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for Wind Installations with Novel Developments

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Definitions

AHP	Analytical Hierarchy Process
ANP	Analytic Network Process
ASL	Above Sea Level
CAPEX	Capital Expenditure
DEA	Data Envelopment Analysis
DSS	Decision Support System
EOHT	Electric Over-Head Travelling
GBF	Gravity Based Foundation
GIS	Geographic Information System
HLCV	Heavy Lift Cargo Vessels
LAT	Lowest Astronomical Tide
LOA	Length Over All
MCDA	Multi-Criteria Decision Analysis
MLWS	Mean Low Water Spring
O&M	Operations and Maintenance
OEM	Original Equipment manufacturer
OPEX	Operating Expenses
OREI	Offshore Renewable Energy Industry
OWI	Offshore Wind Industry
POI	Point of Interconnection
PPA	Power Purchase agreement
SPMT	Self-Propelled Modular Transport
WTG	Wind Turbine Generator

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Executive Summary

Over the last decade, Europe has led the world in supporting the wind industry to step offshore into coastal waters and at scale, underpinning the potential creation of an interconnected Europe-wide offshore electricity grid through which clean and affordable energy can be harvested and transported to EU member states as required.

As a direct consequence, an increased number of larger & heavier power generation systems need to be delivered from their place of manufacture onshore to installation locations which are increasingly further offshore and in deeper waters. Based on industry feedback, this port study, **identifies the most critical technical requirements** that ports need to fulfil in order to efficiently support the installation, operation and maintenance and decommissioning phases of the offshore wind farm lifecycle, including (in no particular order):

a. Availability of component manufacturing/assembly facilities at the port in order to reduce the time, cost and risks associated with the transportation of large wind turbine components.

b. Suitable layout arrangement in the port to facilitate the accommodation of the components within the port.

c. Ability to accommodate large installation vessels at the port.

d. Availability of component handling facilities at the port, including heavy cranes, Lo-Lo and Ro-Ro facilities, SPMTs, Pontoons, etc. to help with the swift manoeuvring of the components and efficient loading and unloading.

e. Location of the port and its distance from the wind farm, the component suppliers, and road networks which can influence the component transportation's time and cost.

f. Security and health and safety measures in the ports.

Furthermore, this study **proposes a decision making model** which could aid developers and designers in selecting the most suitable base for an offshore wind farm for a particular phase of its lifecycle (installation, operation and maintenance or decommissioning) based on the following port suitability criteria group.

a. Port's connectivity including the port's distance to the wind farm, distance to component suppliers, distance to road networks, and distance to heliports (for O&M phase).

b. Port's physical characteristics including port's length, port's depth, seabed suitability, quay load bearing capacity, availability of component handling equipment

c. Port's Layout including Storage availability, component laydown area, component fabrication facility, workshop area at the port, and recycling facilities (for the decommissioning phase)

This decision making model has two applications. The first application is to reveal the most important characteristics in the port for each phase of the offshore wind farm development from a decision maker's point of view. For the installation and decommissioning phases, the port's physical characteristics has been shown to be the determining factor for decision makers and the ports' connectivity and layout come second and third in terms of importance. For the O&M phase, the model shows that for decision makers, the ports' connectivity is the major deciding factor in selecting a port and the port's physical characteristics and layout come second and third respectively.

The second application of the model is to compare the suitability of a number of ports for a given wind farm using the criteria group mentioned above. Based on the criteria, a number of ports are compared and a suitability score is given to each port. Finally the port with the highest score could be suggested as the most suitable option for serving a particular offshore wind farm.

Since ports are critical parts of the offshore wind supply chain and the connecting point between on-land activities and offshore transportation of the components, the selection of a suitable port becomes important. Therefore this model serves as a managerial tool, enabling decision makers to tackle the strategic challenge of selecting the most suitable port for an offshore wind farm which could facilitate the logistics activities related to the entire life cycle of an offshore wind farm.

1. Introduction

This report presents deliverable 5.3 related to 'Ports suitability assessment for offshore wind development-case studies report'. In deliverable 5.3 a systematic assessment of the most important port requirements for the installation, operations and maintenance and decommissioning of offshore wind farms has been undertaken, and the role of ports in the offshore wind industry is examined. Also in this deliverable, a decision making model for port selection based on the identified capabilities has been proposed. The purpose of this model is to help the decision makers in selecting the most suitable port for an offshore wind farm.

Section 2, presents a detailed analysis of the ports' most critical requirements for handling offshore wind activities. In section 3, the ports' involvement in installation, operations and maintenance and decommissioning phases of the offshore wind farms is further elaborated. In section 4, a decision making model for port selection along with a case application is proposed, and in the final section, the conclusions are presented.

Task 5.3 led by University of Hull, has received valuable input from partners in University of Portsmouth, University of Edinburgh, Kongsberg Maritime AS, Cork institute of Technology, and European Wind Energy Association.

2. Assessment of ports in the offshore wind industry

By the end of 2014, 8.7 GW of offshore wind capacity was installed worldwide with 91% of these activities in European waters, mainly in the North Sea (5,094.2 MW: 63.3%), Atlantic Ocean (1,808.6 MW: 22.5%) and in the Baltic Sea (1,142.5 MW: 14.2%) [1].
In Europe, 2,488 turbines are installed and grid connected, making a cumulative total of over 8 GW (8,045.3 MW) in 74 wind farms in 11 European countries [2]. Various forecasts have predicted between 55 and 75 GW of cumulative offshore wind capacity worldwide by 2020 [3].

The role of ports becomes more significant with regard to Europe's 2020 target of electricity generation and delivering 40 GW of electricity through offshore wind power [4]. Ports are the major links in the offshore supply chain as the transportation, assembly, staging, installation, operations and maintenance and decommissioning of the turbines are carried out through them. The trend towards employing larger wind turbines will require more ports with larger lay-down areas and facilities to build lift and transport heavy equipment [5]. A large percent of stakeholders agree that further development of port infrastructure and logistics will be a driver of installation cost reduction in the coming years [6]. Hence, ports as important nodes in the offshore wind's logistics have to meet certain technical requirements for handling the components for installation, servicing the offshore wind farms, and undertaking the decommissioning of the components.

For gathering the information regarding the technical requirements of ports, we identified and contacted several offshore wind stakeholders, including ports already involved in the offshore wind industry and ports under development with manufacturing facilities planned as part of the overall port capability. Our discussion with these stakeholders helped us to explain the most important factors in offshore wind ports, which we further used to develop a port selection model capable of selecting the most suitable port for a given phase of the offshore wind life cycle. These discussions provided us with a better appreciation of offshore wind farm logistics such as storing, assembling, scheduling, and deploying wind turbines and foundations to the offshore sites. We also used secondary sources and industry examples which helped us to better explain each criterion and its implication in the port.

In section 2, after providing a brief explanation of offshore wind turbines and substructures, we delve into assessing the critical technical requirements for ports in the offshore wind industry.

2.1 Offshore wind turbines

According to the NREL report [7], no consensus exists yet on the maximum physical size of offshore wind turbines in the future, although most wind engineers agree that there is no hard physical limit preventing 10 MW turbines or greater. NREL [7] also argue that with turbine costs representing only one third of the life cycle cost of the wind project, turbine growth will continue until overall system costs are minimised.
From the point of view of substructure and foundation costs, larger turbines are usually favoured, as mobilisation of the installation and service equipment is a major cost driver, and fewer turbines mean lower geotechnical costs, fewer electrical terminations, more

generating capacity per ocean area, less inter turbine cable length and trenching, and fewer service trips to and from the towers [7]. In this section a brief explanation of offshore wind turbine components, export cables, substation and the supporting structures is provided.

Tower:

Towers are tubular structures consisting of steel plates cut, rolled, and welded together into large sections. The tower provides support to the turbine assembly and the balance of plant components, including a transformer located in the base, a yaw motor located at the top, and communication and power cables. The tower also provides a ladder and/or an elevating mechanism to provide access to the nacelle. In installation, tower sections are bolted to each other during assembly, or are preassembled at port. Tower height is determined by the diametre of the rotor and the clearance above the water level. Typical tower heights are 60–80 m giving a total hub height of 70–90 m when added to the substructure height above the water line. Tower's diametre and strength depend on the weight of the nacelle and expected wind loads [8].

Blade:

Blades are aerofoils made of composite or reinforced plastics, and are bolted to the hub either onshore or offshore. Due to the low weight and long length (50–60 m), blades are sensitive to high winds during lifting operations. Moreover, the size and shape of assembled configurations complicate onshore and offshore transport [8].

Nacelle:

The nacelle houses the generator and gearbox and monitors communications, control, and environmental maintenance of the equipment. The nacelle is principally composed of a main frame and cover. The main frame is the element to which the gearbox, generator, and brake are attached, and must transmit all the loads from the rotor and reaction loads from the generator and brake to the tower [8]. Nacelles are large units and their installation usually imposes the heaviest and highest lift. Therefore, the nacelle weight plays an important role in determining installation vessel suitability. A new generation of 'direct drive' offshore wind turbines is evolving, capable of generating in excess of 6 MW at very low rotor speeds and without an internal gearbox [9].

Export cables:

Export cables connect the wind farm to the onshore transmission system and are typically installed in one continuous operation. Export cables are buried to prevent exposure, and in some places, may require scour protection. Electricity collection and transmission come onshore and may be spliced to a similar cable and/or connected to an onshore substation. Water depths along the cable route, soil type, coastline type, and many other factors determine the cable route, time, and cost. At the onshore substation or switchyard, energy from the offshore wind farm is delivered to the power grid. If the point of interconnection (POI) voltage is different from the submarine transmission, transformers are used to match the POI voltage; otherwise, a switchyard is used to directly interconnect the wind

farm. At this point, power generated is metreed and purchased via a PPA with a local utility or by entering the Independent System Operator's merchant market. Export cables are composed of three insulated conductors protected by galvanized steel wire. Medium voltage cables are used when no offshore substation is installed and usually range between 24 and 36 kV. High voltage cables are typically 110–150 kV and are used with offshore substations. High voltage cables have the capacity to carry more power than a medium voltage cable but are heavier. These cables may weigh 50–100 kg/m while medium voltage cables may weigh 20–40 kg/m [8]. In distances more than 100 km offshore, HVDC connections are likely to be preferred over HVAC, which requires further equipment to connect back to an onshore AC substation [10].

Substation:

Whether an offshore wind farm has an offshore or onshore substation depends primarily on the size of the wind farm, distance from shore and distance from the grid connection point. Typically, wind farms farther than approximately 10 km from land have substations offshore. The substation accommodates the transformers required to increase the distribution voltage (33 kV or above) of the inter array cables to a higher voltage of typically 110 – 245 kV. From the offshore substation, the export cables then carry the power to the landfall location. As wind farm capacities increase and move farther offshore, there is a requirement for increased electrical equipment ratings and hence, for larger substations. When wind farms are located at substantial distances from shore, the losses in the electrical system can become significant. To minimise losses as much as possible, voltages are stepped up, for example from 33 kV to 115 kV [11].

Parametre	4MW	5MW	6MW	7MW	8MW
Rotor diametre(m)	120	135	150	164	175
Blade length(m)	59	66	73	80	85
Blade weight(t)	19	23	28	34	40
Nacelle weight(t)	162	239	330	390	450
Tower length(m)	66	74	81	88	94
Tower weight(t)	185	215	250	280	310

Table 1: Generic wind turbine specification [11]

2.1.1 Supporting structures

Monopiles:

Monopiles are large diametre, thick walled, steel tubular that are driven (hammered) or drilled (or both) into the seabed. Outer diametres usually range from 4 to 6 m and typically 40–50% of the pile is inserted into the seabed. The wall thickness and depth of penetration of the monopiles depend on the design turbine load, soil conditions, water depth, environmental conditions, and the adopted design codes. Pile driving is more efficient and less expensive than drilling; however its application may not be feasible in certain seabed conditions. Monopiles are currently the most common foundation in shallow water (<30 m) developments due to lower cost and the fact that monopiles are a proven concept. In soft soil regions, monopiles with larger embedment lengths and wall thicknesses are required. Suitability of monopiles in deeper water sites is a highly debated topic at present, as deeper water sites increase the structural demand and lead to larger diametre piles and increased wall thicknesses [8]. According to EWEA [2] 78.8% of substructures (by 2014) are monopiles.

Jackets:

Jacket foundations are an open lattice steel truss template consisting of a welded frame of tubular members extending from the mould line to above the water surface. Piles are driven through each leg of the jacket into the seabed or in the form of skirt piles, outside the jacket legs, to secure the substructure against lateral forces. Jackets are robust and heavy structures and require expensive equipment to transport and lift. To date, jacket foundations have not been used extensively in the offshore wind industry, due to the prevalence of shallow, near-shore wind farm sites. At around 50 m water depth, jacket structures become the preferred concept. Jackets have been used for two of the deepest developments, Beatrice (45 m) and Alpha Ventus (30 m), supporting large 5 MW turbines. Jackets are also commonly used to support offshore substations. They can be used in deep water sites (100s of metres), although economic considerations are likely to limit their deployment to water depths under 100 m [8]. According to EWEA [2], 4.7% of substructures (by 2014) are jackets.

Gravity Based Foundations (GBF):

A gravity base foundation is a very heavy structure usually made of concrete, which resists the lateral loads and overturning moments by its self-weight. The base is usually 15 to 25 m in diametre and all of the forces and bending moments are transported through the base of the foundation. Typically, a gravity base is used on semi-hard, uniform seabed condition and at shallower water depths, compared to jacket structures. The deepest gravity base foundations in operation are in Thornton bank (27m) [8]. The size and weight of the foundation make the transportation and installation onerous and it is worth noting that the seabed must be prepared by dredging and backfilling material in order to install the foundation. Hence while GBFs fabrication cost is low, in some cases high transportation and installation cost make them unattractive options [12]. According to EWEA [2], 10.4 % of substructures (by 2014) are GBFs.

Tripods:

Tripods consist of a central steel shaft connected to three cylindrical steel tubes through which piles are driven into the seabed. Tripods are heavier and more expensive to

manufacture than monopiles, but are more useful in deep water. The only operating wind farm that employs tripod foundations is the Alpha Ventus project located in Germany [8]. According to EWEA [2], 4.1% of substructures (by 2014) are tripods.

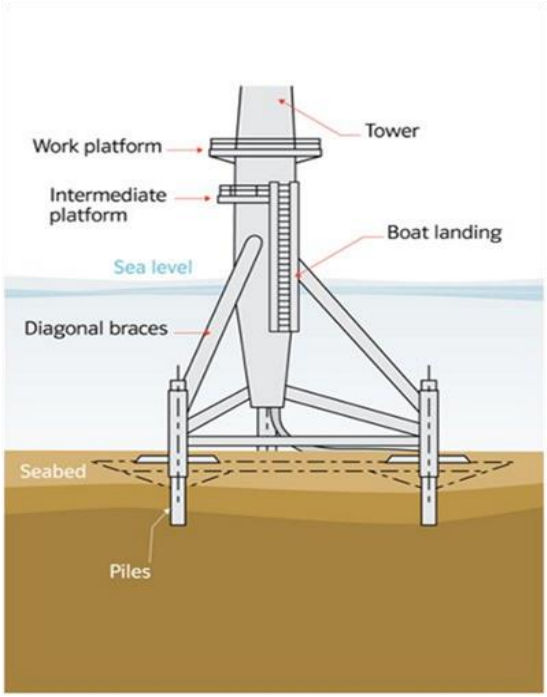


Figure 1: Tripod foundation [13]

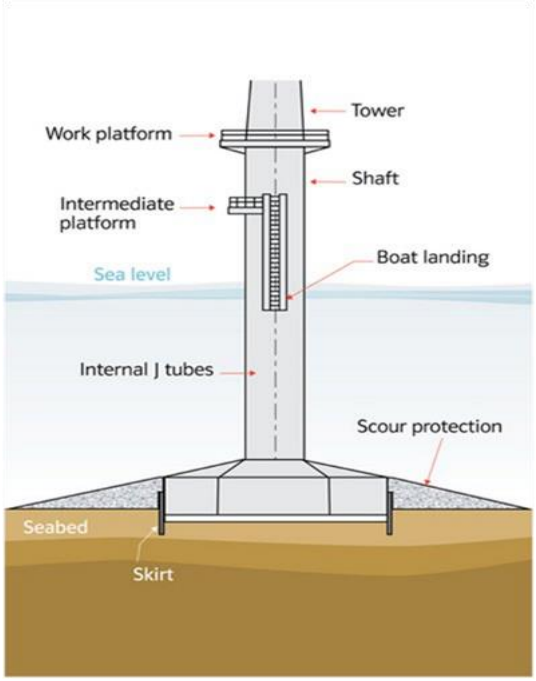


Figure 2: Gravity based foundation [13]

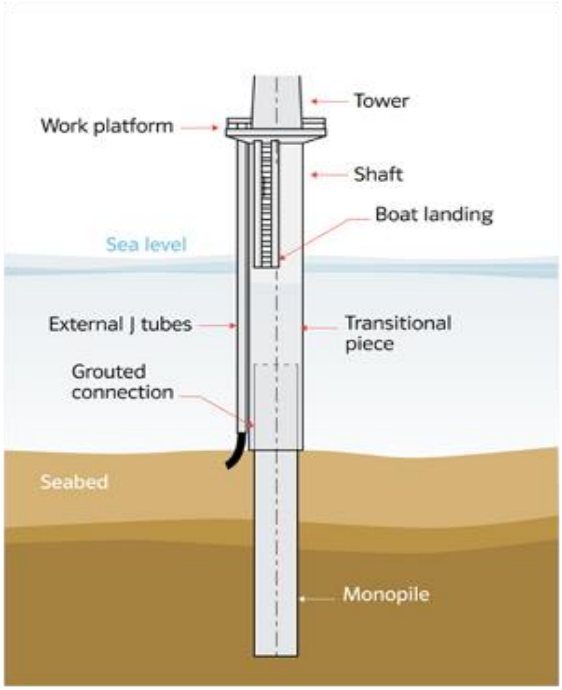


Figure 3: Monopile foundation [13]

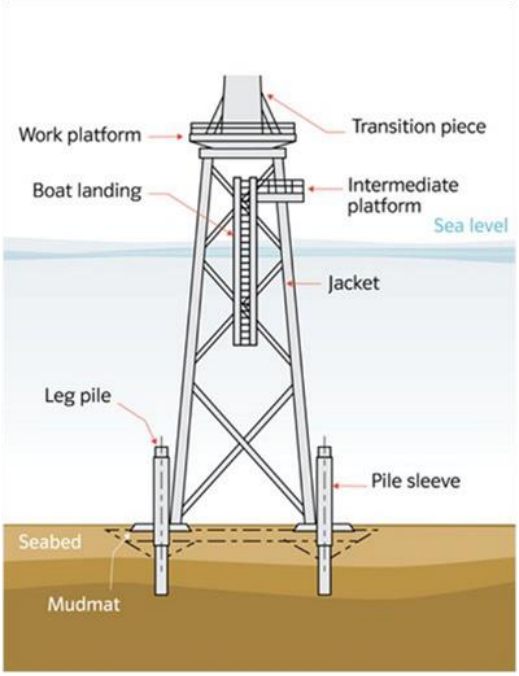


Figure 4: Jacket foundation [13]

2.1.2 Floating structures

Semi-submersible:

A semi-submersible is a free-surface stabilised structure with relatively shallow draft. It is a versatile structure due to its relatively low draft and flexibility to the seabed conditions. In general, semi-submersible structures are heavy structures with a relatively high steel mass and manufacturing complexity due to the large number of welded connections.
Wind Float, the most developed concept using the semi-submersible philosophy, has had a full scale demo since 2011. A small array of semi-submersible structures is estimated to be operational by late 2015 and a large commercial array is estimated to be deployed in 2021/2022 [14].

Spar buoy:

The spar buoy is a weight-buoyancy stabilised structure with relatively large draft. The concept uses simple (few active components), well-proven technology with inherently stable design and few weaknesses. The spar will face challenges due to its large draft for the actual site, but primarily in terms of assembly sites and transportation routes, which could limit the deployment in parts of the world. Hywind is the spar concept which has reached the highest technology readiness level so far. Hywind has had a full scale prototype in operation since 2009. A small array of Hywind turbines is expected to be deployed in 2015 and a large commercial array is estimated to be deployed in 2020 [14].

Tension Leg Platform (TLP):

The Tension Leg Platform is a tension restrained structure with relatively shallow draft. The tension leg concept enables low structural weight of the substructure, and thus lower material costs. TLPs could potentially have a higher operational risk, caused by the risk of total loss of the structure in the event of a tendon failure, if not countered in the design. TLP designs also add requirements with regard to soil conditions at site.
PelaStar is probably the TLP concept which is furthest in development and closest to deploying a large scale demonstration unit. A full scale demo is planned in 2015 following by a small array in 2020 and a large commercial array is estimated to be deployed in 2025 [14].

Figure 5: Floating foundations [15]

2.2 Port requirements for Offshore Wind Industry

For the development of an offshore wind farm, proper setup in the port area is needed. The ports must be arranged in a manner that various tasks can be carried out in the safest, quickest, the most cost-effective way. As the size and weight of the turbines is increasing, the port must have large land area and suitable handling equipment to address the offshore wind requirements. In this section, the most important requirements of offshore wind ports are detailed.

2.2.1 Component fabrication facility

Given the increase in the size of wind turbines and wind farms, the logistic challenges associated with transporting these components from the manufacturing facility to the offshore site have become more complex. Due to these factors, wind turbine manufacturers are increasingly looking towards European portside turbine assembly facilities [16]. EWEA [17] defines the manufacturing ports as ports where the fabrication facility is closely located at the port and the components are exported directly to the offshore site. In order to reduce the transportation cost and handling of these components, it is suggested to have turbine manufacturing facilities at the installation ports where the components can be shipped to the site with less handling. Whereas this option might not be feasible for all installation ports mainly due to the lack of space and commercial restrictions, developing manufacturing facilities within certain port clusters to feed several offshore wind developments seems reasonable.

In Port of Bremerhaven in Germany [19] a number of companies such as AREVA Wind GmbH and Repower Systems AG are located. Both companies have established production capacities of approximately 100 turbines a year and a range of activities including handling, pre-assembly, storage and export of offshore wind turbines is taking place in a single port which further enhances the efficiency of the supply chain in terms of transporting the components, reduces the risk, and ultimately helps reducing the cost through the supply chain refinement. Port of Bremerhaven has been used for production and assembly of foundation, tower, nacelle and blades [19], and has also served as the installation base for the Nordsee Ost project, around 35 km to the north-east of the island of Helgoland in the German North Sea region.

Although UK has the biggest share in the offshore wind market, only recently development of such facilities within the port has started and prior to that, majority of turbine components for UK offshore projects were being imported from continental Europe. Among the major investments that have taken place in the UK for development of offshore wind supply chain is the Green Port Hull project. In 2014, Siemens along with its British partner, Associated British Ports, invested in a blade manufacturing facility for Siemens next generation blade technology, Siemens SWT-6.0-154 6 MW wind turbine, at Green port Hull with the factory to be operational by 2017 [20].

For a port to accommodate manufacturing facilities, [21] suggests up to 500 ha of flat area for factory and product storage, direct access to high load bearing and deep water quayside, ease of logistics and access to skilled workforce, as requirements. According to [11] a fabrication facility for Nacelles, towers and blades should have the following characteristics:

Nacelles:

Wind turbine nacelles are manufactured under the cover of a fabrication facility which has suitable gantry cranes to lift and transfer components that constitute the nacelle (gearboxes, generators, etc.). Upon leaving the fabrication facility, nacelles are usually transported around the port facility using self-propelled modular transport (SPMTs) [11].

- Requires Electric Over-Head Travelling (EOHT)crane capacity of up to 75 tonnes
- SPMTs are required to manoeuvre underneath the nacelle's tower-top flange crane, jack-up and transit out of the facility.

Blades:

Blades are manufactured under the cover of a fabrication facility which has suitable gantry cranes to lift and transfer the blades to bespoke trolleys, which are themselves used to ship the blades to a long/medium-term storage area [11].

- A number of blades may be fabricated in parallel, requiring facilities that are wider than the sum of the fabrication moulds used to pre-lay the carbon fibre-reinforced plastic that constitutes the blade structure.
- Light internal cranage for the transfer of the blades to their transport trolleys are required, since turbine blades are made of lightweight composites.

Towers:

Wind turbine towers are manufactured under the cover of a fabrication facility with a production line set-up where steel plates are rolled into tower cans, which are in turn welded together into tower sections. Bespoke trolleys can be used to lift the tower sections and transport these around the port facility [11].

- Workshops with adequate headroom under the cranage will be necessary to ensure the tower bases can be lifted from rolling equipment.
- Towers require conical rolling, and their rolling is more onerous than for cylindrical piles. Besides this, the tower walls are far thinner, therefore the equipment required is much smaller.

Port of Cuxhaven in Germany is another example of a port with manufacturing facilities in which companies such as Cuxhaven Steel Construction GmbH, as subsidiary of BARD Group (producing foundation structures and components for offshore wind turbine generators), and AMBAU GmbH, manufacturer of steel towers and foundation structures, are located. Cuxhaven has a heavy load platform, a specialised hydraulic engineering structure with an area of 1,500 m^2, which is suited for both standing transport of completely assembled offshore wind turbine generators and for landing, as well as for conventional shipping of individual components. The heavy load platform can withstand loads up to 90 tonnes/m^2, and therefore, can support an upright, completely assembled wind turbine generator. The financial investment in the heavy load platform totalled € 7.57 million (c. £5.4 million) [22].

Some of the projects in which Cuxhaven has been successfully involved are:

1. Production and handling of tower sections for Nordsee Ost, around 35 km to the north-east of the island of Helgoland in the German North Sea region.

2. Production, storage and handling of tower section for Global tech 1.
3. Service port for Bard Offshore 1 (100 km off the coast of Borkum, comprising 80 Turbines, totalling 400 MW).

Cuxhaven's characteristics as one of the leading industry examples for manufacturing ports are listed in the table below.

Offshore terminal 1 : (Specialised port for the offshore wind industry)	Ship Facilities:		
		Quay Length (m)	160 m
		Vessel LOA	110 m
		Water depth (m)	7.4 Chart Datum
	Port berth	Length	116 m
		Width	42 m
		Water Depth	7.4 CD
	Heavy load gantry crane (T)		650 tonnes
	Total Terminal area (ha)		11 ha

Table 2: Key characteristics of Cuxhaven [22]

Offshore terminal 2 :	Ship Facilities (4 ship berths):	Quay Length (m)	734 m
		Vessel draft	12.7 m
	Port facility is accessed via a 60m wide dike ramp which was also designed for heavy load traffic		
	Total Terminal area (ha)		11.6 ha

Table 3: Key characteristics of Cuxhaven terminal 2 [22]

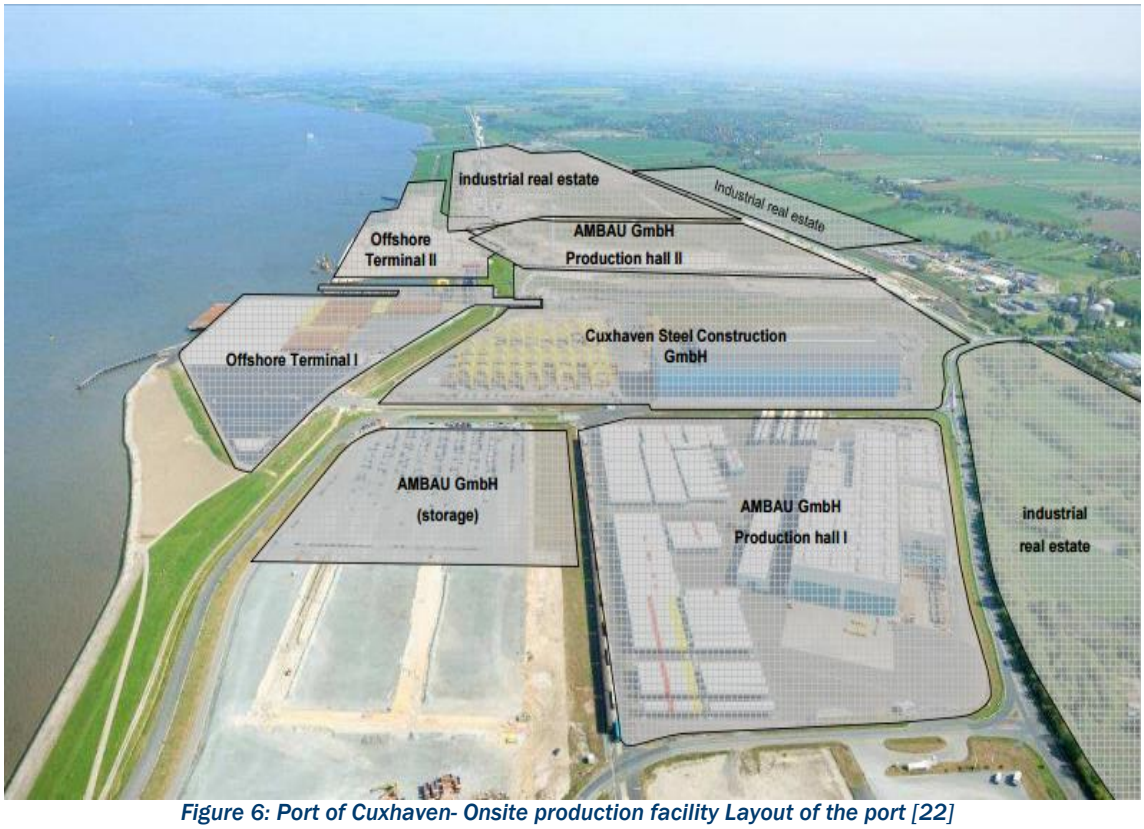


Figure 6: Port of Cuxhaven- Onsite production facility Layout of the port [22]

2.2.2 Port's layout

The port's layout configuration plays an important role in the efficiency of operations related to installation of the components and the impact of a suitable or an unsuitable port on a project is significant. The turnaround time -the time it takes for transporting and installing one turbine for an installation cycle- could be shortened if the port's layout and access lanes are suitable [12]. However the opposite case, will constrain all parts of the project as for example a small port with poor access could cause a slow down on the supply of components. If due to poor layout and handling in the port, components are stacked up at the quayside which is used for loading and offloading, the waiting time for the vessels will be longer, which will impact the cost and timing of the project. Figure 6 shows the layout of an installation port where manufacturing facilities are located within the port. This layout allows for the components to be taken directly from their point of manufacturing to the quayside where they can be loaded onto the installation vessels.

Figures 9, 10, 11 illustrate suitable layouts suggested for installation, O&M and decommissioning ports. A suitable port for offshore wind development must have adequate space for delivery and assembly of turbine components. Based on [16] developers do not necessarily have to stage foundations for offshore deployment out of the same port that is staging the turbine construction. The value of the convenience of utilising a common port or port facility generally would not outweigh the cost savings associated with improved logistics, less assembly, and minimised storage space and handling needs [16].

The storage space availability is needed to supply the manufacturing and assembly of turbine components (figure 7). 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. Area of 6.5 to 7.5 ha to store enough components before the projects starts is suggested [12]. Hence 50-70% of all components must be delivered to the storage area in the installation port prior to the start of the project [12].

Furthermore, the new components delivered to the port need to be stored for later assembly. For supporting the routine inventory at the port, a large storage area is required. For instance, Vestas generally require 20 turbines to be assembled ahead of time before transport to the installation site [16]. The storage space could also create a hedge against inclement weather conditions, and accommodate the components until the condition is ready for delivery to the site. Towers require storage in large numbers and, if laid down, will require individual access to lifting and thus large areas. They are not typically stacked when stored horizontally. If space is at a premium they can be stored upright, at the cost of additional cranage [11]. Nacelles are stored in frames, with the frame bolted to the nacelle at the tower/nacelle transition [11]. As the foundations are major sized components, allocating storage space to these structures might not be feasible in all ports. Alternatively in some cases barges or pontoons, i.e. floating storage, may be used to store the foundations (Figure 8). Foundations can be delivered and/or stored on barges fully assembled, then tugged to the installation site which results in less handling and cranage cost.

Figure 7: Onsite port storage for wind turbine components [23]

Figure 8: Jacket structure stored on a pontoon [24]

Suggested layout for Installation port:

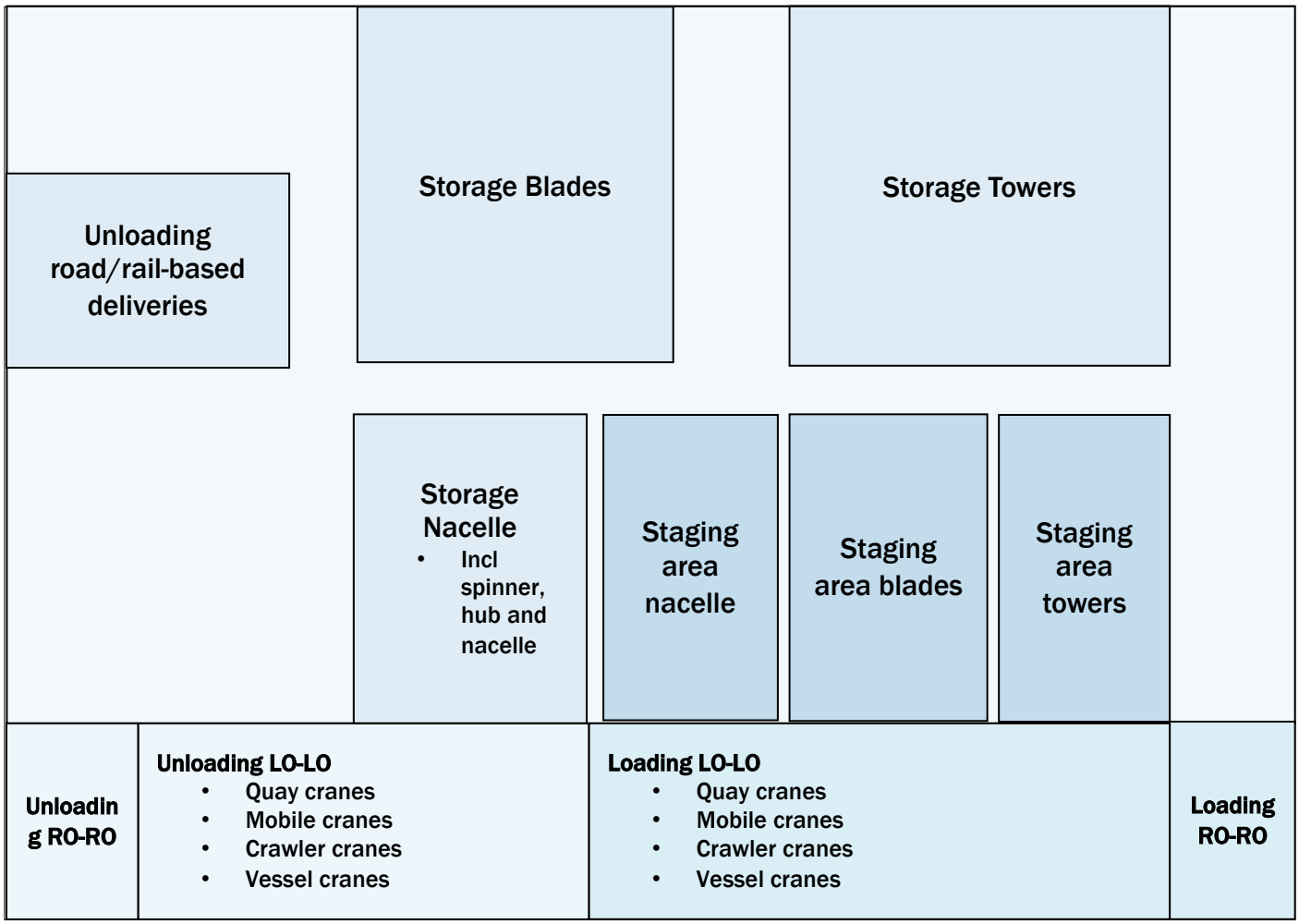


Figure 9: suggested layout for an installation port [25]

Inbound transport of components:
One vessel per component type or one vessel with several component types

- Blades
- Towers
- Nacelle

Note: assuming transition piece and foundation delivered directly to offshore site

Outbound transport of wind turbine:
Loading to one installation vessel

Blades

- Racks for 1-blade installation
- Installed at hub for rotor star installation

Towers

- Single pieces for multiple-lift offshore installation
- Fully installed at staging areas, one-lift offshore installation

Nacelle

- Single pieces for multiple-lift offshore installation
- Fully installed at staging areas, one-lift

<u>Suggested layout for O&M port:</u>

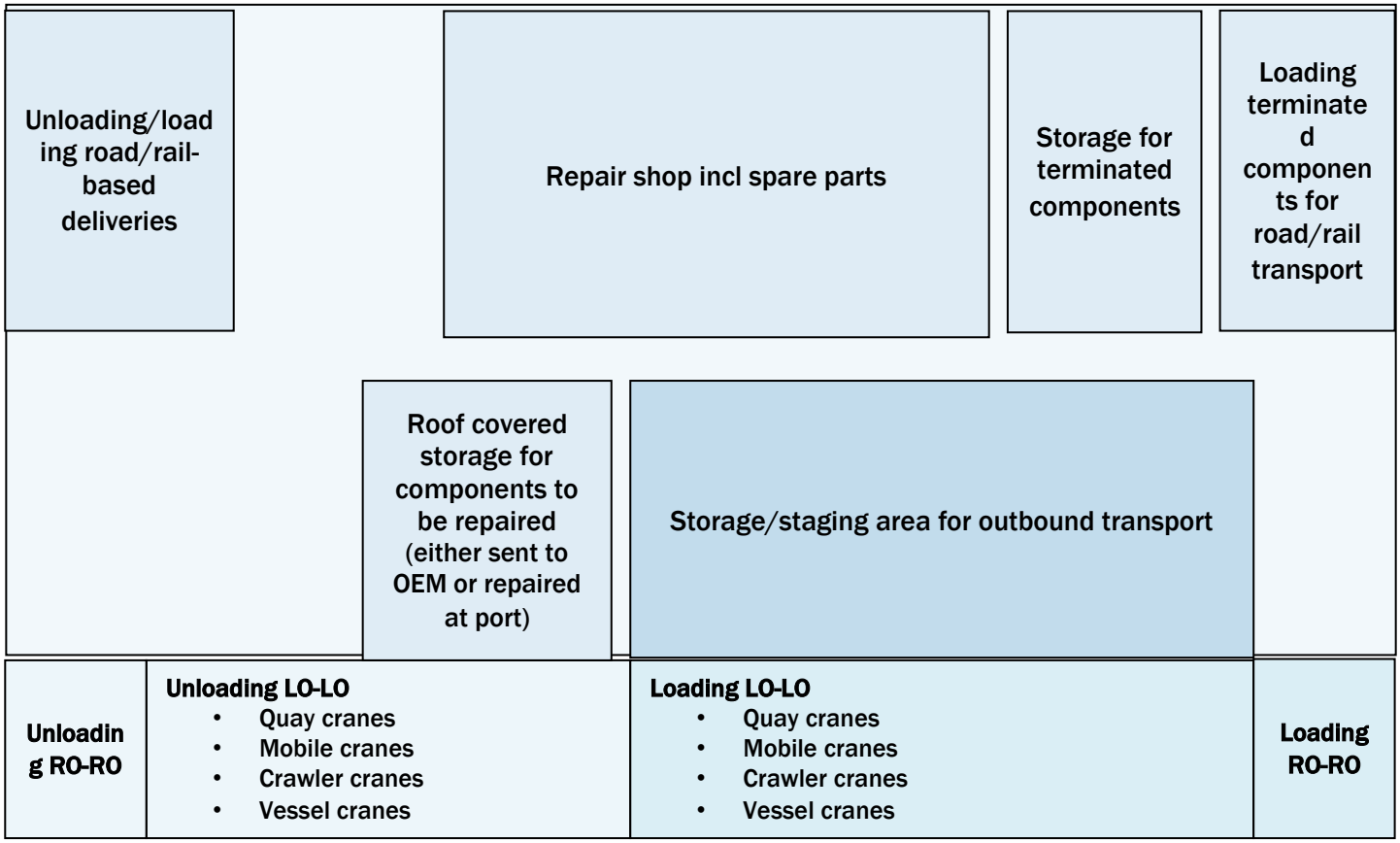


Figure 10: Suggested layout for O&M port [25]

Inbound transport

- Multiple types of components per vessel
- Nacelles and towers very infrequently transported to port
- Broken blades
- Lightweight components to repair or replaced

Outbound transport

- Outbound transport of equipment, spare parts and repaired components
- Outbound transport of personnel to troubleshoot, reset, and repair WTGs (corrective maintenance)
- Outbound transport of personnel to perform planned maintenance

<u>Suggested layout for Decommissioning port:</u>

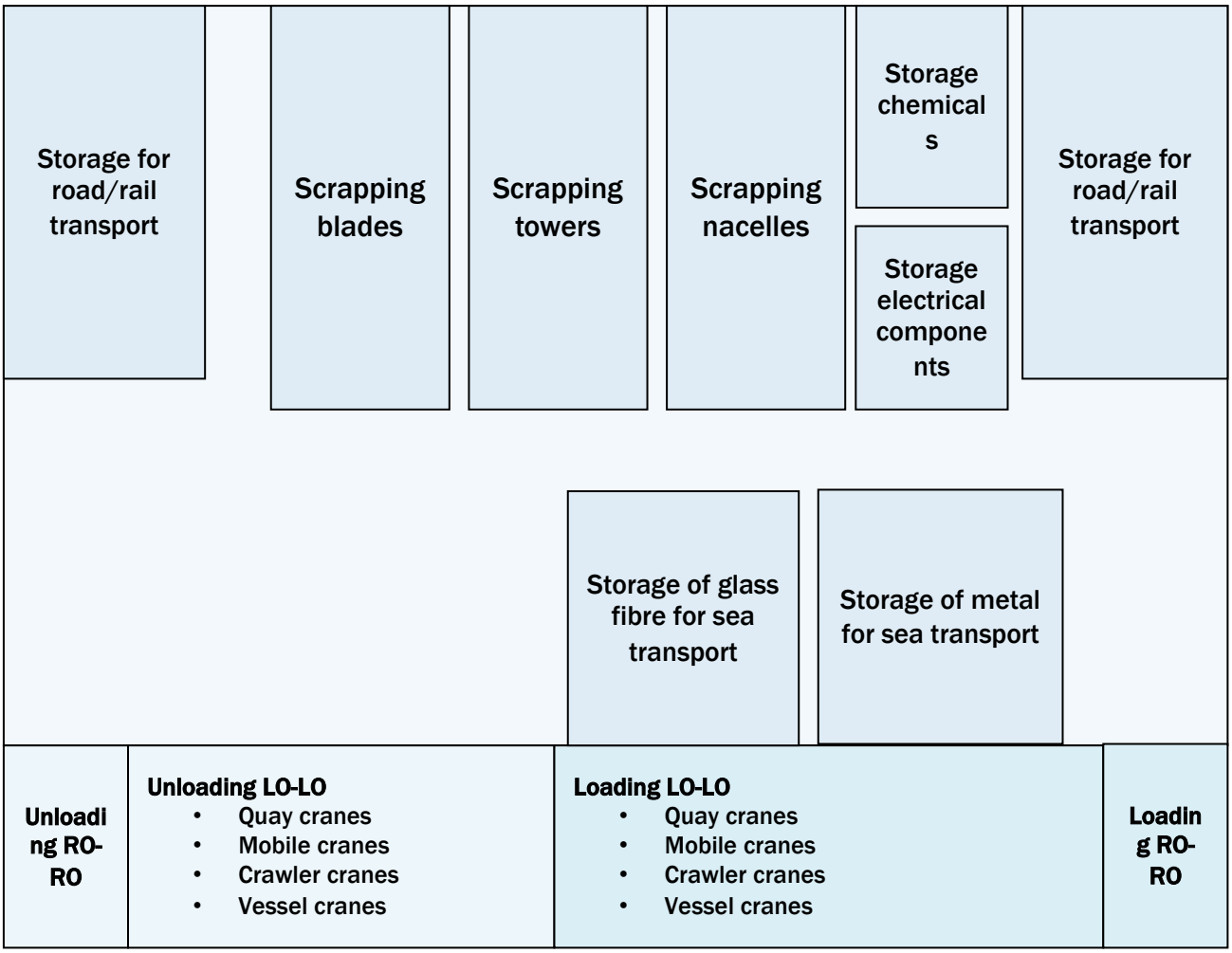


Figure 11: Suggested layout for Decommissioning port [25]

Inbound transport:
Installation vessels with

- Blades
- Towers
- Nacelle

Outbound transport:
Loading on bulk vessels for transporting the parts to recycling

2.2.3 Component handling capabilities

While day-to-day personnel and light equipment transfers benefit greatly from short transit times, wind turbine overhauls or planned major component replacement are less distance sensitive but require more substantial load-out and crane capacity [26]. In order to minimise the waiting time for the installation vessels, the ports should assure that the components are ready for loading at the quayside by the time the installation vessel arrives at the port. The agreed number of components will be placed in the quayside in a setup that allows the crane on-board the installation vessel to lift them without having to move around more than necessary or to relocate the vessel [12].

Hence an accurate scheduling and the availability of necessary component handling equipment at the port would help avoiding the excess cost associated with the vessels waiting for the components to be loaded. Furthermore, since bad weather conditions may occur when the vessels arrive offshore, the waiting time at the port for loading and preparing components should be as low as possible. This could prevent the contractor asserting that the missed usable weather windows were due to the delay in loading the vessel, restricting the claim that the client or wind farm owner has against the supplier [12].

A. Cranes:

Availability of cranes in the port for offshore operation is of vital importance. Although every offshore project requires different types of cranes, the industry suggests the availability of large cranes (up to 1000 tonnes) in the ports [17, 18]. Wind turbine components including the nacelle, blade and towers require carnage at the port. Nacelle is one of the heaviest components of the wind turbine and for nacelles a mobile crane capacity of up to 350 tonnes is desirable. Wind turbine blades weigh in the order of tens of metric tonnes, but, these weights are likely to increase as technology trends push towards larger offshore machines. It is likely that transport vessels will load-out significant numbers of blades; however, blade weights are well within the capacity of suitable mobile cranage. For towers, it is becoming increasingly common to install complete towers offshore to reduce offshore operations, so a large crane capacity may be required [11].

For the foundation structures, it is preferable that they are fabricated, either close to the quay edge or by a manufacturer with unrestricted access and ability to move the foundations to the edge of the quay or from the manufacturing facility directly to the offshore site by using barge or crane vessel [12]. From the port facility, the foundations are either lifted or rolled on board. Among the most cost effective solutions is rolling, when using a barge. A crane vessel can also be used for that purpose; however the cost would be higher [12].

Crawler cranes:

A crawler crane consists of an upper carriage mounted on a crawler type undercarriage (Figure 12). The upper deck and attachments rotate 360º. A crawler crane features either a box or a lattice type straight boom and it may be equipped with an optional jib (boom extension). At the end of the boom and/or jib is a wire rope suspended implement such as a grapple, clamshell, crane hook, or electric magnet. Crawler cranes are implemented for many applications and are therefore exposed to a wide range of external hazards during normal operation, not only to the operator but also to the maintenance personnel and others nearby [27].

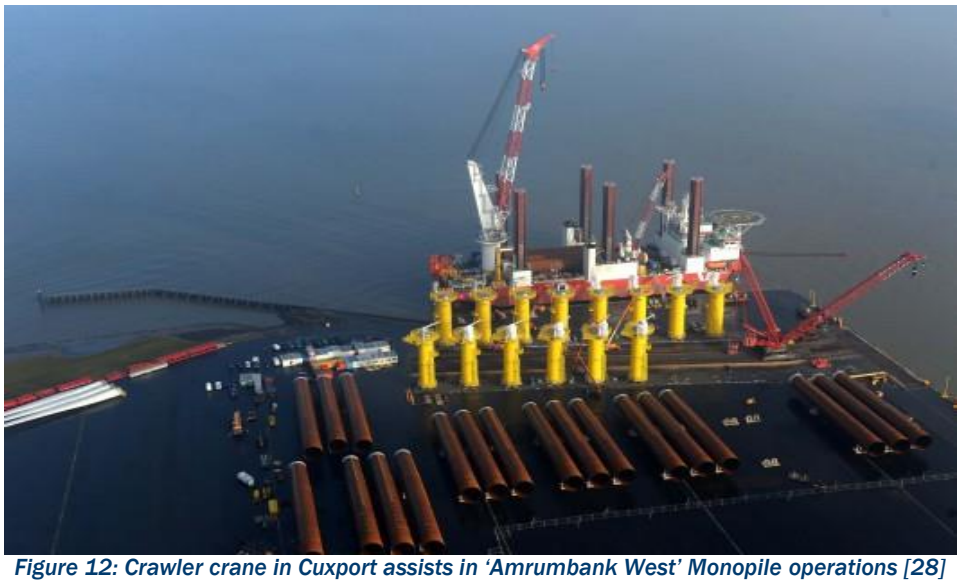


Figure 12: Crawler crane in Cuxport assists in 'Amrumbank West' Monopile operations [28]

Floating cranes:

Floating cranes are the cranes that execute the lifting of the components while operating on water (Figure 13). Hence their positioning may change and it is not fixed. Floating cranes areas of use include: general salvage work, installation and maintenance of wind turbines, loading and unloading heavy goods or repair work. The platforms are located in ports or out at sea. In either case, for floating cranes precise manoeuvring to their destination is essential [29].

Figure 13: Matador 3 floating crane is loading the jackets at Bremerhaven (RWE) [30]

B. Self-Propelled Modular Transport (SPMT):

Some offshore projects have managed to avoid the need for heavy cranage at the port facilities by loading turbines and foundation components onto SPMTs (Figure 14). The components can then be loaded by using Roll-on Roll-off (explained in section C) ship-type vessels or transport barges loaded from Ro-Ro link-spans or the SPMTs can deliver the component to the quayside where it is then lifted onto the vessel using an onshore or on-board crane [11]. SPMTs have been a common means of transporting large offshore wind components between the quayside and the storage area [11]. Common forms of SPMTs have individual two-axle units with a load carrying capability of up to 30 metric tonnes per axle (tonnes/axle) and can be arranged side-by-side or end-to-end in a rolling transporter for extremely large loads. Nacelles and towers which mainly are transported via SPMT in the port could exert a pressure of 10 tonnes/m^2.

Figure 14: 2×6 axle line SPMT assembled as one self-propelled modular transporter (SPMT) [11]

C. Roll-on/Roll-off capability:

Roll-on Roll off capability refers to access ramps used for loading the components and has been identified as an important requirement for offshore wind ports [17]. This capacity is desirable since rolling load out is far cheaper than lifting in some circumstances [11]. This capability is important since it reduces the use of heavy cranes and provides a more convenient way to load the components. If the ports do not have permanent Ro-Ro berths, it is possible to accommodate this facility by using a mobile Ro-Ro ramp [11]. This is a highly specialised piece of equipment, as it enables extension of a port's capability beyond that of its fixed infrastructure. Ro-Ro ferries have been used in the Gwynt y Mor project, where the components of the wind turbines were regularly delivered to port of Mostyn by a Ro-Ro ferry from their manufacturing factory in Brande, Denmark [31].

D. Lift on/ Lift off capability:

Lo-Lo vessels can transport a range of different products as a result of their flexible cargo space, container capacity, and on-board cranes. Lo-Lo cargo is either containerised cargo or other types of cargo that may be too large to ship in containers or on Ro-Ro ships. A Lo-Lo operation is when cargo is loaded and discharged over the top of the vessel using cranes or derricks. Lo-Lo vessel load and unload cargo at Ro-Ro ports, Lo-Lo ports and at un-serviced jetties, using its own cranes. Self-geared Lo-Lo type vessels are loaded and unloaded by a crane, which lifts cargo to a specific location in the Lo-Lo ship [32].

E. Dry dock:

Availability of a dry dock at the port could be ideal for the construction and fabrication of large scale components such as gravity based (concrete) foundations, allowing for a variety of manufacture and load out concepts to be tested and implemented. The dry dock can be used for prototype and serial manufacture of gravity based foundations [33], as well as floating foundations including semi-submersible and tension leg platforms [14].

Figure 15: Floating dry dock [34]

F. Pontoon:

For offshore wind, pontoons could be used as a temporary storage for foundations and for the transport of heavy load components. BLG logistics [35], based in Bremen, Germany, has developed a special pontoon which allows for

- Swift loading and unloading
- Different applications, in particular transport of further large components for offshore wind farms
- Quick retrofitting of the pontoon for different loading cases and operations at short notice
- Control of the inclination of the pontoon and the load on the quay via an efficient ballast system

Pontoons are also being used for the transfer of crew and technicians. The multi-million pontoon developed for the Gywnt Y Mor wind farm, was commissioned with power, water and re-fuelling locations built in and has reduced the transfer time to the site. Also, since the pontoon is less tidally restricted, the access to and from the port is greatly enhanced [36].

Figure 16: Two tripods are transported using BLG's OFFSHORE BHV 1 pontoon [35]

2.2.4 Vessel access

In the offshore wind industry, vessels are used for the execution of different phases of the project and the ports must have suitable quayside and draft for accommodating these deep draft vessels. For the construction phase, wind turbine components are either directly transported from the manufacturing facility to the offshore wind farms, or transported to an installation port where they are stored and assembled and then shipped to the offshore site. For the operations and maintenance phase, smaller components and crew are transferred by smaller vessels or boats, and for the decommissioning phase, it

is expected that the turbine components will be shipped back to an onshore facility for recycling normally via the same vessels used for the installation phase [54].

For all the phases mentioned above, suitable ports where the vessels can dock, load and un-load the components are needed. The offshore wind industry is expected to use both specialised vessels and vessels 'diverted' from the oil and gas sector as long as the latter are available on time. Examples of vessels active in the oil and gas industry include Seaway Heavy Lifting's Stanislav Yudin performing monopile and substation installation, and Seajack's new build vessels Kraken, and Leviathan specified with both wind farm and oil and gas work in mind, being chartered for wind turbine installation [17].

The majority of dedicated vessels used by the offshore sector are in the site construction vessel category [3]. Within this category, the installation of substructures and turbines are the main operations and many technical specifications have to be met by the vessels in order to carry out the work. Different options for site construction vessels are: jack–up vessels, leg stabilised crane vessels, dynamic positioning (DP2) Heavy Lift Cargo Vessels (HLCV), semi–submersible heavy lift vessels, shear-leg crane barges, and floating dumb barges with crane [3].

Nacelles are normally carried on heavy lift cargo vessels and the suitable draft to accommodate HLCVs is a minimum of 8 metres. Jack-up barges have also been used for carrying and installing the nacelles. An example of a jack-up barge used in the industry is JB 117 (Figure 18), suitable to be equipped with a portable dynamic positioning system (DP 2) [37].

For blades, HLCVs are used, as they are increasingly fitted with container-twist-locked frames and loaded in groups of three at a time, which requires significant cranage lift weight and outreach, only found on larger heavy-lift crane vessel.
Tower transportation could be via barges, but may use HLCVs, so the draft of the latter has been used as the limit [11].

The port serving these jack-up vessels must have a suitable sea bed, and jack-up capacity assessment will be required for the quayside. Measurements of the soil strength adjacent to the quayside will be needed to ensure that layering of sub strata does not include thin hard layers of soils overlaying weaker soils which can lead to jack-up leg punch-through failure [11]. For ports to accommodate installation vessels, developers require the following characteristics [17, 18]:

- Draft of up to 10 metres
- Quayside of up to 300 metres
- No locks, tidal restrictions, or overhead restrictions
- Water way of up to 200 metres
- Quay bearing capacity of up to 10 tonnes/m^2

Figure 17: Hub with blades in star configuration assembled at the port for the Borkum West II Windfarm, Germany [80]

Figure 18: JB-117 installing the nacelle [37]

For transporting foundations from the ports to the offshore site, different methods exist. Monopiles can be transported via HLCVs or barges. Gravity base foundations and jackets are normally transported on a barge and then lowered into position. For the Thornton Bank project, Rambiz a crane barge able to lift unusual structures that would otherwise require two separate vessels, was used to carry the gravity base foundations (Figure 19). For the Oremond project, foundation jackets and a substation jacket on barges (4 jackets on each barge on a vertical position) were shipped from fabrication yard at the north-east coast of

UK to the mid-west coast of UK. Once on site, the HLV Rambiz lifted jackets from the barge and mounted it on top of the pre-installed piles. Once the jacket was placed, a separate DP2 grout vessel inserted grout into the annulus between jacket and the piles [38].

Future wind turbine installation vessels are expected to focus on improving construction efficiency by increasing their transit speeds, payload capacity, and ability to erect turbines in higher wind speeds and harsher sea states. Some firms are developing designs that accommodate the transport and installation of fully assembled turbines [16].

In the table below, a list of some installation vessels currently being used in the industry for foundations and turbine components has been compiled.

Installation vessels:	LOA (m)	Min draft (m)	Max draft (m)	Beam (m)	Max crane (tonnes)	Purpose
Thialf	201.3	11.8	31.6	88.4	14200	Deep water construction vessel, customised of installation of foundation, moorings, Spars, TLPs.
Svanen	102.75	3.5	4.5	71.8	8700	Designed specifically for offshore installation projects involving large and heavy structures.
Saipem 7000	197.95	10.5	27.5	87	14000	Has the capacity to handle the entire work scope of offshore construction developments.
Rambiz	85	3.6		44	3300	Can operate in deep and shallow water. Combination of two cranes enables her to lift unusual structures that would otherwise require two separate vessels.
Innovation	147.5		7.33	42	1500	Innovation enables safe loading and installation of 6 MW wind turbines with overall height of more than 120 m as well as heavy foundations in water depths of up to 65 m.

Table 4: Installation vessels [39]

Figure 19: Rambiz lifting GBF at port of Oostende [40]

Figure 20: Scaldis Salvage & Marine Contractor's heavy lift vessel Rambiz was used to install the jacket foundations for the Ormonde project located at the North West coast of the UK. Image courtesy of Vattenfall [41]

Figure 21: Innovation loaded with monopiles and transition pieces at Aalborg, Denmark for Westermost Rough wind farm, UK [42]

Figure 22: 5000 tonnes mono-hull DP crane vessel Oleg Strahnov, installing wind turbine foundation tripods at Borkum West II Windfarm, Germany [43]

Tugs boats:

Tug assistance is usually not required for self-propelled wind turbine installation vessels, since these vessels are able to move and position themselves using their own propulsion and dynamic-positioning systems. Barges, however, require at least one tug of approximately 4,000 to 5,000 horsepower (hp). In addition, a smaller tug of around 1,000 hp may be needed to help position the vessel for jacking operations. Additional necessary vessels include high-speed crew boats during wind farm construction and several auxiliary vessels to complete the marine fleet. Tug boats could be provided by the port or third party companies offering services to the offshore wind industry.

Figure 23:Self-Elevating Platform towed from Borwin Alpha site [44]

2.2.5 Port's bearing pressure and surface area

Ground bearing capacity has been identified as one of the most important parametres for a suitable offshore wind port due to the heavy weight of the wind turbines components and substructures. 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 [11]. A minimum ground bearing capacity of 10 tonnes/m^2 has been identified suitable by the industry [11, 17].

Once a port has been chosen, the port's bearing capacity must be documented. If the port is not suitable to handle the axle loads of the trucks and trailers moving the components, the surface must be repaved, which could add a significant cost to the contract [12]. For heavy components, regular asphalt is not enough and the surface must be strengthened so that it does not crush under the weight of the components [12]. A surface of concrete or asphalt will prevent dust and nicks from pebbles from damaging the outer layer of the turbine components. This is important since all the components are painted or fibreglass coated. The Marine Warranty surveyor and installation contractor will be very wary about

these types of damage because this could also pass a scratch when loading or installing the component [12].

2.2.6 Port's connectivity

a. To the wind farm:

Snyder and Kaiser (2008) [45] suggest that the distance to shore is positively related to the capital costs. The distance from the port to the wind farm has an impact on the construction and O&M costs. During the construction phase, vessels have to make few trips between the site and the port for loading additional equipment. Given the cost of these trips, the closer the site is to the port, the less expensive the installation will be. The distance to the port, also dictates the amount of transmission cabling.

For the O&M phase, the crew have to make regular trips to the wind farm for monitoring the turbines and the foundations. Locating the crew as close as possible to the wind farms will decrease the environmental impact and costs of maintenance. The current trend shows that, the future projects are moving further from shore and in deeper waters. The average water depth of completed or partially completed wind farms in 2014 was 22.4 m and the average distance to shore was 32.9 km [2]. Hence, the port's proximity and accessibility to the wind farm could be a significant factor influencing the developers' decision for selecting the suitable port for their operation.

b. To the component supplier sites:

Denmark and Germany have been and continue to be the host to a significant amount of established infrastructure, particularly in terms of wind turbine manufacturing facilities [17]. The Netherlands and Belgium have also enjoyed significant participation, especially by the provision of installation services drawing on significant North Sea oil and gas and coastal engineering experience. Electrical equipment and subsea cable supply has a more distributed supply base with notable contributions from Norway, Sweden, Germany and Italy.

The UK, which until recently had not played a significant role in the supply to the offshore wind sector, has seen substantial recent investments, with new facilities being established primarily along its east coast to serve domestic and export markets in the North Sea [17]. For instance, JDR Cables based at the port of Hartlepool has secured their third order for inter-array cables into German offshore wind farms, the most recent one being the Vattenfall AB Sandbank project, announced in September 2014. The company has now won more than £100 million of orders [46]. For The Gwynt y Mor project, located 13 km off the North Wales coast, two offshore substations were fabricated. Siemens had appointed Belfast shipyard Harland and Wolff (H&W) for fabrication of these substations, and BiFab, based in Fife, for the design and manufacture of both substation foundation jacket structures [47]. BiFab used a proven design in delivering the contract and worked alongside H&W to design and manufacture the substations [47].

c. To road, rail, air transport:

Proximity of a port to road networks will facilitate the transportation of components such as blades. Also, during the decommissioning phase, the dismantled components can be transported to the recycling centres via the road networks. Use of rail system, however, is much less common for the transport of larger components and the manufacturers tend to ship the components to or from the ports.

For the O&M phase, proximity of the port to heliports is particularly important. In some recent offshore projects, e.g. Greater Gabbard, UK, Helicopters capable of carrying 2-3 technicians, are complementing work boats and are employed during inclement weather and when quick access to the wind farm is required. Technicians could be transported and placed directly on the nacelle and start the work with a short transition time from the port to the site.

Figure 24: 63.5 m blade transported to the Port of Oostende [24]

Figure 25: Use of helicopters for servicing turbines [48]

2.2.7 Security at the port

Since 2001, the security level of the ports worldwide has drastically increased. Ports used for the offshore wind are no different from ports used for other purposes and they are subject to international regulations and security measures (i.e. International Standard for Port Security, ISPS). With almost 500 personnel working in the port on a project, managers have a difficult task fencing in the area and accounting for all the people working on the project. Every person entering or leaving the port, or a vessel in the port, must be accounted for with personal details, company references, and the type of business to be carried out [12].

For addressing these security issues, authorities have created control measures through a tagging system which is able to record the position of all personnel using chip identity cards and monitoring points at every entry or exit possibility [12].

3. Installation, operations and maintenance and decommissioning strategies from ports

3.1 Installation

In projects where the components cannot be directly shipped from the manufacturing facility to the offshore site, they are first delivered to an installation port where the components are pre-assembled and stored, before loading onto the vessel and transferred to the offshore wind farm site [49]. Installation ports could also be used for servicing the offshore wind farms, an example of which is Mostyn in North Wales. This port is capable of supporting construction of up to 300 MW turbine capacity per year. Large areas of land are required due to the space taken when turbines are stored lying down on the ground. Two turbines take up nearly 2 ha of space. Port of Mostyn has provided a base for offshore wind construction as well as offshore wind support. Port of Mostyn has been the installation base for North Hoyle, Burbo Bank, Robin Rigg, Rhyl Flats, Walney 1, Walney 2 and Gwynt-y-Mor projects and supports the servicing of the North Hoyle, Rhyl Flats and Gwynt-y-Mor wind farms [50].

According to [51], 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. The components could be loaded on the installation vessels in different configurations depending on the available deck space on the vessel, port facilities such as lifting equipment, available space on the ports, distance from the offshore site and weather windows (different installation methods are shown in Figure 26).

As the installation operations take place offshore with varying wave and weather conditions, by choosing the best installation strategy, the weather windows can be used optimally. For larger sites located further from shore, however, new concepts such as the Dutch harbour at sea, consisting of multi-purpose platforms which could allow for better usage of weather windows and reduction in sailing times are in the research phase [17]. Additionally, there is a general move away from installation (mobilisation) ports and alternatively components are exported directly from manufacturing facilities to the offshore wind site in order to save costs [17].

However, the trend of exporting directly from the manufacturing facility may reverse or slow down due to alternative scenarios in the supply chain. Access to lower labour costs has persuaded many of the manufacturers to relocate the production facilities to Eastern Europe. Also, there is a drive in certain regions towards initiatives such as cluster building for offshore wind manufacturing in closely located ports. This is being pursued via co-operation between the public and private sectors [17].

3.1.1 Installation methods

As illustrated in Figure 26 in the installation method number 1, all parts are assembled offshore and the port will be used minimally for assembling purposes. On the contrary, in the installation method number 6, the port will be used for assembling the full turbine before delivering it to the site. By assembling most of the components or the full turbine onshore, the installation time will be decreased as the turbines could be lifted and installed in fewer movements. However, this method is constrained by vessel availability.

As of today there are very few vessels capable of carrying a fully assembled turbine offshore as there are limitations on the cranes' capacity and the available deck space. Based on an analysis done by [52], the most cost-effective method is the bunny ears strategy with 1-part tower (installation method number 5), and the most expensive is the fully pre-assembled strategy (installation method number 6).

This is due to the fact that although the single lift strategy requires the least offshore operations time, the method is affected significantly by weather limits and the availability of vessels and heavy lift cranes. All other methods have a wind and wave limit of 8 m/s and 2 m, respectively, while the fully pre-assembled method has a wave height limit of 0.75 m. Additionally, the heavy lift sheerleg crane used for fully assembled turbine, is substantially more expensive than the jack-up vessels used for the other installation strategies [52].

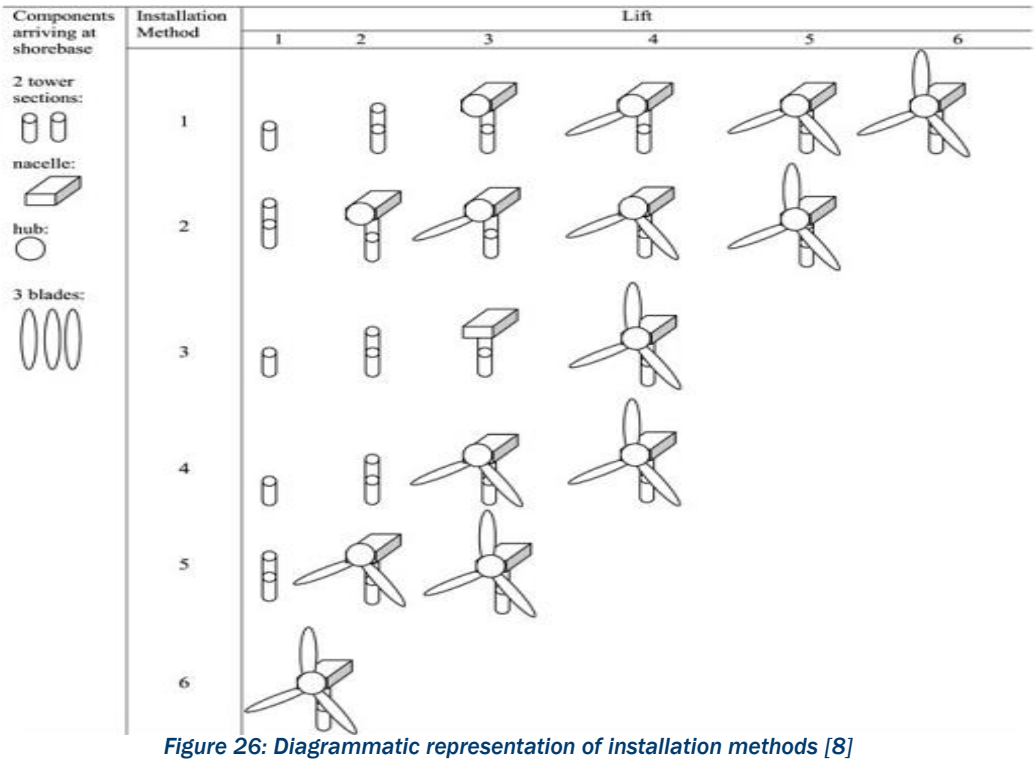


Figure 26: Diagrammatic representation of installation methods [8]

3.2 Operations and maintenance

Operations and maintenance of the wind farm is the longest of all phases as the wind farm needs servicing during the entire almost 25 years of its lifecycle. Developers normally look for ports which are willing to commit to this long period and provide regular service for the wind farms. Pointed out by one of the interviewees, a harbour master at an O&M port located in south of England, although the O&M ports must satisfy the technical requirements, but O&M has a very strong commercial side for developers and the negotiations with ports mostly concerns the commercial issues rather than the technical issues at ports.

Operations and maintenance ports, smaller ports compared to installation ports, are normally within close proximity to the wind farm, which can provide support services to

the wind farm. The main requirements of operations and maintenance ports are proximity to the site and a storage area for accommodating small to medium size components in the case of component failures. While there is no fixed or standard distance from the site to O&M base and the figures vary depending on the project, a range of 15 km to 75 km has been observed in projects across the UK. Also, as shown in Table 5, vessels used for O&M activities, normally do not exceed 100 m in length and 5 m in draft, hence O&M ports need not to be deep water ports with long quays.

Operations normally consists of activities such as remote monitoring, control, electricity sales, coordination, and back office administration of the wind farm operations and 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.
Maintenance activities are divided into two parts:

- **Scheduled (preventive, pro-active) maintenance**: including the repair or replacement of known wear components, based on routine inspections or information from conditioning monitoring systems, and routine surveys and inspections [26]. For a suitable O&M port, the industry suggests, a suitably sized quay (200 m in total) with 24/7 access, loading and unloading area with load bearing capacity of at least 5 tonnes/m^2 with Good access to transport links and skilled workforce [23].
- **Unscheduled (corrective, reactive) maintenance:** including unplanned activities occurring offshore, such as repair or replacement of failed or damaged components.

According to [7] for ports used for spontaneous maintenance operations, short transfer time to the offshore site (about 2 hours) is desirable; the other requirements are as follow:

- Quay length of 80 m
- Tide independent berth with depth of 3.5 m
- Unrestricted water access
- Bunkering capabilities
- Storage area of 2000 m^2
- Good connection to public road networks

Wind farm service vessels:	LOA(m)	Max draft (m)	Purpose
DP Galyna	70.1	3.3	O&M work, accommodation and transportation vessel
Njord Avocet	20.6	1.4	Crew transfer
Marian array	18	1.6	Crew transfer

Table 5: Service vessels for O&M [39]

3.2.1 Operations and maintenance strategies:

- Port-based work boats: up until now many offshore projects employed onshore bases, and work boats have been used for transporting technicians from port to the site. Here they transfer onto the offshore structures using a simple “step over” approach. The

'onshore based marine access' method uses specialised work boats based at a coastal port. Although this strategy has relatively low running costs, it is limited by the sea states. However, developments in the work boat designs, and methods of transfer from boat to the turbine offer some potential for increasing the limiting wave height and speed of transit [26].

- Helicopters: In situations where the wind farm is located further offshore, with a high risk of inclement weather and sea conditions, the O&M strategy of using only workboats may not be optimal, as the longer transit times can result in missing the short favourable weather windows. In such situations, helicopters can provide fast access to the site. It is often shown that the reductions in down time achieved by using helicopters outweigh their operation costs [53]. The Greater Gabbard project located in southern North Sea was the UK's first helicopter support strategy. Greater Gabbard is almost 74 km (40 NM) away from its O&M base in the port of Lowestoft. Since September 2012 Helicopters are routinely deployed to hoist the technicians onto specially designed turbines. Helicopter access is especially important in winter time when the turbines cannot be accessed via sea transfer due to the inclement weather.

- Fixed or floating offshore base (e.g. 'motherships'): As projects begin to be based further offshore, work boats may also operate from fixed or floating offshore bases to significantly reduce the time required for transit to and from site. Such offshore based approaches require technicians to live for some or all of the year on offshore accommodation near the vicinity of the wind farm, on one of the following:

  1. Fixed base: A platform with accommodation, boat landings and helipad. Work boats and/or helicopters provide access from the base to the turbines.
  2. Hotel Ships: Accommodation vessels which cannot dock directly with the turbines. Turbine access is achieved by "daughter craft" work boats or quick access vessels [26].
  3. Floatels and Offshore Support Vessels (OSVs): Accommodation vessels, 50–100 m long, with dynamic positioning (DP) capabilities and an access system or gangway to enable direct access to the turbines [26].
  4. Motherships: Accommodation vessels, 50–100 m long, with one or more deployable "daughter crafts", and specialist access system for direct access to the turbines. The mothership would return to port every 2-4 weeks for crew exchange. These strategies have higher capital and operating costs than a 'work boats only' approach. However, the greater cost is offset by the improved access to turbines, which will boost availability and hence reduce lost production [26].

3.2.2 Availability vs. Cost

Based on [26], whereas the number and reliability of the turbines commissioned in a wind farm impact the cost of O&M, the most influential factor is the distance of the wind farm from the onshore base. Distance from site is generally the key deciding factor, particularly if an onshore-based approach to access is adopted.
The choice of operations and maintenance strategy is made by comparing the cost of operations and maintenance against the potential revenue loss due to turbines being out of operation. According to [26], theoretically, maintaining 100% availability of the turbines

may not the optimal solution to minimise the total cost, but turbine availability of around 92% minimises the total O&M costs.

It should be noted that availability is a technical metric and not directly related to the wind resources. It is important not to confuse this parameter with capacity factor, which is a measure of the output of the project and is influenced by the average wind speed at the site, and is also expressed in percentages. Table 6 lists the cost optimal O&M strategy for a range of wind farm site distances from shore.

Distance from shore	O&M strategy
Less than 22 km (12 NM)	Workboat strategy
22km-75km (12-40 NM)	Heli-support
More than 75km(40NM)	Offshore based strategies (mother ships, floatels)

Table 6: Probable cost optimal O&M strategies [26]

It should also be noted that the development status of the projects significantly reduces as the projects' distance from port increases – no projects further than 40NM from port have yet progressed past the planning consent milestone. As the UK offshore wind sector matures, the workboat-based O&M strategies seen until now will be joined by increasing numbers of turbines being serviced under heli-support and eventually offshore-based strategies [53].

3.3 Decommissioning of the wind farm

Final decommissioning of the wind farm components or their replacements would take place when they have reached the end of their design life which is estimated to be around 25 years. Decommissioning could involve the entire wind farm or removal of selected components [54]. Currently, the industry agrees that decommissioning operations will be performed similarly to the installation activities, but in the reverse order [55]. In an appropriate context this is a reasonable position to take. However, this is based on the assumption that the wind farm components will still be in a reasonable mechanical condition and hence amenable to the *reverse-engineering* required for decommissioning at the end of their service life. It is probable that there will be wind farms that will fall into this category, i.e. a mechanical and structural maintenance schedule has been followed all the way to the end of the farm's active generating life [56].

However, in case the farm's elements are not in reasonably good mechanical and structural condition, then this critical assumption may not hold, imposing significant consequences on the viability of a decommissioning plan based on reversing the installation process [56]. For this study, however, our analysis is based on the assumption that decommissioning will be executed in the reverse order of the installation process.

3.3.1 Decommissioning strategies

Based on the assumption that decommissioning is the reverse of the installation process, it is likely to involve the following sequence [54]:

- Each turbine is disconnected from the electrical distribution and SCADA system.
- Any hazardous or potentially polluting fluids or materials are removed from the nacelle so far as the risk assessment identifies them as posing a potential hazard to the environment during turbine dismantling.
- A vessel similar to that used during installation is mobilised to the site.
- The rotors are unbolted from the nacelle and lifted onto the decommissioning vessel.
- The nacelle is unbolted from the tower and lifted onto the decommissioning vessel.
- The tower sections are unbolted and lifted onto the decommissioning vessel.
- All of the components are transported to the port, and dismantled.
- The decommissioned turbines may be overhauled and sold for re-use.
- Redundant material such as steel from the towers or other components would be recycled where possible and other materials disposed of in an approved manner.

Decommissioning of monopiles and jacket structures is likely to proceed as follows:

- Divers are deployed to inspect each pile footing and reinstate lifting attachments if necessary.
- A jack-up barge or heavy lift vessel is mobilised to the site.
- Any scour protection that has been placed around the base of the support structures is cleared where it is obstructing the cutting process.
- Crane hooks are deployed from the decommissioning vessel and attached to the lift points.
- The pile(s) is cut below the natural level of the seabed, as appropriate.
- Following the pile removal, the seabed is inspected for debris and any found is subsequently removed.
- The pile, transition piece and any debris are transported back to the shore either by lifting on to a jack-up, barge or heavy lift vessel, or by buoyant tow.
- The pile and transition piece, which do not contain any hazardous materials, would then be cut up and the steel could be recycled.

Decommissioning of gravity base structures is likely to proceed as follows:

- ROVs or divers are deployed to establish the base structural integrity and reinstate lifting attachments if necessary.
- A suction dredging vessel is mobilised to remove the gravity ballast.
- The ballast material would be properly disposed of either on shore or in an offshore spoil area.
- Divers are then deployed to inspect the base, and ensure all the remaining ballast is removed.
- A heavy lift vessel is mobilised to lift the bases completely out of the seabed and onto a transportation vessel which would take them to the shore.
- The seabed is subsequently inspected and any debris is removed.
- Steel bases do not contain any hazardous material and would be cut up and the material could be recycled. Concrete bases would be disposed of in an approved manner.

It is envisaged that a port looking to provide recycling facilities for offshore wind farms would require (depending to an extent on whether the wind farm has been dismantled or

demolished), quayside heavy lift facilities, storage areas similar in size to those required at the installation phase and covered warehousing where further component and materials sorting, break-up, etc. could be undertaken [56].

Seaton port, located in the north east of England, owned by ABLE UK, is among the ports with experience in offshore oil & gas structure decommissioning with expertise and suitable facilities. ABLE has been awarded the contract for the disposal of four offshore structures from the Shell operated Brent field. Three platform topsides, as well as a 138m tall steel platform jacket, will be transported from over 100 miles north east of Scotland to ABLE Seaton Port where they will be dismantled and recycled using the latest techniques and technologies. The offshore oil & gas decommissioning experience of ports, such as that of ABLE's Seaton port, could be employed for offshore wind dismantling considering the many similarities of the substructures.

3.4 Port Clusters for the offshore wind industry

In the international sea regions such as the North Sea, where most of the offshore wind projects are located, sea transport of wind turbine components can take place between any of the bordering countries and the offshore wind project. As the ports in the North Sea coast have different capabilities, multi-port strategies, in which certain activities take place in different ports with the most suitable facilities being used by the offshore wind developers, are possible. For example, the multi-port strategy was adopted in the Amrumbank West project in Germany, owned and developed by E.ON Climate & Renewable GmbH. The monopile foundations for this project were produced by Sif group in Roermod in the Netherlands. However, the large installation vessels could not reach the production facility because of the insufficient water depth, locks and bridges. Therefore, the monopiles were shipped via pontoons to the Netherlands, Port of Vlissingen, at Bow Terminal, where they were stored before being shipped to their final terminal in Germany (Cuxport in Cuxhaven), and then to the offshore wind farm [57].

The high costs associated with the logistics of such projects where the operations are dispersed between several countries, raises the issue of consolidating all the activities related to the installation around one single port or ports close to one another and create port clusters. With regards to the ports and infrastructure supporting offshore wind, clustering concept and consolidating the supply chain have gained attention by the industry in the recent years. Porter (1998) [58] defines clusters as "geographic concentration of interconnected companies and institutions in a particular field", and maintains that being part of a cluster allows companies to operate more productively in sourcing input, accessing information, technology, and needed institution, coordinating with related companies, and measuring and motivating improvement. In Germany, consolidation has taken place in several ports on the border of North Sea such as Cuxhaven and Bremerhaven where manufacturing facilities are established around the port and components can be shipped directly to the wind farms. In the UK, ABLE UK's Marine Energy Park [33] aims at building an integrated cluster which can support manufacturing of components during the assembly phase, and provide a storage buffer for the installation & construction phases. ABLE UK's quays are scheduled to be operational by 2017. An integrated port cluster brings cost reductions on delivery and installation vessels, lowers transportation costs by reducing the components trips and the overall carbon footprints, and results in better visibility and control over the supply chain.

Ensuring low risk and cost effective operations is very important, and ports that can accommodate offshore wind projects, in a suitable facility with enough capacity, safety, and infrastructure are needed.

3.5 Ports' investment decisions for offshore wind industry

Engaging in the offshore wind industry can provide ports with various revenue generating opportunities. Revenue can be generated by providing land and facilities for manufacturing and storage, onshore services such as land for substations and offshore marines services such as towage and pilotage services from the port to the wind farms. However, factors such as ownership structure, economics of markets, and the level of maturity of the industry can prevent ports from entering this market.

The offshore wind industry is still in its infancy and the volume of business might not be sufficient for ports to convince them to engage in this industry, considering the significant cost of infrastructure development. Port owners also see the offshore wind stakeholders reluctant to commit to contracts or tenancies which would allow specific infrastructure investment for the long term [59].

3.5.1 The effect of Port's ownership on offshore wind industry

UK:

The UK market is the world's largest offshore wind market, and has been continually ranked as one of the most desirable locations to invest in the offshore wind industry. The UK government has provided support for offshore wind through the Renewable Obligation and in the future through contract for difference, a key pillar for UK's Electricity Market Reform programme [59]. The UK government has also provided support through the Final Investment Decision (FID), enabling the Renewable scheme to eight projects, out of which five were for offshore wind energy [59].

The majority of UK ports however, are privately operated and the investment decisions are made based on commercial factors. The UK port industry is driven by market forces rather than the government or regional policy [21]. Given the private ownership structure, port owners are motivated to maximise the yield on their land and in the presence of more revenue-generating options, they might not invest in the offshore wind industry. The UK government however could participate in providing financial support for upgrading the ports and turning them into hubs where the UK supply chain can be supported. Investments are critical and given the limited fund and resource, it seems logical to develop a number of ports, each serving a wider geographic region [59].

Continental Europe:

Many continental ports are in public ownership and their investment decisions can take into account the broader local economic benefits of a project as well as the direct port revenue [49]. For instance, in Germany, where importance is given to building port clusters, with substantial support from the State of Lower Saxony and the EU, an

infrastructure was created in the port of Cuxhaven to build and ship all of the components necessary for offshore wind turbine generators.

In the recent years, more than €80 million (c. £57 million) has been invested in the infrastructure of the Offshore Base Cuxhaven. In addition to this, private investors in the offshore industry have invested more than €100 million (c. £70 million) in Cuxhaven during 2007 and 2008. Additional private and public investments are forthcoming in the next few years [22]. Projects in the east coast of UK could face competition from continental ports, especially in the Netherlands and Germany where speculative investment from public funds has enabled the establishment of facilities suitable for offshore wind [49].

3.5.2 Port developments in the UK

The growth of the offshore wind industry has created opportunities for many UK ports, and ports are ready to exploit such opportunities. Offshore wind farms provide a potential market for the UK ports worth over £150 million, totalling up to £800 million by 2020, which including O&M charges, could reach a total of £1 billion [59].

In November 2014 with the support of UK government Siemens announced its decision to invest £170 million in wind turbine production and installation facilities in Yorkshire, spread across two sites comprising the previously announced Green Port Hull project construction, assembly and service facility and a new rotor blade manufacturing facility in nearby Paull, in East Riding [20]. This investment which is accompanied by £130 million from Associated British Ports (ABP) is the UK's first major offshore wind manufacturing facility in the offshore wind sector [20].

ABLE Marine Energy Park, the largest enterprise zone in the UK made a £450m investment to develop one of Europe's largest Super- port on the Humber estuary (South Bank). This investment will attract around 750 £ of inward investment and could create about 4100 jobs [60].

Belfast harbour in Northern Ireland in the west coast of UK is another example of a port which made an almost £53 million (c. €70 million) investment in developing a 20 ha purpose-built offshore wind terminal for Dong Energy [61]. This investment will be amortised over a decade, since Dong Energy has an interest in 6 wind farms in the Irish Sea [49].

3.5.3 Future trends

According to [17], location of the port and a cost benefit analysis are among the important parameters to be considered when choosing what operations to be carried out in the port. Future trends in the use and operation of ports show that cluster-building of offshore wind manufacturing can be realised in ports located close to each other. Financial support could be significantly used to develop the necessary onshore infrastructure for the offshore wind energy to become a mainstream technology in the near future [62]. Port capacity could also have an impact on the wider energy infrastructure expansion such as carbon capture and storage (CCS), energy storage and nuclear programmes and is also

vital in serving the infant wave and tidal renewable sector [59]. Key infrastructure upgrade considerations must therefore be inclusive of all low carbon technologies' needs and future budget cuts must take into account the wider benefits of the port redevelopment [6].

In practice, a significant amount of the port development costs may be borne by the initial projects; however, once ports have been developed, future project costs may be expected to decrease [3]. Investment in ports and waterways is one way that public investment could greatly support offshore wind development, as well as other industries that rely on water-based transportation. Therefore, investment in port and navigation projects will have a compounding effect and the cost-benefit ratio will be very favourable for the development of this sector.

4. Port selection model [1]

In the process of development and operation of an offshore wind farm, myriad of decision making problems exist, including but not limited to the selection of the most suitable

[1] This section is part of the working paper 'An assessment of installation and O&M ports for the offshore wind industry: an AHP approach' by Negar Akbari, Chandra Irawan and Dylan Jones presented at Euro July 2015-Glasgow conference.

offshore site, turbine types, foundation types, vessel types, and the most suitable port and onshore infrastructure which could support the three phases of installation, operations and maintenance and decommissioning of an offshore wind farm. Given the magnitude of the growth in the offshore wind industry, the demand for suitable ports and onshore infrastructure comes into spotlight. To date, in most offshore wind projects resources from other marine industries has been utilised, for instance, vessels from the oil and gas industry or the container shipping ports as the onshore base. However, in order to meet the future capacity targets of the industry, the need for specialised infrastructure has been identified

In section 4 a decision support framework is presented with the goal of aiding the decision maker in selecting the most suitable onshore base for a given wind farm based on the criteria defined in section 2. After presenting a literature review regarding the use of decision making methods in particular the Multi-Criteria Decision Analysis (MCDA) method in the offshore wind industry and port selection in section 4.1; the methodology, case application and the final results are presented in sections 4.2, 4.3, 4.4, and 4.5 respectively.

4.1 Related work

Decision makers usually have to make decisions in the presence of multiple, conflicting criteria. In order to evaluate these choices and make the best decision, scholars in the area of decision sciences, offer several methodologies, including Multi-criteria decision analysis (MCDA) methods; MCDA includes methods such as Data Envelopment Analysis, Analytical Hierarchy Process, Fuzzy set theory, Goal programming, ELECTRE (Elimination and choice expressing reality), PROMOTHEE (Preference ranking organisation method for enrichment evaluation), etc. [74] which could be applied for solving complex decision making problems. MCDA has seen a significant amount of use over the last several decades and its role in different application areas has increased significantly, especially as new methods develop and old ones improve [74]. MCDA has also been used in the offshore wind industry. Ederer (2014) has evaluated capital and operating cost efficiency of offshore wind farms, using the Data Envelopment Analysis (DEA) model [63]. For measuring capital cost efficiency, the input is defined as the capital cost and the outputs are defined as installed capacity, distance to shore and water depth. For the operating cost efficiency, the input is defined as operating cost and the outputs are distance to operating port, energy performance, installed capacity, and availability. Ederer (2014) [63] suggests that water depth and the distance from shore are two of the main cost drivers of the offshore wind industry. Findings of this study also show that smaller wind farms should be installed closer to shore and in shallower water sites. Secondly, at least for the range under investigation, it is possible to build a smaller offshore wind farm that is comparatively less expensive than a larger one at the same distance to shore and water depth. Third, the size of the offshore wind farm has a weaker impact on the costs the farther away from shore and the deeper the water at the OWF site.

Jones and Wall (2015) [64] have used extended goal programming for site selection in the offshore wind sector. The model developed serves to demonstrate the multi-criteria, multi- stakeholder nature of decision making in the offshore wind farm sector. This study [64] shows that economic, technical, sociological, and environmental considerations all play a part in determining the optimal course of action.

Fetanat et al. (2015) [65] has used hybrid multi-criteria decision method based on fuzzy Analytic Network Process, fuzzy decision making trail, evaluation laboratory and fuzzy ELECTRE to assist the offshore wind farm site selection in the Persian Gulf.
In the container port selection literature as well, the use of MCDA is recognised. Lee lam et al. (2012) [66] has used analytic hierarchy process (AHP) and proposed a decision support system (DSS) for port selection in container shipping, enabling the port managers to obtain a detailed understanding of the criteria and address the port selection problem utilising multi criteria analysis. Lee lam et al. (2012) [66] also show how technology advancement can bring positive effect of strategic planning to shipping firms. Zavadskas Kazimieras et al. (2014) [67] have used 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 to satisfy economic needs. Ugboma et al. (2006) [68] have used AHP to determine the service characteristics that shippers consider important when selecting a container port. Ugboma et al. (2006) [68] suggest that shippers place high importance on efficiency, frequency of ship visits and adequate infrastructure, and quick response to port users' needs was insignificant to them. Port managers were interested in the results since the study provided essential information on the key factors that come into the decision process of port users.
Guy and Urli (2006) [69] has Assessed whether the accepted rationale of port selection by shipping lines – based on the combined importance of quality of infrastructures, cost, service and geographical location – is useful to account for the selection behaviour observed in the Northeast of North America, particularly the recent arrival of new global carriers in Montreal. They [69] have used a multi-criteria approach in combination with scenarios where the relative importance given to selection criteria and the performance of ports are both varied across a wide range. This allows the authors [69] to assess how port preference is affected by changes in criteria weight (expressing selection rationale) and by changes in evaluation (expressing relative port performance). With criteria weights set to reflect the common selection rationale, their findings suggest that shipping lines should call at New York and bypass Montreal.
After reviewing the literature, it comes apparent that much of the work related to the use of MCDA methods in the offshore wind, is related to offshore wind site selection and there is a gap in the literature related to the assessment of onshore infrastructure suitability for the offshore wind industry. Therefore, we propose the use of a multi-criteria decision making model for the assessment of port suitability for the offshore wind industry. The aim of this port selection model is to provide a decision support framework, enabling the decision makers-developers- to tackle a strategic challenge, which is selecting the suitable onshore base for an offshore wind site.

4.2 Methodology

In order to identify the most suitable ports for each phase of the offshore wind farm, we have used the Analytical Hierarchy process (AHP) method. AHP is a theory of measurement through pairwise comparison and relies on the judgements of experts to derive priority scales [70]. These comparisons may be taken from actual measurements or from a fundamental scale, shown in table 7, which reflects the relative strength of preferences and feelings [70]. The decision problem is structured in a hierarchy form with the goal of the decision at the top level, followed by the factors affecting the decision in gradual steps from the general, in the upper levels of the hierarchy, to the particular in the lower levels [70]. When constructing hierarchies, enough details to represent the problem as

thoroughly as possible must be included. It is a trade-off however, as it is important not to include so many details that the sensitivity of the model to variation of the elements is negatively impacted [70].

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.

Table 7: the fundamental scale of absolute numbers [71]

Saaty (2008) [71] defines the analytical hierarchy process as following:

1) *Define the problem and determine the kind of knowledge sought.*
2) *Structure the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent level elements depend) to the lowest level which usually is a set of alternatives.*
3) *Construct a set of pairwise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below, with respect to it.*
4) *Use the priorities obtained from the comparisons to weight the priorities in the level immediately below. Do this for every element. Then for each element in the level below add its weighed values and obtain its overall or global priority. Continue this process of weighing and adding until the final priorities of the alternatives in the bottom most level are obtained.*

The AHP has been shown to be effective in evaluation problems involving multiple and diverse criteria, measurements of trade-off and with limited data [72]. The AHP exhibits flexibility in dealing with both the qualitative and quantitative factors in a multi-criteria evaluation problem [72].

4.2.1 Consistency

In decision making problems, it is important 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)*. The recommended value of the consistency ratio is 10% [71][72], however in applied settings a ratio of up to 15% is permissible [78].

4.2.2 Hierarchy structures for the port selection model

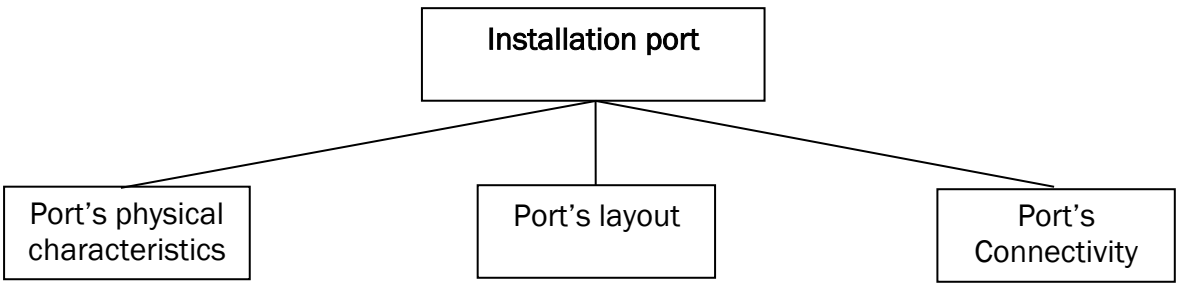
After identifying the most critical technical elements in offshore wind ports, for each phase of the offshore wind farm life cycle, a hierarchy that includes these elements was constructed. The hierarchies are comprised of 5 levels, with the first level stating the objective (the most suitable port), the second level the criteria group, third and fourth levels are the sub-criteria of the group, and the fifth level contains the alternatives, i.e. the candidate ports.

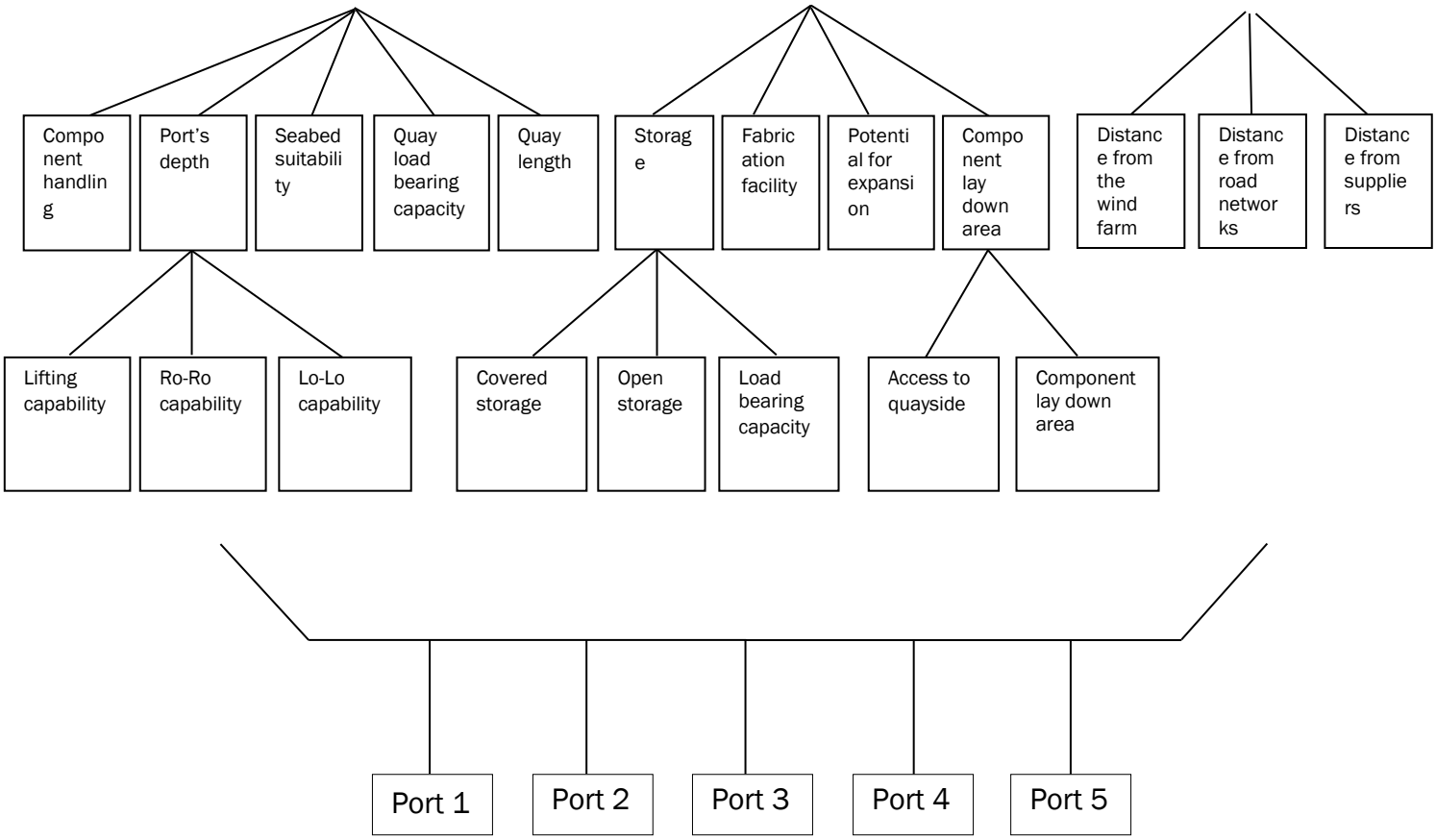
For each phase of the offshore wind lifecycle a separate hierarchy was developed, as each phase requires different criteria within the port and also because even the common criteria could have different weights depending on the type of operations carried out in that port. The models then were validated through industry experts and the questionnaires containing the pairwise comparisons were sent to 5 experts. It should be noted that pairwise comparison of criteria is used, since port requirements do not have the same importance for decision makers. For instance, for an installation port the port's connectivity could be more important than the port's physical characteristics, or vice versa. Hence, for obtaining the relative weight (importance) of each criteria pairwise comparison of criteria must be used. Table 8 shows an example of examination through pairwise comparison of port criteria for installation port.

	Port physical characteristics	*Port Connectivity*	*port layout*	Weights(Eigen Vector)	Consistency Ratio %
Port physical characteristics	1	6	3	0.654	3.63 %
Port Connectivity	1/6	1	6	0.2498	
port layout	1/3	1/6	1	0.09533	

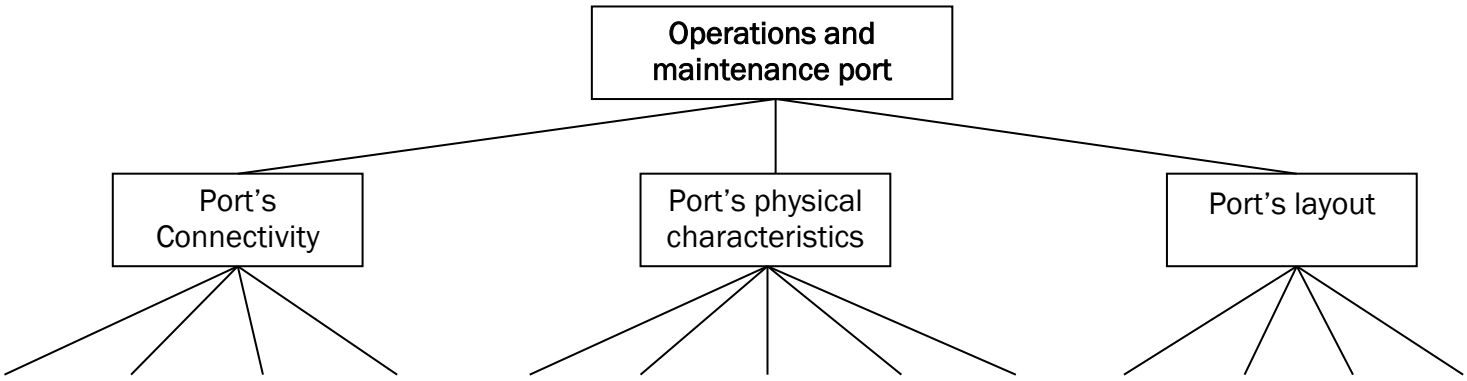
Table 8: Example of a pairwise comparison matrix

Based on the weights shown in table 8, for this expert, between the three port criteria, Port's physical characteristics has been much more important that the port's connectivity, while port's layout had the least importance compared to the other two criteria.





Goal: Choosing the most suitable installation port
Level 1: Port's physical characteristics, Port's layout Port's Connectivity
Level 2 A: Component handling, Port's depth, Seabed suitability, Quay load bearing capacity, Quay length
Level 2 B: Storage capacity, Fabrication facility, Potential for expansion, Component lay down area
Level 2 C: Distance from the wind farm, Distance from road networks, Distance from suppliers
Level 3 A: Lifting capability, Ro-Ro capability, Lo-Lo capability
Level 3 B: Covered storage, Open storage, storage load bearing capacity
Level 3 C: Access to quayside, component lay down area



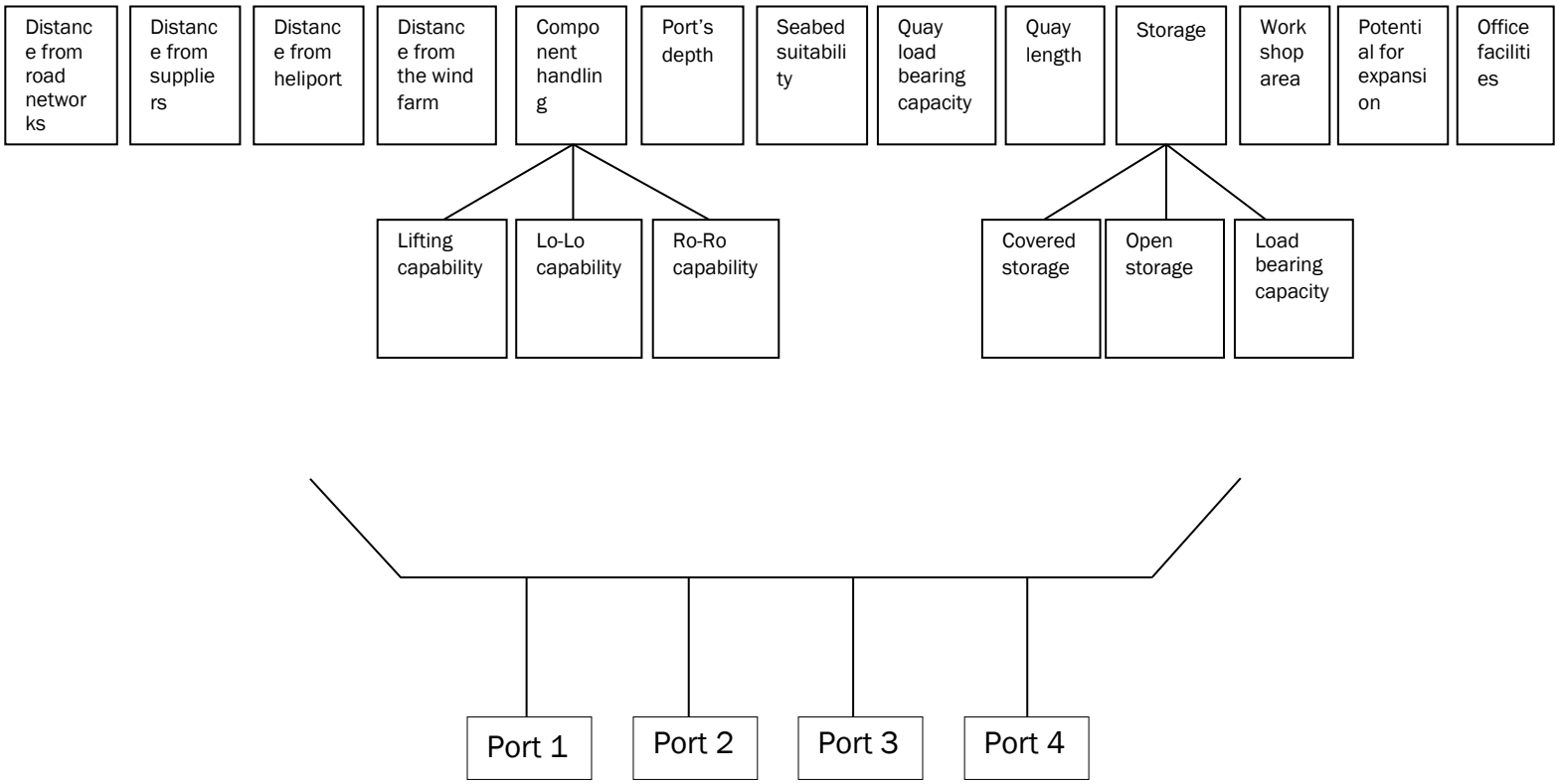
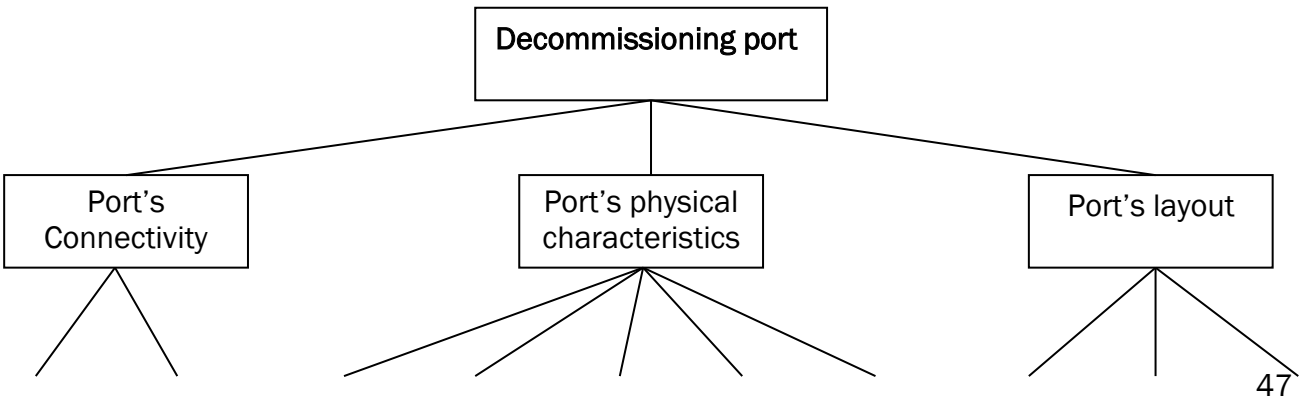
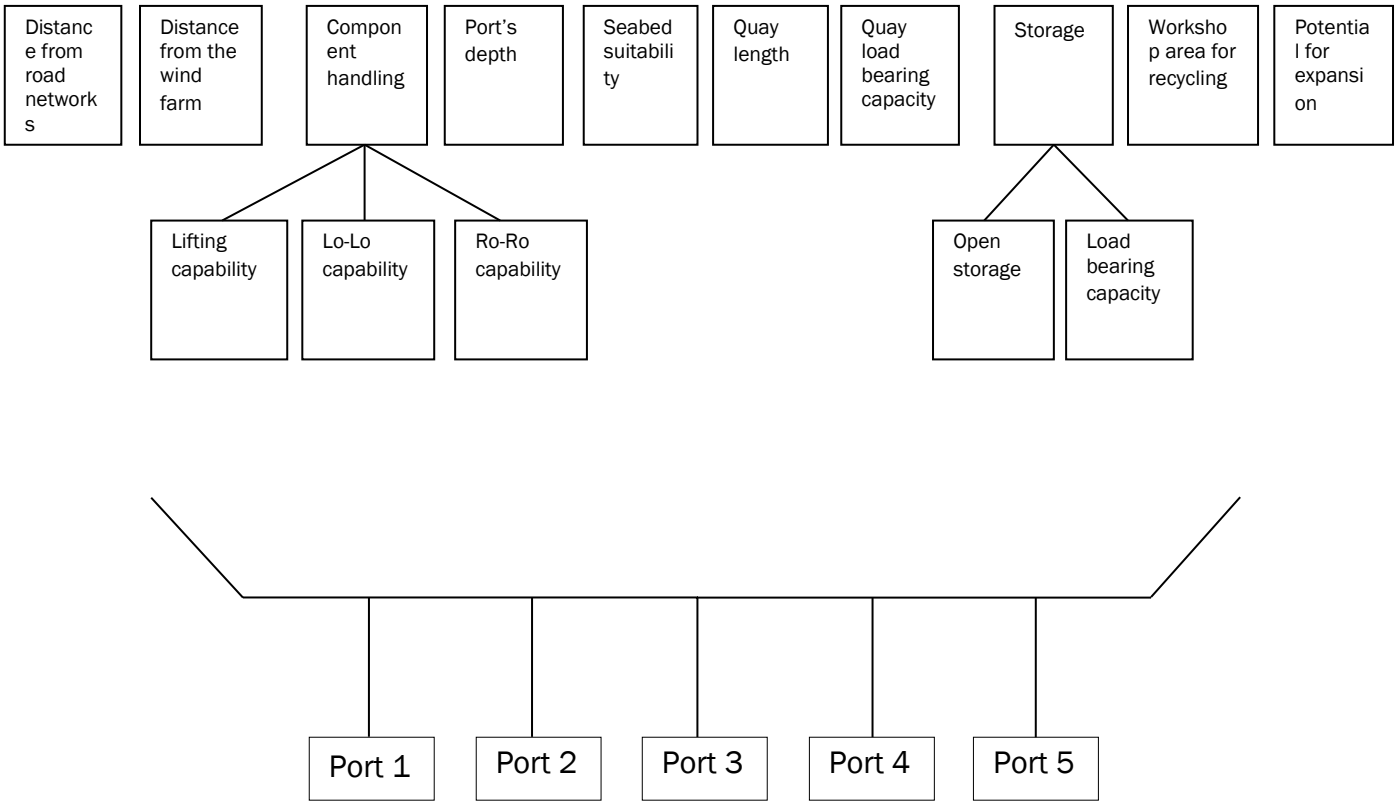


Figure 28: Operations and maintenance port hierarchy

Goal: Choosing the most suitable O&M port
Level 1: Port's physical characteristics, Port's layout, Port's Connectivity
Level 2 A: Distance from the wind farm, Distance from road networks, Distance from suppliers, and Distance from heliport
Level 2 B: Component handling, Port's depth, Seabed suitability, Quay load bearing capacity, Quay length
Level 2 C: Storage capacity, Workshop area, Potential for expansion, Office facilities
Level 3 A: Lifting capability, Ro-Ro capability, Lo-Lo capability
Level 3 B: Covered storage, Open storage, storage load bearing capacity





Goal: Choosing the most suitable decommissioning port
Level 1: Port's physical characteristics, Port's layout, Port's Connectivity
Level 2 A: Distance from the wind farm, Distance from road networks
Level 2 B: Component handling, Port's depth, Seabed suitability, Quay load bearing capacity, Quay length
Level 2 C: Storage capacity, Workshop area, Potential for expansion,
Level 3 A: Lifting capability, Ro-Ro capability, Lo-Lo capability
Level 3 B: Open storage, storage load bearing capacity

4.3 Results of the pairwise comparisons of the port criteria

In this section we present the result of the pairwise comparisons of the port criteria which was completed by 5 industry experts (the results of pairwise comparison are obtained using the AHP software [79]). Tables 9, 11 and 13 present the weights of these criteria for installation, O&M and decommissioning ports. The results clarify the importance of each criterion for different phases of the offshore wind farm's lifecycle and give a better understanding of the requirements in the ports which have the highest relative significance for supporting the offshore wind industry.

4.3.1 Installation port

Table 9 shows the weight of the criteria for an installation port. These finding suggest that for an installation port, where the major components are stored, pre-assembled and loaded onto heavy vessels, the port's physical characteristics are more important than the port's connectivity and port's layout.
Among the physical characteristics, 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.
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 supplier and distance to the road networks.
For the port's layout which was ranked slightly lower than the port's connectivity, the lay down area for component assembly and its accessibility to quayside was ranked the highest, followed by the storage area available at the port, port's potential expansion opportunity and the availability of component manufacturing facility at the port

Criteria			Weight	
Port's physical characteristics		0.483495		
	Seabed suitability		0.201319	
	Component handling		0.130315	
		Lo-Lo capability		0.596114
		Ro-Ro capability		0.10221
		Heavy cranes		0.301676
	Quay length		0.145369	
	Quay load bearing capacity		0.286906	
	Port's depth		0.23609	
Port's Connectivity		0.274774		
	Distance to offshore site		0.705605	
	Distance to key component supplier		0.185777	
	Distance to road		0.108617	
Port's layout		0.24173		
	Potential for expansion		0.256796	
	Component laydown area		0.333861	
		Component laydown area		0.653761
		Laydown area access to quay side		0.346239
	Storage		0.288527	
		Storage load bearing capacity		0.599171
		Open storage area		0.299962
		Covered storage area		0.100867
	Component fabrication facility		0.120816	

Table 9: Installation port criteria weights [77]

Level	Consistency Ratio (%)
1[2]	16.3
2A	1.7
2B	2.1
2C	0.2

[2] Given that the AHP was used in an applied setting involving multiple industry decision makers, the CR for level one has a negligible deviation from the recommended limit suggested in [78].

3A	7.7
3B	6
3C	0
Average consistency of the matrices	4.8

Table 10: Consistency ratio of installation port matrices [77]

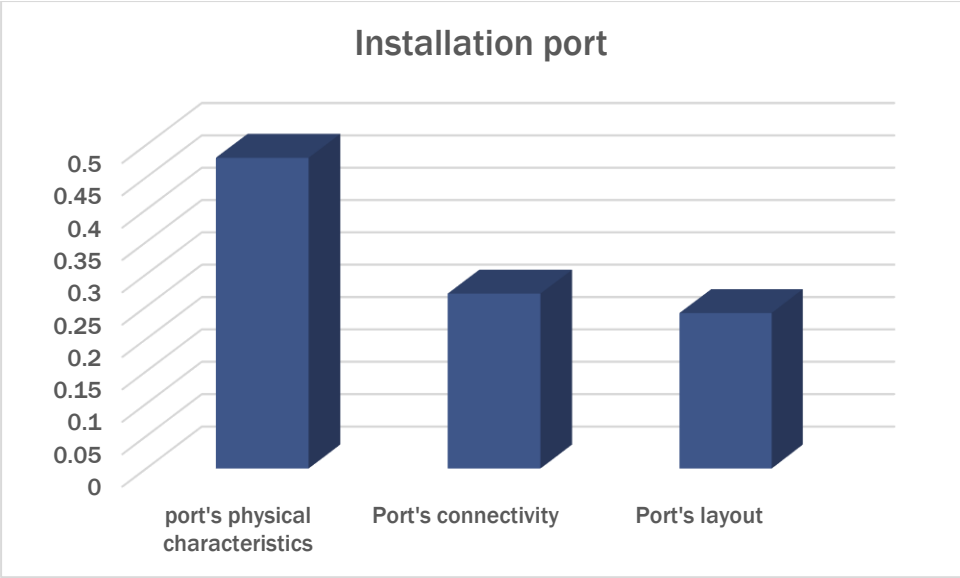


Figure 30: Graph showing the weight comparison of the level 1 criteria group for an installation port

4.3.2 Operations and maintenance port

O&M ports are defined as onshore bases that support the routine operations and maintenance of the offshore wind farms. For these ports, the port's connectivity was ranked the highest in terms of significance, followed by the port's physical characteristics and port's layout.

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

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.

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.

Criteria			Weight	
Port's physical characteristics		0.328355		
	Seabed suitability		0.038918	
	Quay length		0.088263	
	Component handling		0.226789	
		Lo-Lo capability		0.502329
		Ro-Ro capability		0.116736
		Heavy cranes		0.380934
	Quay load bearing capacity		0.560094	
	Port's depth		0.085937	
Port's Connectivity		0.50325		
	Distance to offshore site		0.645413	
	Distance to key component supplier		0.105183	
	Distance to road		0.086335	
	Distance to heliport		0.163069	
Port's layout		0.168394		
	Storage		0.269417	
		Storage load bearing capacity		0.175836
		Open storage area		0.187874
		Covered storage area		0.636289
	Workshop area for component repair		0.246476	
	Potential for expansion		0.14529	
	Office facilitie		[illegible]	

Level	Consistency Ratio (%)
1	0.1
2A	1.1
2B	2.5
2C	2.9
3A	1.4
3B	0.1
Average consistency of the matrices	1.85

Table 12: Consistency ratio of O&M port matrices [77]

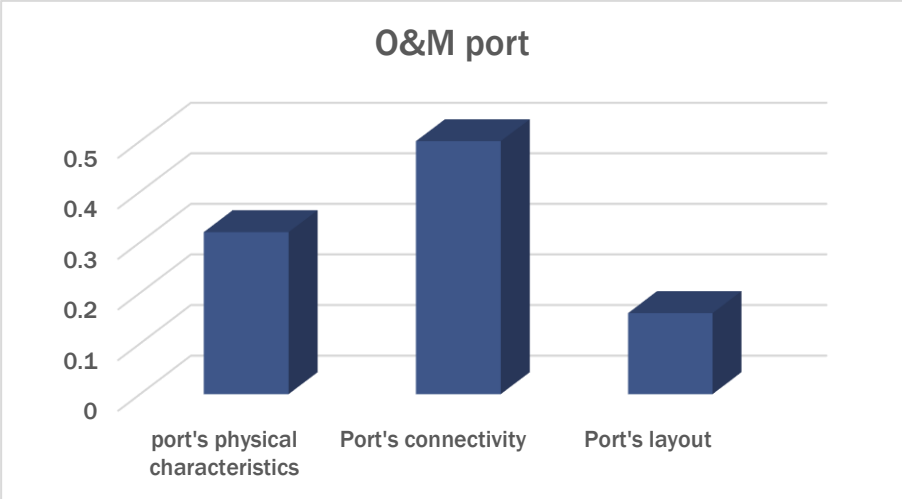


Figure 31: Graph showing the weight comparison of the level 1 criteria group for an O&M port

4.3.3 Decommissioning ports

For decommissioning ports, the port's physical characteristics were considered the most significant factor for the port's suitability, followed by port's connectivity and port's layout. In the port's physical characteristics category, the port's seabed suitability was considered the most important factor, followed by port's depth, quay load bearing capacity, component handling equipment and the quay length.
In the port's connectivity category, distance to offshore site was ranked the most important factor, followed closely by distance to road, since the dismantled component can be carried via trucks to recycling centres.
In the port's layout category, the availability of workshop area for preparing the components for recycling was considered the most important factor, followed by storage availability and the potential for expansion at the port.

Criteria			Weight	
Port's physical characteristics		0.501797		
	Seabed suitability		0.257934	
	Component handling		0.147783	
		Lo-Lo capability		0.493958
		Ro-Ro capability		0.132728
		Heavy cranes		0.373314
	Quay length		0.147345	
	Quay load bearing capacity		0.193281	
	Port's depth		0.253656	
Port's accessibility		0.318146		
	Distance to offshore site		0.583579	
	Distance to road		0.416421	
Port's layout		0.180055		
	Storage		0.368968	
		Storage load bearing capacity		0.549742
		Open storage area		0.450258
	Workshop area for preparing the components for recycling		0.492187	
	Potential for expansion		0.138844	

Table 13: Decommissioning port criteria weight [77]

Level	Consistency Ratio (%)
1	3.9
2A	0
2B	2.7
2C	2.7
3A	12.3
3B	0
Average consistency of the matrices	3.6

Table 14: Consistency ratio of decommissioning port matrices [77]

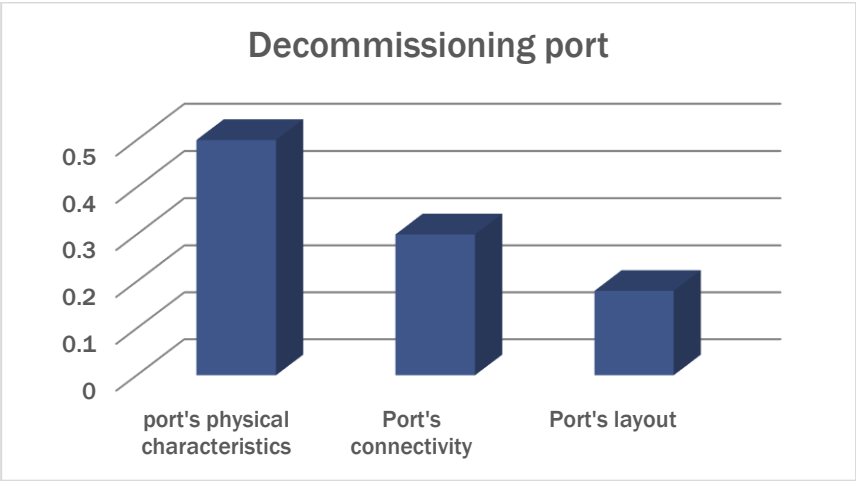


Figure 32: Graph showing the weight comparison of the level 1 criteria group for a decommissioning port

4.4 Case application

The offshore wind farm, West Gabbard, selected by the Leanwind consortium, is considered as an example site and the AHP model discussed in section 4.2 has been applied to assess the suitability of a number of ports for three phases of installation, O&M and decommissioning for this site. For this example the ports were selected based on the:

1) Port's proximity to the site:

All the ports selected for this example are within 300 km from the offshore wind farm since:

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

2) Port's infrastructure and existing supply chain
3) Port's offshore experience (oil & gas, wind, tidal and wave)
4) Port's current involvement or willingness to invest in the offshore wind industry
5) Data availability for the ports

Site Name	West Gabbard
Area (Country)	North Sea (UK)
Depth (m)	33
Distance to shore (km)	30
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

Table 15: West Gabbard specifications [76]

Ports	Distance from the wind farm (km)
Port of Oostende	101
Port of Harwich Navyard	56
Able UK-Humber port/ port of Hull	270
Port of Great Yarmouth	74
Port of Sheerness	110
Port of Lowestoft	61
Port of Ramsgate	86
Port of Grimsby	264

Table 16: Ports' distance from the site [76]

4.4.1 Problem description

The problem is defined, as the decision maker's choice of selecting the most suitable port for a specific offshore wind farm which could satisfy the requirements needed for an offshore wind port. For this example, we have chosen 8 different ports in the east coast of UK and 1 port in Belgium. Figure 33, shows the approximate location of the wind farm and the ports. The 5 ports pointed in red are selected as installation/decommissioning port choices and the 4 ports in green are the O&M port choices. The assumptions for this example are that installation ports are different from O&M ports since O&M ports need not to be as large as installation ports but need to be closer to the site. The choices for decommissioning ports, however, are the same as the installation ports.
This model strives to aid the decision maker to select the most suitable port from a number of ports with similar attributes. The following map illustrates the location of the example ports in relation to the offshore wind farm.

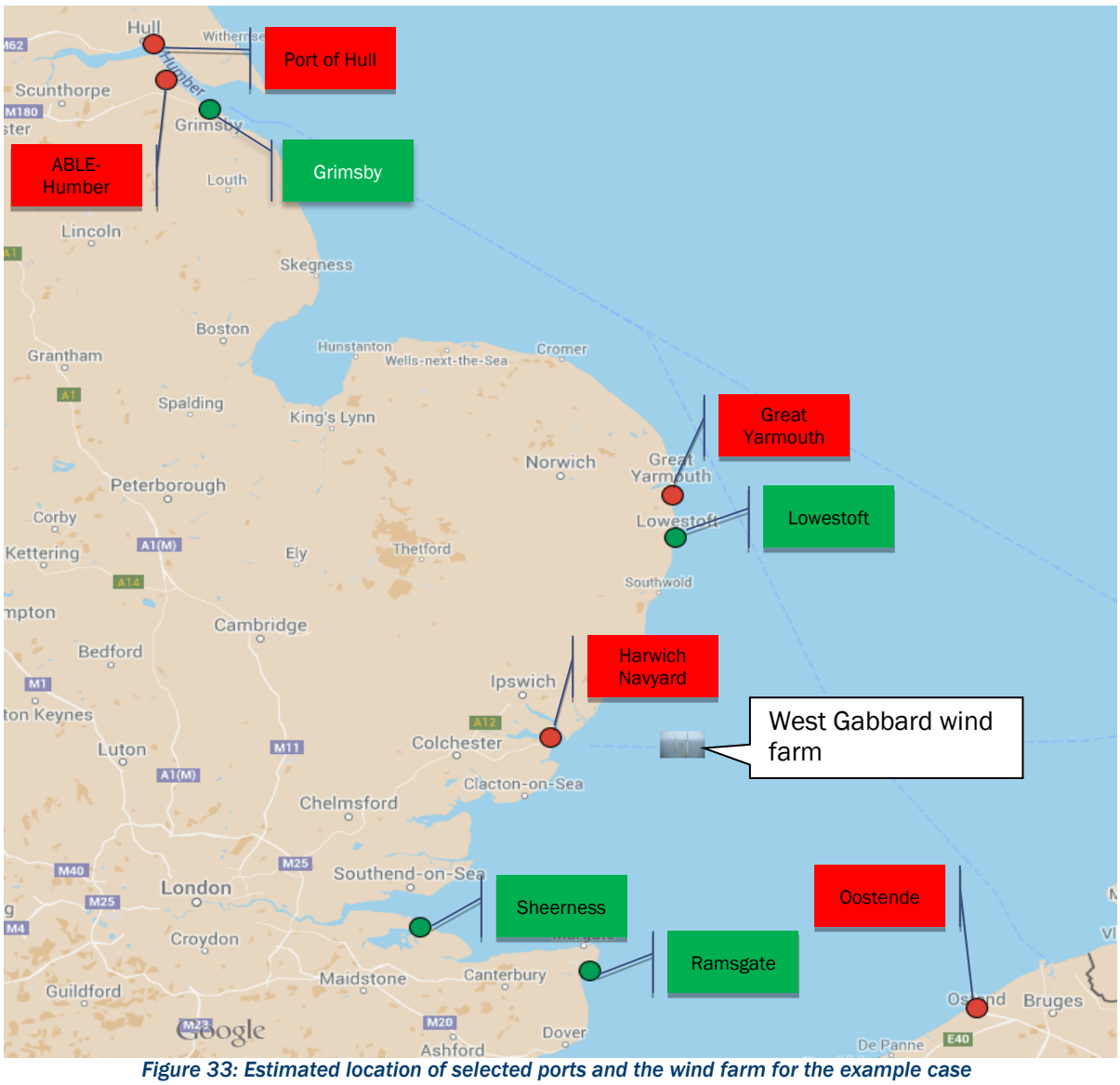


Figure 33: Estimated location of selected ports and the wind farm for the example case

4.4.2 Data collection

The data for the pairwise comparison of the criteria has been gathered by sending questionnaires to 5 industry experts in the areas of port management, maritime industry, and renewable energy consulting.
The data for the ports has been collected from publicly available data. The main resources are 4C offshore (www.4coffshore.com), UK port directory (www.uk-ports.org) and the ports' main websites. Data for port's connectivity has been collected by partners in University of Edinburgh via the GIS tool.

4.4.3 Results

We analysed the suitability of ports for each phase of offshore wind farm lifecycle through using the AHP model. Considering the final rank of the ports, it can be speculated that there is not a significant difference between the port's suitability scores, however it must be noted that for each port, many criteria have been assessed and each port can have different advantages over the other. Hence, expecting a significant difference between the alternative port's weights may not be realistic and slight difference between the weights is meaningful enough to enable the decision makers to choose the most suitable port between different alternatives [73].

Installation port:

The result of our analysis suggests that the most suitable installation base for the West Gabbard wind farm is port of Oostende. Port of Hull is ranked second, followed by ABLE UK, Humber port, Harwich Navyard port, and port of Great Yarmouth (For detailed analysis please see Appendix table 17).

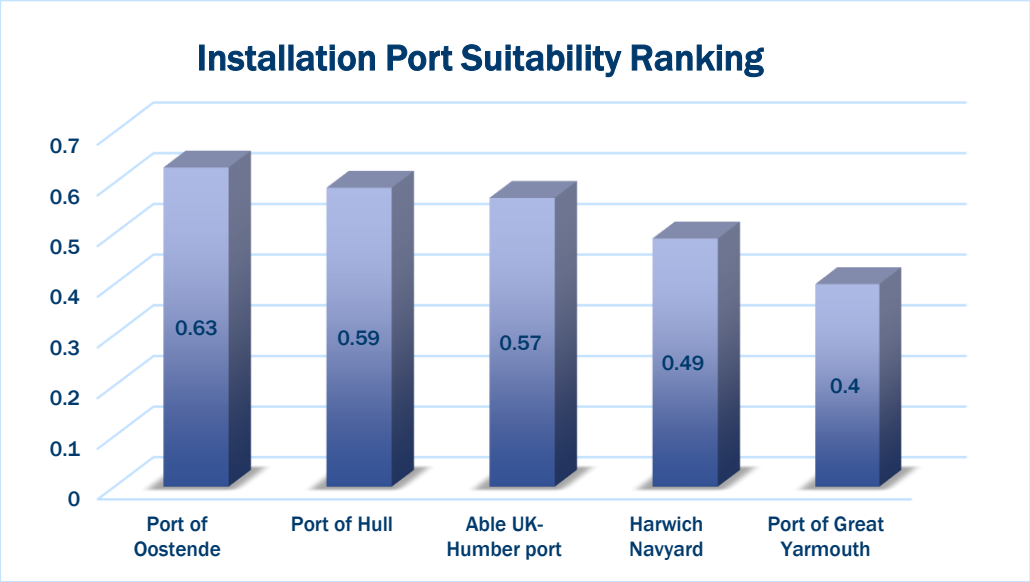


Figure 34: Installation port ranking

Operations and maintenance port:

The result for our analysis suggests that port of Sheerness has the highest suitability ranking for the O&M base for West Gabbard wind farm, followed by the port of Lowestoft, port of Ramsgate and port of Grimsby. The results highlight the importance of the O&M port's proximity to the site, but also the need for O&M ports meeting the technical requirements. Although Lowestoft is closer to the site (61 km), port of Sheerness (110 km from the site) has been ranked higher in terms of suitability, which could suggest that port of Sheerness has more logistical capabilities (For detailed analysis please see Appendix table 18). Port of Grimsby, however, despite good logistics capabilities, is ranked last mainly due to its considerable distance from the West Gabbard wind farm.

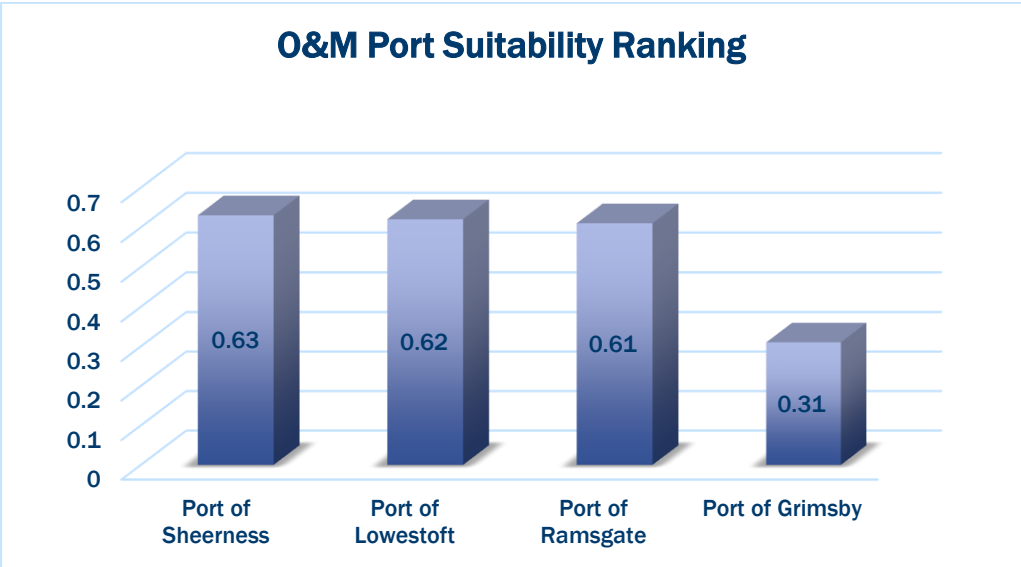


Figure 35: O&M port ranking

Decommissioning port:

The result of our analysis suggests that the most suitable decommissioning base for the West Gabbard wind farm is port of Oostend. ABLE UK-Humber port is ranked second, followed by port of Hull, Harwich Navyard port, and port of Great Yarmouth (For detailed analysis please see Appendix table 19).

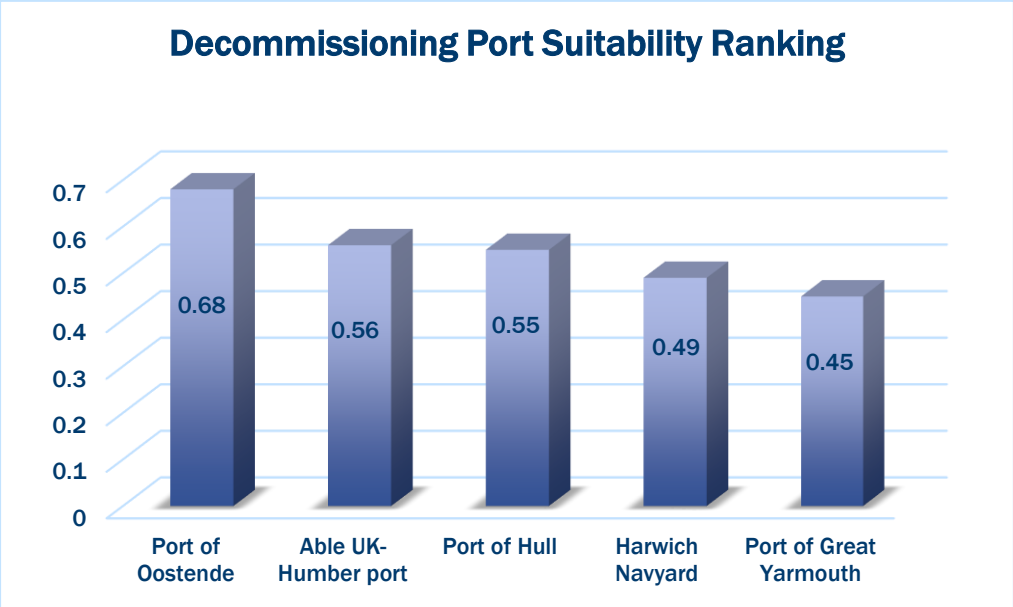


Figure 36: Decommissioning port ranking

4.5 Conclusion and future research

To the knowledge of the authors, the port selection model introduced in section 4 is among the first studies that has systematically assessed the port requirements for the offshore wind industry. By using the AHP methodology and the pairwise comparison of the port requirements, we provided a ranking for the offshore wind port requirements for each phase of the operations of a wind farm, and determined the most suitable port for a given wind farm.

We believe that this decision making tool can provide valuable recommendations to the decision maker for making the strategic decision of choosing a suitable onshore base for installation, O&M and decommissioning phases of their wind farms.

The focus of this study however, has been on the port's requirements and we have not included the factor of cost in the decision making strategy reported in this study. The future research could include the cost as a factor and assess the ports based on cost and other requirements.

5. Conclusions

In this report, a systematic analysis of the ports and their requirements for the offshore wind industry is presented. The port requirements are classified under three general categories of:

1) **Port's physical characteristics:** Including the seabed suitability, quay length, port's depth, quay load bearing capacity, and component handling capabilities,

2) **Port's conn bectivity:** Including the port's distance to the wind farm, to key component suppliers, and to road networks, and heliports,

3) **Port's layout:** Including the storage area, component fabrication facility, facilities for repairing the components, and component recycling facilities.

Based on the result of the analysis described in section 4, for installation and decommissioning ports, the port's physical characteristics, and for the operations and maintenance ports, the port's connectivity is the determining factor of the port's suitability for a particular wind farm. Suitable ports and onshore bases which have the necessary requirements will facilitate the logistics of the activities related to the offshore wind installation, operations and maintenance and decommissioning phases.

Furthermore, a decision support framework which could assist the decision makers in selecting the most suitable port for their offshore wind farm is proposed in section 4, and the model is used for assessing a number of ports for the offshore site, West Gabbard, proposed by the Leanwind consortium.

This analysis however, has only considered the technical requirements that should be present at the ports, and did not consider the cost associated with each port, which can be an important influential factor in making the final decision of selecting a port.

It is assumed however, that the presence of these capabilities (described in section 2 of the report) in the ports will ultimately influence the overall cost, and efficient ports closer to the wind farms could facilitate the logistics of the operations which could bring down the costs, and make the process of installation, O&M and decommissioning lean and efficient.

6. Reference

[1] GWEC, 2014. Global wind 2014 report. Available online at: http://www.gwec.net/wpcontent/uploads/2015/03/GWEC_Global_Wind_2014_Report_LR.pdf (Accessed 12.05.2015)

[2] EWEA, 2015. The European offshore wind industry- key trends and statistics 2014. Available online at: http://www.ewea.org/fileadmin/files/library/publications/statistics/EWEA-European-Offshore-Statistics-2014.pdf (Accessed 27.02.2015)

[3] U.S. Offshore wind market and economic analysis, 2013. Available online at : http://www1.eere.energy.gov/wind/pdfs/offshore_wind_market_and_economic_analysis.pdf (Accessed 04.11.2014)

[4] EWEA, 2011. Pure Power: Wind energy targets for 2020 and 2030- A report by the European Wind Energy Association. Available at: http://www.ewea.org/fileadmin/files/library/publications/reports/Pure_Power_III.pdf (Accessed 10.03.2014)

[5] Infrastructure supply chains: barriers and opportunities. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/31984/11-1058-infrastructure-supply-chains-barriers-opportunities.pdf (Accessed 20.01.2015)

[6] Offshore wind project cost outlook, 2014. Available at: http://www.cleanenergypipeline.com/Resources/CE/ResearchReports/Offshore%20Wind%20Project%20Cost%20Outlook.pdf (Accessed 20.01.2015)

[7] NREL, 2006. Energy from offshore wind. U.S. National renewable energy laboratory. Conference paper, presented at Offshore Technology Conference Texas. Musial, W., Butterfield, S., Ram, B. Available online at: http://www.offshorecenter.dk/log/bibliotek/Energy%20from%20offshore%20wind.PDF (Accessed 10.11.2014)

[8] Kaiser, M.J., Snyder, B.F. (2012). *Offshore wind energy cost modeling*. London: Springer-Verlag

[9] Fraunhaufer, State of the art and new technologies of direct drive wind turbines (Accessed 19.06.2015)

[10] The Crown Estate. East coast transmission network technical feasibility study. Available online at: http://www.uea.ac.uk/~e680/energy/energy_links/transmission/east_coast_transmission_network_technical_feasibility_study.pdf (Accessed 26.07.2015)

[11] Garrad Hassan America, 2014. Assessment of ports for offshore wind development in the United States. Available online at: http://energy.gov/sites/prod/files/2014/03/f14/Assessment%20of%20Ports%20

for%20Offshore%20Wind%20Development%20in%20the%20United%20States_1.pdf (Accessed 12.09.2014)

[12] Thomson, K.E. (2012). *Offshore wind: A comprehensive guide to successful offshore wind farm installation.* Waltham, MA: Elsevier

[13] Figures for supporting structures. 4C offshore. Available at: http://www.4coffshore.com/windfarms/support-structures-for-offshore-wind-turbines-aid268.html (accessed 23.07.2015)

[14] The Crown Estate, 2012. UK market potential and technology assessment for floating offshore wind power. Available online at: http://www.thecrownestate.co.uk/media/5537/km-in-gt-tech-122012-uk-market-potential-and-technology-assessment-for-floating-wind-power.pdf (Accessed: 10.06.2015)

[15] Figure for floating structures. Available at: http://www.carbontrust.com/media/670664/floating-offshore-wind-market-technology-review.pdf (accessed 23.07.2015)

[16] Tetra Tech, 2010. Port and infrastructure analysis for offshore wind energy development. Available online at: http://images.masscec.com/uploads/attachments/Port%20and%20Infrastructure%20Analysis%20for%20Offshore%20Wind%20Energy%20Development/MA%20Port%20Study%20Final%20Report_4-20-10.pdf (Accessed 04.11.2014)

[17] EWEA, 2011. Wind in our sales, Available at: http://www.ewea.org/fileadmin/files/library/publications/reports/Offshore_Report.pdf (Accessed 10.03.2015)

[18] RWE Innogy, 2012. Offshore wind, Port requirements offshore wind farm: construction and operations. Available online at: http://www.merific.eu/files/2012/12/Mike-Carter_Cornwalls-Ports-and-Harbours-Event-26.7.12.pdf (Accessed 20.01.2015)

[19] Bremerhaven offshore wind port. Available online at: http://offshore-windport.de/en/ports-and-land-areas/commercial-areas/ (Accessed 04.11.2014)

[20] Siemens, 2014. Available online at: http://www.siemens.co.uk/en/news_press/index/news_archive/2014/major-uk-offshore-wind-manufacturing-site-to-be-built-by-siemens.htm (Accessed 15.06.2015)

[21] BVG associates, 2009. UK ports for offshore wind industry. Available online at: http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk /files/file49871.pdf (Accessed 03.04.2015)

[22] Offshore basis Cuxhaven. Available online at: http://en.offshore-basis.de/ (Accessed 04.11.2014)

[23] http://www.faehrhafen-sassnitz.de/en/geschaeftsbereiche/offshore/ (Accessed 20.05.2015)

[24] http://www.allenergy.co.uk/__novadocuments/52489?v=635340211333670000 (accessed 23.07.2015)

[25] WP 5 Partner, Kongsberg Maritime AS-Ports' layout illustration, received on 24.06.2015

[26] GL Garrad Hassan, 2013 'A Guide to UK Offshore Wind Operations and Maintenance'. Scottish Enterprise and the Crown Estate. Available online at: http://www.hi-energy.org.uk/Downloads/General%20Documents/guide-to-uk-offshore-wind-operations-and-maintenance.pdf (Accessed 26.01.2015)

[27] https://www.isri.org/docs/default-source/safety/crawler-cranes.pdf?sfvrsn=4 (Accessed 06.04.2015)

[28] http://subseaworldnews.com/2014/09/11/cuxport-assists-in-amrumbank-west-monopile-ops/ (Accessed 26.07.2015)

[29] http://www.voith.com/en/products-services/power-transmission/applications/floating-cranes-14216.html (Accessed 06.04.2015)

[30] http://www.rwe.com/web/cms/en/113648/rwe/press-news/press-release/?pmid=4009481 (Accessed 26.07.2015)

[31] http://www.walesonline.co.uk/business/business-news/first-siemens-turbine-installed-rwe-3867047 (Accessed 06.04.2015)

[32] http://www.tgal.us/lift-on-lift-off-lo-lo (Accessed 06.04.2015)

[33] http://www.ableuk.com (Accessed 17.06.2015)

[34] http://navy.memorieshop.com/Artisan/index.html (Accessed 26.07.2015)

[35] http://www.windpower-international.com/contractors/transportation/blg-windenergy-logistics/blg-windenergy-logistics4.html (Accessed 20.05.2015)

[36] http://www.portofmostyn.co.uk/news.php?title=New_pontoon_commissioned_at_the_Port_of_Mostyn_for_Gwynt-y-Mor_ (Accessed 20.05.2015)

[37] http://www.jackupbarge.com/fleet/detail/dp2-portable-dynamic-positioning-system/ (Accessed 20.05.2015)

[38] http://www.scaldis-smc.com/renewables.php (Accessed 20.05.2015)

[39] 4C offshore, vessel database. Availabe online at: http://www.4coffshore.com/windfarms/vessels.aspx (Accessed 20.01.2015)

[40] http://www.ptmew.pl/media/pdf/transport_week_2013/07_DEME_offshore_port_logistics.pdf (Accessed 26.07.2015)

[41] http://www.power-technology.com/projects/ormonde-offshore-wind-farm/ormonde-offshore-wind-farm3.html (Accessed 26.07.2015)

[42] http://www.power-technology.com/projects/ormonde-offshore-wind-farm/ormonde-offshore-wind-farm3.html (Accessed 26.07.2015)

[43] http://www.heavyliftspecialist.com/cranes/floating-cranes-world/ (Accessed 26.07.2015)

[44] http://www.offshorewind.biz/2014/01/20/self-elevating-platform-towed-from-borwin-alpha-site/ (Accessed 26.07.2015)

[45] Snyder, B., Kaiser, M.J., 2008. Ecological and economic cost-benefit analysis of offshore wind energy. *Renewable Energy*, 34, pp. 1576-1578

[46] Department of energy and climate change, 2015. Delivering UK energy investment: Low carbon energy. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/419024/DECC_LowCarbonEnergyReport.pdf (Accessed 16.06.2015)

[47] Gwynt y Mor project. Available online at: http://www.rwe.com/web/cms/en/1252456/rwe-innogy/sites/wind-offshore/under-construction/gwynt-y-mr/tech-and-spec/ (Accessed 20.05.2015)

[48] http://www.shephardmedia.com/news/rotorhub/bond-support-offshore-wind-farm-operations/ (Accessed 20.05.2015)

[49] BVG associates, 2014. UK offshore wind supply chain: capabilities and opportunities. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/277798/bis-14-578-offshore-wind-supply-chain-capabilities-and-opportunities.pdf (Accessed 30.04.2015)

[50] Port of Mostyn. Available online at:http://www.portofmostyn.co.uk/offshore-wind.php?title=Offshore-Windfarm-Operations-and-Maintenance (Accessed 04.03.2015)

[51] EON offshore wind fact book, 2011. Available online at: http://www.eon.com/content/dam/eon-com/en/downloads/e/EON_Offshore_Wind_Factbook_en_December_2011.pdf (Accessed 04.03.2015)

[52] NREL, 2013. Installation, operation, and maintenance strategies to reduce the cost of offshore wind energy. Maples, B., Saur, G., Hand, M., Van de Piertermen, R., Obdam, T. Available online at: http://www.nrel.gov/docs/fy13osti/57403.pdf (Accessed 04.03.2015)

[53] GL Garrad Hassan, 2013. Offshore Wind – Operations & Maintenance opportunities in Scotland – An insight into opportunities for Scottish ports and the O&M supply chain. Scottish Enterprise and GL Garrad Hassan. Available online at: file:///C:/Users/486315/Downloads/Offshore%20wind%20operations%20and%20maintenance%20opps%20(2).pdf (Accessed 04.03.2015)

[54] Decommissioning strategy for Gywnt y Mor offshore wind farm LTD, 2011. Available online at: http://www.rwe.com/web/cms/mediablob/en/1268920/data/1202906/2/rwe-innogy/sites/wind-offshore/in-operation/gwynt-y-mr/English.pdf (Accessed 20.05.2015)

[55] Kaiser, M.J., Snyder, B., 2010. Offshore wind energy installation and decommissioning cost estimation in the U.S. outer continental shelf. *Energy research group*, LLC, Louisiana.

[56] WP5 partners Cork Institute of Technology, National Maritime College of Ireland. Internal report on decommissioning, received on 25.06.2015

[57] Bow terminal: a heavy lift port, 2014. Available online at: http://www.offshorewind.biz/2014/02/11/bow-terminal-a-heavy-lift-port/

[58] Porter, M.E., 1998. Clusters and the new economic of competition. *Harvard Business review*, pp.78-81.

[59] Deutsche bank, 2011. UK offshore wind: opportunity, costs & financing. Available online at: https://www.db.com/cr/en/docs/UK_Offshore_Wind_Opportunity-112111.pdf (Accessed 15.06.2015)

[60] North Lincolnshire council, February 2015. Available at: http://www.northlincs.gov.uk/your-council/about-your-council/news/latest-news/450m-able-marine-energy-park-can-get-underway/ (Accessed 15.06.2015)

[61] Belfast harbour Renewable. Available online at: https://www.belfast-harbour.co.uk/port/renewables/ (Accessed 15.06.2015)

[62] Athanasia, A., Anne-Bénédicte, G., Jacopo, M., 2012. The offshore wind market deployment: forecasts for 2020, 2030 and impacts on the European supply chain development. *Energy Procedia*, 24, pp.2-10

[63] Ederer, N., 2014. Evaluating capital and operating cost efficiency of offshore wind farms: A DEA approach. *Renewable and sustainable energy reviews*, 42, pp. 1034-1046

[64] Jones, D.F., Wall, G., 2015. An extended goal programming model for site selection in the offshore wind farm sector. *Annals of operations research*

[65] Fetanat, A., Khorasaninejad, E., 2015. A Novel hybrid MCDM approach for offshore wind farm site selection: A case study of Iran. *Ocean & Coastal Management,* 109, pp. 17-28

[66] Lee lam, J.S., Dai, J. , 2012. A decision support system for port selection. *Transportation planning and technology,* 35 (4), pp. 509-524

[67] Zavadskas Kazimieras, E., Turskis, Z., Bagocius, V., 2014. Multi-criteria selection of a deep water-port in the Eastern Baltic Sea. *Applied soft computing,* 26, pp. 180-192

[68] Ugboma, C., Ugboma, O., Ogwude, I.C., 2006. An Analytical Hierarchy Process (AHP) Approach to Port Selection Decisions-Empirical evidence from Nigerian ports. *Maritime Economics and Logistics,* 8, pp. 251-266

[69] Guy, E., Urli, B., 2006. Port Selection and multi-criteria analysis: An application to the Montreal-New York alternative. *Maritime Economics and Logistics*, 8, pp. 169-186

[70] Saaty, T.L., Vargas, L.G. (2012). *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process*. New York, NY: Springer

[71] Saaty, T.L., 2008. Decision making with the analytical hierarchy process. *Int.J. Services Science,* 1 (1) , pp. 83-95

[72] Banai-Kashani, R., 1989. A new method for site suitability analysis: The analytic hierarchy process. *Environmental Management*. 13 (6), pp. 685-693

[73] Onut. S., Tuzkaya. U.R., Torun. E., 2010. Selecting container port via fuzzy ANP-based approach: A case study in the Marmara Region, Turkey. *Transport Policy,* 18, pp. 182-193

[74] Velasquez, M., Hester, P.T., 2013. An analysis of Multi-criteria decision making methods. *International Journal of Operations Research*, 10 (2), pp. 56-66

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

[76] Work Package 5 partner, University of Edinburgh. Data for port's connectivity, received on 15.06.2015

[77] Work Package 5 partner, University of Portsmouth. Analysis of pairwise comparison and ports performance, received on 24.06.2015.

[78] Dolan, J. G., 2010. Multi-criteria clinical decision support: A primer on the use of multiple criteria decision making methods to promote evidence-based, patient-centered healthcare. *The Patient: Patient-Centered outcomes Research*, 3(4), pp. 229-248.

[79] http://bpmsg.com

[80] http://www.power-technology.com/projects/borkum-farm/borkum-farm3.html (accessed 23.07.2015)

7. Appendix

In this appendix we provide the report and pictures regarding the visits to Port of Grimsby and Green port Hull and the data for the Performance of installation, O&M and decommissioning ports.

7.1 Port Visits

Visit to Siemens' Green Port Hull project office and Green port Hull, Date: 07.07.2015

The purpose of this visit was to gain a better understanding of the role of Siemens in the Green port Hull project and offer Siemens a reciprocal update on progress with the Leanwind programme.
Siemens has invested in a blade manufacturing facility which will provide blades for the offshore projects in the North Sea and also for export to other countries. It should be noted that only blades are manufactured in this port, with nacelles currently imported from Brande in Denmark and towers from suppliers throughout Europe and elsewhere. Green Port Hull will be used as an installation base for the offshore wind farms.
Siemens' representative explained that the best method for loading the components in terms of health and safety (Zero Harm), is using Ro-Ro rather than cranes. SMPTs along with other equipment such as tractors and trucks are used in the port. All of these available through hire, lease or purchase.
Siemens representative shared insight about the importance of the layout in the port, confirming that available space within the port is the most important factor, also availability of storage is important. Siemens tries to keep the minimum of inventory at the port and components are ordered almost 3 months prior to installation so they don't have to sit in the port for long.
One of Siemens' challenges is the imposed inclusion of flood defence measures by the Environment Agency striving to protect the wider city of Hull from flooding. Specifically, the flood barrier placed at the quayside causes logistical challenges for cranes whilst lifting the components. Also this barrier is not placed on the entire port and is only placed on half of it hence its inclusion may not totally protect the port from flooding.

Visit to Port of Grimsby, Date: 07.07.2015

Port of Grimsby is an operations and maintenance port which has been involved in the offshore wind industry since 2006. Grimsby was originally a fishing port and fishing is still a bigger business than offshore wind. Nevertheless stakeholders at port of Grimsby believe that the fishing has limited growth capacity and this is why in 2006 they diversified their portfolio by entering into offshore wind. Grimsby's representative mentioned that offshore wind has actually helped the fishing industry to stay within the port and that the industries are complimentary. Grimsby has undergone a major redevelopment in order to better serve the offshore wind industry. Currently Grimsby is the base for E.ON Renewable Energy Systems, Centrica, Siemens, and Dong Energy. Work boats and pontoons could be seen in the port. The only restriction in the port is the beam of 12m which is sufficient for work boats but not for bigger vessels. Grimsby's representative mentioned that there was a steady growth from 2006 to 2015; however 2015 and 2016 are quiet until the next round of business gets underway in 2017.
Asking Grimsby's representative about the possible adverse impact of the industry moving toward floating operation and maintenance platforms and vessels adjacent to the offshore wind farms instead of O&M ports, due the increased distances from the port, he answered that there are still older generation turbines, closer to shore which need maintenance and that could bring business to the port for the next 20 years however they are aware of the possible changes in the industry and the move away from an onshore base for O&M.

Figure 37: Work in progress at Green port Hull, photo taken on 07.07.2015 [78]

Figure 38: Work in progress at Green port Hull, photo taken on 07.07.2015 [78]

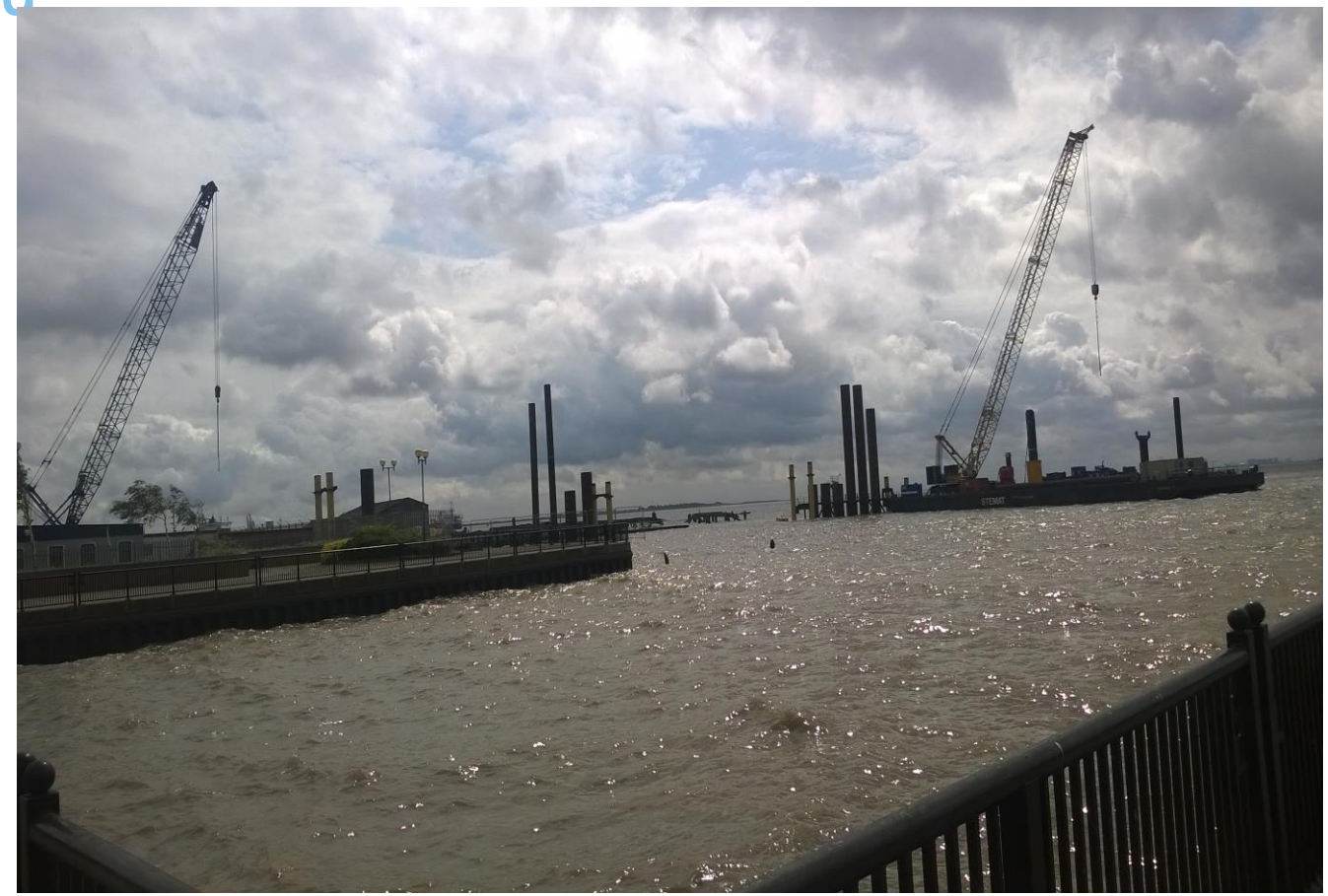


Figure 39: Work in progress at Green port Hull, photo taken on 07.07.2015 [78]

Figure 40: Pontoon at Grimsby port, photo taken on 07.07.2015 [78]

7.2 Port performance data

The performance of installation port

Criteria	Priority Weight	Alternatives weight					Priority weight * Alternatives weight				
		[1]	[2]	[3]	[4]	[5]	[1]	[2]	[3]	[4]	[5]
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 key comp. 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 side	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 fabrication 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

[1] : HARWICH navyard
[2] : OOSTENDE
[3] : port of Hull
[4] : Able UK
[5] : Great Yarmouth

Table 17: Installation port data [77]

The performance of O&M port

Criteria	Priority Weight	Alternatives weight				Priority weight * Alternatives weight			
		[1]	[2]	[3]	[4]	[1]	[2]	[3]	[4]
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

[1] Grimsby
[2] Sheerness
[3] Lowestoft
[4] Ramsgate

Table 18: O&M port data [77]

The performance of decommissioning port

Criteria	Priority Weight	Alternatives weight					Priority weight * Alternatives weight				
		[1]	[2]	[3]	[4]	[5]	[1]	[2]	[3]	[4]	[5]
Seabed suitability	0.129430849	1	1	1	1	1	0.129431	0.129431	0.129431	0.129431	0.129431
Lo-Lo capability	0.036630443	0.767396	0.767396	0.767396	0.136661	0.136661	0.02811	0.02811	0.02811	0.005006	0.005006
Ro-Ro capability	0.009842692	0.67264	0.67264	0.67264	0.67264	0.036819	0.006621	0.006621	0.006621	0.006621	0.000362
heavy cranes	0.027683827	0.767396	0.136661	0.136661	0.767396	0.767396	0.021244	0.003783	0.003783	0.021244	0.021244
quay length	0.07393739	0.200098	0.405423	0.958809	0.358782	0.384107	0.014795	0.029976	0.070892	0.026527	0.0284
quay load bearing capacity	0.096988074	0.163998	0.766672	0.766672	0.766672	0.113979	0.015906	0.074358	0.074358	0.074358	0.011055
port's depth	0.127284057	0.12994	0.908982	0.657161	0.595087	0.196771	0.016539	0.115699	0.083646	0.075745	0.025046
distance to offshore site	0.185663569	0.905413	0.510653	0.164719	0.164719	0.729322	0.168102	0.09481	0.030582	0.030582	0.135409
distance to road	0.13248285	0.312299	0.962962	0.347492	0.347492	0.304117	0.041374	0.127576	0.046037	0.046037	0.04029
Storage loadbearing capacity	0.036521903	0.32736	0.963181	0.32736	0.32736	0.32736	0.011956	0.035177	0.011956	0.011956	0.011956
Open storage area	0.029912721	0.247497	0.22712	0.890827	0.828481	0.22712	0.007403	0.006794	0.026647	0.024782	0.006794
Workshop area for recycling	0.088620719	0.32736	0.32736	0.32736	0.963181	0.32736	0.029011	0.029011	0.029011	0.085358	0.029011
potential for expansion	0.024999629	0.303398	0.322278	0.368081	0.962864	0.318463	0.007585	0.008057	0.009202	0.024071	0.007961
Total							0.498077	**0.689402**	0.550275	0.561718	0.451965
Rank							4	**1**	3	2	5

[1] : HARWICH navyard

[2] : OOSTENDE

[3] : port of Hull

[4] : Able UK

[5] : Great Yarmouth

Table 19: Decommissioning port data [77]