A multi-criteria port suitability assessment for developments in the offshore wind industry

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Abbreviations

AHP, analytical hierarchy process; ANP, analytical network process; CAPEX, capital expenditure; CR, consistency ratio; ELECTRE, Elimination and Choice Expressing Reality; GBF, Gravity Based Foundations; HLV, heavy lift vessel; LCOE, levelised cost of energy; Lo-Lo, lift on/ lift off; MADM, multi-attribute decision making; MCDM, multi-criteria decision making; O&M, operations and maintenance; OPEX, operating expenditure; PROMETHEE, Preference Ranking Organisation Method for Enrichment Evaluation; Ro-Ro; roll on/roll off

Key words

Port selection; Multi-criteria decision-making; Analytical Hierarchy Process (AHP); Offshore wind; Renewable energy

1 Introduction

Renewable energy sources have gained much attention in light of factors such as surges in the world energy demand, limitation of fossil fuel reserves, fossil fuel price instability and global climate change [1]. Many countries have therefore promoted policies to support the growth of renewable energy sources and continue to increase their installed capacity. Over the past decade, wind power has experienced a sustained and rapid global development [2]. Among the renewable sources (biomass, hydropower, solar, wind, wave, tidal, etc.), wind energy is projected to have the highest share of electricity generation by 2030, providing up to 22% of total electricity generation [3]. In 2012, wind energy alone helped the EU to avoid 9.6 billion Euros of fossil fuel costs [4]. This cost saving is predicted to reach up to 27 billion Euros in 2020 [4]. By the end of 2014, a cumulative amount of 127 GW of onshore wind capacity was installed and grid connected, enough to cover 10.2 % of the EU's total electricity consumption in 2014 [5].

While the use of onshore wind for power generation has a long history, offshore wind energy is comparatively a young industry, with the first offshore wind farm established in 1991 in Denmark. The development of the offshore wind industry has been a significant trend in Europe over the past 20 years, due to its contribution to Europe's policy objectives on climate change, energy security, green growth and social progress [6]. Wind turbines placed in the sea benefit from higher speeds and steadier winds, and hence a higher capacity factor [7]. Other important advantages of offshore wind turbines are their relatively low visual impact and the fact that they do not occupy a land area, an important consideration in densely populated regions such as parts of North-Western Europe (e.g. Denmark, UK and Germany) and Japan. Current offshore wind trends show that larger turbines are being deployed (up to 8 MW), and that projects are moving into deeper waters further from shore in order to benefit from stronger wind and fewer user conflicts [8]. Europe is currently in the dominant position in terms of installed capacity with a cumulative installed capacity of over 10 GW in European waters across 82 farms in 11 countries, with the UK holding the leading position [9].

The offshore wind industry is also growing globally. In 2010, China developed its first offshore wind farm with ambitious plans to reach up to 30 GW by 2020. South Korea has also shown interest in offshore wind power with plans to reach 2.5 GW of installed capacity by 2019. Japan has targets of reaching 10 GW by 2030 and Taiwan has proposed the target of 4 GW by the end of 2030 [10]. The United States has also entered the offshore wind market with the Cape Wind and Deepwater Block Island projects, which are already commencing the construction phase [11] and there are plans for reaching a capacity of up to 54 GW by 2030 [2]. Offshore wind power has also recently been evaluated in Brazil and has been suggested as a complimentary source to the country's hydro and thermal resources [12].

Yet offshore wind is still considered as an expensive source of energy compared to other non-fossil sources. Based on the estimations of UK Department of Energy and Climate Change [13], the Levelised Cost of Energy (LCOE) for Round 3 offshore wind projects, starting in 2019 is £114/MWh. This figure is lower than that of large scale solar PV (£123 /MWh) and most biomass technologies that range from £115-£180/MWh. However, the LCOE for offshore wind projects still remains higher compared to that of onshore wind (£99 /MWh) and nuclear n^{th}-of-a-kind (NOAK) (£80 /MWh). The UK has set the target of reaching £100 /MWh for offshore wind by 2020, which should help the industry to become a more competitive source of energy with other established non-fossil fuel sources [13]. The high cost of offshore wind projects is due to several reasons including but not limited to technology uncertainty, turbulent sea conditions, high cost of subsea cables, turbines and foundations and uncertainty related to electricity production especially in the case of failures since immediate repair is not generally an option [14].

Furthermore, the installation, and operations and maintenance (hereafter referred to as O&M) phases of offshore wind projects have a considerable impact on the projects' cost. The installation of the project comprises approximately 26% of the total capital expenditure (CAPEX) and port activities, operations and maintenance comprise almost 85% of the operating expenditure (OPEX) of an offshore wind project [15]. Offshore wind farms typically have a design life of almost 25 years, starting with the process of turbine installation, followed by regular operation and maintenance during the 25 year operating period, and finally decommissioning or in some cases repowering of the turbines. A critical part of the offshore wind supply chain involves ports serving as an on-land base to support the installation as well as the O&M phases of the wind farm.

The current trend of offshore wind farm construction involves the onsite manufacturing or delivery of the components to an installation port where they are assembled and loaded on the installation vessels to be taken offshore. In order to (i) accelerate the expensive offshore installation, (ii) effectively use the limited weather windows, and (iii) reduce the number of required offshore lifts, construction companies tend to minimise the work done offshore by assembling as much of the turbine onshore (at ports) as possible [8]. For the O&M phase, the ports serve as a base from which the offshore wind farms are routinely serviced. Different requirements are placed on the ports' technical and logistical capabilities based on the role that the port plays in the installation and O&M phases of the offshore wind farm [16]. These requirements are numerous and include different criteria. For instance, installation ports preferably must be deep sea ports with a large land area sufficient for the storage and assembly of offshore wind components, whereas O&M ports must be located preferably within 200 km of the site in order to provide a fast and reliable service to the wind farm [17, 18].

Therefore, it is envisaged that a port's suitability can have an impact on the offshore wind farm's project cost, since a suitable port that optimally meets the requirements can facilitate the installation and O&M process whereas a sub-optimal port will incur extra costs and/or delays for the developers. Given the remarkable growth in the offshore wind industry, suitable ports and onshore infrastructure are in demand in order to meet the future capacity targets of the industry [19, 16].

In this paper, we answer the following questions:

a. What are the appropriate criteria to evaluate the port's suitability for undertaking the installation and operation and maintenance of an offshore wind farm?

b. What are the weights (relative importance) of each criterion/sub-criteria?

c. Which methodology is most appropriate to investigate offshore wind farm ports' suitability?

d. How can this methodology can be utilised in order to assess the suitability of ports for a given wind farm?

As the offshore wind industry expands in Europe and worldwide, the ports and onshore bases become strategic hubs in the supply chain from which all the operations of the wind farms are supported. Therefore, the selection of ports, which are logistically suitable for supporting this operation become an important issue. Given the relative immaturity of the offshore wind industry, there is a dearth in the scientific literature concerning decision support models for port selection. In this paper, we provide a detailed overview of the most critical logistical criteria for offshore wind ports. Furthermore, we are interested to understand how these criteria can be used in order to support decision making. Therefore, we first determine the relative importance of these criteria using pairwise comparison of the criteria provided by industry expert judgements. Using these pairwise comparisons, we provide a decision support model for port selection in the offshore wind sector by adopting the analytical hierarchy process (AHP) methodology; it should be noted that the standard form of AHP has been used in this paper and no methodological enhancement to the technique is proposed. . The port selection model can be viewed as a generic model and is applicable for the suitability assessment of ports for any offshore wind project.

Two main groups of stakeholders will benefit from this study; the offshore wind developers, and the port owners/operators. The first group can use this model to assess a port's logistics suitability for the installation and O&M phases of their wind farms and hence to shortlist and select suitable ports. The second group can use this model to understand the important criteria for the offshore wind sector, and also to assess their port readiness (competitiveness) for entering this sector. The application of this port selection model is then shown for the West Gabbard Wind Farm located off the east coast of the UK as an example case.

The remainder of the paper is organised as follows: Section 2 presents a brief review on the use of decision-making methods, in particular the applications of Multiple Criteria Decision Making/Analysis (MCDM/A) methods in the offshore wind industry and the port selection literature. Section 3 gives a detailed description of the research methodology. Thereafter, Section 4 presents the weights (relative importance) of each criterion/sub-criterion for the installation and O&M ports, and in Section 5, the West Gabbard case study is presented. Section 6 provides the discussion and conclusion, and suggestions regarding future research paths.

2 Literature Review

This section presents an overview of the application of MCDM in the offshore wind industry. Moreover, a literature review on container port selection using MCDM is given. Although container ports differ from the offshore wind ports, there may be some commonality in methodology that could be exploited.

2.1 MCDM in the offshore wind industry

Scholars have used MCDM for a variety of problems in the offshore wind sector. Lozano-Miguez *et al*. [20] propose a method for the systematic assessment of the selection of the most preferable support structures for offshore wind turbines. The approach uses the TOPSIS multi-criteria decision-making method (Technique for Order Preference by Similarity to Ideal Solution) for the benchmarking of candidate options. In this study, a monopile, a tripod and a jacket for a reference 5.5 MW wind turbine and a reference depth of 40 metres are compared by taking into account multiple engineering, economic and environmental attributes.

Fetanat *et al*. [21] propose a hybrid multi-criteria decision approach for offshore wind farm site selection based on the fuzzy Analytic Network Process (FANP), fuzzy decision-making trail, evaluation laboratory and fuzzy ELECTRE (Elimination and Choice Expressing Reality). This paper aims to find the best site selection of an offshore wind farm in Bandar Deylam, located in the southwest of Iran. There are six criteria considered which are the depth and height, environmental issues, proximity to facilities, economic aspects, technical resources and levels, and culture.

Jones and Wall [22] implement an extended goal-programming model for demonstrating the multi-criteria, multi-stakeholder nature of decision-making in the field of offshore wind farm site selection based on the United Kingdom future round three sites. Moreover, they discuss the strategic importance of offshore shore wind farms and the use of multi-objective modelling methodologies for the offshore wind farm sector.

Shafiee [23] studies a FANP model for selecting the most appropriate strategy for mitigating the risk associated with offshore wind farms. The model comprises four criteria/attributes namely safety, added value, cost and feasibility. The model is applied to select a suitable risk mitigation strategy with four possible alternatives (variation of the offshore site layout, improvement of maintenance services, upgrading the monitoring systems, and modification in design of the wind turbines) for an offshore wind farm consisting of thirty 2MW wind turbines.

Recently the logistics of offshore renewable energies (wind, wave and tidal) have been considered in the literature. MacDougall [24] considers the uncertainty related to infrastructure and supply chains as well as government policy, financing and environmental impacts as factors causing delays in tidal energy developments in the Bay of Fundy, Canada. It is suggested that for development of this industry, such uncertainties must be reduced via investments in infrastructure and governmental support.

Cradden *et al*. [17] conduct a multi-criteria site selection for combined offshore wind and wave platforms considering two selection criteria groups. The primary selection criteria includes minimum wind speed, minimum wave power density, depth range and minimum distance to shore. The secondary criteria group includes logistics, shipping traffic, electricity networks and environmental protection. Their analysis show that sites in the north-west, off the coasts of Scotland and Ireland, appear to be the most favourable for the combined platform, however logistics issues related to the ports for construction and O&M of such platforms could be significant limiting factors. For example when considering potential construction ports (with a draft of 9.4m and a large shipyard) within 200km distance of suitable sites, 70-90% of potential sites for such platforms are eliminated due to the unsuitability of the ports in that area.

2.2 Container port selection

In the container port selection literature, the use of MCDM is widely recognised. Ugboma *et al*. [25] use AHP to determine the service characteristics that shippers consider important when selecting a container port. The results of their study suggest that shippers place a high importance on efficiency, frequency of ship visits and adequate infrastructure while quick response to port users' needs was less significant to them. Port managers were interested in the results since the study provided essential information on the key factors that port users consider in their decision-making processes.

Based on the combined importance of quality of infrastructure, cost, service and geographical location, Guy and Urli [26] study whether the accepted rationale of port selection by shipping lines can effectively assess the selection behaviour observed in the Northeast of North America, in particular given the recent arrival of new global carriers in Montreal. They combine a multi-criteria approach with scenarios where the relative significance given to selection criteria and the performance of ports are both varied across a wide range. This approach enables the authors to assess how changes in both the criteria weight (expressing selection rationale) and evaluation (expressing relative port performance) affects port preference. Based on the common selection rationale, their findings suggest that New York is the preferred choice for shipping lines, however if the selection criteria change, then the preferred port also changes from New York to Montreal.

Chou [27] uses a fuzzy MCDM method for tackling the marine transhipment container port selection, applying the method to a number of ports in Taiwan. His findings suggest that when choosing a port, decision makers are more concerned about the volume of import/export/ transhipment containers than cost, port efficiency, port's physical attributes and port's location respectively. He recommends the port managers to increase the volume of import/export/transhipment containers and reduce their charges to be become a more attractive choice. Lee *et al*. [28] implements the AHP and proposes a decision support system (DSS) for port selection in container shipping, considering the three criteria of port infrastructure, port charge and container traffic. Their model enables port managers to obtain a detailed understanding of the criteria and address the port selection problem utilising multi criteria analysis.

Zavadskas Kazimieras *et al*. [29] investigate the combination of AHP and fuzzy ratio assessment to tackle the issue of finding a deep water sea port in the Klaipeda region in Baltic Sea in order to satisfy economic needs. Asgari *et al*. [30] study the sustainability performance of five major UK ports. The AHP method is implemented in order to rank the ports using the collected data based on a set of economic and environmental criteria. Sensitivity analysis on the obtained data is also presented in order to verify the consistency of the outcomes. In Table 1, a list of studies in which MCDM methods have been used for the port selection problem is presented. This survey shows that AHP is one of the most common methodologies in this area.

2.3 Analysis of Literature

After reviewing the literature, it becomes apparent that much of the work related to the use of MCDM methods in the offshore wind is related to offshore wind site selection. Furthermore, although MCDM has been applied to different container port selection models, it has not been used to date in the context of offshore wind port selection; therefore a gap is identified in the literature related to the assessment of onshore infrastructure and port suitability for the offshore wind industry. In this study, the use of AHP as a multi-criteria decision making model for the assessment of port suitability is proposed. The AHP has been applied in various decision making scenarios including prioritisation/evaluation, choice, resource allocation, benchmarking of processes, and quality management [76]. Its ease of use for preferential information elicitation from subject experts has made it amongst the most widely used MCDM techniques.

Among the advantages of AHP is that it structures the criteria into a hierarchy allowing for a better focus when allocating the weights. Also, the pairwise comparison of the criteria allows the decision maker to consider just two criteria simultaneously, which is argued to be an easier and more accurate way to express one's opinion rather than simultaneous assessment of all the criteria [64]. Another strength of the method is that it is able to evaluate quantitative and qualitative criteria on the same preference scale. Furthermore, the AHP provides a measure of consistency of decision making that is lacking in some of its competitor techniques [64].

Despite the wide application of AHP in various domains, the method has been subject to criticism. Perhaps the most debated of them is the rank reversal problem that first appeared in the work of Belton and Gear [75]. In many instances, the rankings of alternatives obtained by the AHP may change when a new alternative is added. Also, the preference scale and the absence of zero in the scale has been criticized by [77] and [79]. However, with reference to the key criteria of ease of usage by the decision maker, proven decision support ability in the maritime sector, and the measurement of consistency outlined above, the AHP is chosen as the most suitable methodology to capture and analyse expert opinion in this paper. Further justification and description of the AHP process is given in Section 3.2.

The principal aims of this study are to:

1) Elaborate the most important port requirements for the offshore wind industry and their relative importance for decision makers, and
2) Provide a decision making tool, enabling the decision makers/ developers to address a strategic challenge, which is selecting the suitable onshore port base for an offshore wind farm.

Table 1:Applications of MCDM methods in port selection literature

Author	Article	Methodology
Lirn *et al*. [31]	An Application of AHP on transshipment Port Selection: A Global Perspective	AHP
Ugboma *et al*. [25]	An Analytical Hierarchy Process (AHP) Approach to Port Selection Decisions- Empirical evidence from Nigerian ports	AHP

Guy and Urli. [26]	Port Selection and multi-criteria analysis: An application to the Montreal-New York alternative	AHP
Chou. [27]	A fuzzy MCDM method for solving marine transhipment container port selection problems	Fuzzy- MCDM
Chou. [32]	AHP model for the container port choice in the multiple-ports region	AHP
Kovačić, M. [33]	Selecting the Location of a Nautical Tourism Port by Applying PROMETHEE And GAIA Methods Case Study – Croatian Northern Adriatic	PROMETHEE and GAIA
Onut *et al*. [34]	Selecting container port via fuzzy ANP-based approach: A case study in the Marmara Region	Fuzzy-ANP
Ka [35]	Application of fuzzy AHP and ELECTRE to China dry port location selection	Fuzzy AHP and ELECTRE
Lee and Dai. [28]	A decision support system for port selection	AHP
Wang *et al*. [36]	Selecting a cruise port of call location using the fuzzy-AHP method: a case study in East ASIA	Fuzzy AHP
Zavadskas Kazimieras *et al*. [29]	Multi-criteria selection of a deep water-port in the Eastern Baltic Sea	Fuzzy-AHP
Sayareh and Rezaee Alizmini [37]	A hybrid decision-making model for selecting container seaport in the Persian Gulf	TOPSIS and AHP

3 Methodology

Decision makers frequently have to make decisions in the presence of multiple, conflicting criteria [38]. In order to evaluate these choices and to make the best decision, scholars in the area of decision sciences offer several methodologies including MCDM. MCDM includes methods such as, the AHP, ANP, Fuzzy set theory based decision making, Goal Programming, ELECTRE, and Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE). MCDM has seen a significant amount of use over the last several decades and its role in different applications has increased significantly, especially as new methods develop and old ones improve [39].

In the remainder of section 3, we provide a description of MCDM methods, and the main steps of formulating this research.

3.1 MCDM

MCDM comprises of a set of methods for making choices in the presence of a set of relevant criteria. These methods can be classified into two different categories namely multi-objective decision-making (MODM) and multi-attribute decision-making (MADM) [40]. MODM problems involve finding the best from a large (potentially infinite) number of potential solutions given a set of conflicting objectives.

For example, offshore wind developers may wish to minimize the turbine installation time while minimizing the installation cost at the same time. These two objectives may conflict, hence a multi-objective decision making method is proposed to find the optimal solution [41]. For example in Northern Europe, to minimise the installation cost, the installation of the turbines has to wait until the Summer when the weather is relatively calm, otherwise in Autumn or Spring the installation time of a turbine will incur more disruption due to variable weather conditions which results in an increased installation cost. Multiple Attribute Decision-making (MADM) refers to making preference decisions (e.g., evaluation, prioritization, selection) over a discrete set of available alternatives that are characterized by multiple, usually conflicting, attributes [42]. Methodologies such as AHP, ANP, TOPSIS, ELECTRE, and PROMETHEE are classified under this category. MADM ranks alternatives based on a set of discrete criteria and produces discrete solutions [43].

Let us denote x_j, j = 1…N, as a set of alternatives (choices), defined for evaluation. The objective function of each criterion, Z_i (i = 1...K), can be formulated as follows:

$$\text{Optimize } Z_i = f(x_1, x_2, \ldots, x_N), \quad \forall i = 1, \ldots, K \tag{1}$$

Assume that w_i, i = 1…K, is a set of attributes/criteria, the objective function (Z) considering all criteria/attributes is written as follows.

$$\text{Optimize } Z = \sum_{i=1}^{K} w_i \cdot Z_i \tag{2}$$

Complex problems with different objectives, information, and data can be solved by this approach. Therefore, MADM is used in this study for selecting the suitable onshore base (port) for an offshore wind site.

3.2 AHP

In order to identify the most suitable ports for each phase of the offshore wind farm and in accordance with the rationale in Section 2.3, the AHP methodology is applied. The AHP introduced by Saaty is a theory of measurement through pairwise comparison that relies on the judgements of experts in order to derive priority scales [44]. These comparisons may be taken from actual measurements or from a fundamental scale, which reflects the relative strength of preferences and feelings. The decision problem is structured in a hierarchical form with the goal of the decision at the top level, followed by the factors affecting the decision in gradual steps from the general, at the upper levels of the hierarchy, to the particular at the lower levels. When constructing hierarchies, enough detail to represent the problem as thoroughly as possible must be included. However, it is important not to include so many details that the sensitivity of the model to variation of the elements is negatively impacted. Although in practice it is difficult for researchers to clearly justify their choice of one method over the other [82], the AHP has been selected because of its practicality, ability to provide a framework for group participation in decision-making or problem solving, ease of use for stakeholders, and successful track record of use for analysing similar problems (Table 1). While in outranking methods such as ELECTRE, the process and outcome can be difficult to explain in layman's terms [39], the AHP's output is easily understood and makes intuitive sense [45]. Furthermore, whilst some MCDM methods such as PROMETHEE do not provide a clear method by which to assign weights, the AHP clearly addresses the process [39]. Furthermore, in line with the rationale of Section 2.3, AHP has gained remarkable success as decision making tool and it shows flexibility in dealing with both the qualitative and quantitative factors of a multi-criteria evaluation problem [46].

The main steps of this research are as follows:

a. Identify the main objective:

The objectives are the origin of processes in the MADM. Here in this research, we aim to select/rank the suitable port for both the installation and O&M phases of an offshore wind farm.

b. Identify criteria/attributes:

A set of criteria/attributes along with their sub-criteria related to port selection for the installation and O&M phases need to be determined. Interviews with offshore wind developers, stakeholders and port authorities were conducted to elaborate the criteria. This process will be described in more detail later in Section 4.

c. Score the weight of each criterion:

The experts compare criteria i with j in the corresponding level with respect to the goal, and calibrate them on the numerical scale (Table 3). This requires $n(n-1)/2$ comparisons for each criteria level given the consideration that diagonal elements are equal or 1, and the other elements are the reciprocals of the earlier comparisons [73]. A matrix is then formed for each criteria level using these comparisons, denoted as matrix A where a_{ij} is the comparison between criteria i and j.

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & a_{ij} & \cdots \\ \cdots & \cdots & 1 & \cdots \\ a_{n1} & \cdots & \cdots & 1 \end{bmatrix} \quad (3)$$

d. Calculate the weight of criteria

The largest eigenvalue problem is then solved to find the unique normalized vector of weights that reflect the relative importance of the attributes in each level of the hierarchy. The normalized weights of all hierarchy levels are then combined in order to determine the unique normalized weights corresponding to the final level. These relative weights are then used to accomplish the stated objective of the problem [78].

e. Determine the consistency of the judgements

An important consideration in decision-making problems is to understand how good the consistency of the judgments is, since judgements with low consistency that appear to be random are not desirable. A certain degree of consistency in setting priorities for elements or activities with respect to some criterion is necessary to get valid results in the real world. In the AHP model, the overall consistency of judgments is measured by means of a Consistency Ratio (CR) defined as:

$$CR = \frac{CI}{RI} \tag{4}$$

Where RI is called the *Random Index*, and CI the *Consistency Index* which provides a measure of departure from consistency. The consistency index is calculated as [53]:

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{5}$$

where λ_{max} is the largest eigenvalue of the matrix A and n is the dimension of the matrix. RI is the random index (i.e. the average CI of 500 randomly filled matrices). Other researchers have run simulations with different number of matrices [70]. Their derived RIs are different but close to that of Saaty's [64]. Saaty [48] has provided average consistencies (RI values) of randomly generated matrices (up to size of 11×11) for a sample size of 500. In general, a CR value of 10% or less is acceptable [48].

f. Select a set of potential alternatives:

A number of potential ports which have been involved in, or are in the development process of preparing for, the offshore wind industry have been selected. All the alternatives possess the minimum necessary requirements for supporting the offshore wind industry.

g. Collect data for each alternative related to the criteria proposed.

The potential port data is collected based on the attributes developed. The secondary data, both quantitative and qualitative, is used. The data is normalised as a criterion may have a different unit of measurement as compared to the others.

h. Calculate the final score of each alternative by using the derived criteria weights.

The final score of each port is calculated by summing the product of the normalised data and the weight for each attribute/criterion and the port with the highest overall ranking is suggested as the most suitable port.

4 Hierarchy structures and the weight of each criterion for the model

In this section, hierarchical structures for the port selection model are developed which include the criteria and sub-criteria for the installation and O&M ports. The weight of each criterion and sub-criterion is also derived based on the experts' judgements. The experts were selected from different organisations and were given two weeks to respond to the questionnaires. The response times were variable; expert 5 completed the questionnaire within a day, experts 2, 3 and 4 completed the questionnaires within 2 days, and expert 1 returned the completed the questionnaire within 6 days. The information regarding the experts, and the questionnaires are presented in Table 2 and Appendix 1 respectively.

Table 2:Experts' details

Experts	Their role	Projects
Expert 1	Senior project manager	Worked in Wind Energy for 7 years including the development of a major port based component manufacturing facility on the East coast of the UK for the last four years. Prior to that, Commercial lead for the market introduction of a specific turbine i.e. All European offshore wind projects which have achieved FID (Final Investment Decision) and are therefore in the process of supply chain tendering.
Expert 2	Renewable energy consultant	Worked with a renewable energy company writing the Bid to secure a Round 3 Development Licence from The Crown Estate and then subsequently taking the various Round 3 wind farms within the a given Project (Zone 4) through to formal Development Consent Order (DCO), including leading the socioeconomic aspects surrounding the development of supply-chains
Expert 3	Managing Director	Developed the strategy for a major British utility company round 3 project and led the selection of an O&M port on the East coast of the UK for the company's East Coast Assets.
Expert 4	Operations manager	Worked on support of the installation phases on various North Sea Wind Farms within the German Sector.
Expert 5	General manager	Worked on the design and development of a port for the Norwegian offshore wind sector.

4.1 Hierarchy structures for the port selection model

After identifying the most critical requirements of the offshore wind ports, through interviews with offshore wind developers, stakeholders, port authorities, and the available literature, hierarchies that include these elements were constructed for the two phases of installation and operations and maintenance.

For each phase of the offshore wind lifecycle a separate hierarchy was developed, as each phase requires different criteria within the port and also because even the common criteria could have different weights depending on the type of operations carried out in that port. For both phases of installation and O&M, three groups of criteria were identified including the Port's physical characteristics, Port's connectivity and Port's layout. It should be noted that these three criteria were selected since this study focuses on the logistics capabilities of the offshore wind ports related to the port's location, its ability to accommodate large size vessels and the storage and layout of the port. Hence, other criteria such as the port's environmental credentials, or technical criteria such the rated power of the turbines have not been directly included in the hierarchies

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Port's physical characteristics, including:

a. **Port's depth**: this parameter relates to the ability of the port to accommodate large vessels with deep drafts. Most of the offshore wind construction and O&M vessels have a draft of over 8 meters. Therefore, suitable ports must have adequate depth for such vessels. For the O&M phase, small workboats may also be used with a shallow draft. In addition, the port's depth is an important consideration for the manufacture of substructures such as the Gravity Based Foundations (GBFs) at the port. For example for the manufacture of a GBF for a water depth of 25m, the port depth should be a minimum of 7.5m [81].

b. **Quay length**: this parameter is associated with the vessels' overall length. Offshore wind vessels are necessarily long, with some construction and O&M vessels for the offshore wind installation phase often exceeding 200m in length.

c. **Quay loadbearing capacity**: the bearing capacity is defined as the ability of the ground surface to support the weight of a specific component. The soil bearing capacity is the maximum bearing pressure that soil can support before failure occurs. A ground bearing capacity of 15 - 20 tonnes /m^2 is identified as suitable by the industry [16] [49].

d. **Seabed suitability**: the port's seabed suitability refers to the ability of the port's seabed to accommodate jack up vessels. The seabed must be prepared to support these vessels during the loading and unloading phases.

e. **Component handling equipment** (Ro-Ro, Lo-Lo, heavy lifting equipment i.e. cranes): ports need to have sufficient equipment to handle components such as nacelles, blades and towers. While some of these components are loaded using lift-on lift-off (Lo-Lo) or roll on-roll off (Ro-Ro) type of vessels, the availability of heavy lifting cranes is also needed at the ports [49].

Port's connectivity, including:

a. **Distance from the wind farm**: this parameter is associated with the distance from the port to the given wind farm, since it has a direct effect on the time and cost of the installation and O&M phases.

b. **Distance from the key component suppliers**: large offshore wind components have to be taken from their place of manufacture to the installation ports, where they are stored or assembled prior to offshore installation. Furthermore, fixed offshore wind foundations such as the Gravity Base Foundations are preferably fabricated at the ports, and floating offshore wind platforms, can be built at large shipyards [17]. The Port's distance from the manufacturers' and suppliers could affect the cost of transportation.

c. **Distance from road networks**: for transportation of some of the turbine components, the ports must have access to road networks. Components such as blades have been transported via roads from their place of manufacture in some offshore wind projects. Vehicles such as trucks, SMPTs and low-loader trailers are used for transporting the components and subassemblies [72]. Based on [63] for a reference turbine of 3MW, the road running lane width on straight roads must be a minimum of 5.5 m. The horizontal clearance around the access and site roads must be increased from 5.5m to 11m when a crawler crane is used.

d. **Distance from heliports**: This parameter is considered only for the O&M phase. Helicopters are used to service the turbines during certain types of inclement weather conditions as they provide fast access compared to the workboat solution [50].

Port's layout, including:

a. **Storage space availability**: components delivered to the port need to be stored for later assembly. In order to support the routine inventory at the port, a large storage area is required. The port's layout should be in a way that the storage area is in direct connection with the pier front area in order not to transport the components too far or for too long during storage, preassembly or loading [51]. The storage area criteria also includes the sub-criteria of open storage area, covered storage area and storage load bearing capacity.
b. **Component manufacturing facility availability**: this parameter is considered only for the installation ports. In order to reduce the component transportation cost, and avoid multiple loading/unloading, locating turbine manufacturing facilities at the installation ports is proposed where the components can be shipped to the site directly from the ports. Some existing European ports including Bremerhaven and Cuxhaven in Germany have adopted this strategy and they have established turbine manufacturing facilities located at the port. This is also taking place at a number of the UK ports such as the Greenport Hull project, which are in the development stage of building turbine manufacturing facilities within the port [52].
c. **Component laydown (staging) area availability**: this parameter is considered only for the installation ports. This area is particularly important at installation ports, since some components that are delivered to the port need to be assembled prior to the installation phase, e.g. towers could be delivered to port in two pieces, but they might be assembled and loaded on the installation vessel as one single piece. This criterion includes the sub-criteria of lay down area and laydown's area access to quayside.
d. **Workshop area**: This parameter is considered only for the O&M ports. The workshop area is the area in the O&M ports in which repairing of broken or faulty components take place.
e. **Office facilities**: This parameter is considered only for the O&M ports. Office facilities must be available at O&M ports, since these ports are responsible for daily operations and maintenance activities of the wind farm and the human resource and control rooms are based at the O&M ports.
f. **Potential for expansion**: selecting and investing in a port facility is a long term strategic decision for offshore wind developers and ports that offer the potential for expansion are considered more desirable as opposed to ports with restricted growth potential.

Figure 1 presents the hierarchy structures for the installation port. The model consists of 3 levels where

a. Level 1 includes three criteria namely the port's physical characteristics, the port's connectivity, and the port's layout.
b. Level 2 is divided into three levels (Level 2A, Level 2B, and Level 2C). Level 2A contains the sub-criteria of port's physical characteristics including quay length, port depth, seabed suitability, quay load bearing capacity, and component handling equipment. Level 2B contains the sub-criteria of port's connectivity, which comprises of the distance from wind farm, distance from road networks, and distance from key component supplier and level 2C comprises of the sub-criteria of port's layout, which consists of storage area, manufacturing facility, component laydown area, and potential for expansion.

c. Level 3 is divided into three levels (Level 3A, 3B and 3C). Level 3A comprises of the sub-criteria of component handling equipment and comprises Ro-Ro, Lo-Lo, and heavy cranes. Level 3B comprises of the sub-criteria of storage area, which includes covered storage, open storage, and storage load bearing capacity. Level 3C comprises of the sub-criteria of laydown area availability and includes the sub-criteria of laydown area and laydown area's access to quayside.

The installation model for our case study in Section 5 will assess the suitability of five North Sea ports (shown in Figure 6), all of which have previously been involved in the offshore wind sector or are at the development stage of being involved in this industry. These ports are Port of Oostende located in Belgium, involved in Thornton Bank Phase 1, 2 &3, and Belwind Alstom Haliade demonstration project; Hull-ABP located in the UK, involved in Lincs project; Harwich Navyard located in the UK, involved in Greater Gabbard project; Great Yarmouth located in the UK, involved in Sheringham Shoal, Scorby Sands, Lincs, and Dudgeon projects; and Humber-ABLE UK, located in the UK which is in the development stage to serve the offshore wind market.

Figure 1: Hierarchical structure for Installation port

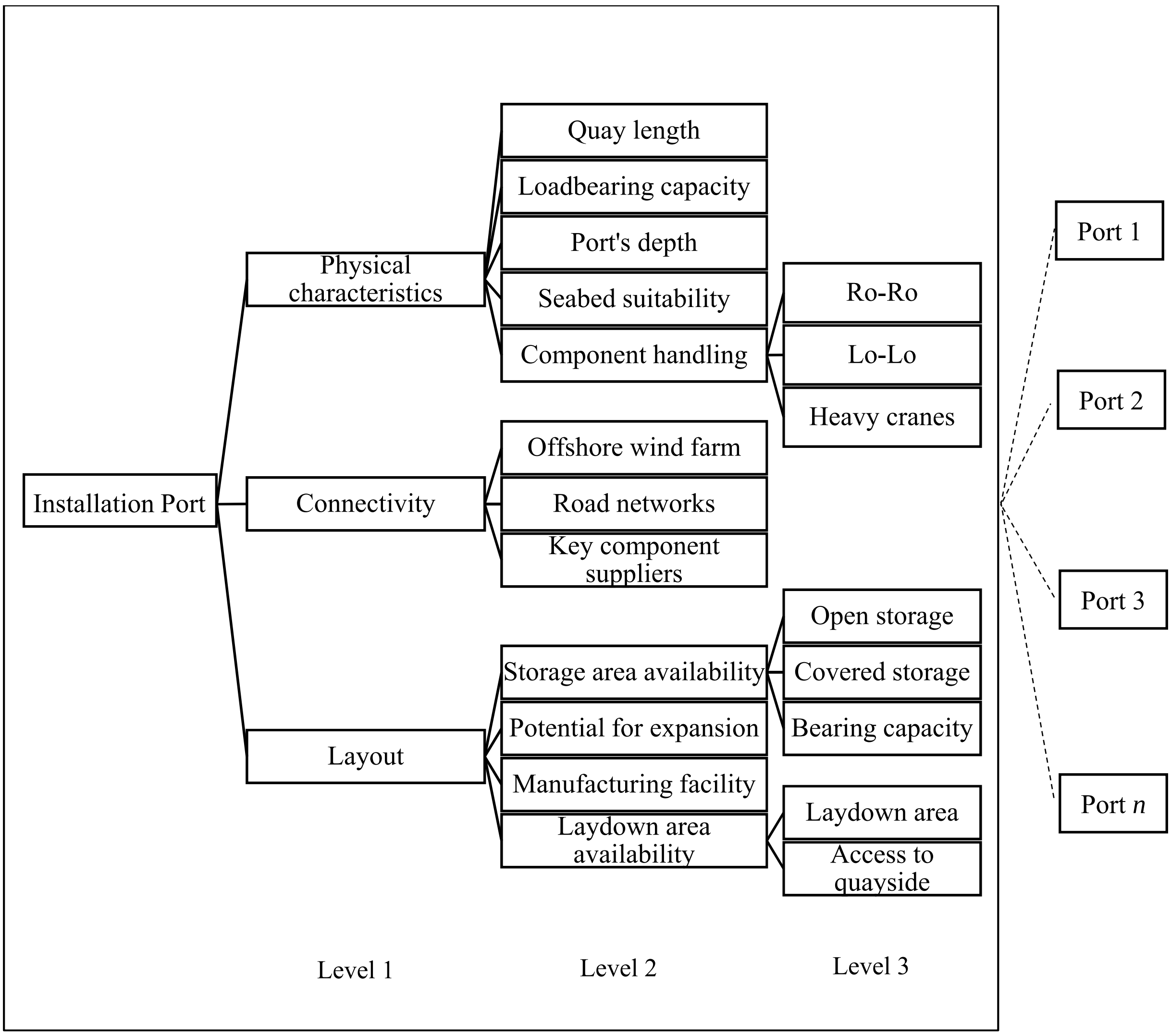
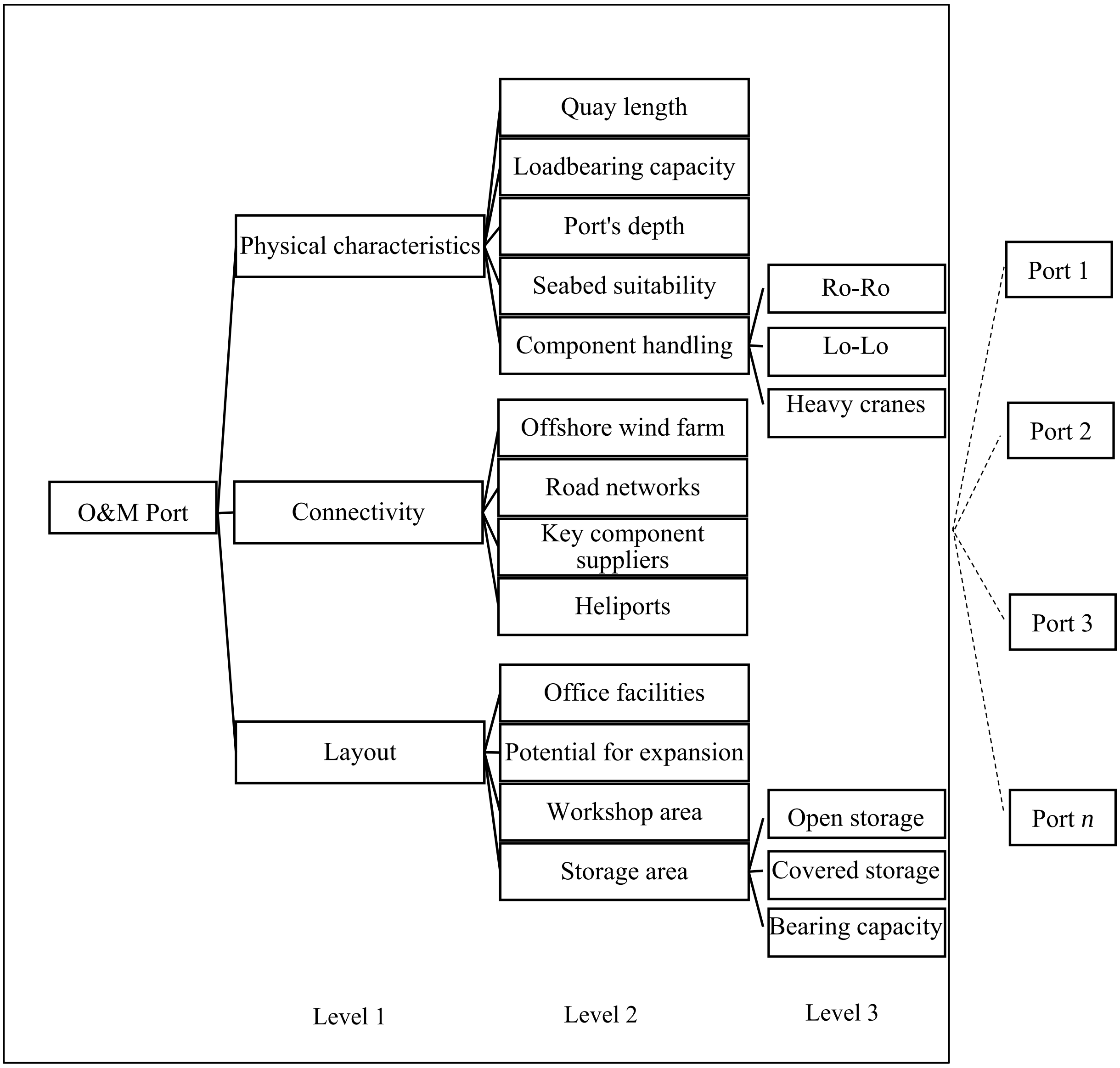


Figure 2 shows the hierarchical structures for the O&M port. The hierarchical structures for an O&M port are similar to those for installation port except that there are additional criteria in some levels. In Level 2B, a sub-criterion, distance from heli-ports, is added and Level 2C now includes storage area, workshop area, office facilities and potential for expansion. In the case study (Section 5), four O&M ports are assessed which either have been involved in servicing the offshore wind farms or offer their services to the sector. These ports include Port of Lowestoft involved in Greater Gabbard project; Port of Ramsgate, involved in Thanet, Kentish Flats Extensions, and London Array projects; Grimsby-ABP involved in Humber Gateway project; and Port of Sheerness, which offers development land for offshore wind use.

Figure 2: hierarchical structure for O&M port



4.2 The weight of the port criteria

In this subsection, the weight of port criteria based on the judgement of the experts are presented. The pairwise comparison of the port criteria is used to calculate the weight based on the steps specified in Section 3.2. The AHP can be effectively applied within a group, where sharing opinions and insight often results in a more complete representation and understanding of the problem, which may not be fully attained when involving a single decision maker [53]. The use of questionnaires has also been suggested as a means of taking individual opinion, the method that is used for this study. For this study, five respondents are chosen, all of which holding senior positions in their respective organisations. The experts are chosen from a range of industries including offshore wind port management, renewable energy consulting, offshore wind O&M consulting, offshore wind turbine manufacturing, and offshore wind farm development (including installation and O&M). In order to conduct the pairwise comparison of criteria, a questionnaire containing all the pairwise comparisons were sent to all five experts. The experts were asked to conduct the pairwise comparisons and give a score based on the values in Table 3. The final values of the questionnaires are derived from the geometric mean of the judgements, e.g. the geometric mean of 1,3,9 is 3; meaning that the first criterion is weakly more important than the second one, according to the AHP comparison scale (Table 3). Adopting the geometric mean method is recommended in order to preserve the reciprocal property [71]. Based on the scale provided in Table 3, the value 1 implies the equal importance of criteria i and j, and 9 implies extreme preference of criteria i against criteria j. All the values in between are equally spread between these two extremes. Based on the AHP review paper by Ishizaka and Labib [64], the 1-9 scale is based on psychological observations by Fechner [65] and Stevens [66] and its use by far dominates all the other scaling methods. The choice of "best" scale however is a debated topic among scientists, and other scales such as quadratic and root square scale [67], geometric scale [68], balanced scale where the local weights are evenly dispersed over the weight range(0.1,0.9) [69] have been proposed in the literature.

Table 3: The comparison scale in AHP method [53]

The value of the scale	Importance levels
1	The first and the second criteria are equally important
3	The first criterion is weakly more important than the second one
5	The first criterion is strongly more important than the second one
7	The first criterion is very strongly more important than the second one
9	The first criterion is absolutely more important than the second one
2, 4, 6, 8	Give the intermediate values

After receiving the completed pairwise comparison of port criteria questionnaires from all five experts, the criteria weight and CR values were obtained by using an open access AHP Excel template [54]. The results clarify the importance of each criterion for different phases of the offshore wind farm and give a better understanding of the requirements in the ports which have the highest relative significance for supporting the offshore wind industry.

4.2.1 Installation port

In most offshore wind projects, the components cannot be directly shipped from the manufacturing facility to the offshore site. Instead, they are first delivered to an installation port where the components are pre-assembled and stored, before loading onto the vessel and transferral to the offshore wind farm site [55]. Completing as much of the operations onshore as possible saves time and money during the installation phase, and it is independent of offshore wind and wave conditions [56]. Therefore, the installation ports play a key role in the development of offshore wind farms. Table 4 shows the weight of the criteria for an installation port based on the steps explained in section 3.2.

Table 4: Criteria weight for installation port

Criteria	Weight		
Port’s physical characteristics	0.483		
Seabed suitability		0.201	
Component handling		0.130	
Lo-Lo capability			0.596
Ro-Ro capability			0.102
Heavy cranes			0.302
Quay length		0.145	
Quay load bearing capacity		0.287	
Port's depth		0.236	
Port’s Connectivity	0.275		
Distance to offshore site		0.706	
Distance to key component supplier		0.186	
Distance to road		0.109	
Port’s layout	0.242		
Potential for expansion		0.257	
Component laydown area		0.334	
Component laydown area			0.654
Laydown area access to quay side			0.346
Storage		0.289	
Storage load bearing capacity			0.599
Open storage area			0.300
Covered storage area			0.101
Component fabrication facility		0.121	

The values in Table 4 suggest that for an installation port the port’s physical characteristics with weight 0.483 are more important than the port’s connectivity (0.275) and the port’s layout (0.242). For the port’s physical characteristics, quay load bearing capacity is the most important sub-criterion, having a score of 0.287. The distance to the offshore site and the component laydown area availability are found to be the most important factors for the port's connectivity and port's layout criterion respectively.

Experts from different sectors possessed different opinions. For the installation phase, four out of five experts ranked the physical characteristics of the installation port as more important than port's connectivity. However, the expert from the turbine manufacturing company has ranked the port's connectivity higher than the port's physical characteristics. This difference in opinion could arise from the fact that, for turbine manufacturing, access to the suppliers, road networks and the wind farm are more significant than other two factors. In the comparison between the port's connectivity and port's layout, three experts have ranked the former more important than the latter, one expert has ranked them equally important and the expert from renewable energy consulting, have ranked the port's layout more important than the port's connectivity for the installation phase.

In the port's physical characteristics category, experts ranked the quay load bearing capacity as the most important factor followed by the port's depth, port's seabed suitability to accommodate heavy jack-up vessels, quay length, and component handling capabilities. The high score of the quay load bearing capacity criterion, suggests that if ports are willing to enter this industry, one of their priorities could be strengthening the quay's surface to be able to support high loads of components such as nacelles and foundations. In level 3A, the Lo-Lo capability has the highest significance compared to the other two factors.

In the port's connectivity category, the port's distance to offshore site had the highest significance followed by the port's distance to key component suppliers and distance to the road networks. This confirms the fact that the installation port's distance from the wind farm is significant from the developers' point of view.

In the port's layout category, the result of the pairwise comparison shows that experts have not placed a high importance on the availability of manufacturing facilities at the ports, but they have ranked the availability of the laydown area at the port as the most significant factor followed closely by storage area and potential for expansion. In level 3B, the storage load bearing capacity has been ranked as the most important factor which is due the fact the turbine components and foundations exert a very high load on the ground and it is important for the storage area as well as the quayside to have a high load bearing capacity. In level 3C, the laydown area was considered more significant than its access to quayside, which could be related to the fact that the port must have adequate space for the assembly of the components.

Table 5 shows the consistency ratio (CR) of each criteria level of the installation port. On average, the CR value is within the limits suggested by Saaty [48] which is 10%. However, in Level 1, it is above the recommended limit, although not at a level that invalidates the analysis. Table 6 and Figure 3 present the final weight of each sub-criterion. The most significant sub-criterion is the port's distance from the offshore site (0.193). This result suggests that the port's distance to the wind farm is a significant factor in the decision-making process, since the ports located closer to the wind farm allow weather windows to be exploited more efficiently and the transportation time and cost will hence be reduced. Ro-Ro capability in the ports has been ranked the least significant factor and this could be due to the fact that in the installation process, typically heavy lifting vessels (HLV) are used.

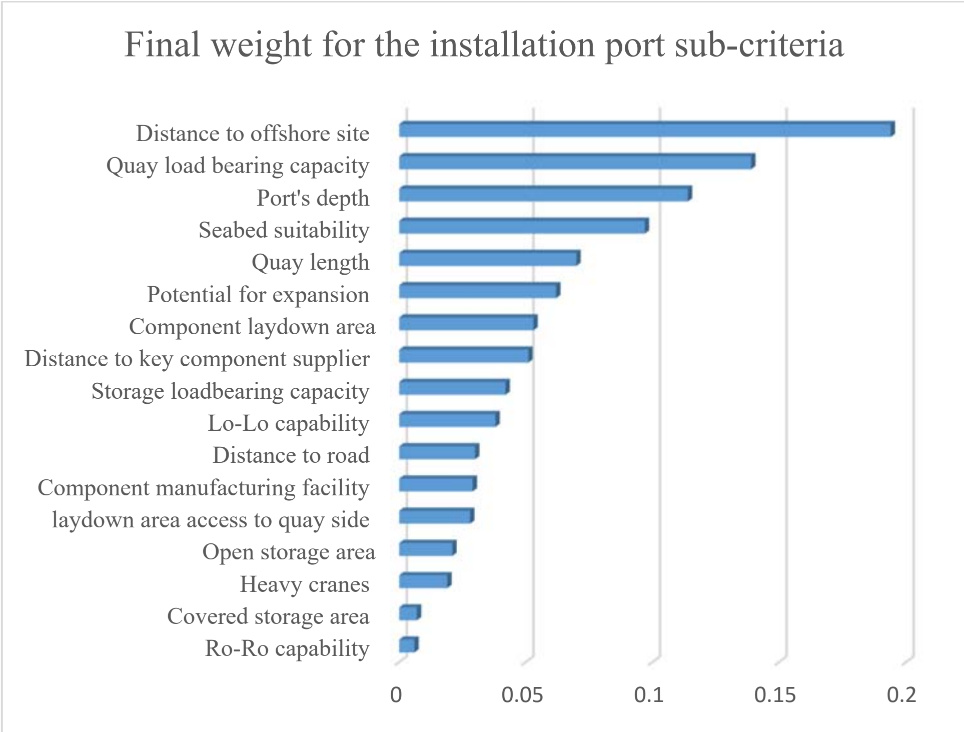
Table 5: Consistency ratio of each criteria level for installation port

Level	Consistency Ratio (%)
1	16.3
2A	1.7
2B	0.2
2C	2.1
3A	7.7
3B	6
3C	0
Average consistency of the matrices	4.8

Table 6: The final weight of the sub-criteria for installation port

No	Sub-criteria	Priority Weight	Rank
1	Seabed suitability	0.097	4
2	Lo-Lo capability	0.038	10
3	Ro-Ro capability	0.006	17
4	Heavy cranes	0.019	15
5	Quay length	0.07	5
6	Quay load bearing capacity	0.139	2
7	Port's depth	0.114	3
8	Distance to offshore site	**0.194**	**1**
9	Distance to key component supplier	0.051	8
10	Distance to road	0.030	11
11	Potential for expansion	0.062	6
12	Component laydown area	0.053	7
13	laydown area access to quayside	0.028	13
14	Storage load-bearing capacity	0.042	9
15	Open storage area	0.021	14
16	Covered storage area	0.007	16
17	Component fabrication facility	0.029	12

Figure 3: Final weight for the installation port sub-criteria



4.2.2 Operations and maintenance (O&M) port

Operations and maintenance of the wind farm is the longest of all the phases as the wind farm needs servicing during its entire design life. Developers normally look for ports that are willing to commit to this long period and provide regular service to the wind farm. Operations consists of activities such as remote monitoring, control, electricity sales, coordination, and back office administration of the wind farm operations which represents a small share of O&M expenditure. On the other hand, maintenance activities including the upkeep and repair of the physical plant and system has the largest share in the overall cost, risk and effort of the O&M phase [50]. Table 7 shows the weight of the criteria for an O&M port. For the O&M port, the port's connectivity was ranked the highest in terms of significance, followed by the port's physical characteristics and lastly the port's layout.

Three out of five experts have ranked the port's connectivity more important than the port physical characteristics, while two experts (from renewable energy consulting and O&M consulting) had the reverse opinion. Four out of five experts have considered the port's connectivity more important than the port's layout. Also, the port's physical characteristics were considered more important than the port's layout by four experts.

Table 7: The weight of O&M port criteria

Criteria	Weight		
Port's physical characteristics	0.328		
Seabed suitability		0.039	
Quay length		0.088	
Component handling		0.227	
Lo-Lo capability			0.502
Ro-Ro capability			0.117
Heavy cranes			0.381
Quay load bearing capacity		0.560	
Port's depth		0.086	
Port's Connectivity	0.503		
Distance to offshore site		0.645	
Distance to key component supplier		0.105	
Distance to road		0.086	
Distance to heliport		0.163	
Port's layout	0.168		
Storage		0.269	
Storage load bearing capacity			0.176
Open storage area			0.188
Covered storage area			0.636
Workshop area for component repair		0.246	
Potential for expansion		0.145	
Office facilities		0.339	

In the port's physical characteristics category, the port's quay load bearing capacity was ranked the most important, followed by the component handling capabilities, quay length, port's depth, and seabed suitability for jack-up vessels.

In the port's connectivity category, the port's distance to the wind farm was ranked significantly higher than the port's distance to a heliport, distance to key component suppliers and distance to road network, which are the second, third and fourth respectively in terms of importance.

For the port's layout category, the availability of office facilities was ranked the highest, followed by the storage capacity, workshop area for component repair and potential expansion opportunities at the port. In level 3B, the covered storage area ranked the highest followed by the open storage area and the load bearing capacity.

Table 8 presents the consistency ratio (CR) value of each criteria level for an O&M port which is within the recommended limit. Table 9 and Figure 4 provide the final weight of each sub-criterion for the O&M port.

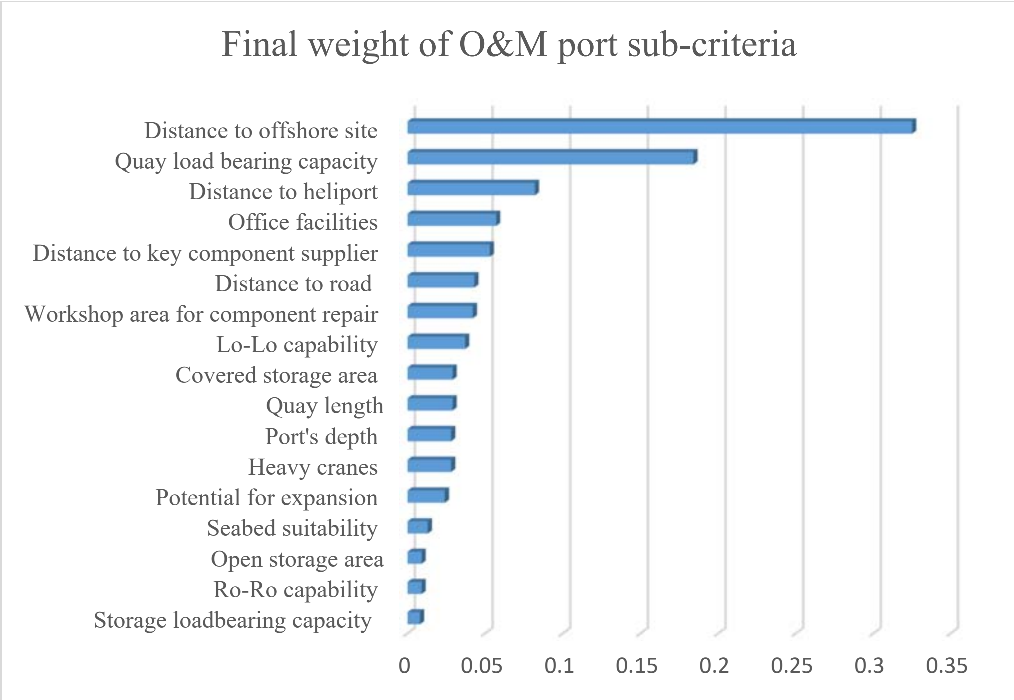
Table 8: Consistency ratio of each criteria level for O&M port

Level	Consistency Ratio (%)
1	0.1
2A	2.5
2B	1.1
2C	2.9
3A	1.4
3B	0.1
Average consistency of the matrices	1.35

Table 9: The final weight of the sub-criteria for O&M port

No	Sub-criteria	Priority Weight	Rank
1	Seabed suitability	0.013	14
2	Quay length	0.029	9
3	Lo-Lo capability	0.037	8
4	Ro-Ro capability	0.009	15
5	Heavy cranes	0.028	11
6	Quay load bearing capacity	0.184	2
7	Port's depth	0.028	12
8	Distance to offshore site	**0.325**	**1**
9	Distance to key component supplier	0.053	5
10	Distance to road	0.043	6
11	Distance to heliport	0.082	3
12	Storage load bearing capacity	0.008	17
13	Open storage area	0.009	16
14	Covered storage area	0.029	10
15	Workshop area for component repair	0.042	7
16	Potential for expansion	0.024	13
17	Office facilities	0.057	4

Figure 4: Final weight for the O&M port sub-criteria



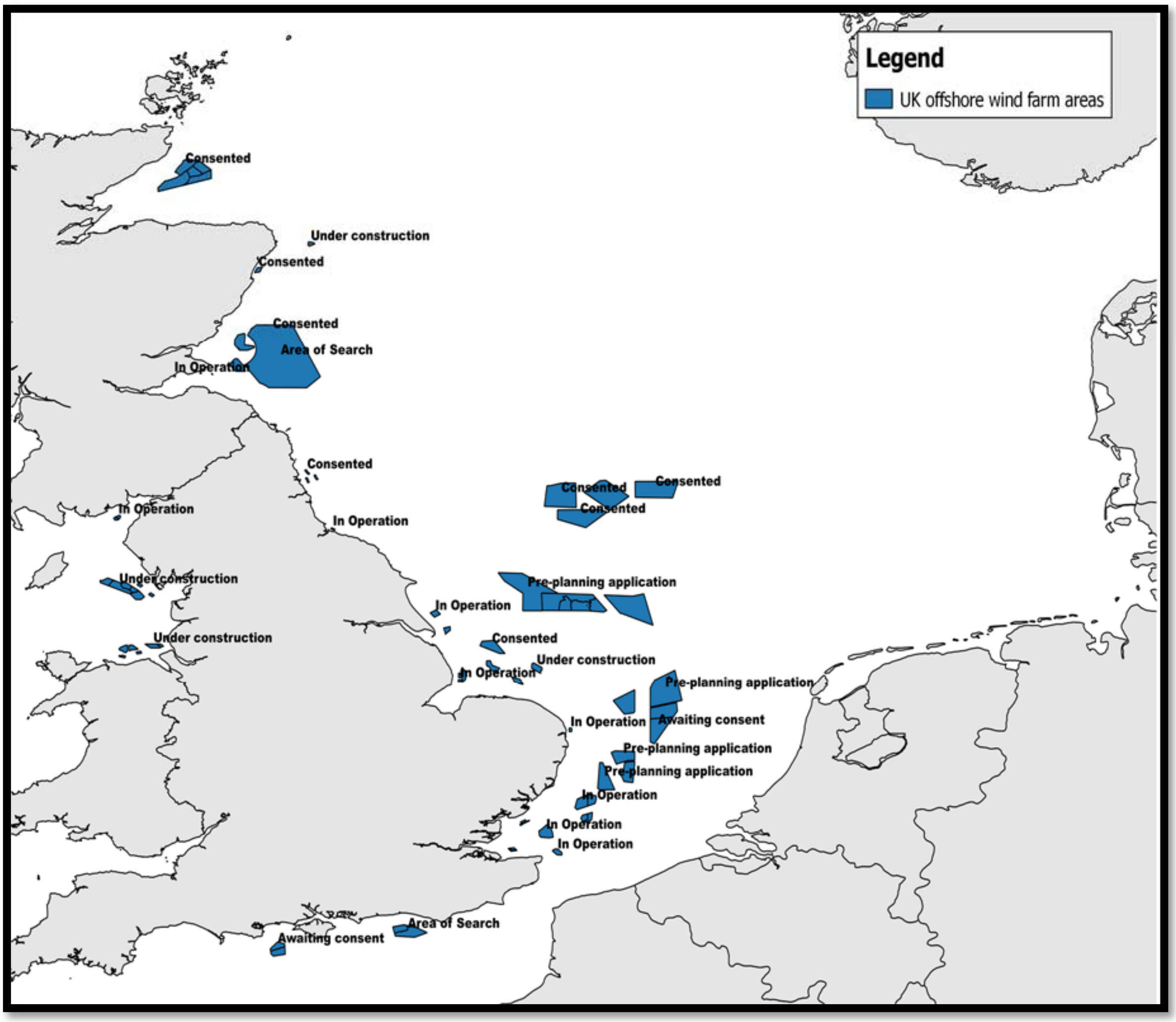
Similar to its counterpart, the installation port, the distance from the offshore site is also the highest importance sub-criterion (0.324). The value of this sub-criterion in an O&M port is higher than the one of the installation port. This could be due to the fact that an O&M port is used for daily operation, and repeated trips to/from the wind farm; therefore, cost and downtime will be reduced if the O&M base is close to the wind farm. The storage loadbearing capacity is the least important sub-criterion as the spare parts for O&M are relatively not heavy.

5 Case application

5.1 Problem Definition

The map given by Figure 5 shows the offshore wind farms located the UK waters that are either in the pre-planning stage, consented, under construction, constructed or in operation. As shown, there is a high concentration of wind farms in the southern part of the North Sea. For this case application, we define the problem as the decision maker's choice of selecting the most suitable port for a specific offshore wind farm, namely the West Gabbard wind farm located in southern part of the North Sea (details of the wind farm are presented in Table 10). For this example, the candidate ports for the installation phase include the port of Oostende, Harwich Navyard port, the port of Great Yarmouth, the port of Hull-ABP and ABLE UK-Humber port. The candidate ports for the O&M phase include the port of Sheerness, the port of Lowestoft, the port of Grimsby and the port of Ramsgate. The application of the methodology developed in Sections 3 and 4 aids the decision maker to select the most suitable port from a number of ports with potentially similar attributes.

Figure 5:Map of UK offshore wind farms[61]



5.2 Data

The AHP method has been used to rank a number of candidate ports on North Sea's coastline for serving the offshore site for the installation and O&M phases for an offshore wind farm located on the east coast of the UK (Table 10). For this example, the ports were selected based on achieving minimal thresholds on the following criteria:

a. The port's proximity to the site: All the ports selected for this example are within 300 km from the offshore wind farm based on the expert opinions and Cradden, et al. [17]. Furthermore,

1. Proximity to the offshore site will reduce the transfer time from the port to the site
2. Proximity offers the most cost effective option for vessels in terms of fuel and consequently the carbon footprint.
3. Proximity offers a wider weather window to maintain the site since the transportation time will be reduced.

b. The port's offshore energy experience (oil & gas, wind, tidal and wave)

c. The port's current involvement or willingness to invest in the offshore wind industry

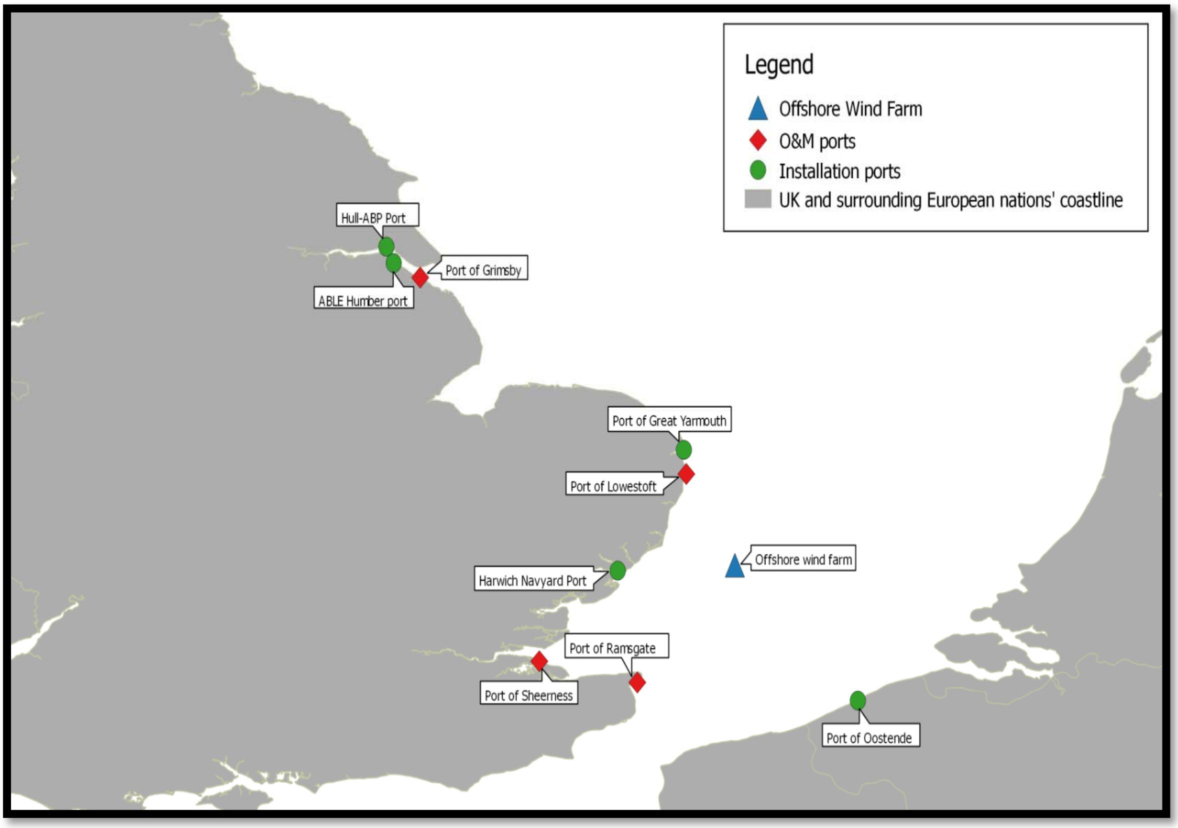
d. Data availability for the port: the data includes qualitative data such as laydown area availability, heavy cranes availability; and quantitative data such as quay length, port depth, and quay loadbearing capacity.

Figure 6 shows the location of wind farm site and the potential ports (both the installation and O&M ports) which are selected in this study. The data for the ports related to the port criteria is collected from publicly available data. The main resources are the 4C offshore database, UK Port Directory, and the World's Port Index (WPI) [58] [59] [60].

Table 10: West Gabbard specification

Site Name	**West Gabbard**
Area (Country)	North Sea (UK)
Depth (m)	33
Latitude (deg)	51.98
Longitude (deg)	2.08
Mean significant wave height (m)	1.1
Mean wave period (Tp, s)	5.44
Mean wind speed @ 10m a.s.l (m/s)	8.34
Mean tidal current velocity (m/s)	0.1943
Max tidal current velocity (m/s)	0.6997

Figure 6: The location of the wind farm site and potential ports [61]



5.3 Results

Each port has been assessed based on a number of criteria discussed in the previous sections. As each port is different in terms of these criteria, each port can have some advantages over the other, while lagging in other factors; however, the final results enable the decision makers to select the port which has the highest overall score as the most suitable port for their wind farm.

5.3.1 Installation port

Table 11 presents the final score of each installation port based on the collected data. In the table, the first column is the list of sub-criteria considered for selecting the installation port and in the second column, the weight of the sub-criteria is given (based on the results in Table 6). Columns 3 to 7 provide the normalised data which are adjusted values measured on different scales to a notionally common scale, for each installation port responding to the sub-criteria. In Columns 8 to 12, the final score of each installation port is presented. As previously shown in Table 4, for installation ports, the physical characteristics of the port dominates the ports' connectivity and ports' layout in the decision making process.

The results of the analysis suggest that the most suitable installation base for this wind farm is the Port of Oostende. The port of Hull is ranked second, followed by Able UK, Harwich Navyard Port, and the port of Great Yarmouth. The port of Oostende, which has the highest suitability ranking, is one of the major European ports in the offshore wind sector with dedicated offshore wind terminal and foundation manufacturing facilities. The Port of Hull and Able UK, as part of the Humber Enterprise Zone are also among the Humber area energy ports that are developing facilities to serve the offshore wind sector. Siemens, together with Associated British Ports (ABP) has invested in building a blade manufacturing facility as part of the Green Port Hull project. The Able Marine Energy Park (AMEP) will provide a facility for the manufacture, storage, assembly and deployment of the next generation of offshore wind turbines. This is estimated to create 4100 jobs when complete [80]. The port of Harwich, operated by Harwich Haven Authority, is a multi-purpose port that has served as the installation base for the Gunfleet Sand and Greater Gabbard projects. The port of Great Yarmouth, owned by the Peel Port Group, is strategically located to serve the planned offshore wind farms on the East coast of the UK, however, as yet, it does not offer component manufacturing facilities [59].

5.3.2 Operations and maintenance port

Similar to Table 11, Table 12 shows the final score of each O&M port where the first two columns show the sub-criteria and their ranking (based on results from Table 7). Columns 3 to 6 show the normalised data for four O&M ports while in columns 7 to 10, the final score for each O&M port is given. As shown in Table 7, for the O&M port, the port's connectivity and specifically the port's distance from the farm are the dominating factors in the decision making process. The results of the analysis suggest that the Port of Sheerness has the highest suitability ranking for the O&M base for the wind farm, followed by the Port of Lowestoft, the Port of Ramsgate and the Port of Grimsby. The port of Sheerness, as part of the Peel Port Group, offers services and development land for the renewable energy sector. The port of Lowestoft, part of the ABP Group, offers services to the offshore wind sector and serves as the O&M base for Round 2 offshore wind projects such as the Greater Gabbard wind farm. The port of Ramsgate, owned and operated by Thanet District Council, serves as the O&M base for the Thanet and London Array wind farm and offers extensive services to the offshore wind sector [59]. The port of Grimsby, owned by ABP, is one of the established centres for the offshore wind sector and serves as the O&M base for a number of Round 1&2 offshore wind projects, however the considerable distance from the West Gabbard wind farm makes it the least suitable port, in this instance.

Table 11: The final score for each installation port

Criteria	Priority Weight	Alternatives weight					Final Score = Priority weight * Alternatives weight				
		Harwich	Oostende	Hull	Able	Yarmouth	Harwich	Oostende	Hull	Able	Great Yarmouth
Seabed suitability	0.097336739	1	1	1	1	1	0.097337	0.097337	0.097337	0.097337	0.097337
Lo-Lo capability	0.037559292	0.767396	0.767396	0.767396	0.136661	0.136661	0.028823	0.028823	0.028823	0.005133	0.005133
Ro-Ro capability	0.006439933	0.67264	0.67264	0.67264	0.67264	0.036819	0.004332	0.004332	0.004332	0.004332	0.000237
Heavy cranes	0.019007667	0.767396	0.136661	0.136661	0.767396	0.767396	0.014586	0.002598	0.002598	0.014586	0.014586
Quay length	0.070285272	0.200098	0.405423	0.958809	0.358782	0.384107	0.014064	0.028495	0.06739	0.025217	0.026997
Quay load bearing capacity	0.138717948	0.163998	0.766672	0.766672	0.766672	0.113979	0.02275	0.106351	0.106351	0.106351	0.015811
Port's depth	0.114148506	0.12994	0.908982	0.657161	0.595087	0.196771	0.014832	0.103759	0.075014	0.067928	0.022461
Distance to offshore site	0.19388221	0.905413	0.510653	0.164719	0.164719	0.729322	0.175543	0.099006	0.031936	0.031936	0.141403
Distance to supplier	0.051046677	0.232504	0.232615	0.863339	0.863339	0.232695	0.011869	0.011874	0.044071	0.044071	0.011878
Distance to road	0.029845285	0.312299	0.962962	0.347492	0.347492	0.304117	0.009321	0.02874	0.010371	0.010371	0.009076
Potential for expansion	0.062075161	0.303398	0.322278	0.368081	0.962864	0.318463	0.018833	0.020005	0.022849	0.05977	0.019769
Component laydown area	0.052761147	0.960727	0.368781	0.368781	0.368781	0.225444	0.050689	0.019457	0.019457	0.019457	0.011895
Laydown area access to quay	0.027942883	0.36286	0.36286	0.700637	0.919735	0.109746	0.010139	0.010139	0.019578	0.0257	0.003067
Storage loadbearing capacity	0.041789479	0.32736	0.963181	0.32736	0.32736	0.32736	0.01368	0.040251	0.01368	0.01368	0.01368
Open storage area	0.020921008	0.247497	0.22712	0.890827	0.828481	0.22712	0.005178	0.004752	0.018637	0.017333	0.004752
Covered storage area	0.007034996	0.480769	0.386158	0.820235	0.820235	0.067463	0.003382	0.002717	0.00577	0.00577	0.000475
Component manufacturing facility	0.029204786	0.136661	0.767396	0.767396	0.767396	0.136661	0.003991	0.022412	0.022412	0.022412	0.003991
Total							0.49935	**0.631048**	0.590605	0.571384	0.402547
Rank							4	**1**	2	3	5

Table 12: The final score for each O&M port

Criteria	Priority Weight	Alternatives weight				Final Score = Priority weight * Alternatives weight			
		Grimsby	Sheerness	Lowestoft	Ramsgate	Grimsby	Sheerness	Lowestoft	Ramsgate
Seabed suitability	0.012778818	1	1	1	1	0.012779	0.012779	0.012779	0.012779
Quay length	0.028981505	0.410167	0.926964	0.34134	0.206787	0.011887	0.026865	0.009893	0.005993
Lo-Lo capability	0.037407015	0.308538	0.933193	0.308538	0.308538	0.011541	0.034908	0.011541	0.011541
Ro-Ro capability	0.008692965	1	1	1	1	0.008693	0.008693	0.008693	0.008693
Heavy cranes	0.028367065	0	0	0	0	0	0	0	0
Quay load bearing capacity	0.183909433	0.199635	0.869473	0.199635	0.712925	0.036715	0.159904	0.036715	0.131114
Port's depth	0.02821776	0.25066	0.92861	0.273105	0.42479	0.007073	0.026203	0.007706	0.011987
Distance to offshore site	0.324803959	0.109407	0.416613	0.879178	0.606177	0.035536	0.135317	0.28556	0.196889
Distance to key component supplier	0.052933117	0.312767	0.24805	0.93098	0.376582	0.016556	0.01313	0.04928	0.019934
Distance to road	0.043448349	0.729535	0.839997	0.111235	0.349797	0.031697	0.036496	0.004833	0.015198
Distance to heliport	0.082064742	0.196851	0.189692	0.806748	0.806748	0.016155	0.015567	0.066206	0.066206
Storage loadbearing capacity	0.007977375	1	1	1	1	0.007977	0.007977	0.007977	0.007977
Open storage area	0.008523493	0.155119	0.632409	0.286467	0.892552	0.001322	0.00539	0.002442	0.007608
Covered storage area	0.028867234	0.303888	0.932293	0.354473	0.272069	0.008772	0.026913	0.010233	0.007854
Workshop area for component repair	0.041505152	1	1	1	1	0.041505	0.041505	0.041505	0.041505
Potential for expansion	0.024465917	0.278988	0.932826	0.324317	0.324317	0.006826	0.022822	0.007935	0.007935
Office facilities	0.057054778	1	1	1	1	0.057055	0.057055	0.057055	0.057055
Total						0.312089	**0.631526**	0.620352	0.610266
Rank						4	1	2	3

6 Discussion and conclusion

Offshore wind is a growing industry globally and particularly in Northern European countries. Therefore, managerial tools, which can enable decision makers to make supported optimal choices, are needed. A significant contribution of this research is the development of a methodology that uses industry expert judgments for determining the relative significance of different port criteria for port selection. The results show that the most significant sub-criterion for the installation port is the port's distance from the offshore site followed closely by the port's quay loadbearing capacity and the port's depth. This result suggests that the port's distance to the wind farm is an influential factor in the decision-making process, since the ports located closer to the wind farm allow for weather windows to be exploited more efficiently and the transportation time and cost will hence be reduced. In addition, since large offshore wind components are assembled at the installation port, the port must have adequate quay loadbearing capacity to support the heavy load of the component. Furthermore, deep-water ports are preferred to accommodate the large draft vessels required. Ro-Ro capability in the port is ranked the least significant factor and this could be due to the fact that for the installation process, typically heavy lifting vessels (HLV) are used.

For the O&M ports, the most dominant sub-criterion is the distance from the site with a significantly higher weight value compared to other sub-criteria. This result is in line with the current practice in the industry where ports near the offshore wind farms are selected for the O&M phase in order to benefit from fast access to the port, resulting in lower turbine downtime. The least significant criteria is the storage loadbearing capacity, which is due to the fact that for the O&M phase, the stored components are relatively lighter and smaller compared to the installation phase.

In addition to providing a port selection decision-making model, this research provides insight for port owners/operators wishing to pursue a sustainable future for their port. The emergence of offshore renewable energy projects (wind, wave, tidal) provides an opportunity for ports to diversify or expand their activities into undertaking the installation and O&M of offshore wind technology. For example, the decline in the fishing industry in some regions could make diversification into offshore wind industry an attractive option for ports and can provide job opportunities and boost the local economy as evidenced by the case of UK Humber region ports [80]. In order to support the decision-making for such diversifications, this study provides an overview of the necessary requirements for offshore wind ports and their relative importance in order to provide a clear understanding for the decision makers.

While this research has focused on the two phases of installation and O&M of the offshore wind farms, future research could include the suitability of onshore infrastructure to undertake the decommissioning phase of the offshore wind farms, also extending the focus on the suitability assessment of onshore infrastructure to support other marine renewables such as wave and tidal energy. Additionally, the focus of this study has been on the port's requirements from a logistical perspective and the factor of cost has not been explicitly included in the decision-making strategy reported in this study. The future research could also include the cost as a direct factor and assess the ports based on cost and other requirements. Our model made no account for existing operations at a port facility. For instance, a firm that had existing operations at a particular port might select that port even if the model shows it to be suboptimal because very little additional investment may be needed. A further model could be developed to take into account these situations, which will occur more often as the industry continues to develop.

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References

[1] Z. Abdmouleh, R.A.M Alammari, A. Gastli
Review of policies encouraging renewable energy integration & best practices
Renew Sustain Energy Rev., 45 (2015), pp. 249-262
http://dx.doi.org/10.1016/j.rser.2015.01.035

[2] X.G. Zhao, L.Z. Ren
Focus on the development of offshore wind power in China: Has the golden period come?
Renew Energy, 81 (2015), pp. 644-657
http://dx.doi.org/10.1016/j.renene.2015.03.077

[3] European Commission, EU Energy, transport and GHG emission trends to 2050, reference scenarios 2013. https://ec.europa.eu/energy/sites/ener/files/documents/trends_to_2050_update_2013.pdf ,2013 (accessed 07.09.2015).

[4] European Wind Energy Association (EWEA), Avoiding fossil fuels costs 2014.
http://www.ewea.org/fileadmin/files/library/publications/reports/Avoiding_fossil_fuel_costs.pdf, 2014 (accessed 10.03.2015).

[5] Global Wind Energy Council, Global wind report, annual market update 2014.
http://www.gwec.net/wp-content/uploads/2015/03/GWEC_Global_Wind_2014_Report_LR.pdf, 2014 (accessed 12.05.2015).

[6] A.J. Wieczorek, S.O. Negro, R. Harmsen, G.J. Heimeriks, L. Luo, M.P. Hekkert.
A review of the European offshore wind innovation system
Renew Sustain Energy Rev., 26 (2013), pp. 294-306
http://dx.doi.org/10.1016/j.rser.2013.05.045

[7] R. Green, N. Vasilakos
The economics of offshore wind
Energy Pol., 39 (2) (2011), pp. 496-502
http://dx.doi.org/10.1016/j.enpol.2010.10.011

[8] B. Snyder, M.J. Kaiser
A comparison of offshore wind development in Europe and the US: patterns and drivers of development
Appl Energy, 86 (2009), pp. 1845-1856
http://dx.doi.org/10.1016/j.apenergy.2009.02.013

[9] European Wind Energy Association, European offshore wind industry- key trends and statistics 1st half 2015.
http://www.ewea.org/fileadmin/files/library/publications/statistics/EWEA-European-Offshore-Statistics-H1-2015.pdf, 2015 (accessed 01.10.2015).

[10] Y.C. Tsai, Y.F. Huang, J.T. Yang
Strategies for the development of offshore wind technology for far-east countries- A point of view from patent analysis
Renew Sustain Energy Rev., 60 (2016), pp. 182-194
http://dx.doi.org/10.1016/j.rser.2016.01.102

[11] S. Rodrigues, C. Restrepo, E. Kontos, R. Teixeira Pinto, P. Bauer
Trends of offshore wind projects
Renew Sustain Energy Rev., 49 (2015), pp. 1114-1135
http://dx.doi.org/10.1016/j.rser.2015.04.092

[12] A.R. Silva, F.M. Pimenta, A.T. Assireu, M.H.C. Spyrides
Complementarity of Brazil's hydro and offshore wind power
Renew Sustain Energy Rev., 56 (2016), pp. 413-427
http://dx.doi.org/10.1016/j.rser.2015.11.045

[13] Department of Energy and Climate Change. Electricity Generation costs 2013. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/269888/131217_Electricity_Generation_costs_report_December_2013_Final.pdf, 2013 (accessed 02.02.2015).

[14] Dd. Jager, M. Rathmann, Policy instrument design to reduce financing cost in renewable energy technology projects. ECOFYS. By order of the: IEA Implementing Agreement on Renewable Energy Technology Deployment (RETD) 2008.
http://iea-retd.org/wp-content/uploads/2011/10/Policy_Main-Report.pdf, 2011 (accessed 09.04.2015).

[15] BVG Associates, Value breakdown for the offshore wind sector. A report commissioned by the Renewables Advisory Board, 2010. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48171/2806-value-breakdown-offshore-wind-sector.pdf, 2010 (accessed 09.04.2015).

[16] European Wind Energy Association (EWEA), Wind in our sales, 2011.
http://www.ewea.org/fileadmin/files/library/publications/reports/Offshore_Report.pdf, 2011 (accessed 10.03.2015)

[17] L. Cradden, C. Kalogeri, I. Martinez Barrios, G. Galanis, D. Ingram, G. Kallos
Multi-criteria site selection for offshore renewable energy platforms
Renew Energy, 87 (2016), pp. 791-806
http://dx.doi.org/10.1016/j.renene.2015.10.035

[18] S. Kota, S.B. Bayne, S. Nimmagadda
Offshore wind energy: A comparative analysis of UK, USA and India
Renew Sustain Energy Rev., 41 (2015), pp. 685-694
http://dx.doi.org/10.1016/j.rser.2014.08.080

[19] P. Higgins, A. Foley

The evolution of offshore wind power in the United Kingdom
Renew Sustain Energy Rev., 37 (2014), pp. 599-612
http://dx.doi.org/10.1016/j.rser.2014.05.058

[20] E. Lozano-Minguez, A.J. Kolios, F.P. Brennan
Multi-criteria assessment of offshore wind turbine support structures
Renew Energy, 36 (2011), pp. 2831-2837
http://dx.doi.org/10.1016/j.renene.2011.04.020

[21] A. Fetanat, E. Khorasaninejad
A Novel hybrid MCDM approach for offshore wind farm site selection: A case study of Iran
Ocean Coast Manage., 109 (2015), pp. 17-28
http://dx.doi.org/10.1016/j.ocecoaman.2015.02.005

[22] D.F. Jones, G. Wall
An extended goal programming model for site selection in the offshore wind farm sector
Ann Oper Res., 2015.
DOI: 10.1007/s10479-015-1828-2

[23] M. Shafiee
A fuzzy analytic network process model to mitigate the risks associated with offshore wind farms
Expert Syst Appl., 42(4) (2015), pp. 2143-2152
http://dx.doi.org/10.1016/j.eswa.2014.10.019

[24] S.L. MacDougall
The value of delay in tidal energy development
Energy Pol., 87 (2015), pp. 438-446
http://dx.doi.org/10.1016/j.enpol.2015.09.034

[25] C. Ugboma, O. Ugboma, I.C. Ogwude
An Analytical Hierarchy Process (AHP) Approach to Port Selection Decisions-Empirical evidence from Nigerian ports
Marit Econ Logist., 8 (2006), pp. 251-266
http://dx.doi.org/10.1057/palgrave.mel.9100160

[26] E. Guy, B. Urli
Port Selection and multi-criteria analysis: An application to the Montreal-New York alternative
Marit Econ Logist., 8 (2006), pp. 169-186
DOI: 10.1057/palgrave.mel.9100152

[27] C.C. Chou

A fuzzy MCDM method for solving marine transhipment container port selection problems
Appl Math Comput., 186 (1) (2007), pp. 435-444
http://dx.doi.org/10.1016/j.amc.2006.07.125

[28] J.S.L. Lee, J. Dai
A decision support system for port selection
Transport Plan Techn 35 (4) (2012), pp. 509-524
http://dx.doi.org/10.1080/03081060.2012.680822

[29] E. Zavadskas Kazimieras, Z. Turskis, V. Bagocius
Multi-criteria selection of a deep water-port in the Eastern Baltic Sea
Appl Soft Comput., 26 (2014), pp. 180-192
http://dx.doi.org/10.1016/j.asoc.2014.09.019

[30] N. Asgari, A. Hassani, D. Jones, H. Nguye
Sustainability ranking of the UK major ports: Methodology and case study
Transport Res E-Log., 78 (2015), pp. 19–39
http://dx.doi.org/10.1016/j.tre.2015.01.014

[31] T.C. Lirn, H.A. Thanopoulou, M.J. Beynon, A.K.C. Beresford
An Application of AHP on transshipment Port Selection: A Global Perspective
Marit Econ Logist., 6 (2004), pp. 70-91
http://dx.doi.org/10.1057/palgrave.mel.9100093

[32] C.C. Chou
AHP model for the container port choice in the multiple-ports region
J Mar Sci Tech., 18 (2) (2010), pp. 221-232

[33] M. Kovačić
Selecting the Location of a Nautical Tourism Port by Applying Promethee and Gaia Methods, Case Study- Croation Northern Adriatic
PROMET-ZAGREB, 22 (5) (2010), pp. 341-351
DOI: 10.7307/ptt.v22i5.199

[34] S. Onut, U.R. Tuzkaya, E. Torun
Selecting container port via fuzzy ANP-based approach: A case study in the Marmara Region, Turkey
Transport Pol., 18 (2010), pp. 182-193
http://dx.doi.org/10.1016/j.tranpol.2010.08.001

[35] B. Ka
Application of fuzzy AHP and ELECTRE to China Dry Port Location Selection
AJSL; 27(2) (2011), pp. 331-354

http://dx.doi.org/10.1016/S2092-5212(11)80015-5

[36] Y. Wang, K.A. Jung, G.T. Yeo, C.C. Chou
Selecting a cruise port of call location using the fuzzy-AHP method: a case study in East ASIA
Tourism Manage 42 (2014), pp. 262-270
http://dx.doi.org/10.1016/j.tourman.2013.11.005

[37] J. Sayareh, H. Rezaee Alizmini
A Hybrid Decision-Making Model for Selecting Container Seaport in the Persian Gulf
AJSL 30 (1) (2014), pp. 75-95
http://dx.doi.org/10.1016/j.ajsl.2014.04.004

[38] P.K. Yoon, C.L. Hwang
Multiple Attribute Decision Making
SAGE Publication, Thousand Oaks:CA, 1995.

[39] M. Velasquez, P.T. Hester
An analysis of Multi-criteria decision making methods
Int J Oper Res., 10 (2) (2013), pp. 56-66
DOI:10.1.1.402.1308

[40] C.L. Hwang, A.S.M. Masud
Multiple Objective Decision Making- Methods and Applications
Springer-Verlag, Berlin Heidelberg, 1979.

[41] C.A. Irawan, D. Jones, D. Ouelhadj
Bi-objective optimisation model for installation scheduling in offshore wind farms
Comput Oper Res, 2016
http://dx.doi.org/10.1016/j.cor.2015.09.010i

[42] C.L. Hwang, K. Yoon
Multiple Attributes Decision Making Methods and Applications
Springer, Berlin Heidelberg, 1981.

[43] G.A. Mendoza, R. Prabhu
Multiple criteria decision making approaches to assessing forest sustainability using criteria and indicators: a case study
Forest Ecol Manag 131 (1) (2000), pp. 107–126
http://dx.doi.org/10.1016/S0378-1127(99)00204-2

[44] T.L. Saaty, L.G. Vargas. Models, Methods, Concepts & Applications of the Analytic Hierarchy Process. N
Springer, New York, 2012.

[45] W.C. Wedley

Combining qualitative and quantitative factors- an analytical hierarchy approach
Socioecon Plann Sci., 24 (1) (1990), pp. 57-64
doi:10.1016/0038-0121(90)90028-6

[46] R. Banai-Kashani
A new method for site suitability analysis: The analytic hierarchy process
Environ Manage., 13 (6) (1989), pp. 685-693
DOI: 10.1007/BF01868308

[47] R. Ramanathan
A note on the use of the analytic hierarchy process for environmental impact assessment
J Environ Manage., 63 (2001), pp. 27-35
DOI:10.1006/jema.2001.0455

[48] T.L. Saaty
Fundamentals of Decision Making and Priority Theory with The Analytic Hierarchy Process
RWS Publications, Pittsburgh, 2000.

[49] Garrad Hassan America, Assessment of ports for offshore wind development in the United States 2014, http://energy.gov/sites/prod/files/2014/03/f14/Assessment%20of%20Ports%20for%20Offshore%20Wind%20Development%20in%20the%20United%20States_1.pdf, 2014 (accessed 12.09.2014).

[50] Garrad Hassan, A Guide to UK Offshore Wind Operations and Maintenance. Scottish Enterprise and The Crown Estate 2013. http://www.hi-energy.org.uk/Downloads/General%20Documents/guide-to-uk-offshore-wind-operations-and-maintenance.pdf, 2013 (accessed 26.01.2016).

[51] K.E. Thomson
Offshore wind a comprehensive guide to successful offshore wind farm installation
Elsevier, Waltham: Massachusetts, 2012.

[52] BVG associates, Offshore wind: delivering more for less. An independent analysis commissioned by STATFRAT UK (2015), http://www.bvgassociates.co.uk/Portals/0/publications/BVGA%20Offshore%20wind%20more%20for%20less%201507.pdf, 2015 (accessed 05.08.2015).

[53] T.L. Saaty
Decision making for leaders: The analytic hierarchy process for decisions in a complex world
RWS Publications, Pittsburgh, 2012.

[54] AHP excel template:
http://bpmsg.com, (accessed 20.07.2015).

[55] BVG Associates, UK Ports for the Offshore Wind Industry: Time to Act. Report for the Department of Energy and Climate Change, 2009. http://webarchive.nationalarchives.gov.uk/+/http:/www.berr.gov.uk/files/file49871.pdf, 2009 (accessed 20.01.2015).

[56] EON offshore wind fact book 2011.

http://www.eon.com/content/dam/eon-com/en/downloads/e/EON_Offshore_Wind_Factbook_en_December_2011.pdf, 2011 (accessed 04.03.2015).

[57] BVG Associates, A guide to an offshore wind farm. Published on behalf of The Crown Estate (2011). http://www.thecrownestate.co.uk/media/5408/ei-km-in-sc-supply-012010-a-guide-to-an-offshore-wind-farm.pdf, 2011 (accessed 09.04.2015).

[58] 4Coffshore port database.

www.4coffshore.com, (accessed 20.01.2016).

[59] UK ports directory,

www.uk-ports.org, (accessed 20.01.2016).

[60] World port index data base, http://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_pageLabel=msi_portal_page_62&pubCode=0015, (accessed 25.01.2016).

[61] Data set for the GIS map.

https://www.gov.uk/guidance/oil-and-gas-offshore-maps-and-gis-shapefiles, (accessed 25.11.2015).

[62] J.J. Wang, Y.Y. Jing, C.F. Zhang, J.H. Zhao

Review on multi-criteria decision analysis aid in sustainable energy decision-making

Renew Sustain Energy Rev., 13 (2009), pp. 2263-2278

http://dx.doi.org/10.1016/j.rser.2009.06.021

[63] Road, Crane Pad, and hardstand specifications for Vestas Turbines, V100-1.8MW and V112-3.0MW, http://www.vindbrukdalsland.se/Kingebol%20B%20Milj%C3%B6tillst%C3%A5ndsans%C3%B6kan%20Teknisk%20beskrivning%20Bil%202%20Transportmanual%20V112.pdf, (accessed 15.08.2016).

[64] A. Ishizaka, A. Labib

Review of the main development in the analytic hierarchy process

EXPERT SYST APPL, 28 (2011), pp. 14336-14345

http://dx.doi.org/10.1016/j.eswa.2011.04.143

[65] G. T. Fechner

Elemente der psychophysik

Leipzig: Breitkopf und Härtel; 1860

[66] S. S. Stevens

On the psychophysical law

Psychological Review, 64 (3) (1957), pp. 153–181

[67] P. Harker, L.G. Vargas
The theory of ratio scale estimation: Saaty's analytic hierarchy process
Manag Sci., 33 (11) (1987), pp. 1383–1403
doi:10.1287/mnsc.33.11.1383

[68] F.A. Lootsma
Conflict resolution via pairwise comparison of concessions
EUR J OPER RES., 40 (1) (1989), pp. 109–11
doi:10.1016/0377-2217(89)90278-6

[69] A. Salo, R. Hamalainen
On the measurement of preference in the analytic hierarchy process
JMCDA, 6 (6) (1997), pp. 309–319
DOI: 10.1002/(SICI)1099-1360(199711)6:6<309::AID-MCDA163>3.0.CO;2-2

[70] J. Aguaron, J.M. Moreno-Jimenez
The geometric consistency index: Approximated thresholds
EUR J OPER RES., 147(1) (2003), pp. 137-145
http://dx.doi.org/10.1016/S0377-2217(02)00255-2

[71] J. Aczel, T.L. Saaty
Procedures for synthesizing ratio judgements.
J. Math. Psychol, 27 (1) (1983), pp. 93-102
http://dx.doi.org/10.1016/0022-2496(83)90028-7

[72] Ships and marine technology-offshore wind energy-port and marine operations.
International Standard-ISO 29400. First Edition, May 2015.
http://www.bizmdosw.org/wpcontent/uploads/2016/06/ISO_29400_2015en.pdf,
(accessed 14.08.2016).

[73] O.S. Vaidya, S. Kumar
Analytic hierarchy process: An overview of applications
EUR J OPER Res 169 (2006), pp. 1-29
http://dx.doi.org/10.1016/j.ejor.2004.04.028

[74] S.D. Pohekar, M. Ramachandran
Application of multi-criteria decision making to sustainable energy planning-a review
Renew Sustain Energy Rev., 2004 (8), pp. 365-381
http://dx.doi.org/10.1016/j.rser.2003.12.007

[75] V. Belton, A.E. Gear
On a shortcoming of Saaty's method of analytic hierarchies

Omega 11(3) (1983), pp. 227-230
doi:10.1016/0305-0483(83)90047-6

[76] N. Bhushan, K. Rai
Strategic decision making applying the analytic hierarchy process
Springer-Verlog, London, 2004.

[77] F.J. Dodd, H.A. Donegan
Comparison of prioritization techniques using interhierachy mappings
J OPER RES SOC., 46 (1995), pp. 492-498
DOI: 10.2307/2584596

[78] R. Karni, P. Sanchez, V.M. Rao Tummala
A comparative study of multiatribute decision making methodologies
Theory Decis., 29 (1990), pp. 203-222
DOI: 10.1007/BF00126802

[79] J. Barzilai
Measurement and preference function modelling
Intl Trans in Op Res 12 (2005), pp. 173-183 DOI: 10.1111/j.1475-3995.2005.00496.x

[80] Humber Enterprise Zone.
http://enterprisezones.communities.gov.uk/enterprise-zone-finder/humber-enterprise-zone/, (accessed 14.08.2016).

[81] N. Akbari, A. Attari, L. Cradden, P. Doherty
A GIS-based approach for port selection and bottleneck identification for the application of Self-Buoyant Gravity Based Foundations for offshore wind projects.
Proceedings of the EWEA conference, Paris, 2015.

[82] A. Guitouni, J.M. Martel
Tentative guidelines to help choosing an appropriate MCDA method.
EUR J OPER Res 109 (1998), pp. 501-521
http://dx.doi.org/10.1016/S0377-2217(98)00073-3

Appendix:

Port assessment questionnaire

Offshore wind port suitability Questionnaire

Participant Name:

Position:

Company:

Please follow the example and provide your answers to the following comparisons given the scale provided in the table below:

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with I	A reasonable assumption
1.1-1.9	If the activities are very close	May be difficult to assign the best value but when compare with other contrasting activities the size of small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Fundamental scale of absolute numbers (Saaty TL. Fundamentals of Decision Making and Priority Theory with The Analytic Hierarchy Process. Pittsburg: RWS Publications; 2000)

Example: If you were to compare these two criteria in terms of importance, e.g. Port's physical characteristics Versus Port's connectivity, which score you would give to the first criteria VS the second one?
If your answer is 1, it means that these two criteria are **equally important.**
….
if your answer is 5 it means that the first criteria is **strongly more important** compared to the second one
…..
If your answer is 9 it means that the first criteria is **extremely more important** compared to the second one.

*Please note: if you think that the second criteria is more important, then your answer should be the reciprocal of the above.
For example: if you think that the port's connectivity extremely more important than the port's physical characteristics, then your answer should be 1/9.

Installation port:

	Pairwise comparisons	Score
1	Port’s physical characteristics VS Port’s connectivity	
2	Port’s physical characteristics VS Port’s Layout	
3	Port’s connectivity VS Port’s layout	
4	Port’s seabed suitability for jack up vessels VS available component handling equipment	
5	Port’s seabed suitability for jack up vessels VS the quay length	
6	Port’s seabed suitability for jack up vessels VS quay load bearing capacity	
7	Port’s seabed suitability for jack up vessels VS port’s depth	
8	Available component handling equipment VS quay length	
9	Available component handling equipment VS quay loadbearing capacity	
10	Available component handling equipment VS port’s depth	
11	Quay length VS quay load bearing capacity	
12	Quay length VS port’s depth	
13	Quay load bearing capacity VS port’s depth	
14	Lo-Lo capability VS Ro-Ro capability	
15	Lo-lo capability VS lifting capacity	
16	Ro-Ro capability VS lifting capacity	
17	Distance to offshore site VS distance to key component suppliers	
18	Distance to offshore site VS distance to road networks	
19	Distance to key component supplier VS distance to road networks	
20	Potential for expansion VS component laydown area	
21	Potential for expansion VS storage capacity	
22	Potential for expansion VS component fabrication facility	
23	Component laydown area VS storage capacity	
24	Component laydown area VS component fabrication facility	
25	Storage Capacity VS fabrication facility	
26	Component laydown area VS laydown’s area access to quayside	
27	Storage load bearing capacity VS open storage area	
28	Storage load bearing capacity VS covered storage area	
29	Open storage area VS covered storage area	

O&M Port:

	Pairwise comparisons	Score
1	Port’s physical characteristics VS Port’s connectivity	
2	Port’s physical characteristics VS Port’s Layout	
3	Port’s connectivity VS Port’s layout	
4	Port’s seabed suitability for jack up vessels VS available component handling equipment	
5	Port’s seabed suitability for jack up vessels VS the quay length	
6	Port’s seabed suitability for jack up vessels VS quay loadbearing capacity	
7	Port’s seabed suitability for jack up vessels VS port’s depth	
8	Available component handling equipment VS quay length	
9	Available component handling equipment VS quay loadbearing capacity	
10	Available component handling equipment VS port’s depth	
11	Quay length VS quay load bearing capacity	
12	Quay length VS port’s depth	
13	Quay load bearing capacity VS port’s depth	
14	Lo-Lo capability VS Ro-Ro capability	

15	Lo-lo capability VS lifting capability	
16	Ro-Ro capability VS lifting capacity	
17	Distance to offshore site VS distance to key component suppliers	
18	Distance to offshore site VS distance to road networks	
19	Distance offshore site VS distance to heliport	
20	Distance to key component supplier VS distance to road networks	
21	Distance to key component supplier VS distance to heliport	
22	Distance to road networks VS distance to heliport	
23	Storage capacity VS workshop area for component repair	
24	Storage capacity VS potential for expansion	
25	Storage capacity VS office facilities	
26	workshop area for component repair VS potential for expansion	
27	workshop area for component repair VS office facilities	
28	Potential for expansion VS office facilities	
29	Storage load bearing capacity VS open storage area	
30	Storage load bearing capacity VS covered storage area	
31	Open storage area VS covered storage area	

1245 # Questionnaires completed by experts :

1246 Expert 1

Expert 1

Position: Senior Project manager

Installation port:

	Pairwise comparisons	Scores
1	Port's physical characteristics VS Port's connectivity	1/6
2	Port's physical characteristics VS Port's Layout	1
3	Port's connectivity VS Port's layout	6
4	Port's seabed suitability for jack up vessels VS available component handling equipment	9
5	Port's seabed suitability for jack up vessels VS the quay length	1
6	Port's seabed suitability for jack up vessels VS quay load bearing capacity	1/3
7	Port's seabed suitability for jack up vessels VS port's depth	1/3
8	Available component handling equipment VS quay length	1/6
9	Available component handling equipment VS quay loadbearing capacity	1/7
10	Available component handling equipment VS port's depth	1/9
11	Quay length VS quay load bearing capacity	7
12	Quay length VS port's depth	1
13	Quay load bearing capacity VS port's depth	1
14	Lo-Lo capability VS Ro-Ro capability	1
15	Lo-lo capability VS lifting capacity	3
16	Ro-Ro capability VS lifting capacity	1
17	Distance to offshore site VS distance to key component suppliers	9
18	Distance to offshore site VS distance to road networks	9
19	Distance to key component supplier VS distance to road networks	1
20	Potential for expansion VS component laydown area	7
21	Potential for expansion VS storage capacity	7
22	Potential for expansion VS component fabrication facility	9
23	Component laydown area VS storage capacity	1
24	Component laydown area VS component fabrication facility	9
25	Storage Capacity VS fabrication facility	9
26	Component laydown area VS laydown's area access to quayside	1
27	Storage load bearing capacity VS open storage area	3
28	Storage load bearing capacity VS covered storage area	7
29	Open storage area VS covered storage area	8

O&M Port:

	Pairwise comparisons	Scores
1	Port's physical characteristics VS Port's connectivity	1/6
2	Port's physical characteristics VS Port's Layout	2
3	Port's connectivity VS Port's layout	7
4	Port's seabed suitability for jack up vessels VS available component handling equipment	1/9
5	Port's seabed suitability for jack up vessels VS the quay length	1/9
6	Port's seabed suitability for jack up vessels VS quay loadbearing capacity	1/9
7	Port's seabed suitability for jack up vessels VS port's depth	1/9
8	Available component handling equipment VS quay length	3
9	Available component handling equipment VS quay loadbearing capacity	3
10	Available component handling equipment VS port's depth	1/5
11	Quay length VS quay load bearing capacity	1/3
12	Quay length VS port's depth	1/4
13	Quay load bearing capacity VS port's depth	1/4
14	Lo-Lo capability VS Ro-Ro capability	6
15	Lo-lo capability VS lifting capability	6
16	Ro-Ro capability VS lifting capacity	1/6
17	Distance to offshore site VS distance to key component suppliers	9
18	Distance to offshore site VS distance to road networks	9
19	Distance offshore site VS distance to heliport	7
20	Distance to key component supplier VS distance to road networks	1
21	Distance to key component supplier VS distance to heliport	1/6
22	Distance to road networks VS distance to heliport	1/6
23	Storage capacity VS workshop area for component repair	3
24	Storage capacity VS potential for expansion	1/3
25	Storage capacity VS office facilities	1
26	workshop area for component repair VS potential for expansion	1/2
27	workshop area for component repair VS office facilities	1/4
28	Potential for expansion VS office facilities	1/2
29	Storage load bearing capacity VS open storage area	1
30	Storage load bearing capacity VS covered storage area	1/6
31	Open storage area VS covered storage area	1/6

1247

Expert 2

Expert 2

Position: Senior renewable energy consultant

Installation port:

	Pairwise comparisons	Score
1	Port's physical characteristics VS Port's connectivity	6
2	Port's physical characteristics VS Port's Layout	1 / 4
3	Port's connectivity VS Port's layout	1 / 8
4	Port's seabed suitability for jack up vessels VS available component handling equipment	1 / 6
5	Port's seabed suitability for jack up vessels VS the quay length	1 / 4
6	Port's seabed suitability for jack up vessels VS quay load bearing capacity	1 / 9
7	Port's seabed suitability for jack up vessels VS port's depth	1 / 8
8	Available component handling equipment VS quay length	4
9	Available component handling equipment VS quay loadbearing capacity	1
10	Available component handling equipment VS port's depth	1
11	Quay length VS quay load bearing capacity	1 / 5
12	Quay length VS port's depth	1 / 3
13	Quay load bearing capacity VS port's depth	5
14	Lo-Lo capability VS Ro-Ro capability	7
15	Lo-lo capability VS lifting capacity	1
16	Ro-Ro capability VS lifting capacity	1 / 7
17	Distance to offshore site VS distance to key component suppliers	3
18	Distance to offshore site VS distance to road networks	7
19	Distance to key component supplier VS distance to road networks	3
20	Potential for expansion VS component laydown area	1 / 5
21	Potential for expansion VS storage capacity	1 / 3
22	Potential for expansion VS component fabrication facility	2
23	Component laydown area VS storage capacity	5
24	Component laydown area VS component fabrication facility	5
25	Storage Capacity VS fabrication facility	2
26	Component laydown area VS laydown's area access to quayside	3
27	Storage load bearing capacity VS open storage area	5
28	Storage load bearing capacity VS covered storage area	4
29	Open storage area VS covered storage area	3

O&M Port:

	Pairwise comparisons	Score
1	Port's physical characteristics VS Port's connectivity	5
2	Port's physical characteristics VS Port's Layout	1 / 5
3	Port's connectivity VS Port's layout	1 / 3
4	Port's seabed suitability for jack up vessels VS available component handling equipment	1/ 5
5	Port's seabed suitability for jack up vessels VS the quay length	1 / 5
6	Port's seabed suitability for jack up vessels VS quay loadbearing capacity	1
7	Port's seabed suitability for jack up vessels VS port's depth	1 / 2
8	Available component handling equipment VS quay length	1 / 3
9	Available component handling equipment VS quay loadbearing capacity	3
10	Available component handling equipment VS port's depth	2
11	Quay length VS quay load bearing capacity	2
12	Quay length VS port's depth	4
13	Quay load bearing capacity VS port's depth	1 / 2
14	Lo-Lo capability VS Ro-Ro capability	6
15	Lo-lo capability VS lifting capability	1
16	Ro-Ro capability VS lifting capacity	1 / 5
17	Distance to offshore site VS distance to key component suppliers	5
18	Distance to offshore site VS distance to road networks	5
19	Distance offshore site VS distance to heliport	1 / 8
20	Distance to key component supplier VS distance to road networks	1
21	Distance to key component supplier VS distance to heliport	1 / 7
22	Distance to road networks VS distance to heliport	1 / 8
23	Storage capacity VS workshop area for component repair	1 / 2
24	Storage capacity VS potential for expansion	1
25	Storage capacity VS office facilities	1 / 5
26	workshop area for component repair VS potential for expansion	2
27	workshop area for component repair VS office facilities	1
28	Potential for expansion VS office facilities	1 / 3
29	Storage load bearing capacity VS open storage area	2
30	Storage load bearing capacity VS covered storage area	1 / 4
31	Open storage area VS covered storage area	1 / 4

Expert 3

Expert 3

Position: Manger

Installation port:

	Pairwise comparisons	Score
1	Port's physical characteristics VS Port's connectivity	4
2	Port's physical characteristics VS Port's Layout	1
3	Port's connectivity VS Port's layout	1
4	Port's seabed suitability for jack up vessels VS available component handling equipment	1
5	Port's seabed suitability for jack up vessels VS the quay length	1
6	Port's seabed suitability for jack up vessels VS quay load bearing capacity	1
7	Port's seabed suitability for jack up vessels VS port's depth	1
8	Available component handling equipment VS quay length	1
9	Available component handling equipment VS quay loadbearing capacity	1
10	Available component handling equipment VS port's depth	1/3
11	Quay length VS quay load bearing capacity	1
12	Quay length VS port's depth	1
13	Quay load bearing capacity VS port's depth	1
14	Lo-Lo capability VS Ro-Ro capability	
15	Lo-lo capability VS lifting capacity	
16	Ro-Ro capability VS lifting capacity	
17	Distance to offshore site VS distance to key component suppliers	3
18	Distance to offshore site VS distance to road networks	4
19	Distance to key component supplier VS distance to road networks	1
20	Potential for expansion VS component laydown area	1/5
21	Potential for expansion VS storage capacity	1/5
22	Potential for expansion VS component fabrication facility	2
23	Component laydown area VS storage capacity	1
24	Component laydown area VS component fabrication facility	4
25	Storage Capacity VS fabrication facility	4
26	Component laydown area VS laydown's area access to quayside	1/5
27	Storage load bearing capacity VS open storage area	5
28	Storage load bearing capacity VS covered storage area	5
29	Open storage area VS covered storage area	1

O&M Port:

	Pairwise comparisons	Score
1	Port's physical characteristics VS Port's connectivity	4
2	Port's physical characteristics VS Port's Layout	3
3	Port's connectivity VS Port's layout	3
4	Port's seabed suitability for jack up vessels VS available component handling equipment	1/5
5	Port's seabed suitability for jack up vessels VS the quay length	1/4
6	Port's seabed suitability for jack up vessels VS quay loadbearing capacity	1/7
7	Port's seabed suitability for jack up vessels VS port's depth	1/3
8	Available component handling equipment VS quay length	4
9	Available component handling equipment VS quay loadbearing capacity	1/5
10	Available component handling equipment VS port's depth	4
11	Quay length VS quay load bearing capacity	1/7
12	Quay length VS port's depth	1
13	Quay load bearing capacity VS port's depth	6
14	Lo-Lo capability VS Ro-Ro capability	1
15	Lo-lo capability VS lifting capability	
16	Ro-Ro capability VS lifting capacity	
17	Distance to offshore site VS distance to key component suppliers	7
18	Distance to offshore site VS distance to road networks	6
19	Distance offshore site VS distance to heliport	7
20	Distance to key component supplier VS distance to road networks	1/6
21	Distance to key component supplier VS distance to heliport	1/5
22	Distance to road networks VS distance to heliport	1/5
23	Storage capacity VS workshop area for component repair	1
24	Storage capacity VS potential for expansion	5
25	Storage capacity VS office facilities	1
26	workshop area for component repair VS potential for expansion	1
27	workshop area for component repair VS office facilities	1/4
28	Potential for expansion VS office facilities	1/6
29	Storage load bearing capacity VS open storage area	5
30	Storage load bearing capacity VS covered storage area	1
31	Open storage area VS covered storage area	1

Expert 4

Expert 4
Position: Operations Manager

Installation port:

	Pairwise comparisons	Score
1	Port's physical characteristics VS Port's connectivity	6
2	Port's physical characteristics VS Port's Layout	3
3	Port's connectivity VS Port's layout	6
4	Port's seabed suitability for jack up vessels VS available component handling equipment	1
5	Port's seabed suitability for jack up vessels VS the quay length	5
6	Port's seabed suitability for jack up vessels VS quay load bearing capacity	1/2
7	Port's seabed suitability for jack up vessels VS port's depth	5
8	Available component handling equipment VS quay length	7
9	Available component handling equipment VS quay loadbearing capacity	1
10	Available component handling equipment VS port's depth	7
11	Quay length VS quay load bearing capacity	1/3
12	Quay length VS port's depth	1/3
13	Quay load bearing capacity VS port's depth	5
14	Lo-Lo capability VS Ro-Ro capability	8
15	Lo-lo capability VS lifting capacity	1
16	Ro-Ro capability VS lifting capacity	1/8
17	Distance to offshore site VS distance to key component suppliers	1
18	Distance to offshore site VS distance to road networks	7
19	Distance to key component supplier VS distance to road networks	1
20	Potential for expansion VS component laydown area	1
21	Potential for expansion VS storage capacity	2
22	Potential for expansion VS component fabrication facility	1/4
23	Component laydown area VS storage capacity	1
24	Component laydown area VS component fabrication facility	1
25	Storage Capacity VS fabrication facility	1/5
26	Component laydown area VS laydown's area access to quayside	1
27	Storage load bearing capacity VS open storage area	7
28	Storage load bearing capacity VS covered storage area	4
29	Open storage area VS covered storage area	8

O&M Port:

	Pairwise comparisons	Score
1	Port's physical characteristics VS Port's connectivity	1/8
2	Port's physical characteristics VS Port's Layout	5
3	Port's connectivity VS Port's layout	8
4	Port's seabed suitability for jack up vessels VS available component handling equipment	1/4
5	Port's seabed suitability for jack up vessels VS the quay length	1
6	Port's seabed suitability for jack up vessels VS quay loadbearing capacity	1
7	Port's seabed suitability for jack up vessels VS port's depth	1
8	Available component handling equipment VS quay length	5
9	Available component handling equipment VS quay loadbearing capacity	8
10	Available component handling equipment VS port's depth	8
11	Quay length VS quay load bearing capacity	1
12	Quay length VS port's depth	1
13	Quay load bearing capacity VS port's depth	1
14	Lo-Lo capability VS Ro-Ro capability	2
15	Lo-lo capability VS lifting capability	1/5
16	Ro-Ro capability VS lifting capacity	1/3
17	Distance to offshore site VS distance to key component suppliers	8
18	Distance to offshore site VS distance to road networks	9
19	Distance offshore site VS distance to heliport	7
20	Distance to key component supplier VS distance to road networks	7
21	Distance to key component supplier VS distance to heliport	7
22	Distance to road networks VS distance to heliport	7
23	Storage capacity VS workshop area for component repair	6
24	Storage capacity VS potential for expansion	7
25	Storage capacity VS office facilities	1
26	workshop area for component repair VS potential for expansion	4
27	workshop area for component repair VS office facilities	2
28	Potential for expansion VS office facilities	1/3
29	Storage load bearing capacity VS open storage area	1/3
30	Storage load bearing capacity VS covered storage area	1/5
31	Open storage area VS covered storage area	1/8

Expert 5

Expert 5

Position: General Manager

Installation port:

	Pairwise comparisons	Score
1	Port's physical characteristics VS Port's connectivity	5
2	Port's physical characteristics VS Port's Layout	6
3	Port's connectivity VS Port's layout	3
4	Port's seabed suitability for jack up vessels VS available component handling equipment	6
5	Port's seabed suitability for jack up vessels VS the quay length	5
6	Port's seabed suitability for jack up vessels VS quay load bearing capacity	4
7	Port's seabed suitability for jack up vessels VS port's depth	5
8	Available component handling equipment VS quay length	1/5
9	Available component handling equipment VS quay loadbearing capacity	1/6
10	Available component handling equipment VS port's depth	1/7
11	Quay length VS quay load bearing capacity	1/2
12	Quay length VS port's depth	1/6
13	Quay load bearing capacity VS port's depth	1/3
14	Lo-Lo capability VS Ro-Ro capability	7
15	Lo-lo capability VS lifting capacity	5
16	Ro-Ro capability VS lifting capacity	¼
17	Distance to offshore site VS distance to key component suppliers	8
18	Distance to offshore site VS distance to road networks	8
19	Distance to key component supplier VS distance to road networks	4
20	Potential for expansion VS component laydown area	4
21	Potential for expansion VS storage capacity	1/3
22	Potential for expansion VS component fabrication facility	2
23	Component laydown area VS storage capacity	1/3
24	Component laydown area VS component fabrication facility	4
25	Storage Capacity VS fabrication facility	3
26	Component laydown area VS laydown's area access to quayside	4
27	Storage load bearing capacity VS open storage area	1/5
28	Storage load bearing capacity VS covered storage area	4
29	Open storage area VS covered storage area	4

O&M Port:

	Pairwise comparisons	Score
1	Port's physical characteristics VS Port's connectivity	1/3
2	Port's physical characteristics VS Port's Layout	4
3	Port's connectivity VS Port's layout	5
4	Port's seabed suitability for jack up vessels VS available component handling equipment	1/3
5	Port's seabed suitability for jack up vessels VS the quay length	½
6	Port's seabed suitability for jack up vessels VS quay loadbearing capacity	1/2
7	Port's seabed suitability for jack up vessels VS port's depth	1/3
8	Available component handling equipment VS quay length	4
9	Available component handling equipment VS quay loadbearing capacity	4
10	Available component handling equipment VS port's depth	1/3
11	Quay length VS quay load bearing capacity	¼
12	Quay length VS port's depth	¼
13	Quay load bearing capacity VS port's depth	1/4
14	Lo-Lo capability VS Ro-Ro capability	3
15	Lo-lo capability VS lifting capability	4
16	Ro-Ro capability VS lifting capacity	1/2
17	Distance to offshore site VS distance to key component suppliers	9
18	Distance to offshore site VS distance to road networks	9
19	Distance offshore site VS distance to heliport	9
20	Distance to key component supplier VS distance to road networks	5
21	Distance to key component supplier VS distance to heliport	4
22	Distance to road networks VS distance to heliport	3
23	Storage capacity VS workshop area for component repair	¼
24	Storage capacity VS potential for expansion	1/3
25	Storage capacity VS office facilities	3
26	workshop area for component repair VS potential for expansion	5
27	workshop area for component repair VS office facilities	4
28	Potential for expansion VS office facilities	1/3
29	Storage load bearing capacity VS open storage area	¼
30	Storage load bearing capacity VS covered storage area	1/6
31	Open storage area VS covered storage area	1/2