shown in Figure 6, where these 77 articles were selected during Step 4; Detailed Analysis articles are ordered from most recent to oldest (1 being the most recent article), which allows for a visual understanding distribution of these themes.

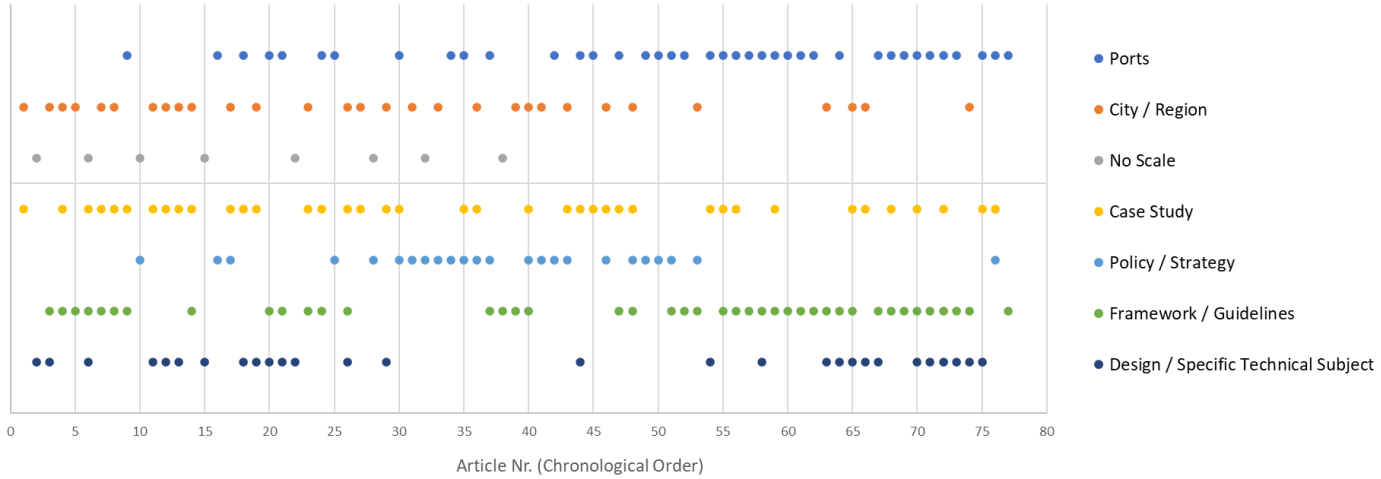


**Figure 6.** Classification of the 77 selected articles (with #1 being the most recent).

Table 1 and Figure 6 highlight that relating to the scale of the articles and despite all having the keyword "ports" in the abstract, nearly 40% focused on larger scale themes, often focusing on city- and regional-scale climate change subjects.

Regarding the subjects of the articles, just over half (51%) focused on specific case studies.

A significant fraction of the articles (47%) focused on high-level policies, larger scale strategies and different economic aspects related to climate change.

A significant number of articles (55%) presented and discussed frameworks, guidelines or methodologies related to adaptation to climate change. It should be noted that of these, none specifically tackled new port developments, rather focusing on adaptation actions required for existing infra-structures.

Finally, several articles (36%) focused on specific technical design aspects (sea level rise, wave action, breakwater response, among others).

From the detailed review, several articles were selected as the main references to be used in the definition of guidelines for the incorporation of climate change mitigation measures in the design of new ports and other maritime projects. These articles are identified in Table 2.

**Table 2.** Main references with relevance to the integration of mitigation measures in maritime projects.

| Article Title | Year/Publication | Case Study/ Studies | Policy/ Strategy | Framework/ Guidelines | Design/ Technical Subject |
|---|---|---|---|---|---|
| Proposing DAPP-MR as a disaster risk management pathways framework for complex, dynamic multi-risk [15] | 2022 IScience | | | X | X |
| Modeling and Simulating Adaptation Strategies Against Sea-Level Rise Using Multiagent Deep Reinforcement Learning [28] | 2022 IEEE | | X | | |
| Evaluation of flexibility in adaptation projects for climate change [29] | 2022 Climatic Change | | | X | X |
| Framework for incorporating climate projections in the integrated planning and management of urban infrastructure [30] | 2022 Urban Climate | X | | X | |
| Climate-proofing coastal cities: What is needed to go from envisioning to enacting multifunctional solutions for waterfront climate adaptation? [31] | 2022 Ocean and Coastal Management | | X | | |

**Table 2.** *Cont.*

| Article Title Year/Publication | | Case Study/ Studies | Policy/ Strategy | Framework/ Guidelines | Design/ Technical Subject |
|---|---|---|---|---|---|
| Understanding preferences for coastal climate change adaptation: A systematic literature review [32] | 2021 Sustainability | | X | | |
| Climate Change Risk Indicators (CCRI) for seaports in the United Kingdom [10] | 2021 Ocean and Coastal Management | X | | | |
| Role of spatial analysis in avoiding climate change maladaptation: A systematic review [33] | 2021 Sustainability | | X | | |
| Adaptation strategies for port infrastructure and facilities under climate change at the Kaohsiung port [11] | 2020 Transport Policy | X | | | |
| Climate change adaptation in the port industry: A complex of lingering research gaps and uncertainties [27] | 2020 Transport Policy | | X | | |
| Demand for Ports to 2050: Climate Policy, Growing Trade and the Impacts of Sea-Level Rise [34] | 2020 Earth's Future | | X | | |
| Port Decision Maker Perceptions on the Effectiveness of Climate Adaptation Actions [35] | 2018 Coastal Management | | | X | |
| A new approach to assessing port infrastructure resilience to climate risks and adaptive solutions prioritization [36] | 2017 Journal of Maritime Research | | | X | |
| Towards port infrastructure adaptation: a global port climate risk analysis [37] | 2017 Journal of Maritime Affairs | | | X | X |
| A review of potential physical impacts on harbours in the Mediterranean Sea under climate change [12] | 2016 Regional Environmental Change | X | | X | X |
| A three-tier framework for port infrastructure adaptation to climate change: Balancing breadth and depth of knowledge [38] | 2016 Maritime Transport | | | X | X |
| A note on climate change adaptation for seaports: A challenge for global ports, a challenge for global society [24] | 2013 Climatic Change | | | X | |

In addition to the articles listed in the previous table, several others were identified that focused on other themes, but which may be relevant to complement design guidelines. Some of these themes include models supporting decision-making [15,28,39,40], perceptions around climate change [5,7,41–44], regional policies [16,45,46] nature-based solutions [47,48] and the bibliometric/literature review of different themes [16,32,33].

No article was found that specifically presents guidelines on how to incorporate climate change adaptation measures in the design of new port and other maritime infrastructure projects.

## 3. Discussion

The chronological analysis of the articles selected during the literature review process clearly shows an upward trend in the number of published papers related to climate change adaptation and mitigation actions in coastal areas. This interest, naturally, includes ports and other infrastructures from 2011. The analysis of the selected articles showed that a significant fraction of the selected articles focuses on existing facilities and on case studies.

There is a prevalence of articles focusing on case studies [11,42,43,49–51], which illustrate how to mitigate the impact of climate change actions and the associated need to develop adaptation measures for specific ports or project areas.

On the other hand, several articles focus on policies, economic models and stakeholder engagement, presenting high-level, strategic options for regional/international areas [5,27,46,52–54].

Additionally, these articles often reflect a perspective that emerges from industrialized countries, where most of the research originates from [43,55,56].

When addressing the uncertainty associated with climate change projections, different articles usually refer to two or three representative concentration pathways (RCPs), namely RCP 8.5 and RCP 2.6, corresponding to the maximum and minimum sea level change, respectively [34].

Some articles also focus on the impact that ports and maritime transport have on the environment and, consequently, on the potential contributions to climate change [39], revealing a trend in the development of "green ports" or "sustainable ports".

Figure 4 shows how "Climate Change" assumes a central point in the analysis of the selected articles, highlighting two clusters (blue and orange). On one side, "Ports and Harbors" stands in the periphery of the blue cluster, while "Coastal Protection"—as associated with "coastal protection structures"—in the orange cluster is at a much shorter distance from "Climate Change". This visualization confirms the article analysis that the authors conducted, based on professional experience and expertise. Although the subject is complex, the impact of climate change in ports, when mentioned specifically, is often equated or simplified to the impact that sea level rise may have in the structures or operations of those facilities [34,49]. However, even in what relates to this issue, there is a lack of standards (for example in the USA) on how to incorporate sea level rise projections in the design or ports and other maritime facilities [5]. Still in the USA, on a project level, only 29% of respondents to an oriented survey indicated that their organization had a policy or planning document on how future sea level rise should be incorporated into port infrastructures projects [5]. Of these, only a third use it on every project. More relevant even was the identification that over 50% of the respondents to a survey identified a lack of standards as the main reason for not incorporating sea level rise in the design of port infrastructures.

Climate change is one of the factors that contribute to the uncertainty in the planning and design of port and other maritime projects. Other factors include ever increasing vessel sizes, new logistics/equipment/handling concepts, variable traffic forecasts, volatile market conditions, changing focus and importance of different stakeholder and environmental protection among others [9].

The focus given to existing ports through the analysis of case studies and the need to improve or retrofit existing facilities illustrates a bias towards shorter-term planning. This also reflects a reactive approach to climate change, where improvement works are developed after structures are damaged or destroyed. However, given the significant costs associated with raising protection structures, quays, rail lines and other infrastructure and the limitations present in existing ports, it may be more efficient to build new facilities, with added flexibility to improve long-term resiliency [5,29,57].

## 4. Conclusions

The main objective of this literature review was to identify the trends relating to the design of port and other maritime projects and the corresponding adaptation to climate change through an analysis of peer-reviewed papers published between 2001 and October 2022 on subjects related to incorporating climate change adaptation measures in the design of ports and maritime projects. Through a systematic literature review process covering peer-reviewed articles written in English and published scientific journals recorded in the SCOPUS database, the identified articles were analyzed, and the main trends in the publication of scientific papers were identified.

The initial selection of the keywords had a wide range to allow for the identification of those that provided the best match with the theme of this study. The search using the selected keywords ("climate change adaptation", "ports" and "design") resulted in 577 articles, which provides a broad and representative sum.

Given the large number of selected articles, it was decided not to include results from other scientific platforms such as Web of Science (WoS). Similarly, no books or conference papers were included, as these are often published without a formal per review process. Through this analysis, it is clear that the scientific community believes that climate change will have an impact and play an important role in the design of future port and maritime projects. The number of published papers related with these themes has increased in the past 10 years, supported by an interconnected publishing community spread over more than 35 countries.

However, there are limited publications proposing guidelines for the incorporation of climate change adaption measures in the design of new port and other maritime projects. This is justified by two main factors. On the one hand, most of the articles originate from the industrialized world, where projects often relate to the upgrade and expansion of existing ports and structures, not new projects. On the other hand, the uncertainty associated with climate change and its impact on future projects often pushes researchers into the analysis of specific projects and case studies, diverting them from the development of general guidelines.

Still, it is crucial to propose, discuss and validate a general framework that addresses this uncertainty in the design of ports [9] and other maritime projects due to climate change. Through this review, no articles were found that present concise and practical guidelines on how to incorporate climate change adaptation measures in the design of new maritime projects.

While designing maritime projects, the teams target common engineering vectors, focusing on quality (function and performance), time (efficiency and operations) and cost (CAPEX, OPEX, cash flow and profit margins). Taking the complete infrastructure's life cycle—one exposed to significant uncertainty—should allow for other factors that increase the project's likelihood of success. These can include adaptability, durability, flexibility, reliability and sustainability among others. Of these, the most important uncertainty management concept for large projects is that of flexibility [9].

This literature review confirms the importance of climate change actions in the design of new port and other maritime projects and the lack of guidelines on the integration of adequate mitigation measures in these projects. Still, the most relevant articles that touch this theme have been identified, as they provide valuable insights that can form the basis for the development of such guidelines.

In parallel, through a non-systematic review of published documents focusing on this field, it was found that the 2020 Climate Change Adaptation Planning For Ports And Inland Waterways (EnviCom WG Report nº 178), issued by PIANC [1] can form the basis for these guidelines with the defined four stages: 1. Context and Objectives; 2. Climate Information; 3. Vulnerabilities and Risks; 4. Adaptation Options. This document specifically focuses on existing ports and infrastructure and will, therefore, require significant adjustments before it can serve as a suitable tool for new projects (greenfield/bluefield).

Thus, this exercise validates the need for further studies that can bridge the existing gap between scientific knowledge and the development of practical guidelines for the design of new port and other maritime projects, adequate to real-life conditions.

As part of a larger project dedicated to the definition of practical design guidelines for the implementation of climate change mitigation measures in new port and other maritime projects, this paper validates the relevance of the subject. This project's objective is to provide guidance to designers, operators and other stakeholders, with a framework tested in real-world case studies. The proposed framework will be the focus of a separate article, supported by additional publications related to case studies.

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