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Floating into the Future: A Systematic Review of Floating Ports' Evolution as a Resilient Maritime Solution

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Abstract

This study systematically reviews the evolution, present focus, and future potential of floating ports/ harbours within the wider maritime industry. Using a bigram-based search strategy across Scopus and Web of Science, 884 relevant publications were identified, of which 140 directly addressed floating ports or related applications. A structured classification based on the "Elements of the Maritime Industry" framework revealed a strong concentration on construction aspects, with significant gaps in management, logistics, and ancillary activities. Keyword mapping through VOSviewer highlights a progression from safety-driven designs to sustainable, multifunctional, and climate-resilient infrastructures. In addition, the study introduces two working definitions; I) offshore floating ports and II) floating solutions for onshore/nearshore port infrastructure, to clarify emerging directions in the conceptual and functional development of floating port systems. The findings underline both the scarcity and growing importance of floating ports as a critical component of future maritime logistics and governance.

Keywords: Floating ports, floating harbors, floating future, port governance, maritime transportation, ports and harbors, port systems

1. Introduction

The global maritime industry is undergoing rapid transformation as traditional port infrastructures face mounting pressures from urbanization, land scarcity, climate change, and growing trade volumes (UNCTAD, 2024). Floating structures, once limited to small-scale berthing facilities and protective breakwaters, are now emerging as credible alternatives for large-scale, multifunctional, and sustainable maritime infrastructures (Weerasinghe et al., 2025). In this context, floating ports and harbours have gained renewed attention as potential solutions that combine flexibility,

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resilience, and inclusivity (Johnson et al., 2019). Yet, despite their growing relevance, the concept of "floating ports" remains poorly defined and relatively underexplored within mainstream maritime research.

Previous studies on floating structures have largely focused on technical aspects such as construction feasibility, hydro-dynamic performance, and structural integrity (Souravlias et al., 2020; Wu et al., 2017). While these are critical foundations, much less attention has been paid to governance, logistics integration, regulatory frameworks, and socio-ecological implications. Understanding these dimensions is essential if floating ports are to evolve from experimental prototypes into operationally viable components of global maritime logistics and port governance systems (Weerasinghe et al., 2025).

This paper addresses this gap by conducting a systematic review of existing literature, combining bigram-based keyword searches with the "Elements of the Maritime Industry" framework to classify and analyse studies (Notteboom et al., 2022). Keyword mapping that uses VOSviewer as the tool, further illustrates the temporal evolution of research themes, highlighting both achievements and persistent gaps. The paper proceeds by outlining the review method and analytical framework, followed by results on classification and thematic evolution. It concludes with a discussion of future directions for floating ports across maritime, governance, and sustainability dimensions, integrating the development of working definitions; i) offshore floating ports and ii) floating solutions for onshore/nearshore port infrastructure. The findings not only reveal the current concentration of research but also point toward pressing future directions, including governance models, legal frameworks, environmental sustainability, and socio-economic impacts.

2. Review Method

This systematic review method outlines the comprehensive methodology used to identify and analyse publications on floating ports. The study set out to collect all publications related to floating structures, particularly their potential in delivering large-scale multifunctional and inclusive living spaces on water. Given the poorly defined scope of the subject "floating ports," a systematic search method was selected to reduce bias (Weerasinghe et al., 2025, 2024). Single keywords were found inadequate, so a bigram-based approach was adopted, focusing on combinations that included "floating" or "float*." Well-established terms such as "Very Large Floating Structures (VLFS)" were used alongside broader phrases like "floating structures," enabling the capture of both direct and related applications. This initial step generated 41 bigrams from 13 papers and existing project reports, forming the basis for database searches. The search across Scopus and Web of Science resulted in 17,896 and 8,338 records respectively, with 19,473 unique studies after duplicates were removed. Screening titles, abstracts, and keywords revealed 9,962 bigrams, but only 22 directly referenced floating ports, harbours, or terminals. This highlighted a relative scarcity of targeted research in the area. To overcome this, a structured keyword framework was developed, combining the 22 bigrams with broader maritime port concepts.

This refined approach ensured focus while maintaining sufficient scope. Applying the framework yielded 443 results from Scopus and 462 from Web of Science (WoS), leaving 817 unique studies. Reference checks added another 67, bringing the total to 884 publications. This comprehensive process demonstrates how systematic, iterative keyword strategies can bridge gaps in underexplored fields. Beginning broadly with floating structures before narrowing to floating ports allowed both context and specificity, ensuring a reliable foundation for analysing applications and identifying future research directions in this emerging area. Ultimately we identified 140 studies indexed in Scopus or WoS that deal with the topic of floating ports and harbors. However, a closer look reveals that not all of these studies are solely focused on floating ports or harbors, with many addressing broader or related floating technology.

3. Framework for Analyzing Literature

To position each study within the wider maritime sector, we first applied the "Elements of the Maritime Industry" classification proposed by Notteboom et al., (2022). This framework divides the industry into four domains; maritime shipping, ports, management, and ancillary activities, allowing a structured categorization of research themes. By linking studies on floating ports to these domains, we were able to generate a clearer, more comprehensive picture of how this niche topic connects with the broader maritime industry.

Next, we used the VOSviewer tool to map keywords derived from the titles of 140 identified studies. Titles were preferred over author-provided keywords because much of the older literature lacks standardized author keywords. Using titles allows VOSviewer to extract repeating terms in a consistent and fair manner (van Eck and Waltman, 2014). This approach is particularly effective for capturing long-term patterns and ensures comparability across both older and newer studies.

The keyword mapping in VOSviewer is based on the technique which relies on multidimensional scaling. The process is underpinned by three key equations which are presented under Appendix A. The first equation (1) calculates normalized association strength, which functions as the core similarity measure by adjusting for overall keyword frequency. This prevents very common terms from being falsely linked with all others. The second equation (2) specifies the values used in normalization, including the total co-occurrence count for each keyword and the total weight of all network connections. The third equation (3) is a minimization function that positions keywords in two-dimensional space, using association strengths as weights so that closely related terms cluster together while unrelated terms are pushed apart. To avoid trivial outcomes, the equation includes a constraint that standardizes average distances. Finally, VOSviewer overlays a color gradient to represent the average publication year of each keyword, producing a visual timeline of research trends in floating port studies.

4. Results and Discussion

A thorough analysis of the identified publications reveals a clear picture of the current research landscape. The literature can be classified into distinct elements of the maritime industry, which in turn highlights the technical evolution of floating ports and harbours from early engineering concepts to integrated, system-level solutions.

4.1. Classifying Literature: Elements of the Maritime Industry

Below Our analysis shows that the majority of publications can be classified under "Ports" (Figure 5). Only a small number address "Maritime Shipping," just one study covers "Management," and none focus on the "Ancillary" domain. A closer look at the "Ports" category and its sub-elements reveals that more than 86% of studies concentrate on Construction, while 22% examine Terminal Operations (see Figure 1). This leaves significant research gaps in other sub-elements, including maintenance, equipment manufacture, port-centric industries, dredging, port authorities and inland carriers, as well as storage and distribution.

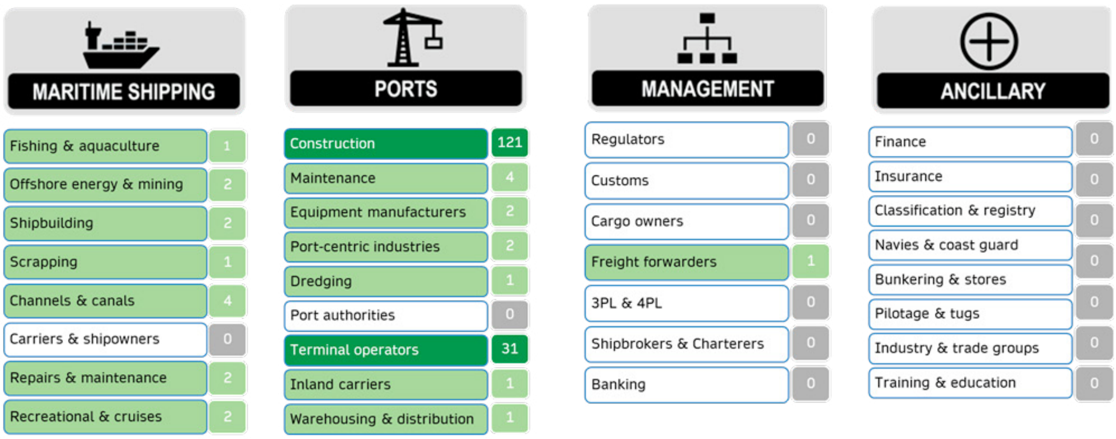

Figure 1: Categorisation of Literature;

Source of the framework - Theo Notteboom, Athanasios Pallis and Jean-Paul Rodrigue (2022) Port Economics, Management and Policy

These findings highlight the relative immaturity of floating ports within the broader framework of the "Elements of the Maritime Industry." Current research is heavily concentrated on the construction phase, with very limited in-situ evidence available. This underscores the urgent need to expand investigations into the overlooked sub-elements, which are essential for developing a more comprehensive theoretical foundation and supporting the advancement of this emerging field.

4.2. Technical Background and Evolution of Floating Ports/ Harbors

The evolution of research on floating structures can be broken down into four distinct phases; early stages, mid-1990s to early 2000s, late 2000s to early 2020s, and most recent stage, each characterized by a shift in focus from basic engineering principles to complex, system-level applications. This progression is evident in the types of studies conducted across different decades, as detailed. The development of floating ports and harbours has followed a gradual but distinct trajectory, evolving from early conceptual explorations of safety and berthing systems to complex designs for very large floating structures (VLFS) and multipurpose maritime infrastructures (Flikkema and Waals, 2019). The keyword map highlights this progression: earlier studies cluster around pier, dock, construction, and berthing, while recent work emphasizes hydro-elastic response, performance, system, and design framework (see Figure 2). This reflects a shift from fundamental safety-driven solutions toward performance optimization and integrated floating port concepts.

In the early stages, research was primarily concerned with safety, practicality, and protection in maritime berthing and docking systems. Early works tested innovative fendering mechanisms to mitigate ship impact, such as hydraulic-pneumatic and floating donut fender systems (Lee, 1967; March and Davis, 1979). Similarly, studies emphasized protective infrastructure against waves and ship collisions, such as floating breakwaters and floating berths for naval and commercial uses (Hayward and Lees, 1984; SUTKO, 1975). During this era, construction feasibility and material innovations, including reinforced concrete and ferrocement, also gained attention (Brache, 1989; SINTSON et al., 1972). These early efforts created the foundation for treating floating piers as serious engineering alternatives rather than experimental novelties.

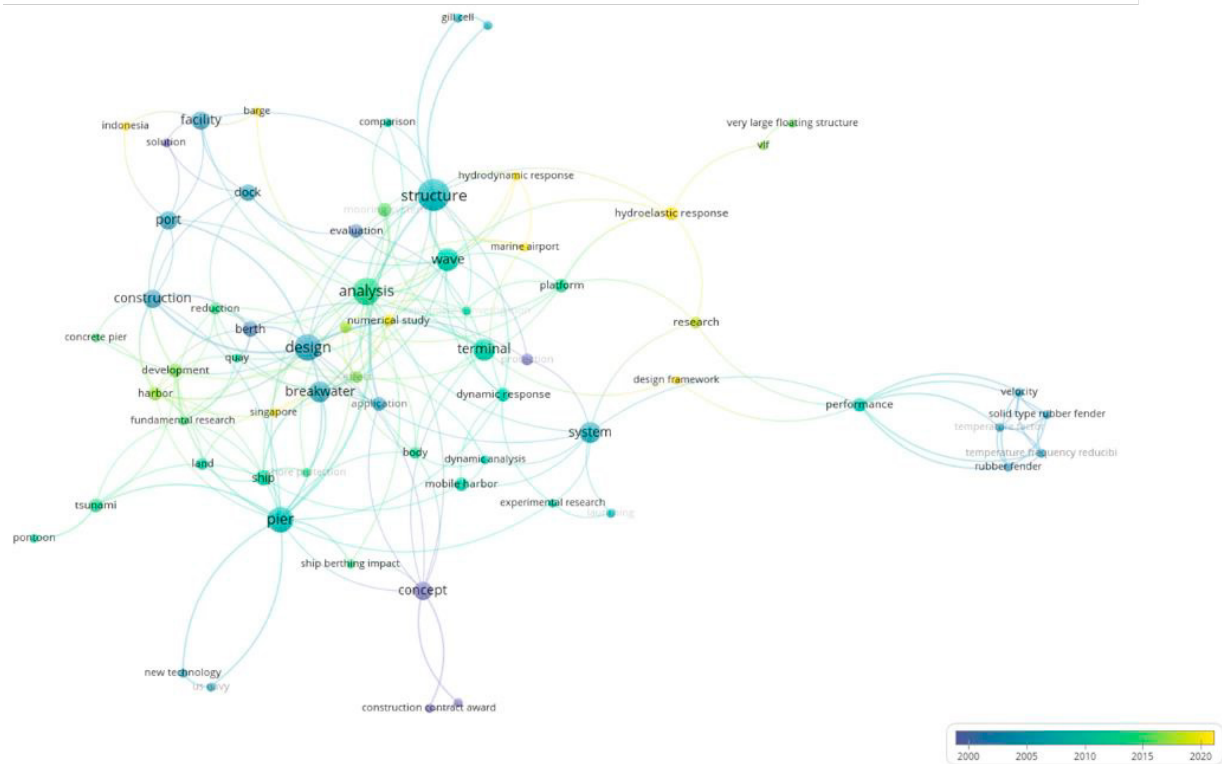

Figure 2: Evolution of Floating Ports

By the 1980s and early 1990s, the focus expanded beyond single-component safety systems to include larger facility designs and operational efficiency. Research investigated floating terminals for bulk cargo and miniport concepts aimed at flexibility and cost-effectiveness (Johansson, 1986; Lindemalm, 1982). At the same time, studies explored the modernization of dock and advanced pier concepts for naval infrastructure (Chow and Haynes, 1983; Tanner et al., 1983). This period marks the transition where floating structures were no longer limited to defensive or berthing roles but became increasingly tied to port development strategies.

The mid-1990s to early 2000s introduced an era of large-scale experimentation with mega-floats and VLFS. Research addressed the hydrodynamic and structural responses of floating platforms in waves, emphasizing both numerical and experimental studies (Sukeyasu et al., 2004; Takaishi et al., 1998). The feasibility of floating airports, container terminals, and passenger ferry berths demonstrated that floating harbours could serve as genuine port extensions rather than temporary stopgap measures (Dessi et al., 2003; Joque et al., 1999). During this time, the keyword "analysis" began dominating the research landscape, reflecting the rise of computational modelling as a complement to physical testing.

From the late 2000s onward, floating ports research increasingly focused on integration with broader maritime logistics systems. Mobile harbour concepts and modular floating piers attracted attention as flexible responses to space limitations in coastal cities (Cho et al., 2012; Wernli and Zueck, 2008). Performance-driven studies investigated berthing impact reduction, mooring optimization, and dynamic analysis of multi-body floating systems (Chegenizadeh et al., 2015; Ma et al., 2016). This period also highlighted resilience against natural hazards, with studies on floating piers under tsunami conditions (Masuda et al., 2013).

The most recent phase, spanning the 2010s to the 2020s, demonstrates a pivot toward sustainable, multipurpose, and climate-resilient floating port infrastructure. Research on hydro-elastic responses of VLFS and modular container terminals reflects the growing ambition of floating structures to replace or supplement traditional land-based port expansions (Souravlias et al., 2020; Wu et al., 2017). Case studies from Singapore, Indonesia, and Brazil emphasize floating ports as practical responses to land scarcity and sea-level rise (Ang et al., 2020; Esteban et al., 2020; Ruggeri et al., 2017). Furthermore, sustainability-oriented studies promote floating breakwaters for tourism and coastal protection (Rahman et al., 2018). The inclusion of logistics frameworks, environmental considerations, and advanced numerical models in recent research indicates that floating harbours are no longer experimental technologies but critical solutions within port governance and maritime logistics.

In summary, the evolution of floating port and harbour research has moved from practical solutions for berthing safety and breakwaters to modular, resilient, and sustainable infrastructures designed for global logistics. The trajectory shown in the keyword map and supported by titles highlights a field that has matured into a core component of future maritime infrastructure planning.

4.3. Future Directions for Floating Ports/ Harbors

Floating elements will be integrated into hinterland logistics and terminal layouts to increase capacity, flexibility, and climate adaptability. Research should explore operational protocols, scheduling algorithms, and productivity impacts for hybrid land-floating terminals (Souravlias et al., 2020; Sung et al., 2013). Beyond hydro-dynamics, pressing questions include port governance models for mixed land-floating assets, cost and revenue allocation mechanisms, customs and inspection logistics, workforce training, and safety management. Studies on regulatory frameworks and commercial contracts will be needed to unlock scalable adoption.

Nearshore and offshore floating ports enable land-scarce or vulnerable coastlines to expand, but they require new institutional and environmental arrangements. Future work must examine jurisdictional and maritime law implications, insurance and liability for multi-actor floating systems, ecosystem impacts of anchoring and wake, and socio-economic effects on coastal communities. Research integrating ecological monitoring, adaptive governance, and participatory planning will be essential for sustainable siting and operation.

After reviewing the existing literature and prevailing definitions of seaports and inland ports, it becomes evident that the evolving logistics and infrastructural demands point toward a new categorization of port development. Accordingly, we conceptualize the future of this domain in two interrelated directions: I) offshore floating ports and II) floating solutions for onshore/nearshore port infrastructure, as defined below.

1) *A floating port (or offshore floating port) is defined as a self-contained, complex, and multifunctional maritime infrastructure built on floating or semi-submersible structures that functions as a high-capacity load breakpoint and extended gate in global supply chains. It serves as an interface between maritime and inland systems of circulation, strategically located offshore to overcome constraints of land scarcity, urbanization, and deep-water access, while providing a value-adding transit point for cargo and people flows*.
2) *Floating solutions for onshore/nearshore port infrastructure are defined as flexible and resilient floating structures (such as breakwaters, piers, berths, or specialized terminals) that are integrated into or supplementary to any conventional port development, encompassing both the upgrade of existing facilities and the construction of entirely new port sites (coastal, estuarine, or riverine)*.

These solutions serve to enhance the port's infrastructural valorization and transport and terminal efficiency. They achieve this by strategically improving the nautical profile and operational capacity of the port site, addressing challenges like constrained water depth, variable water levels, land scarcity, societal pressure, ecological challenges and climate change impacts where fixed-structure limitations apply. By providing adaptable components, they bolster the port's overall flexibility, resilience, and inclusivity within the global logistics network. These definitions are introduced here as preliminary working definitions, open for further refinement and discussion in future research.

5. Conclusion

This review demonstrates that research on floating ports remains fragmented, with construction-related studies dominating while other crucial dimensions such as management, governance, logistics, and environmental impacts are largely underexplored. The evolution of floating port research reflects a gradual yet distinct trajectory—from basic berthing safety and construction feasibility to complex, performance-driven, and sustainability-oriented infrastructures. While the technical potential of very large floating structures and modular systems is increasingly established, their integration into real-world port governance and logistics frameworks is still limited. In this context, the proposed working definitions of offshore floating ports and floating solutions for existing seaports offer a conceptual foundation for future research, helping to distinguish between large-scale offshore infrastructures and modular floating extensions within current port systems. This imbalance highlights the urgent need for interdisciplinary research that goes beyond engineering to address institutional, regulatory, economic, and social challenges. Future studies should focus on governance models for hybrid land-floating terminals, ecological monitoring of offshore installations, and the socio-economic consequences for coastal communities. By advancing research in these overlooked areas, floating ports can evolve from experimental concepts into practical, resilient, and inclusive infrastructures that address land scarcity, climate change, and the global need for adaptable maritime logistics.

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Appendix A. Mapping Technique in Vosviewer Tool

Equation 1: The association strength normalization

$$s_{ij} = \frac{2ma_{ij}}{k_i k_j} \quad (1)$$

Equation 2: The total weight of all edges in the network

$$k_i = \sum_j a_{ij} \text{ and } m = \frac{1}{2}\sum_i k_i \quad (2)$$

Equation 3: VOS mapping technique - minimization function

$$V(x_1, \dots, x_n) = \frac{1}{2}\sum_{i<j} s_{ij} \left|\left|X_i - X_j\right|\right|^2 \text{ and } \frac{2}{n(n-1)}\sum_{i<j} \left|\left|X_i - X_j\right|\right| = 1 \quad (3)$$

Where,

a_{ij}	The weight of the edge between nodes i and j. a_{ij}= 0 if there is no edge between the two nodes.
k_i	The total weight of all edges of node i
k_j	The total weight of all edges of node j
m	The total weight of all edges in the network.
n	The number of nodes in the network
x_i	The location of node i in a two-dimensional space
$\|x_i - x_j\|$	The Euclidean distances between nodes i and j

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