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Fuzzy-Set QCA on Performance and Sustainability Determinants of Ports Supporting Floating Offshore Wind Farms

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Abstract: The present study explores the relationship between the characteristics, performance, and sustainability of ports that will, in the future, support the logistical chains of new floating offshore wind farms, considering the crucial advancement and expansion of the offshore wind energy sector for the transition to a low-carbon economy. Through a detailed analysis, which includes international case studies in America and Europe utilizing expert interviews and quantitative methods through surveys, the importance of the location, new types of infrastructure and superstructure, and new planning and governance models for the performance and sustainability of ports that will be involved in this new energy industry is highlighted. Also, the context in which ports associated with floating wind turbines are located influences the performance and sustainability. This research employs Fuzzy-Set Qualitative Comparative Analysis (fsQCA), based on a survey of 22 European sector company experts, to emphasize the critical port characteristics for the performance and sustainability. This study reveals the significant contribution of supporting ports for the future floating offshore wind sector for the gross added value and the expansion of regional employment, and the need for new planning, construction, operation, and management models for ports instead of the traditional models applied to simple cargo loading and unloading ports, offering valuable new insights for port managers, policymakers, and academics. However, a future research trajectory with a more geographically diverse sample is suggested to enhance the applicability and generalizability of the results.

Keywords: floating wind offshore; port performance; port sustainability

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1. Introduction

The offshore energy sector has witnessed remarkable growth and attention in recent years, primarily driven by global concerns over energy and issues related to climate change [1]. In this context, various nations have formulated policies to explore renewable energy sources and meet the growing energy demand [2,3]. There is an increasing importance of offshore energy in addressing global energy challenges and environmental sustainability issues [1], and, on the other hand, the research clarifies the development and implementation of port policies aimed at harnessing renewable energy sources, including offshore wind energy [2,3].

In particular, the investigation, testing, and investment plans in the industry for future new floating offshore wind turbines are expanding, requiring new specialized, dedicated, and large-scale port infrastructures that are more complex than those for fixed offshore wind turbines. These are future new structures that will consume a lot of space in ports due to the size of the components, transforming large port areas into veritable factories for floating wind turbine components. Floating offshore turbines have the advantage of being installed farther from the coast, harnessing stronger winds. However, ports and terminals with specific characteristics are needed for the various phases of construction, assembly, and maintenance, with an increasing demand, and there are advantages in assembling the equipment on the land, including saving time and costs, and in considering the water depth requirements [4]. There are additional costs, expertise, and requirements for floating turbines compared to fixed structures, with a view to transitioning oil and gas operators to renewable energies in the oceans worldwide. The current focus is on the commercial exploitation of floating wind energy, which is still in the early stages of development.

Floating offshore wind structures require the international collaboration of shipyards, ports, and special installation vessels. The installation phases, particularly the maximum draft of the substructure, are affected by the construction materials, i.e., steel or concrete. Steel semi-submersible floating platforms have a shallower draft than concrete substructures and, therefore, require assembly docks with less depth. Offshore wind energy has been the subject of many studies due to its great potential for clean and sustainable energy generation. According to the literature [5], offshore wind turbines, especially the floating ones, can generate up to 50% more energy than their onshore counterparts due to the stronger and more consistent winds at sea. Globally, the potential of offshore wind energy is about 420,000 TWh per year, which is sufficient to meet approximately 18 times the current global electricity demand [6].

The installation of floating offshore wind turbines requires the support of ports with favorable locations, which, in turn, promotes new requirements and demands on port infrastructures, and thus is considered an important opportunity for investigation. There is a lack of studies addressing the factors that characterize port infrastructure for the offshore wind industry, especially for floating structures. There is little knowledge detailing the concept of a port industry able to support the development of floating offshore wind exploration. There is a shortage of updated studies on ports that ensure sustainability alongside socioeconomic conditions and performance optimization in this offshore wind industry, especially in the floating aspect. Existing studies need to be updated to reflect the latest changes and developments in the offshore renewable energy sector in terms of the technological advancement of turbines and support vessels, the increased turbine size, changes in government policies and energy goals, the infrastructure requirements of ports, and opportunities in the sector [7].

There is a gap in the research linking the importance of ports in offshore wind energy projects, especially with a cluster structure [8]. The academic literature has neglected the importance of port resources and infrastructure associated with the offshore wind energy industry. Brown et al. [9] conducted a comprehensive assessment of ports to support offshore wind farms, where they highlighted the importance of adopting specific criteria, for example, the physical characteristics of ports, the layout, and the connectivity, when selecting the most suitable location for the assembly, installation, operation, and maintenance.

The theory of port logistics with offshore wind farms emphasizes the energy efficiency, its generation potential, and the expansion to which port specialization contributes [5,6]. It also refers to the energy potential of offshore wind turbines. The growth of the offshore wind energy industry, especially in Northern European countries, implies a careful choice of ports for the installation and operation of floating wind farms [10]. In this study, the appreciation of industry experts is used to determine the relative importance of port selection criteria. For the treatment of the information and data obtained, due to the nascent stage and limited examples of floating wind projects, this study utilizes case studies from established fixed offshore wind industries. The methodology employs a thorough data analysis of the information gathered from these case studies. This study covers the various international contexts of ports in different countries and latitudes.

This study aims to understand the relationship of the characteristics with the performance and sustainability of new ports supporting the logistic production chains of the new floating offshore wind farms. The objectives are as follows: (1) to analyze the effect of the location of ports associated with floating offshore wind farms on the performance and sustainability; (2) to analyze the importance of the infrastructure of ports associated with floating offshore wind farms on the performance and sustainability; (3) to analyze the role of the superstructure of ports supporting floating offshore wind farms on the performance and sustainability; (4) to analyze the influence of the planning and governance model of ports associated with floating offshore wind farms on the performance and sustainability. The innovation of this study lies in addressing a literature gap identified by the authors, focusing on analyzing the shifts induced by the burgeoning floating wind industry in Europe and America, which places more demanding requirements on ports for the construction of large floating structures [3,4]. To address the identified literature gap, the research question is formulated as follows: What are the characteristic factors influencing the performance and sustainability of ports that support new floating offshore wind farms, thereby ensuring optimal conditions? This includes considerations of space and support for industries and assemblies, which significantly increases the complexity because everything is constructed and assembled on the port premises. The Introduction presents an understanding of the essentials of the work, including the purpose and objectives. This is followed by a literature review, structured by the essential topics of the model, the method, the analysis and results, and the discussion. Finally, the conclusions and contributions are presented.

2. Literature Review

The port industry integrates an essential logistics complex beyond the physical facilities of the ports [11]. The authors identified in this literature review consider ports integrated into complex supply chains, playing a crucial role in the overall efficiency of operations. The focus is generally on traditional ports and does not apply the concepts to the offshore wind energy industry. This industry has been the subject of considerable recent research, mainly focused on optimizing installation logistics under challenging weather conditions and on operation and maintenance (O&M) schedules. Offshore wind energy is based on the high potential availability of wind, resulting in a high number of full-load hours and the good characteristics of the offshore wind farm. An offshore wind farm refers to a power generation plant with all the necessary facilities to capture wind energy and transform it into electricity that supplies the main terrestrial electrical grid. It presents itself as a viable and promising option for the global energy matrix, requiring substantial commitment in terms of research, investment, and planning for its potential to be realized efficiently and sustainably.

The theory of port logistics points to the integration of logistics and ports with offshore wind energy [6]. It postulates that the efficient integration between shipyards, ports, and installation vessels is crucial for the successful deployment of offshore wind turbines. This integration is not only physical, but also involves the coordination of data, communication, and operational strategies. The theory of performance and sustainability for floating offshore wind energy focuses on optimizing the performance of offshore wind turbines and the sustainability of the operation, including the socioeconomic impact. On the other hand, [6] explored the global potential of offshore wind energy, estimating that it could supply about 18% of the global electricity demand. This latter work expands the scope to a more global perspective and focuses on the relevance of offshore wind energy to meet energy needs in a sustainable way. Both sets of authors provide critical information that can guide the development of infrastructure, including the decisions related to port management and logistics needed to support the offshore wind industry.

The emergence and perspective of the significant growth of floating wind farms as a viable and sustainable form of renewable energy generation have driven the demand for new specialized support infrastructures [12]. The challenges are not insurmountable, but they require a balanced approach that considers economic, engineering, and environmental aspects. For this, it is crucial to invest in research and development to optimize technology and minimize negative impacts. There are high initial costs associated with the installation of offshore wind turbines, especially those mounted on floating platforms, which allow for the exploitation of new ocean expansion areas, which can be several times more expensive than onshore installations [13]. The costs of offshore wind generation are much higher than those of onshore wind farms due to the additive cost of the transmission network to inland substations and the maintenance costs against corrosion and weather damage, raising environmental concerns such as the impact on marine ecosystems and bird migration. Moreover, there is the issue of the enormous logistical complexity and the associated support ports [14,15].

The approach to the installation of floating wind farm operations has created a model that allows for the planning of key logistical and installation aspects [16]. This method aims to preserve the coherence between logistical methods and project performance, as it is a complex problem due to the number of components that impose specific constraints in areas such as transportation and manufacturing. For the installation phase, the results highlight that the most significant criterion is the distance from the port to the offshore site. Closer ports allow for the more efficient exploitation of time windows, reducing the transportation time and cost. Furthermore, the loading capacity of the dock infrastructure and the port pavement, and the depth of the port, are also crucial factors, as the heavy components of wind turbines are assembled at these locations. In the operation and maintenance (O&M) phase, the distance to the offshore site is again the most dominant criterion. Ports that are close by are preferred to minimize turbine downtime. In contrast, the storage load capacity is rated as the least significant criterion, since the components stored during O&M are lighter compared to the installation phase.

To facilitate the installation and minimize costs, key aspects must be strategically considered, such as the type of vessels required, the distance between the assembly port and the site, and weather constraints. The assembly port should be as close as possible to the offshore installation site to minimize downtime due to weather conditions during transport. The optimization of maritime activities related to installation, operation, maintenance, and decommissioning represents a significant cost reduction opportunity [17,18].

2.1. Port Characteristics

The construction capacity of port shipyards in the floating wind sector is fundamental [4]. They must be capable of building multiple floating offshore wind turbines simultaneously, especially for commercial projects with multiple turbines. Ports need to have sufficiently robust docks to allow for side or stern loading onto heavy transport ships. Additionally, the dock depth must be sufficient to keep such a ship afloat even at low tide, with clearance under the hull. Assembly and storage are also critical factors. Ports need dry and wet storage areas for floats, blades, and towers, and must have cranes with sufficient lifting capacity for assembly operations, especially for the floats, which is the heaviest lifting operation.

Port characteristics are the primary criterion for port selection, and this outcome indicates that port conditions are influential factors in the decision-making process. Ports close to offshore wind farms and logistic centers allow for more efficient exploitation, reducing transportation time and cost. Moreover, the port needs to have the capacity to support the reception and assembly of components. Deepwater ports facilitate the assembly of floating turbines and meet the requirements of supply vessels, although they lack calm waters, deepwater ports facilitate the assembly of floating turbines and meet the requirements of supply vessels, although they sometimes lack calm waters free from significant agitation.

The staging and integration (S&I) site is a location used to receive, organize, and store the components of offshore wind energy, in addition to assembling the floating turbine system to be towed to the offshore wind energy area [19]. The manufacturing site is a port location situated on a navigable waterway that receives raw materials via road, rail, or sea transport and manufactures larger components in the offshore wind energy supply chain. Typically, this site includes buildings such as factories, warehouses, and spaces to store finished components. The operations and maintenance (O&M) site is a base location for wind installation operations, with warehouses, offices, spare parts storage, and a marine facility to support the supply of vessels and refueling and loading during the operational period of the offshore wind farm. Akbari et al. [10] used the analytical hierarchy process to evaluate and rank ports based on various criteria, such as physical attributes, layout, and connectivity. The research aimed to identify the most suitable port for installation and for operation and maintenance (O&M) tasks.

Fixed offshore wind projects lack port infrastructure, which includes a minimum access channel width of 120 m, preferably 200 m [7]. The minimum depth of the access channel should be 9 m, with 12 m being ideal. The depth at the dock should be at least 10 m, preferably 12 m. The minimum length of the dock should be 200 m, with 300 m as preferred, while the width of the dock should be at least 60 m, ideally 80 m. The dock load capacity should be at least 15 t/m^2, with more than 25 t/m^2 being ideal. Storage areas for turbines and foundations require a minimum of 15 hectares, preferably 20 hectares, 10 hectares for turbines only, and 5 hectares for foundations only. The load capacity of the storage area should be at least 7.5 t/m^2, ideally more than 20 t/m^2.

For floating wind projects, requirements include a minimum access channel width of 150 m, preferably 200 m. The depth of the access channel should be at least 9 m, 15 m as ideal. The depth at the dock should be at least 9 m, preferably 15 m. The minimum dock length for turbine assembly, it should be 300 m, preferably 600 m, and for manufacturing plus turbine assembly, it should be 600 m, with 900 m as ideal. The minimum width of the dock should be 40 m, ideally 80 m. The dock load capacity should be at least 15 t/m^2, with 50 t/m^2 as ideal. Storage areas for substructure assembly require at least 12 hectares, preferably 18 hectares, while, for turbine assembly, at least 6 hectares, but ideally 12 hectares, are needed. For manufacturing plus substructure assembly and turbine assembly, at least 34 hectares are required, with 50 hectares as ideal. The load capacity of the storage area should be at least 7.5 t/m^2, ideally more than 20 t/m^2. The water storage area, assuming 10 substructures in storage, should be at least 30 hectares, preferably 70 to 80 hectares. The draft of the water storage area should be at least 13 m, ideally 23 m [7].

It is important to conduct a detailed analysis of the different types of ports related to offshore wind energy [20]. The concept of the cluster port concentrates all activities related to wind energy in a single geographical location to save costs and to increase the efficiency, and applies to other partial concepts. The installation port concept focuses on the assembly and supply of components to offshore installation sites. The preparation port concept is like the installation port but is used for centralized assembly before transportation to the offshore site. The manufacturing port concept specializes in the production of components but without support for installation and operation and maintenance (O&M). The assembly port concept is used for the final assembly of devices, usually located closer to the offshore installation site. The base port is used to store components received from the production ports before installation. The O&M port is focused on the operation and maintenance activities. The decommissioning port is focused on the recycling and reuse of turbines and components at the end of a wind installation project's life. Finally, the super-hub port concept of the cluster implies being equipped to perform various functions, including the construction and assembly of large turbines, economically and efficiently [20].

Operationally, the quantity and type of segments of the offshore wind production chain at the port are crucial. Diversification into different segments such as base, blades, towers, support and electrical cables, assembly, transportation, maintenance, and storage can not only improve the port's resilience to market fluctuations but also increase its efficiency by allowing more integrated operations. The diversification of the phases and subphases of production, assembly, and maintenance by various distant ports or by inland locations implies inefficiency, with consequences on the sustainability and viability of offshore facilities.

2.2. Location

The logistics and maintenance of offshore wind installations necessitate the development and optimization of ports. However, the success of these new ports is not only linked to their operational capacity but also to a variety of factors ranging from the geographical location to governance models [21,22]. The port's location, for example, determines not only the logistical feasibility but also the access to skilled labor, railroads, and airports, as well as supporting industrial clusters [23,24]. On the other hand, physical characteristics such as maritime access and dock availability play a crucial role in the port's daily operations [25,26].

In developing a methodology to determine the most suitable locations for floating offshore wind energy installations off the north coast of Scotland, through the application of a multi-attribute decision analysis [27], environmental, logistical, and infrastructure factors were analyzed to choose the best locations. The selection of an ideal port for the storage and assembly of floating offshore wind energy components aims to reduce the total transportation cost [3]. Considering an ideal hub or cluster port that includes all phases of production, installation, and maintenance is an important problem in the supply chain that affects the installation of floating wind farms. These authors used a methodology applied to the Atlantic ports of the Iberian Peninsula as a case study.

The success of a port specialized in supporting floating offshore wind installations is based not only on the operational capacity but on a complex interaction of factors. Firstly, geographical location plays a crucial role. A port ideally situated within 50 to 300 km from offshore wind installation areas can significantly reduce logistical and maintenance costs. Additionally, access to nearby airport facilities, which allows for the movement of international technicians necessary for the development of this highly technological industry, and access to an available and highly qualified and specialized labor force in operations and maintenance, is vital. The presence of nearby supporting industrial clusters in the hinterland, such as metallurgy, cement, shipbuilding, electronics, and logistics, can also provide a valuable network for efficient operations. It is observed that the distance to suitable port facilities seems to have less impact on the location of offshore wind farms, indicating that more distant ports, which require less investment, may be a more economical solution [28]. The following working hypothesis is presented.

2.3. Infrastructure

The port is divided into different functional areas, such as the unloading, storage, preparation, assembly, and loading zones. An important literature reference suggests an optimized layout for a port that supports an offshore wind farm, focusing on minimizing the transportation cost of the main turbine components [29]. The physical characteristics of the port are fundamental to its performance. Waterways with a minimum depth of 12 to 15 m are essential to accommodate the types of ships used in wind installation operations. Additionally, the availability of several docks, ranging from 500 m to 2 km, equipped with high-capacity cranes, and between 60 and 200 hectares of embankment adjacent to the docks can make the difference between an efficient port and a congested port facing operational delays. This setup can accommodate the different phases and production chains of floating wind turbines, from the bases, towers, blades, support cables, electrical cables, and engines, as well as the final assembly and subsequent maintenance areas [29].

A dedicated terminal requiring high investment and ongoing management over time, considering the different phases of each country's tenders for the installation and exploitation of turbines, as well as the occupation and use of ports, should involve different operators and industries with various phases and operation chains over time (decades), with a low use of the dock in terms of loading and unloading operations, unlike traditional container terminals, but a high use and intensive occupation of the embankments adjacent to the docks, not allowing for other complementary uses. It also implies a fleet of specialized vessels and support docks for them, as well as temporary deposition areas of the bases for subsequent transportation to the deployment zone. A review of existing studies reveals various works that underscore the important attributes a base port must have to support different phases of offshore wind projects [30]. The requirements for a port in terms of installation, operation, and maintenance, in the broader context of cooperation in the North Sea, including variables such as the dock depth, ship maneuverability capacity, infrastructure for transportation, and storage of large wind components, are essential for the port's effectiveness [30]. The following working hypothesis is presented.

2.4. Superstructure

As the industry matures, there will be a high demand for different types of offshore support vessels [31]. Optimizing the use of these vessels is crucial to maintaining the competitiveness of floating offshore wind energy. Furthermore, support ports for survey and supply vessels must be available 24 h a day and independent of tides. They should provide fuel, lubricants, drinking water, and food supplies for the vessel crews. The port requirements can vary depending on the type of substructure, with semi-submersibles being required. The port's capacity can influence the substructure design choices. Lastly, minimizing the usage time of large crane ships is crucial, as these pieces of equipment are expensive. Cooper and Marrone [32] discuss the fundamental prerequisites for ports to support the development of offshore wind energy in North America. These authors also offer a brief comparison between traditional ports and those designed for offshore wind activities. Variables such as engineering and construction capabilities, special maritime transport equipment and large cranes, logistics systems adapted for wind components, and environmental and safety policies are fundamental. And Matson [33] details a proposal for a logistics port in the United States for offshore wind turbines, highlighting crucial and essential elements for port development in this sector. To achieve the economies demanded by the US market, innovative terminal handling methods and ship-loading technologies must be implemented. These technologies have already been applied in Europe and are contributing significantly to reducing the leveled cost of offshore wind energy. The following working hypothesis is presented.

2.5. Planning and Governance

The issue of governance is important, and there are different port management models [20], such as public ports, tool ports, landlord ports, and private ports. Each model has its own advantages and disadvantages, influenced by the country's socioeconomic structure, historical development, port location, and types of cargo handled. In the case of the floating offshore industry, these models must be rethought due to these specificities. The port construction model, whether public, private, or a public–private partnership, has significant implications for efficiency and sustainability. This is not a type of intensive-use infrastructure, housing industrial facilities next to the dock and the construction of large pieces and components next to the dock.

On the other hand, occupancy depends on the speed and outcomes of auctions for the installation of wind farms. Public–private partnerships often result in better outcomes due to the combination of expertise and resources, although some states develop terminals exclusively with public funding. The management structure, whether centralized or decentralized, by direct management of the port authority or through concessions of private use or public service, also has a considerable impact on operational efficiency. In terms of the concession term, long-term contracts, usually between 30 and 75 years, depending on the volume of investment and use, can be more attractive to investors and, therefore, more conducive to the sustainable development of the port, especially in this segment of non-intensive movement and whose viability can only be ensured in the long term. The following working hypothesis is presented.

2.6. Context

In the economic context, the industry could create up to 300,000 jobs by 2030 in the United States and investment in offshore wind energy in Europe could reach 60 billion euros by 2030, contributing significantly to the economy [2,34]. Castro [35] provides guidance on the essential elements a port must have to effectively support offshore wind projects. His study is based on case studies of ports in the United Kingdom, Denmark, and the United States, but does not provide a conceptual framework for an industrial port specifically designed for this purpose. In the same vein, there are infrastructural modifications required for ports to support the floating offshore wind industry, with impacts on regions and cities [36]. The Irish offshore wind industry faces several challenges, among them, the lack of public supporting ports that must be built [37]. There are various types of stakeholders involved in operation and maintenance, and port facilities are crucial for the construction and transportation of turbines, components, and technicians. Choosing a suitable port is crucial, considering the distance to the wind farm zone and the quality of the facilities.

Crowle and Thies [38] discuss the importance of energy management in ports and the role of ports in energy, focusing on the following two European ports as case studies: Hamburg and Genoa. They highlight that ports are areas of high energy demand and supply due to their proximity to energy generation facilities and metropolitan regions. In recent years, there has been an increase in the need to better understand and monitor energy-related activities in ports, driven by the increase in energy transactions, public environmental awareness, and the industry's focus on energy efficiency. Few port authorities have active energy management strategies. This is seen as a growing need, not only for efficiency, but also for sustainability and competitiveness. The ports of Hamburg and Genoa show different approaches and motivations for energy management, but in both cases, energy management is seen primarily to promote energy efficiency and conservation rather than as a potential source of revenue. The role of adjacent cities is also highlighted; in Hamburg, the city is the driving force behind energy efficiency practices, while, in Genoa, it is the port authority that takes on this role. The following working hypothesis is presented.

2.7. Performance and Sustainability

The performance of a port supporting offshore wind farms is a complex and multidimensional topic. Financial performance indicators, such as the turnover volume and the viability of terminals, are essential for assessing the profitability and sustainability of the port. A high turnover generally indicates a steady flow of activities and, therefore, a quicker return on investment. The financial viability of terminals is intrinsically linked to operational efficiency and can serve as an excellent indicator of the port's overall financial health. Efficiency in logistics is an essential part of the project lifecycle, and its costs can represent up to 20% of the total cost of wind installation. Ports, ships, and installation equipment are indispensable resources in this process. From an economic perspective, job creation and the gross added value for the region offer a glimpse into the broader impact of the port on local and national economies. Job generation not only benefits the immediate community through wages but can also have multiplier effects on the local economy. Gross added value, which includes profit, taxes less subsidies, and wages paid, is another important metric for assessing the economic impact.

The rapidly developing technology of offshore wind turbines is changing the traditional function of ports and making them more industrial and focused on sustainability [20]. The port's location, proximity to wind farm areas, and operational strategies are critical factors. There is a list of minimum requirements a port must have to support the offshore wind energy sector effectively and sustainably. In a world increasingly aware of climate change, sustainability has become a crucial pillar for any project. The port's contribution to the decarbonization process, i.e., the reduction in carbon emissions, not only helps in the climate change process but can also represent a competitive advantage in an increasingly sustainability-focused market. The studies refer to the broader supply chain requirements needed for a green transition, especially regarding offshore wind logistics, and emphasize the fundamental role of ports in this transformation [39]. Meanwhile, the literature also addresses technical aspects, such as the heavy load capacity and areas for loading and assembly, that ports must have to adequately serve this industry [40]. The regional supply chain of this industry is divided into the following five main functions: the supplier, component manufacturer, logistic service provider, port operator, and construction or installation company [20]. These functions are optimized by different companies sharing information on weather forecasting, port capacity, and ship availability for installation.

The requirements for ports supporting the offshore wind industry were analyzed for staging and integration sites [19], and an area ranging from 12 to 40 hectares is required (the same for manufacturing sites), with a minimum quay length of at least 457 m (244 m in the case of manufacturing sites). The minimum depths at the quay for support to staging and manufacturing areas should be 11.6 m, while the depths in the storage basin range from 12.2 to 30.5 m. The load capacity on quays should be 54.4 t/m^2, and the on-land load capacity for wind turbine components ranges from 9.8 to 14.7 t/m^2. For operations and maintenance sites, the required area ranges from 0.8 to 4 hectares, with a minimum quay length of at least 91.4 m. The minimum depths at the quay range from 6.1 to 9.1 m. The load capacity on the quay and on land varies from 4.9 to 24.5 t/m^2. For staging and integration sites with a unit area of 32.37 to 80.94 hectares, investments range from 589.91 to 940.66 million euros, with a planning to licensing schedule of 4 to 10 years and a construction period of 4 to 6 years. For manufacturing sites, with a unit area of 16.19 to 32.37 hectares, investments are in the range of 235.63 to 321.62 million euros, with a planning to licensing schedule of 4 to 8 years and a construction time of 4 to 5 years. Finally, for operations and maintenance sites, with a unit area of 0.81 to 4.05 hectares, costs can reach up to 7.67 million euros, with a planning to licensing schedule of 4 to 7 years and a construction period of 3 years [19].

3. Research Model and Methodology

3.1. Research Model

The research model establishes the relationship between the independent construct comprised of the location, infrastructure, superstructure, and planning and governance models, and the construct of the performance and sustainability explained by the efficiency, regional economy, and sustainability (Figure 1). The moderating construct of the context is considered, referring to the set of regions where the evaluated ports are located by country.

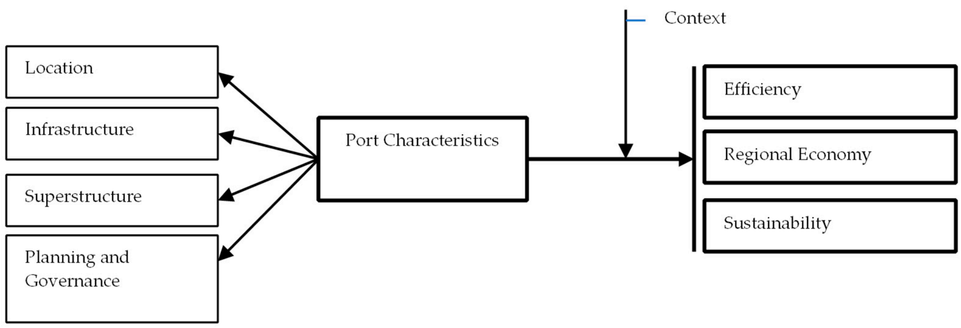

Figure 1. Research model.

Hypothesis 1. *The location of ports associated with floating wind farms influences the performance and sustainability.*

Hypothesis 2. *The infrastructure of ports associated with floating wind farms influences the performance and sustainability.*

Hypothesis 3. *The superstructure of ports associated with floating wind farms influences the performance and sustainability.*

Hypothesis 4. *The panning and governance model of ports associated with floating wind farms influences the performance and sustainability.*

Hypothesis 5. *The context in which the ports associated with floating wind farms are located influences the performance and sustainability.*

3.2. Research Variables

In the proposed research model, the main explanatory and moderating constructs (Table 1)—the location, infrastructure, superstructure, planning and governance model, and context—are crucial for assessing the performance and sustainability of ports associated with floating wind turbines. Each construct and its variables provide a detailed view of the factors influencing the operational efficiency, regional economy, and environmental sustainability of ports (Table 2). Analyzing these variables helps us to understand how ports can adapt and evolve to meet the demand of the renewable energy sector, particularly in the development of floating offshore wind farms, highlighting the importance of a strategic location, adequate infrastructure, specialized superstructure, effective planning and governance, and sensitivity to the political, socioeconomic, and environmental context.

Table 1. Independent variables.

Construct/Variable	Acronym	Authors
Location		
Proximity to wind farm facilities	Proximity	[1–10,12,13,15,16,19,20,34,35,37–41]
Access to skilled labor	Labor	[20,23,24]
Transportation infrastructure (railroads, airports)	Airport	[20,23,24]
Presence of industrial clusters	Cluster	[20,23,24,42]
Infrastructure		
Quay length	Quay	[4,7,19,20,23,30]
Depth of quays	Dept	[4,7,19,20,23,30]
Year-round quay water protection	Calmwater	Authors
Superstructure		
Load capacity of the pavement	Pavement	[4,7,19,20,23,30]
High-capacity cranes	Equipment	[7,32]
Specialized offshore support vessels	Vessels	[17,32]
Large facilities and buildings for manufacturing, assembly, and maintenance	Warehouses	[4,7,19,20,23,30]
Planning and Governance		
Adaptability of spaces for different stages of production/assembly, water storage, maintenance, and decommissioning	Flexibility	[4,7,19,20,23,30]
Available water area for the storage of floating bases	Waterstorage	[4,7,19,20,23,30]
Areas available for the construction of quays and terminals for production, storage, and assembly alongside quays, with limited environmental impacts	Areas	[4,7,19,20,23]
Availability of space for circular economy clusters	Circular	Authors
Availability of space for supply chain concentration	Concentration	Authors
Types of investment and management (public, private, and public–private partnerships)	Governancemodel	[20]
Flexibility of the governance model to accommodate different wind producers, supply chain processes, and types of activities or other loads over time	Governanceflexibility	Authors
Extended concession periods	Concessiontime	[20]
Context	Economic, Political, and Environmental Context and Local Community	[16,20,34,38]

Table 2. Dependent variables.

Construct/Variable	Acronym	Authors
Performance and Sustainability		
Efficiency impact	Efficiency	[16,19,39]
Regional economy impact	Econimpact	[20]
Sustainability impact	Sustainability	[16,20]

The location of ports is crucial, as the proximity to wind farm installation areas facilitates logistical operations. Access to skilled labor and proximity to transportation infrastructures such as railways and airports are essential for operational efficiency. Moreover, being close to industrial clusters can enhance business synergies and innovation. The infrastructure of ports, such as the depth of quays and load capacity, determines their ability to accommodate large loads, ships, and equipment for floating wind turbines. While there are no exclusive requirements that determine the absolute need for deepwater ports, Panamax ports with shallower bottoms are suitable, depending on the phases of the supply chain covered by the port, if they are compensated with the proximity and availability of areas. Calm waters at the dock all-year-round are necessary conditions for the support port, being one of the main reasons for the exclusion of outer deepwater ports. Adequate areas for large-scale storage and assembly next to the docks, even if dispersed, are fundamental for efficient operations, being one of the main reasons for the exclusion of ports without expansion areas. The adaptability of infrastructures for the different phases of production and maintenance of floating wind turbines is also crucial. Specialized superstructures, such as high-capacity cranes and offshore support vessels, are essential for handling and transporting the heavy and bulky components of floating wind turbines. Adequate facilities for manufacturing, assembly, and maintenance ensure the efficiency and safety of operations. Different planning and governance models, whether public, private, or public–private partnerships, directly influence the operational efficiency, management capacity, and long-term sustainability of ports. Choosing the appropriate model is vital for the success and sustainability of port operations. The regional context, including socioeconomic characteristics, the potential for job creation, and energy and environmental policies, affects the sustainability and social acceptance of port projects. Interaction with local communities and the broader industry is key to ensuring a balance between economic development and social and environmental responsibility.

Despite the importance of each of these variables in the model and their relationships with performance and sustainability, it is necessary to verify the trade-offs that can be made between variables, i.e., to what extent a greater dose of one of the variables and explanatory constructs may obviate or replace one of the others without impairing the performance and sustainability. For example, can a greater distance to installation sites be compensated by a higher degree of concentration of adequate infrastructures and cluster activities in a single port? Or vice versa? Can the dispersion of activities across several terminals or ports be compensated with the specialization of infrastructures and the proximity of ports or with the location of terminals in the same port? Can the lack of deep waters, provided there is a minimum of 13 m at low tide, be compensated with the proximity to installation sites and the existence of extensive expansion areas next to the docks that allow the concentration of supply chain activities in the same port? Can calm waters all-year-round and the existence of expansion areas and embankments next to the docks, where industrial clusters can be developed, compensate for shallower water depths next to the docks? Do these trade-offs justify the use of smaller ports, with calm inland waters, close to the installation sites instead of large cargo-handling ports and deep-draft ships? The construction and operation model must be flexible to ensure continuous use by different wind developers who win various national and international tenders over time, or even be prepared for the movement of other types of general cargo or bulk during pauses in wind turbine production activity.

Does this imply any specific governance model as preferable? Who should be the investor and manager of the terminal? Shipyards? Existing industries? Port operators or port authorities? Wind developers? The variables for each main construct in the research model are summarized in Table 1.

3.3. Research Methodology

The analysis for determining the results uses the following two methodologies: (a) a methodology based on the case studies of existing ports and future port projects supporting offshore wind installations in Europe and America, developed from (a1) qualitative sources from two Port of Setubal (Portugal) expert interviews, (a2) data collection of quantitative physical data from existing European port terminals for wind support, and (a3) qualitative interviews with three experts in the American future floating wind market; (b) information collected from a survey about the general perception of 22 European experts regarding the future needs of support ports for floating offshore wind turbines, quantitatively, based on questionnaires addressed to these experts in floating wind clusters and ports worldwide.

The experts approached for the survey are from 20 world-leading companies in the industry, with these anonymous communications targeted at specialists residing in Europe. For data processing, factor analysis was used to determine the constructs and modeling with Fuzzy-Set Qualitative Comparative Analysis, a methodology used in social sciences to analyze structures and behaviors in complex cases in samples of limited size.

Fuzzy-Set Qualitative Comparative Analysis (fsQCA) is a methodological approach increasingly used in various fields of research, including economy, social sciences, business studies, and environmental policy analysis, among others. It allows researchers to identify complex patterns of causality in systems characterized by configurations of multiple and interacting conditions. This method is particularly valuable for examining cases where traditional quantitative or qualitative approaches may not fully capture the nuances of causation or where the research involves limited numbers of cases that do not lend themselves to large-scale statistical analysis, as in this case [43,44]. Fuzzy-Set Qualitative Comparative Analysis (fsQCA) is ideal in this situation for several reasons, each reflecting the unique strengths of fsQCA in handling complex research questions, especially those involving the performance and sustainability of ports based on expert assessments. Ports operate within complex systems influenced by numerous factors, including the geographical location, infrastructure, superstructure, governance, and environmental policies. The fsQCA is well-suited to analyze how different combinations of these factors contribute to outcomes like performance and sustainability, embracing the complexity rather than simplifying it excessively. The perspectives of industry experts are invaluable, but they often include nuances that cannot be easily quantified or may not fit into rigid categorical variables. The fsQCA allows for the integration of this expert knowledge by treating the data as sets with varying degrees of membership, capturing the subtleties in expert opinions.

Table 3 describes the sample of 22 individuals collected through a direct survey of 44 experts located in various European countries, with a response rate of 50%. The survey contained questions about the experts' opinions regarding the importance of each variable in the relationship under analysis, using a Likert scale on the degree of importance from not important to very important. Additional more complex questions were also asked about the possibility of substituting variables by others to ensure the same performance. The sample participants are divided by age and professional activity. Regarding the participants' ages, three are under 30 years old, corresponding to 13.6% of the total; the majority, eleven individuals, are in the age range of 30 to 50 years, representing 50% of the sample; and the remaining eight are over 50 years old, making up 36.4%. As for professional activities, eight are consultants, which equals 36.4% of the sample. Two participants are port authorities, making up 9.1%. The production of specialized parts for the industry, including towers, flanges, and components for offshore wind energy, is represented by six experts, i.e., 27.3% of the sample. Other activities add up to four experts, representing 18.2%. Finally, there is one shipyard professional and one specialist in logistics for large cargo, both corresponding to 4.5% each of the total sample.

Table 3. Sample.

Age	Freq.	Weight
<30 years	3	13.6%
30 to 50 years	11	50.0%
>50 years	8	36.4%
Total	**22**	**100.0%**
Activity	**Freq.**	**Weight**
Consultant	8	36.4%
Port Authority	2	9.1%
Wind Floating Towers Production	6	27.3%
Other	4	18.2%
Shipyard	1	4.5%
Heavy Cargo	1	4.5%
Total	**22**	**100.0%**

4. Results and Discussion

4.1. European and American Case Studies

The initial findings comparing cases in European and American ports allow for the confirmation of several hypotheses. The case of the Port of Setúbal, in Portugal, which is a new case study that will play an important role in the floating wind industry in the Iberian Peninsula, regarding two experts interviewed, refers to an important example of port management that encompasses both the private sector and public–private partnership, directly collected by the authors from the experts at this port. This port plays a vital role as an infrastructure supporting the new future industry, serving as a base for the assembly, installation, and operation of offshore wind energy-related projects. With a depth of 13.5 to 17 m, depending on the tides, and an impressive quay length of 3 km, the Port of Setúbal has the capacity to support substantial loads, ranging from 10 to 50 tons per square meter. Operations at this port can be diversified, spanning from the manufacturing and assembly of foundations, towers, blades, and electrical support cables to the storage and transport of these essential components for the offshore wind energy industry. With the ability to support up to 18 offshore wind towers per year, the Port of Setúbal plays a key role in boosting the new renewable energy sector in the region. A notable feature of this port is the availability of space near the port quay, providing flexibility to handle a variety of operations. Moreover, the unrestricted air draft makes it accessible for various vessels. With over 100 hectares of potential storage area and dedicated facilities for manufacturing, preparation, assembly, and testing, this port offers a complete infrastructure for future wind energy-related activities. The Port of Setúbal can also become a center for administrative and training activities, with partnerships with universities and training centers, ensuring the development of the skills necessary for the offshore wind industry. Furthermore, its strategic location at up to about 300 km from future Portuguese wind parks makes it a focal point for the logistics of this growing industry. Governance for sustainability is a priority at this port, with compensation measures aimed at the development of the city, job creation, and a positive economic impact on the region. The Port of Setúbal is not just an example of potential excellence in this segment but also a key piece in the future advancement of offshore wind energy and the sustainable economic development of the region.

To verify the type and physical characteristics of the existing infrastructure of port terminals supporting the wind industry in Europe, an additional sample of 24 European port terminals engaged in wind offshore activity was selected and the data were collected from the ports' pages and their geographical information, with the results described below. The European offshore wind industry support ports analyzed have an average quay length of 448 m and 21.8 hectares of terminal area. These average values are indicative of the space and infrastructure needs to support offshore wind operations, which include the assembly, maintenance, and storage of bulky wind turbine components. There is notable variation in the dimensions of quays and support areas. For example, the shortest quay is 100 m, while the longest extends to 1090 m. Similarly, the terminal area ranges from 1 hectare to 87.2 hectares, demonstrating a wide diversity in the capacities of European ports to accommodate different operations related to the wind industry. The list includes 24 port terminals from various regions of Europe, such as Cork, Nigg, and Hull in the British Isles; Esbjerg in Denmark; Alborg and Ronne in Danish territory; Eemshaven and Amsterdam in the Netherlands; Oostend and Antwerp in Belgium; and Bremen in Germany. Ports from France, such as Dieppe and Caen; from Spain, such as Bilbao, Ferrol, and Seville; and from Portugal, with Aveiro, are also included. The variability in the dimensions of quays and terminals reflects the diversity in the capacities and specializations of European ports. Ports with larger quays and terminals, like Esbjerg, are better equipped to handle the larger logistical needs of the offshore wind industry. Ports with smaller infrastructures may specialize in niche activities or specific stages of the wind energy value chain. Ports located in areas with a strong presence of offshore wind activities, such as the North Sea and the Baltic Sea, tend to have larger infrastructures, reflecting the intensity of operations in that region. The port capacity to support the offshore wind industry varies across Europe, with some ports clearly positioned as leaders due to their extensive infrastructures. However, a network of ports with different capacities can be seen as a complementary ecosystem that, collectively, effectively supports the growing offshore wind energy sector.

The future governance model project data from 10 offshore wind energy ports in America, including floating farms, were also analyzed, based on interviews conducted with three industry experts in the American offshore wind industry, including information about the developers involved, specific projects, estimated costs, and the cost division between the public and private sectors. The ports analyzed for future offshore wind energy developments in the United States are in Salem in Massachusetts, New Bedford in Massachusetts, New London in Connecticut, South Brooklyn in New York, New Jersey in New Jersey, Maryland, Norfolk in Virginia, Albany in New York, Coeymans in New York, and Providence in Rhode Island. In several projects, it is evident that both public and private entities share the costs and management, for example, in Salem and New London. This indicates a choice for a collaborative governance approach and partnership to develop the necessary infrastructure. In New Bedford, the project was developed by the state of Massachusetts and later carried out by private entities. There are cases like Norfolk, where private investment predominates, but there is also an agreement for the concession of public land and infrastructure. Public investment varies significantly, with some projects receiving USD 160 million to USD 175 million. These public investments generally cover infrastructure and access improvements to support the projects. Private investment also varies, with projects receiving up to USD 200 million from private sources, reflecting the significant contribution of private companies to the development of wind energy ports. Significant investment is required to improve port infrastructure to support new developments. This includes quay expansion, land reinforcement, and access improvements. Some projects are in the initial phases, but several are developed as part of larger supply chains for specific companies. The foundations and infrastructures developed will support offshore wind energy installations. The governance models for the development of offshore wind energy ports in the US vary and depend on the level of involvement and investment of public and private entities, as well as the specific needs of each project.

4.2. Survey Results

The data analysis regarding the correlations between variables shows that the coefficient between the “waterstorage” and “concentration” variables is high, indicating a strong positive correlation. This suggests that, as one of these variables increases, the other tends to increase as well. The “governanceflexibility” variable has a strong negative correlation with the "proximity" variable, which may indicate that the greater the port's governance flexibility, the less proximity is required for offshore wind exploitation. The "vessels" variable has a very high correlation with "equipment", which is quite significant and indicates that these two areas are closely related. There are many coefficients close to zero, such as the correlation between "political context" and "labor", suggesting there is no linear relationship between these two variables. It is noticeable that some variables have both positive and negative correlations with different variables, highlighting the complexity of the interactions.

An initial analysis was conducted based on general questions reflecting the average perceptions of experts on various crucial aspects for the management and development of ports, particularly in terms of supporting operations related to offshore wind farms. The data from Table A1 in Appendix A, indicating higher agreement or perceived need, allow for the identification of priorities and trade-offs in port planning. A minimum depth of 9–13 m next to the quay is considered quite important, with an average of 6.55 on the Likert7 scale, reflecting the need to accommodate larger draft ships and wind bases, essential for efficient operations, especially in offshore wind energy contexts, where transporting large and heavy components is constant. Public investment in the port supporting offshore wind, with an average score of 5.68, is also seen as relevant, suggesting that public and state funding is crucial for the development and expansion of port infrastructures due to the high capital requirement for such projects, the long duration of financial return, and the variation in users due to various public tenders for the establishment of offshore wind farms over the concession period and in the different maritime spaces to be served by the port.

The quay's capacity to allow stern cargo movements has an average of 4.86, indicating moderate importance. This feature facilitates logistical operations and can be crucial for certain types of cargo, especially those related to the wind industry with large parts. The need for the port to have about 200 hectares of area near the quay and the port concession duration between 50 and 75 years both have an average of 4.41, which is both new and different from normal port terminal models. These factors are considered of moderate importance, suggesting that while space and long-term stability are important, there may be other more critical considerations in port planning. The concentration of the supply chain in a single port, to compensate for a greater distance to wind farms, has an average of 4.05, suggesting the perception that logistical efficiency and the proximity of suppliers can mitigate the challenges associated with distance. Interestingly, the port's efficiency as a compensating factor for the distance to wind farms has a lower average of 3.41, indicating that while efficiency is important, it may not be sufficient to overcome the limitations imposed by distance. The possibility of calm waters compensating for the lack of industry concentration in a single port has an average of 3.32, reflecting the idea that favorable maritime conditions can mitigate, but not necessarily overcome, the need for a solid local industrial base in the port. Finally, the possibility of large areas near the quay compensating for shallower quay depths is considered the least important factor, with an average of 2.95, indicating that while space is valuable, the capacity to accommodate large draft ships and floating wind turbines is seen as more critical for port operations, especially in highly specialized contexts like offshore wind energy.

This analysis suggests a new delicate balance between physical infrastructure, financial support, operational efficiency, and logistical and industrial conditions in maximizing the potential of ports to support the floating offshore wind energy industry. Clear priorities emerge, such as the importance of quay depth and public investment, while other factors, like the concession duration and compensation with large areas, play a more nuanced role in port development strategies. The analysis of port characteristics (Tables A2 and A3 in Appendix A) is based on averages that reflect the perceived importance of various attributes to optimize the performance and sustainability of ports specialized in supporting wind farms, particularly floating ones. These data provide information on infrastructural and operational priorities and needs to facilitate port efficiency in this sector. The maximum depth of quays and the maximum load capacity of the pavement, both with an average of 6.73 on the Likert7 scale, emerge as the most critical factors. These attributes are fundamental to ensure that ports can accommodate large ships and heavy equipment, essential for the transport and installation of wind turbine components. The proximity to floating wind farms and the total available length of the quay, with averages of 6.41, underline the importance of the strategic location and docking and port operation capacity. These factors are crucial for minimizing logistical costs and optimizing turbine assembly and maintenance operations.

The proximity of skilled labor, with an average of 6.09, highlights the need to access experts and trained workers for advanced technical operations, while the model of investment and flexible governance, both with averages of 5.95, point to the importance of adaptable and effective organizational and financial structures. Extended concession periods, with an average of 5.82, and calm waters all-year-round, with an average of 5.77, are also valued. These factors contribute to operational stability and safety, essential for long-term planning and risk reduction in wind energy projects. Suitable terminal areas, also with an average of 5.77, and proximity to industrial clusters, with an average of 5.55, are considered important for logistical efficiency and supply chain integration. Special facilities and warehouses, with an average of 5.23, port terminal flexibility, with an average of 5.14, and the concentration of the supply chain in the port, with an average of 5.05, reflect the need for adaptability and responsiveness. Specialized equipment and specialized vessels, both with averages of 4.91, are critical for specific operations, while proximity to circular economy clusters, with an average of 4.59, indicates a growing interest in sustainable practices and recycling. Water storage areas, with an average of 4.27, and proximity to railways and airports, with an average of 4.00, are considered less critical but still relevant for operational and logistical efficiency.

To maximize the performance of ports focused on wind energy, it is essential to invest in robust infrastructure, a strategic location, and operational flexibility, in addition to developing strategic partnerships and adopting sustainable practices. Prioritizing these factors can facilitate the efficient integration of ports into the renewable energy ecosystem, promoting sustainable growth and innovation in the sector. Table A4 in Appendix A outlines the key phases and corresponding requirements for support ports servicing offshore wind farms. Each phase, from fabrication to maintenance, is characterized by specific depth, area, quay length, and pavement specifications tailored to the tasks involved. For instance, during fabrication and integration, depths of 9 to 15 m are required, with quay lengths ranging from 300 to 600 m, and pavements rated at 15 tons per square meter (t/m^2). As the process advances to assembly, higher pavement load capacities of 15 to 50 t/m^2 become necessary to accommodate heavier components. Additionally, the water storage phase requires deeper depths of 13 to 30 m and larger areas of up to 80 hectares to house vessels and equipment. Finally, for maintenance operations, ports must maintain adequate depths and quay lengths while ensuring durable pavements capable of withstanding varying loads.

Factor analysis with varimax rotation was used to reduce the factors. The KMO value measures the sampling adequacy for the factor analysis. KMO values between 0.5 and 0.7 are considered moderately adequate, but values above 0.7 are preferable, indicating that factor analysis is appropriate. In the presented case, the KMO value is 0.547, suggesting that the sampling adequacy is moderate. Factors were extracted, and the weights (loadings) of each variable on the constructs were determined (Table 4). The weights indicate the strength and direction of the relationship between the variables and the factor. Higher weights (close to 1) suggest a strong association with the factor. In the conducted factor analysis, variables were grouped into constructs representing different aspects of port management and operability. For the Location: Offshore Activity construct, the high weight of 'cluster' (0.89) indicates that a location near a concentration of maritime-related companies is a critical factor in determining a port's relevance for offshore operations. Regarding the Location: Surrounding construct, the variables 'airport' (0.85) and 'labor' (0.79) highlight the importance of proximity to transport infrastructures, like airports, and the availability of skilled labor, respectively. These factors are essential for port efficiency and attractiveness.

Table 4. Factorial analysis.

Variable	Weight	Construct
cluster proximity	0.89 0.64	Location: Offshore Activity
airport labor	0.85 0.79	Location: Surrounding Area
dept calmwater quay	0.87 0.86 0.79	Infrastructure
equipment vessels concessiontime	0.74 0.68 0.63	Maritime Superstructure
pavement warehouses	0.88 0.71	Land Superstructure
waterstorage governancemodel areas circular governanceflexibility flexibility concentration	0.91 0.84 0.84 0.81 0.75 0.67 0.63	Planning and Governance
Econimpact Sustainability Efficiency	0.87 0.80 0.70	Performance and Sustainability

Observing the Infrastructure construct, water protection (‘calmwater’, 0.86), quay length (‘quay’, 0.79), and quay depth (‘depth’, 0.87) are all identified as fundamental elements for safe and effective port operations. The Maritime Superstructure construct is represented by the variables ‘equipment’ (0.74) and ‘vessels’ (0.68), which highlights the importance of the port’s capacity to accommodate ships, a key aspect for the movement of industry cargo. For the Land Superstructure construct, ‘pavement’ (0.88) and ‘warehouses’ (0.71) are critical for supporting on-land operations, with the pavement playing a crucial role in internal logistics and warehouses in industrial activity. The Planning and Governance construct is comprehensive, with variables such as ‘governancemodel’ (0.84), ‘areas’ (0.84), ‘waterstorage’ (0.91), and ‘circular’ (0.81) emphasizing the need for effective governance models, good management of space for industry on land and water, and for sustainable practices. Flexibility in governance (‘governanceflexibility’, 0.75) and terminal flexibility (0.67) are also highlighted, suggesting that adaptability is a valuable quality in the port environment of this industry.

Finally, the dependent construct Port Performance and Sustainability incorporates ‘Econimpact’ (0.87), showing that the economic impact of ports is a high-level consideration. Sustainability (‘Sustainability’, 0.80) is also valued, reflecting the growing importance of responsible port operation. And efficiency (‘Efficiency’, 0.70), although with a slightly lower weight, is still recognized as an important factor for overall performance and sustainability. Each of these variables, with their respective weights, plays a role in shaping the profile and evaluating the capacity and potential of a port, providing valuable information for port management and strategy.

Contextual factors act as essential moderating variables that influence a port’s ability to support the floating offshore wind industry and, consequently, its overall performance and sustainability. The economic context, rated by experts with an average importance weight of 5.18 on the Likert7 scale, is crucial, as it determines the available investment, operational costs, and market potential for wind energy. A robust economy can facilitate financing and incentives, while a weaker one may limit expansion and innovation opportunities. The political context, with the highest score of 6.00, reflects the significant influence of government policies, regulation, and institutional support. The environmental context, with a weight of 5.86, is also a fundamental moderating variable. The environmental sensitivity of the region where the port operates can affect operations, from the construction phase to the maintenance of wind turbines. Community support or resistance can affect the agility with which projects are implemented and the port's ability to operate efficiently. Harmonious relationships with the local community can facilitate operational procedures, while tensions can result in delays and increased costs. Therefore, the performance and sustainability of a port in the floating offshore wind industry depends not only on its physical characteristics and technical capacities but is significantly influenced by these moderating contexts. A port that effectively understands and navigates this multifaceted framework is better positioned to contribute to the success of the floating offshore wind industry.

From the analysis of the results in Table 5 of the Fuzzy-Set Qualitative Comparative Analysis (fsQCA), understanding that consistency refers to the extent to which cases sharing a specific condition also share a particular outcome, and coverage refers to the proportion of cases with the outcome that are explained by the condition, is crucial. Analyzing the necessary conditions in terms of performance and sustainability (fs_Performance&Sustainability) and non-performance and sustainability (~fs_Performance&Sustainability) separately, for example, fs_Location: Surrounding Area has moderate consistency (0.68) and high coverage (0.77), suggesting that this condition is relatively important for explaining performance and sustainability; fs_Location: Offshore Activity shows lower consistency and coverage (0.54 and 0.76, respectively), indicating a weaker relationship with performance and sustainability; fs_Infrastructure shows the highest consistency (0.96), with moderate coverage (0.66), standing out as a critical condition for performance and sustainability. Consistency for negative conditions (~) tends to be more varied, with ~fs_Location: Offshore Activity and ~fs_Maritime Superstructure showing the highest consistencies (0.77 and 0.84, respectively), indicating a strong relationship between these negative conditions and the absence of performance and sustainability. Coverages for negative conditions also vary, with ~fs_Infrastructure presenting the highest coverage (0.86), suggesting that the lack of infrastructure is a significant or critical factor in explaining the absence of performance and sustainability. In conclusion, fs_Infrastructure is a critical condition for performance and sustainability, given its high consistency and coverage. That is, without adequate infrastructure, there can be no port to support the floating offshore wind industry, being considered in all solutions.

Table 5. Necessary conditions—Fuzzy-Set QCA.

Condition fs_Performance&Sustainability	**Consistency**	**Coverage**	**Condition ~fs_Performance&Sustainability**	**Consistency**	**Coverage**
fs_Location: Surrounding Area	0.68	0.77	fs_Location: Surrounding Area	0.62	0.54
~fs_Location: Surrounding Area	0.59	0.68	~fs_Location: Surrounding Area	0.74	0.63
fs_Location: Offshore Activity	0.54	0.76	fs_Location: Offshore Activity	0.51	0.53
~fs_Location: Offshore Activity	0.67	0.64	~fs_Location: Offshore Activity	0.77	0.56
fs_Infrastructure	0.96	0.66	fs_Infrastructure	0.85	0.44
~fs_Infrastructure	0.19	0.63	~fs_Infrastructure	0.35	0.86
fs_Land Superstructure	0.90	0.62	fs_Land Superstructure	0.85	0.44
~fs_Land Superstructure	0.19	0.63	~fs_Land Superstructure	0.27	0.66
fs_Planning and Governance	0.68	0.77	fs_Planning and Governance	0.48	0.40
~fs_Planning and Governance	0.46	0.54	~fs_Planning and Governance	0.72	0.63
fs_Maritime Superstructure	0.67	0.85	fs_Maritime Superstructure	0.48	0.45
~fs_Maritime Superstructure	0.57	0.59	~fs_Maritime Superstructure	0.84	0.66

Note: The symbol '~' denotes the absence or negation of the condition or characteristic under examination.

Table 6 presents a truth table analysis using the Quine–McCluskey algorithm, structured into four sections, each representing different sets of solutions for the functional performance and sustainability—fs_Performance&Sustainability; solutions not covered by the literature were excluded. The algorithm is used to simplify Boolean expressions and find the most efficient way to represent a logical function. In the parsimonious solution for fs_Performance&Sustainability, the most simplified solutions are highlighted. Besides the general influence of "fs_Infrastructure" across all solutions, there are two main configurations. The first (1) is linked to assembly and maintenance port functions, "fs_Maritime Superstructure", with a raw coverage of 0.67, indicating that this condition applies to 67% of cases; a unique coverage of 0.28, showing that, in 28% of cases, this is the only applicable condition; and a consistency of 0.85, suggesting that, in 85% of cases, where the condition is true, the expected outcome is achieved. The second (2), linked to the fabrication port function, "fs_Location: Surrounding Area" and "fs_Planning and Governance", has slightly lower raw and unique coverage but higher consistency, suggesting that, although less frequent, when applied, it is more reliable in predicting the expected outcome. The total coverage and consistency of this section indicate that the solutions presented are applicable to 81% of cases with a consistency of 83%. The intermediate fs_Performance&Sustainability solution (3), linked to the integration port function phase, involves "fs_Planning and Governance" and "fs_Maritime Superstructure", with a raw coverage of 0.48 and a high consistency of 0.89, indicating that, when these combinations of conditions are true, they are very reliable in predicting the expected outcome.

Table 6. Fuzzy-Set QCA true table.

	fs_Performance&Sustainability			**~fs_Performance&Sustainability**			
Configurations fs_Performance	**1**	**2**	**3**	**4**	**5**	Freq.	Freq. Consistency
fs_Location: Offshore Activity					⊗	0.20	0.18
fs_Location: Surrounding Area		●			⊗	0.40	0.35
fs_Infrastructure	●	●	●	⊗	⊗	1.00	0.88
fs_Maritime Superestructure	●			⊗	⊗	0.60	0.53
fs_Land Superestructure			●			0.20	0.18
fs_Planning and Governance		●	●	⊗	⊗	0.80	0.70
Raw Coverage	0.67	0.53	0.48	0.64	0.44		
Unique Coverage	0.28	0.14	0.16	0.47	0.05		
Consistency	0.85	0.92	0.89	0.76	0.81		
Port support function phase	Assembly& Maintenace	Fabrication	Integration	Assembly& Maintenace	Fabrication& Assembly		
Overall Coverage	**0.73**						
Overall Consistency	**0.88**						

Note: Black circle indicate presence of a condition, circle with x indicate absence and blank space indicate don´t care condition. Consistency reflects the sample supports the solutions, coverage reflects the power of the solutions. The symbol '~' denotes the absence or negation of the condition or characteristic under examination.

In the negative parsimonious solution for ~ fs_Performance&Sustainability, the configuration (4), also linked to assembly and maintenance phases, "~fs_Planning and Governance" and "~fs_Maritime Superstructure", presents a raw coverage of 0.64, meaning that 64% of lower performance and sustainability cases imply reduced levels in planning and governance and the maritime superstructure. However, this condition has the highest unique coverage of 0.47, indicating it is the most influential singular condition in the considered cases and has a consistency of 0.76. The second combination (5), linked to fabrication and assembly port functions, has a raw coverage of 0.44 and a consistency of 0.81, and includes practically all considered explanatory variables, except for fs_Land Superstructure, which, with fs_Location: Offshore Activity, appears to have a lower explanatory degree of port performance and sustainability support for offshore wind exploration. Beyond the constant need for infrastructure, which includes maritime access funds, quay length, and calm waters all-year-round, a decisive condition for the development of all combinations of solutions for offshore wind port performance and sustainability, there are two other fundamental variables. Port planning and governance, which includes the prior existence or creation of conditions for flexibly managed areas dedicated to various phases of industrial production focused on the circular economy, integration and assembly, storage, and maintenance, and the maritime superstructure, dedicated to the loading and unloading phases of materials and the transport of wind towers and parts, and which includes terminals with sufficient concession time, with suitable equipment, as well as being prepared to receive specialized vessels that must be available for this purpose. The importance of the existence of an airport and workforce near the port is also verified.

4.3. Discussion

The best solutions in the analyses are considered those with the highest consistency and a unique coverage, as they indicate conditions that are both reliable and specific to producing the desired performance and sustainability. Solutions 1, 2, and 3 from Table 6 have the highest consistencies of 0.85, 0.92, and 0.89, respectively, indicating a strong relationship between the combination of these factors and the desired functional performance and sustainability. All variables are incorporated into at least one potential solution, yet certain solution sets have a more significant impact on the performance and sustainability. The highest scoring solution encompasses factors such as the surrounding areas of the location, infrastructure, planning, and governance, indicating that these elements collectively contribute most effectively to the desired outcomes. This suggests that the existence of essential port and industry space and land adjacent to the water and quays of sufficient size and depth, along with proper state and port authorities planning and the implementation of terminals with feasibility and investment, are crucial elements for achieving success. The overall solution has a raw coverage of 0.73 and a consistency of 0.88, indicating a good level of explanation and adequacy of the model in explaining the performance and sustainability. These solutions highlight the importance of the land infrastructure, the maritime and land superstructures, the location relative to offshore facilities, and city and international access, as well as governance and planning in functional performance and sustainability within the analyzed context. It is important to note that the relevance of each solution may vary depending on the specific context and objectives of the analysis.

The findings of the authors are confirmed [1,4], highlighting the importance of the port location to maximize the utilization of offshore wind potential, emphasizing that well-located ports facilitate logistics operations and reduce costs, corroborating Hypothesis 1, that location is a crucial factor for the performance and sustainability of ports associated with floating wind turbines. The statements discussing the need for specialized port infrastructures equipped with quays to support high-capacity cranes and support for offshore vessels to efficiently support the operations of floating wind turbines [19,32] were validated, confirming Hypothesis 2, that infrastructure is fundamental for the performance and sustainability. This confirms the hypothesis that infrastructure is important for the performance and sustainability of ports supporting floating wind turbines. The results confirm the research and the studies on port construction requirements highlight the importance of superstructures, such as the terminal pavement load capacity, maritime and land equipment and facilities for manufacturing, assembly, and maintenance, reinforcing Hypothesis 3, that superstructures play a vital role in supporting floating wind operations, and the competitivity and sustainability of ports [4,20]. Furthermore, the results confirm the research analyzing different new port management models, and suggest that the chosen governance structure can significantly impact the efficiency and sustainability of port operations in support of floating wind turbines [20]. This confirms Hypothesis 4, that proper governance and planning are crucial for the performance and sustainability of ports associated with floating wind turbines. Hypothesis 5 has also been proven, indicating that contextual factors are crucial in shaping a port's ability to support the floating offshore wind industry and its performance and sustainability [37]. Economic conditions dictate investment and operational costs, impacting the market potential for wind energy. Political context highlights the role of government policies and support, while environmental concerns address the sensitivity of operations to regional conditions. Community support can accelerate or hinder project implementation. Thus, a port's success in the offshore wind sector depends on its ability to navigate these contextual influences beyond just its physical and technical capabilities.

The geographical scope of the study is limited, focusing primarily on American and European ports. While this selection provides a diverse look at European and American ports, it potentially overlooks the varied and possibly unique characteristics of ports in other regions that are also engaging with the offshore wind sector. Expanding the geographical range could enhance the generalizability and applicability of the findings across different global contexts. Secondly, this study's reliance on a survey of 22 European worldwide industry experts, while invaluable for gaining in-depth insights, may introduce biases based on the experts' personal experiences and perspectives. Future studies could benefit from a broader and more diverse pool of respondents to capture a wider range of viewpoints and experiences, thus enriching the analysis. Another limitation is this study's focus on current port infrastructures and operations. As the floating offshore wind industry is a new sector and continues to evolve rapidly, with technological advancements and changing regulatory environments, the findings may quickly become outdated. Continuous research and updates are necessary to keep pace with the industry's dynamics and to ensure that the recommendations remain relevant and actionable. This study's methodological approach, using Fuzzy-Set Qualitative Comparative Analysis, while innovative and suited for complex case analyses, may limit the ability to capture and quantify the nuanced impacts of certain variables on port performance and sustainability. Future research could incorporate more quantitative methods or a mixed-methods approach to provide a more detailed and nuanced understanding of these relationships.

5. Conclusions

This research rigorously explored the determinants of performance and sustainability in ports supporting the specific floating offshore wind industry, filling this gap in the research and affirming the pivotal role of port characteristics such as the location, infrastructure, superstructure, and planning and governance. By corroborating hypotheses through empirical evidence and aligning with prior studies [1,4,19,20,32], our findings underscore the critical importance of strategic port location, specialized infrastructure, and robust superstructures in maximizing the operational efficiency and reducing the costs associated with floating offshore wind energy logistics. This study also elucidates the significant influence of new governance models on the sustainability and efficiency of port operations, emphasizing the need for adaptive and strategic planning to navigate the complexities of the new floating offshore wind sector. Quantitative analysis revealed that ports strategically positioned near offshore wind sites, with large expansion areas and equipped with advanced infrastructure, can achieve greater performance and sustainability. Such efficiency and results not only support the wind energy sector but also contribute to regional economic growth and job creation, enhancing the socioeconomic fabric of the surrounding communities.

The major novelty of this study was the discovery that the traditional characteristics of ports associated with the handling of bulk cargo, general cargo, or containers, or even supporting the offshore oil and gas industries or fixed offshore wind production, do not apply to the future new reality of ports supporting floating offshore wind farm operations. New models for the selection and choice of ports based on the location near the wind farms, airports, and skilled labor are crucial, requiring new characteristics for the construction of quays and terminals with larger dry areas, deep quays of significant size, and with a high capacity for heavy pieces and equipment. The construction of floating wind turbines demands the continuous production of large-sized parts in vast backlands adjacent to the quays. The choice of support ports requires the definition of completely different requirements from the usual, and ports traditionally defined as more efficient or attractive may not possess the necessary characteristics to support this new industry. Calm waters and zones to park the wind turbines in waiting at sea are required. The sector demands specialized equipment on land and at sea from companies specialized in heavy cargo. The planning and exploitation models cannot be the traditional ones. Port authorities have to consider that there will be no daily cargo movement, as with container terminals, and that the terminals will be industrial areas and shipyards with multiple users, according to the companies that win the bids for the various nearby explorations, but also the various bids for the same explorations or additional ones over the concession period. Moreover, they will have to consider adaptation to the phases of wind turbine construction, assembly and disassembly, or maintenance as potential phases without significant activity, in which terminals will have to undergo the normal movement of other port cargo to make the investments profitable, needing new concession models and new flexible concession public service requirements not based on the quantity of cargo, but on the area used at each moment, with public support flexibility in the construction, financing, and viability during the operation being very important.

However, this study is not without its limitations. The geographical focus on ports in European and American contexts suggests the need for a broader investigation across different global regions to ensure the findings' applicability and generalizability. Furthermore, the reliance on expert surveys, although invaluable, introduces potential biases that could be mitigated through a more diverse and extensive respondent pool in future research. The rapid evolution of the floating offshore wind industry, with continuous technological advancements and changing regulatory landscapes, necessitates ongoing research to maintain the relevance and applicability of our findings. This study contributes to the literature by quantifying the impact of port characteristics on the support of the floating offshore wind industry and provides actionable insights for port managers, policymakers, and academics. Looking forward, we recommend further exploration into the effects of emerging technologies on port efficiency, comparative analyses across regions, and analyses of the long-term economic and environmental impacts of floating wind turbines on port performance and sustainability. These directions promise to enrich the field of port management and support the sustainable development of the renewable energy sector, paving the way for a more resilient and low-carbon future.

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Appendix A

Table A1. Port characteristics—complementary questions.

Question	Mean
Should the port have at least 9–13 m at the quay?	6.55
Is public investment in the port a requirement?	5.68
Must quays allow stern load movements?	4.86
Should the port have almost 200 hectares of area near the quay?	4.41
Is a fifty- to seventy-five-year period of port concession a need?	4.41
Does the supply chain concentration compensate for the distance to the wind farms?	4.05
Does the port efficiency compensate for the distance to the wind farms?	3.41
Do calm waters compensate for the lack of industry concentration?	3.32
Do large areas near the quay compensate for shallower quay depths?	2.95

Table A2. Port characteristics—importance.

Variable	Mean
Maximum depth of the quays	6.73
Maximum load capacity of the pavement	6.73
Proximity to floating wind farms	6.41
Total length of the quay available	6.41
Proximity to skilled labor	6.09
Investment and governance model	5.95
Flexibility of the governance model	5.95
Extended concession periods	5.82
Calm waters all-year-round	5.77
Adequate terminal areas	5.77
Proximity to industrial clusters	5.55
Special facilities and warehouses	5.23
Port terminal flexibility	5.14
Supply chain concentration in the port	5.05
Specialized equipment	4.91
Specialized vessels	4.91
Proximity to circular economy clusters	4.59
Water storage areas	4.27
Proximity to railway and airport	4.00

Table A3. Descriptive statistics.

Variable	Mean	SD	Min	Max	Sum	Count
proximity	6.41	0.96	4	7	141	22
labor	6.09	0.87	4	7	134	22
airport	4.00	0.93	2	6	88	22
cluster	5.55	0.96	4	7	122	22
circular	4.59	1.01	3	7	101	22
calmwater	5.77	1.07	3	7	127	22
quay	6.41	0.73	5	7	141	22
dept	6.73	0.55	5	7	148	22
pavement	6.73	0.55	5	7	148	22
areas	5.77	1.31	2	7	127	22
flexibility	5.14	1.04	3	7	113	22
concentration	5.05	0.95	4	7	111	22
waterstorage	4.27	1.42	2	7	94	22

Table A3. *Cont.*

Variable	Mean	SD	Min	Max	Sum	Count
equipment	4.91	1.54	3	7	108	22
vessels	4.91	1.51	3	7	108	22
warehouses	5.23	1.60	2	7	115	22
governancemodel	5.95	1.13	4	7	131	22
concessiontime	5.82	0.96	4	7	128	22
governanceflexibility	5.95	0.90	4	7	131	22
economic context	5.18	0.85	4	7	114	22
political context	6.00	0.62	5	7	132	22
environmental context	5.86	0.83	4	7	129	22
local community	5.59	0.85	4	7	123	22
Efficiency	6.23	0.43	6	7	137	22
Sustainability	5.77	1.07	3	7	127	22
Econimpact	6.50	0.51	6	7	143	22

Table A4. Requirements per port support function phase.

Phase	Description	Quay Depth (Meters)	Port Area (Hectares)	Quay Length (Meters)	Pavement Capacity (Tons/ Square Meter)
1	Fabrication	9/15 m	30/40 ha	300/600 m	15 t/m^2
2	Integration	9/15 m	7/20 ha	300/600 m	15 t/m^2
3	Assembly and shipping	12/15 m	6/12 ha	300/600 m	15–50 t/m^2
4	Water storage	13/30 m	30/80 ha		
5	Maintenance	12/15 m	4 ha	300 m	15–50 t/m^2

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