Decision Analytical Models for the Sustainable Development of Marine Renewable Energy

By

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Abstract

This thesis presents a set of decision analytical models for the sustainable development of marine renewable energies (MREs) including offshore wind, tidal and wave energy, with a case application for United Kingdom. The MRE industry is a growing sector, which could significantly contribute to meeting the future energy demand and the realization of a low carbon energy system. For the development of these technologies, a multi-dimensional approach that takes into account the environmental, social, economic and technical factors is required. In this thesis, contributions are made towards the development of models that address the problems related to the efficiency assessment, evaluation of the infrastructure, and portfolio selection.

In the first part of this research, a benchmark study of the offshore wind sector is provided by assessing the efficiency of a set of 70 offshore wind farms across five North-Western European countries based on environmental, social, technical and economic criteria. The Data Envelopment Analysis method (DEA) has been utilised and the median efficiency score results are interpreted on a country level.

In the second part of this research, the focus is on the logistics capabilities of the infrastructure (namely the ports) for supporting the development of MREs in the two phases of construction and operations and maintenance. A number of different logistical criteria are considered for the assessment of the suitability of ports for serving the MRE projects. The Analytical Hierarchy Process method (AHP) is applied as a selection tool with which the decision makers are able to identify the most suitable potential port for a given wind farm.

In the third part of this research, a non-deterministic goal programming model based on interval data for solving a project selection problem is proposed. Sustainability criteria including economic, environmental, social, and technical are considered and the model determines the optimal portfolio of marine renewable energy across the UK. This model offers a practical

decision analysis tool to stakeholders for the selection of MRE projects and identifying potential development zones within a region.

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Declaration of Authorship

I, Negar Akbari, declare that whilst registered as a candidate for the PhD degree at University of Portsmouth, I have not been registered for any other research award. The results and conclusions embodied in this thesis are the work of the named candidate and have not been submitted for any other academic award.

This thesis contains 40569 words including Bibliography, and Appendix.

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Abbreviations

AHP: Analytical Hierarchy Process

ANP: Analytical Network Process

BCC: Banker, Charnes, Cooper

BRIC: Brazil, Russia, India, China

CCR: Charnes, Cooper, Rhodes

CI: Consistency Index

CR: Consistency Ratio

CRS: Constant Return to Scale

DEA: Data Envelopment Analysis

DF: Degree of Freedom

DMU: Decision Making Unit

EU: European Union

GP: Goal Programming

GW: Gigawatt

Lo-Lo: Lift-on/lift off

MADM: Multi-attribute decision-making

MCDM: Multi-criteria decision-making

MODM: Multi-Objective decision-making

MRE: Marine Renewable Energy

MW: Megawatt

NIMBY: Not in my backyard

O&M: Operations and maintenance

RI: Random Index

Ro-Ro: Roll-on/Roll off

SBM: Slack Based Measure

SFA: Stochastic Frontier Analysis

TCT: Tidal Current Turbines

UK: United Kingdom

VRS: Variable Return to Scale

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To my loving parents

Chapter 1

Introduction

Energy is used in every sector of a nation’s economy including industrial, commercial, agricultural and residential sectors, as well as being the final consumer product for heating, transportation and electricity [1]. Greater industrial production and increased population have influenced the energy demand, and the concerns related to climate change, and the finite reserves of fossil fuels have been amongst the most significant motivations for governments to reach for alternative and more sustainable energy sources. The development of renewable energy is a sustainable choice for countries that aim to address the aforementioned challenges, and expand their energy supply portfolio [2] . Renewable energies are regenerative, clean and non-depletable sources of energy that could address some of the key global environmental challenges of the 21st century such as energy security, reduction in greenhouse gas emissions and global warming [3]. Biomass, hydroelectric, wind, solar geothermal, and marine energy (Tidal, wave and offshore wind) are different types of renewable energy sources amongst which the progress of the commercialization of the marine renewable energy has been slower than some other renewable energy sources. That is not due to energy potential of the oceans, but rather related to the technological development for the exploitation of ocean energy sources [3].

The sustainable development of renewable energy is inherently a complex and multifaceted problem and stands on the pillars of environmental, economic and social factors [4]. These factors could drive or constrain the transition to a cleaner energy economy, and governments and policy makers can incentivise renewable energy investments through various policy tools such as setting pollution standards and penalties for fossil fuel energy production for encouraging the developments of these energy types [5] .

1.1 Research Background

In order to increase the share of renewable energies, new approaches to decision making for supporting the policies, which could lead to the development of these energy sources, are required. Renewable energy planning should comply with the sustainability indicators and provide the decision makers with a robust map that could show how the proposed projects can efficiently and effectively meet the decision makers’ goals. Decision makers usually have several, conflicting goals for the development of renewable energy sources and therefore multi-criteria decision making models could provide a framework for dealing with the multidimensionality of this problem [1].

The United Kingdom government has imposed the legally binding target aimed at reducing its Greenhouse gas emissions by 80% by 2050 against a 1990 baseline for transition towards a low carbon economy and society. To achieve this goal several measures can be taken; from a supply side perspective, these measures are carbon capture and storage, switching to renewable energies and nuclear power stations [6]. Following the 2010 Electricity Market Reforms (EMR) introduced in 2010, the emissions from the power sector have decreased and the growth of the renewable generation has been very rapid, generating electricity from renewable from 10 TWh in 2000 to 64 TWh in 2014, comprising nearly 20 % of the UK power. Although coal production in the UK in now negligible and the government has set an end date for the coal plants, gas generation plants are still a major part of the energy mix and up to 26 GW of capacity is expected to be added by 2030 [6]. Figures 1 and 2 compare the electricity generated by different energy sources in 2017 and 2018. The renewable electricity capacity was 44.4 GW at the end of 2018, a 9.7% increase from the previous year [7].

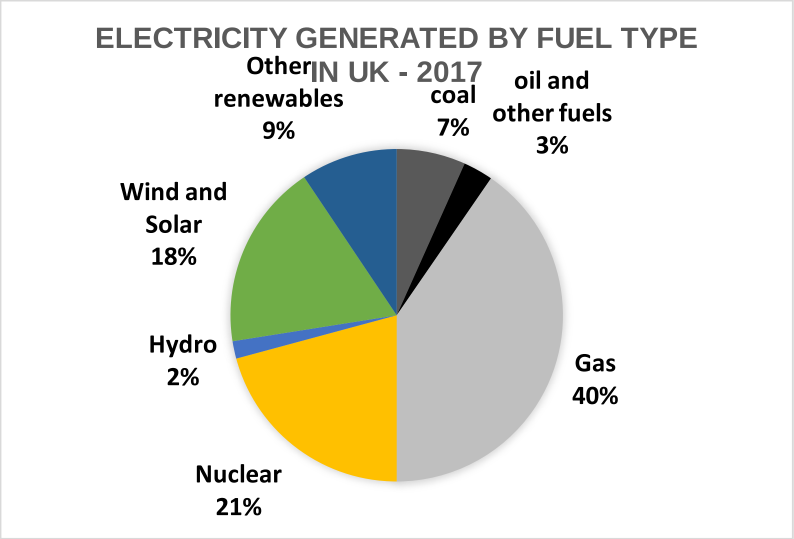

Figure 1: Generated Electricity 2017

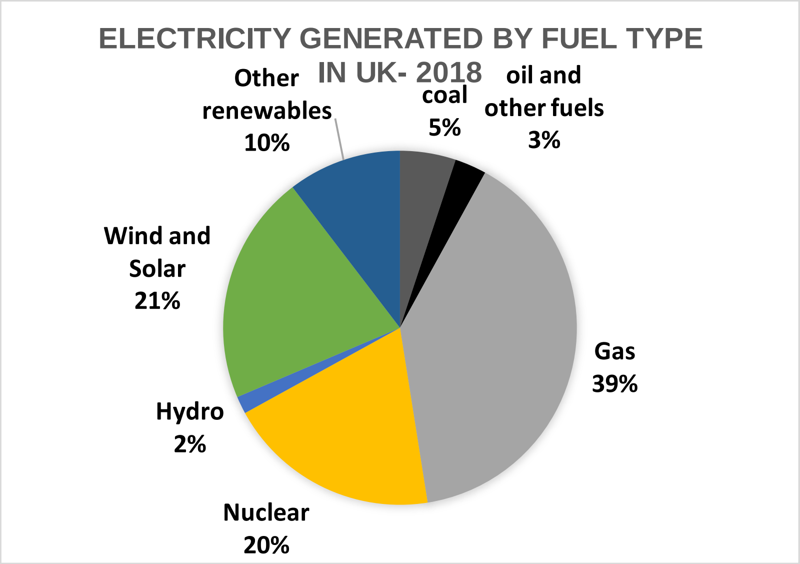

Figure 2: Generated Electricity 2018

The renewable energy in Figures 1 and 2 is comprised of solar, onshore wind, offshore wind, hydro, and bioenergy. Renewable electricity generation was a record of 111.1 TWh in 2018 , which is a 12% increase, compared to previous year (2017) and wind energy was the major contributor to this increase.

1.2 Marine Renewable Energy (MRE)

More than 70% of the earth’s surface is covered by oceans and they could potentially provide abundant, high load factor and predictable sources of energy. The environmental imperative to decarbonise the energy system has been one of the most important drivers for the development of offshore marine renewable energy (to be called MRE hereafter) including offshore wind, tidal and wave energies. Europe benefits from significant marine resources and therefore these technologies have attracted much attention in the recent years as viable candidates for clean electricity generation. The estimated global potential energy generation for tidal and wave energy has been reported 800 TWh, and 8000-80000TWh per annum respectively [8]. The EU aims to reach 100 GW of combined wave and tidal capacity by 2050 given that challenges related to technology readiness financing, market establishment, administrative and environmental issues and grid connections are addressed [9]. Amongst these energy types, offshore wind energy is at a much more advanced stage of development and has reached 18.7 GW of installed capacity globally [10] , and is growing in a much faster rate compared to tidal and wave energy. Although the deployment of wave and tidal power projects is not directly comparable to the process of installing offshore wind farms, they are expected to fall under the same legislation [11].

While these three offshore renewable energy sources are in a less mature state compared to biomass, onshore wind and solar energy [3], their remarkable potential for contributing to UK’s renewable energy supply have motivated this research. In the remainder of this section the three types of marine renewable energies are introduced.

1.2.1 Tidal Energy

Evidence shows that extracting the energy of ocean tides goes back to at least c.630 AD when tidal mills were used in the Irish coast [12]. Tidal energy has the potential to make significant contributions towards a low carbon energy mix and a green energy economy in a number of areas worldwide, including straits between islands, sites in the nearby of headlands [13] , or enclosed bodies of water, like estuaries [14]. For example, the exploitable UK tidal energy resource has been estimated as being sufficient to generate 94 TWh per year of electricity in water depths of 40 m or less, equivalent to about 25% of the UK's annual electricity consumption [11].

Tidal energy is abundant, reliable, regular, and one of the most predictable renewable energy sources which can be used as a sustainable resource for electricity production. Although renewable energy sources are intermittent in nature, tides are considered highly predictable since they are generated by the astronomical oscillatory gravitational forces and their sinusoidal character [15] which facilitates the grid management issues compared to other stochastic renewable energy types.

Currently tidal barrages and dams are established technologies providing commercial scale electricity. Tidal barrages (dams) are built across an estuary with turbines located along its length and tidal range power is created using a head difference between two bodies of water. To create this difference, a wall is used to separate the two areas and as the tide flows in or out, the wall blocks the flow of the tide and creates a head difference. When the head difference has reached an optimum level, the water passes through the barrage and creates energy due to the turbines placed within the holes in the wall. With two tidal cycles per day, this head difference is created 4 times each day (as the tide comes in and out) .

On the other hand, Tidal current turbine (TCT) technology, extracts energy in a cheaper and easier process using tidal current convertors and with less harmful environmental effects compared to tidal barrages [16]. TCTs are very similar to the functional design parameters of wind turbines, with a configuration of typically three blades, either mounted on a horizontal or vertical axis to a hub (together called a rotor), and connected to a gearbox, which is connected to a generator. The technology is fixed on the ocean floor through various different engineering options and extracts kinetic energy dissipated by tidal movements to turn the blades, rotate the rotor, and turn the generator via a gearbox, converting the speed of the rotor shaft to the anticipated output speed of the generator shaft [14].

While TCTs have advantage in terms of lack of visual obstruction, unwanted odour, and noise pollution over other types of devices, they face challenges in terms of operations in hostile marine environment, operation and maintenance cost, high axial stress, and cavitation [17]. Furthermore, tidal stream energy projects require high amounts of capital investment and the cost of electricity generation from tidal stream energy resource is currently much higher than that of traditional energy sources [14].

1.2.2 Wave energy

Ocean wave energy is a frequent, and periodic renewable energy source which has the potential to compete with the current use of fossil fuels. Depending on the force and consistency of the wind blowing over the surface of the ocean, continuous waves are created that contain huge energy potential [3]. The wave energy can be extracted directly from the surface waves or from the pressure fluctuations below the surface. The wave energy devices convert the wave energy into high pressure hydraulic and this energy is used to drive a hydraulic motor which is coaxially connected to an electric generator [18]. The theoretical extractable annual mean of UK’s wave power has been estimated as 43 GW [19], however, wave energy technology has not reached the same level of reliability and technological readiness of their tidal counterparts. One of the main reasons impeding the development of this type of energy has been the lack of a standardised design consensus of the wave energy devices. Amongst the EU countries, UK has the highest number of proposed projects [9].

1.2.3 Offshore wind energy

Wind energy is one of the promising sustainable energy resources due to its maturity and relatively low cost. Offshore wind resources are steadier and stronger in comparison to onshore wind, and have higher energy density, lower turbulence, lower wind sheer and lower visual impact [20]. The UK currently has the largest amount of installed offshore wind capacity worldwide and the European Union (EU) suggests that the offshore wind capacity could reach 150 GW by 2020 meeting 14% of the EU's final electricity consumption. This sector shows a high pace of sectoral growth since 2010 and by the end of 2018, the global installed capacity reached more than 18.5 GW with estimations up to 150 GW by 2030 [21]. The success of this sector is due to technological improvements and economies of scale which are cost reduction drivers along the value chain [22] with consented offshore wind farm tenders in 2018 as low as 46.6€/MWh [21]. In line with the technological advancements, in addition to bottom fixed platforms such as the monopile, jacket and gravity based foundations, floating platforms could also spur the diffusion offshore wind turbines further offshore and in deeper waters [23].

1.3 Research aims and objectives

In this research, a set of decision analytical models for the development of marine renewable energy with a case application in the UK are developed. As an island, the UK benefits from vast marine energy potential which could be a significant addition to the UK's renewable energy portfolio. The adoption of these technologies also contributes to the UK's objectives of lowering the overall carbon emissions, increasing energy security by utilising a domestic energy resource and providing new manufacturing jobs [24] . Therefore, for the development of MREs, decision makers and regulators are required to responsibly evaluate the trade-offs between economic benefits, social and environmental values [25].

The principal objectives in this thesis are:

1) The application of descriptive analytical methods, namely the Data Envelopment Analysis (DEA) method for the assessment of the relative efficiency of offshore wind farms across North-Western Europe.
2) The application of statistical analysis for interpreting the results of DEA performance assessment of offshore wind farms.

3) The application of the Analytical Hierarchy Process (AHP) method as a decision making tool for the suitability assessment of the infrastructure supporting the construction and operations of offshore wind energy.
4) The application of multi-objective methods for the development of a model for determining a marine renewable energy portfolio for the UK given the sustainability indicators including economic, technical, social, and environmental criteria.
5) Incorporation of the uncertainty related to the data in the decision making model framework relating to the selection of MRE projects with sustainability considerations.

1.4 Contributions

The body of this thesis is composed of three main chapters, each one using a unique methodology and case application in order to address the aforementioned objective. In the first part of this research, a benchmark study of the North-Western European offshore wind sector is provided. Different variants of the DEA methodology is used for the assessment of the relative efficiency of offshore wind farms. Furthermore, statistical analysis is conducted to understand the performance of UK's offshore wind sector against different major European players.

In the second part of this research, the Analytical Hierarchy Process (AHP) method is applied as a decision making tool to address the question related to the logistics suitability assessment of the infrastructure (namely the ports) by using expert judgements for deriving the criteria weights. These models can help different stakeholders within the offshore wind sector in selecting the ports for handling the construction and operation and maintenance of offshore wind farms.

In the third part of this research, an interval coefficient goal programming method is utilised to answer the question of how a set of marine renewable energy projects, including offshore wind, wave and tidal energy, can be selected in the UK given the uncertainty associated with the data and the decision makers' goals. Furthermore, a clustering analysis is provided for identifying the potentially attractive zones for the UK's marine renewable energy. This framework can aid the decision makers (developer / government body that issues planning permit) reach a decision on which set of projects should be chosen given a set of different sustainability objectives and considering the uncertainty in the data.

The concluding remarks of this thesis are presented in chapter 5, in which the findings of this research, possible policy implications, and future research directions are discussed.

1.5 Publications

The material presented in this thesis have been published as a book chapter and journal article. Additionally, some of the unpublished work, has been presented in several conferences throughout the course of this degree. The list of these publications and conference presentations, which are the building blocks of this thesis is presented below.

1.5.1 Journal articles

1. Akbari, N., Jones D., Treloar, R. (2020) A cross European efficiency assessment of offshore wind farms: A DEA approach. *Renewable Energy 151, 1186-1195.*
2. Irawan, C. A., Akbari, N., Jones, D. F., Menachof, D. (2018) A combined supply chain optimisation model for the installation phase of offshore wind projects. *International Journal of Production Research 56 (3), 1189-1207.*
3. Akbari, N., Irawan, C., Menachof, D., Jones, D. (2017) The role of ports in the offshore wind industry. Port Management: Cases in Port Geography, Operations and policy.
4. Akbari, N., Irawan, C. A., Jones, D., Menachof, D. (2017) A multi-criteria port suitability assessment for developments in the offshore wind industry. *Renewable Energy (102), 118-133.*

1.5.2 Conference Presentations & Proceedings

1. Akbari, N. Jones, D. “A goal programming model with interval coefficients and target intervals for selection and planning of marine renewable energies in the UK” Euro 2019 Conference, Dublin, Ireland, June 2019.
2. Akbari, N., Jones, D., Treloar, R. “A Cross-European efficiency assessment of offshore wind farms using the DEA approach” Operational Research Society Conference, Lancaster, UK, September 2018.
3. Akbari, N., Jones, D., Treloar, R. “A Cross-European Efficiency assessment of offshore wind farms using the DEA approach” Euro 2018 Conference, Valencia, Spain, July 2018.
4. Akbari, N., Jones, D. “A combined DEA/GP method for efficiency assessment of offshore wind and tidal stream energies”. MOGP Conference, Metz, France, November 2017.
5. Akbari, N., Menachof, D. “Offshore wind project assessment under uncertainty”, Euro 2016 Conference, Poznan, Poland, July 2016.
6. Akbari, N., Menachof, D. “Offshore wind project assessment under uncertainty”, Wind Europe, London, UK, July 2016.
7. Akbari, N., Attari, A., Cradden, L., Doherty, P. “Buoyant gravity based foundation for offshore wind, Infrastructure challenges” Poster presentation, Wind Europe Conference, Paris, France, November 2015.
8. Akbari, N., Irawan, C. A., Jones, D. **“**Assessment of the suitability of ports for installation and operations and maintenance for the offshore wind industry: An AHP approach” EURO 27, Glasgow, UK, July 2015.

1.6 Organisation of the thesis

This thesis is composed of five chapters and three parts. The first chapter is the introduction of the thesis with an overview of the main research objectives, contributions and publications. In Chapter 2 (Part I) the benchmark study of a set of North-Western European offshore wind farms by using the Data Envelopment Analysis methodology is presented. Chapter 3 (part II) delves into the application of the Analytical Hierarchy Process methodology for the infrastructure assessment for the development of offshore wind farms. Chapter 4 (Part III) presents the application of goal programming for the marine renewable energy project selection problem. The conclusions of this thesis are presented in chapter 5 followed by the bibliography and the appendix.

Part I

Chapter 2

Efficiency based approaches to performance assessment of European offshore wind industry

2.1 Introduction

Data Envelopment Analysis is a non-parametric method that evaluates the relative efficiency of a set of Decision Making Units (DMUs) by a scalar measure ranging between zero and one which is measured through a linear programming model. Specifically, the Charnes, Cooper, Rhodes (CCR) model deals with the ratio of multiple inputs and outputs in an attempt to estimate the relative efficiency of a particular DMU amongst a set of DMUs. The optimal objective value, is called the ratio, or radial efficiency of the DMU. The DEA method divides the DMUs into efficient and inefficient subsets, where efficient units receive value of 1 and inefficient ones receive values less than 1. Therefore, the method allows for the identification of

DMUs exhibiting best practice and the consequent formation of an efficient frontier [26].

In contrast to parametric methods such as Stochastic Frontier Analysis (SFA), for which an explicit functional form for the technology and frequency for the distribution of the inefficiency term is imposed, no prior assumption on the underlying functional relationship between inputs and outputs is required in the DEA method [27] . Based on a survey by Liu et al. [28], DEA has been used in traditional industries such as agriculture, manufacturing and health care, as well as modern industries such as software and e-business, and is particularly an accepted approach for efficiency evaluation and benchmarking in the energy and environment sector [29]. Within the context of benchmarking, DEA could be considered as a multiple criteria decision analysis method, however its main goal is to evaluate the relative efficiency of a set of comparable entities (DMUs) rather than choosing a specific alternative as it is usually the case in decision analysis methods [30].

2.2 Contributions

The contributions of this chapter are threefold including:

1) Providing a benchmark study of the current efficiency status of the European offshore wind industry.
2) Providing a ranking of the offshore wind farms via the application of the super efficiency DEA method.
3) Determining the factors affecting the efficiency of offshore wind farms in the sensitivity analysis.
4) Providing a statistical analysis of the difference in efficiency scores of the countries by grouping the windfarms into three categories of UK, Germany-Denmark and Netherlands-Belgium.

In the next section, a review of the applications of DEA in the renewable energy sector is presented and the gaps are identified.

2.3 Applications of DEA in the renewable energy sector

In this section, some of the applications of DEA in the renewable energy sector are presented in order to review the inputs and outputs that have been used in the literature. Ederer (2015) [31] has applied the DEA methodology for assessing the efficiency of 22 offshore wind farms in Europe in terms of capital cost efficiency and operating cost efficiency. For the assessment of capital cost efficiency, the capital cost is considered as the input and installed capacity, distance to shore and water depth as the outputs. For the operating cost efficiency, the operating cost is the input and the installed capacity, distance to operating port, energy performance and availability are the outputs. Using both BCC and CCR methods, the scale efficiency of the wind farms is determined. The learning-by-doing rate for capital cost efficiency shows that the efficiency has increased with accumulated experience. Furthermore, the Tobit regression applied in their study shows increasing capital cost efficiency as a function of time, and a decreasing operating cost efficiency as a function of operating year.

Saglam [32]uses a two stage DEA model for efficiency assessment of onshore wind energy in 39 states in the United States. In the first stage of the model, a BCC and CCR model is developed that takes the installed wind capacity, number of wind turbines, total project investment and annual land lease payment as inputs. The net generation, percentage of in-state energy production, number of US homes powered, wind industry employment, annual water savings and CO2 emissions avoided as the outputs. Sensitivity analysis is also conducted for assessing the robustness of the model and shows that electricity generation related output variables and capital and technology related inputs are critical factors affecting the efficiency scores. Furthermore, Tobit regression models investigate the effectiveness of the invested money and the productivity of the wind turbine technologies and shows that early installed wind power was more expensive and less productive than the current installed wind power.

Wu et al. [33] apply a two stage DEA for efficiency assessment of 42 onshore wind farms in China. They use the installed capacity, electricity consumption and wind power density as the inputs and the generated electricity and availability as the outputs. The Tobit regression analysis is used to assess the relationship score of the CCR model with the uncontrollable variables (age, wind curtailment rate, dummy variable for ownership effect). The regression findings suggest that age and wind curtailment rate have a negative effect on the productive efficiency while the ownership effect does not have a significant impact.

Recently, DEA has been applied to for the evaluation of wind power performance in 29 Chinese provinces. The cumulative installed capacity and the annual operation and maintenance cost are selected as inputs; and the amount of electricity sold to local grid companies, and energy substitution income of wind power generation are selected as outputs. The factors affecting the performance of wind farms are identified by a regression model and are described as local power consumption capacity, economic development degree and the rate of wind abandonment [34]. The DEA method is also used to understand the development of wind power at the micro level in China by using the labour and capital as the inputs and the income as the output of the model. The study reports non-efficiency problems (average efficiency value of 32.5%) in the wind sector in the period of 2011-2015 arising from diseconomies of scale [35].

Iglesias et al. [36] use DEA and SFA to measure the efficiency of 57 Spanish onshore wind farms using the capital, labour and fuel (wind) as inputs and the electrical energy produced by the wind farm. Their results show that the DEA BCC model has the highest efficiency score, followed by SFA and CCR model. High average technical efficiency (exceeding 75%) is reported and they show correlation of the average size of the standard wind turbine with the year of installation.

Halkos and Tzeremes [37], apply a bootstrapped DEA model for evaluation of financial performance of 78 firms operating in the Greek renewable energy sector and concluded that firms operating in the wind power energy sector had higher financial efficiency compared to firms in the hydroelectric power sector. They have considered debt/equity ratio, current ratio and asset turnover ratio as input variables and return on equity, return on asset gross profit margin and operating profit margin as output variables. San Cristobal [38] uses DEA to assess the efficiency of thirteen different renewable energy technologies related to wind power, hydroelectric, solar, biomass and biofuel using the investment ratio, implement period and operating and maintenance cost as inputs and power generation, operating hours, useful life and CO_2 avoided as outputs. Kim et al. [39] apply DEA to assess the investment efficiency of photovoltaic, onshore wind power and fuel cells in South Korea considering policy objectives of public investment, technological development and wider dissemination of new and renewable energy in South Korea. Based on their analysis, wind power turns out to be the most efficient technology from a government investment perspective.

Stallard et al. [40] use the DEA method to compare the efficiency of a set of three hypothetical and one prototype wave energy conversion technologies at eight distinct UK wave climates considering 7 inputs and one output. It is suggested that the DEA provides straight forward means of selecting the technology that maximises aggregate electricity generation with minimum inputs and without recourse to conducting a cost study for each site.

DEA has also been used for the analysis of energy efficiency on country level. DEA has been applied to assess the efficiency of BRIC countries and Mediterranean countries respectively, both using energy consumption, labor force and gross fixed capital formation as inputs and the GDP as an output by

[41] and [42]. Location optimization of wind plants in Iran has been conducted using fuzzy DEA in which in addition to wind speed, local and social criteria such as population of the region, geological and geographical consideration and cost have been considered by [43].

It is noted that, whilst the above papers conducted successful and informative DEA analyses, they concentrate on onshore rather than offshore wind farms in their assessment of wind energy. Furthermore, there is often, but not exclusively, an emphasis on the constant return to scale (CCR) and variable return to scale (BCC) DEA methods and other DEA variants such as the slack based measure (SBM) and super efficiency method have not been applied as frequently. This chapter presents an efficiency analysis for a large number of offshore wind farms across North West Europe considering social, technical, environmental and economic factors and fills the gap in the current literature via the application and comparison of several variants of the DEA method to the offshore wind energy sector. Thus, DEA can be regarded as a descriptive analytical method, although an analysis of its results can lead to some prescriptive recommendations.

2.4 DEA methodology

The initial idea of DEA can be traced back in the economics literature through defining a simple measure for efficiency that could account for multiple inputs and outputs within the context of technical, allocative and productive efficiency [44]. DEA was extended by Charnes et al. [26] and Banker et al. [45] to propose the Charnes-Cooper-Rhodes model (CCR) with constant returns to scale (CRS) and Banker-Charnes-Cooper (BCC) with variable returns to scale (VRS).

In this chapter, five main variants of the DEA methodology, including the constant return to scale, variable return to scale, scale efficiency, slack based measure, and the super efficiency methods are applied and the results are compared and contrasted. In the remainder of this section, these methodologies are introduced.

2.4.1 The constant return to scale method

The Charnes Cooper Rhodes (CCR) model is formulated below assuming that there are j DMUs to be evaluated $(j = 1, \dots, n)$, r is the output index $(r = 1, \dots, s)$; i is the input index $(i = 1, \dots, m)$. x_{ij} the value of the i_{th} input of the j_{th} DMU; and y_{rj} the value of the r_{th} output; u_r is the weight assigned by the DEA model to the r_{th} output; v_i is the weight assigned by the DEA model the i_{th} input; and θ the relative efficiency of DMU$_j$ in the following manner:

$$Max\ \theta = \sum_{r=1}^{s} u_r y_{rj} \tag{1}$$

Subject to:

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0 \tag{2}$$

$$\sum_{i=1}^{m} v_i x_{ij} = 1 \tag{3}$$

$$u_r, v_i \geq 0 \quad \forall\, r, i \tag{4}$$

The CCR method is a radial efficiency method that assumes a constant return to scale. Returns to scale measure the changes in output levels due to changes in the input level. Constant return to scale (CRS), therefore implies that an increase in input level results in a proportional increase in the output level.

2.4.2 The variable return to scale method

The model developed by Banker, Charnes, Cooper (BCC) [45] assumes that an increase in the input levels does not necessarily result in a proportional increase in the output levels, and the output levels can increase (Increasing return to scale) or decrease (decreasing return to scale) by a different proportion than the input increment.

In order to permit for a variable return to scale, The BCC model adds an additional convexity constraint $\sum_{j=1}^{n} \lambda_j = 1$ to ensure that the region specified form a convex set, and ε is a positive non-Archimedean infinitesimal. The Dual problem of the BCC model is stated as:

$$Min \quad \theta_0 - \varepsilon(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+) \tag{5}$$

Subject to

$$\sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = \theta_0 x_{i0}, \qquad i = 1, \dots, m \tag{6}$$

$$\sum_{j=1}^{n} \lambda_j y_{r0} - s_r^+ = y_{r0}, \qquad r = 1, \dots, s \tag{7}$$

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{8}$$

$$\lambda_j, s_i^-, s_i^+ \geq 0 \tag{9}$$

$$\theta_0 \; unrestricted \tag{10}$$

Similar to the CCR model, a DMU_0 is BCC-efficient if there exists a solution such that $\theta_0 = 1$ and all slacks s_i^-, s_i^+ are zero in value and any CCR efficient DMU is also BCC efficient. It should be noted that the results of the CCR input-minimised or output maximized formulations are the same, which is not the case in the BCC model. In the output oriented BCC model, the formulation maximises the outputs given the inputs and in the input oriented BCC model, the formulation minimises the inputs given the outputs.

2.4.3 The scale efficiency method

The CCR score is termed the global technical efficiency, and the BCC score is the local pure technical efficiency. If both the BCC and CCR scores indicate full efficiency (100%), then that DMU is operating on the most productive scale size. In other words, a DMU with full BCC score but a low CCR score is operating efficiently only locally and not globally as a result of its scale size. The scale efficiency score can be defined as following:

$$\theta_{scale} = \frac{\theta_{CCR}}{\theta_{BCC}} \tag{11}$$

Since $\theta_{CCR} \leq \theta_{BCC}$, $0 < \theta_{scale} \leq 1$.

2.4.4 The slack based measure method

In discussing total efficiency, it is important to consider both the radial efficiency and the slacks. The CCR and BCC methods are both radial methods. However, the SBM is a non-radial method, which only segregates efficient and inefficient DMUs by taking into account the slack variables. The optimal solution in the SBM reveals, the existence, if any, of excesses in the inputs (s_i^-) and shortfalls in the outputs (s_r^+) (i.e. slacks). A DMU with the full ratio efficiency , and with no slacks in any optimal solution is called CCR efficient, otherwise the DMU has a disadvantage against the DMUs in its reference set [46]. In the Slack adjusted DEA method, a weakly efficient DMU will now be evaluated as inefficient, due to the presence of input and output oriented slacks s_i and σ_r, respectively. The optimal function value f_k is the efficiency of the kth DMU, and L_{kj} denotes super efficient slacks,s_i and s_r denotes the inefficient slack variables related to input excess and output shortage respectively.

$$Min \quad f_k - \varepsilon(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+) \tag{12}$$

Subject to:

$$-\sum_{j=1}^{n} L_{kj}\, x_{ij} + f_k x_{ik} - \ (s_i^-) = 0 \quad for\ i = 1, \dots, m \tag{13}$$

$$\sum_{j=1}^{n} L_{kj} y_{rj} - (s_r^+) = y_{rk}\ for\ r = 1, \dots, s \tag{14}$$

$$L_{kj}, s_i \geq 0 \quad for\ j = 1, \dots, n \tag{15}$$

2.4.5 The super efficiency method

From a ranking perspective, an important problem in the DEA literature is that all efficient units have a score of unity, therefore no discrimination can be made between efficient units. The difference between the super efficiency DEA and the original DEA is that DMU_0 under evaluation is excluded from the reference set, and efficient units can receive score above 1. The super efficiency method developed by [47] allows for outlier detection, sensitivity analysis, and scale classification. The output based super efficiency BCC model and can be expressed as [48] :

$$Max\ \varphi \tag{16}$$

Subject to :

$$\sum_{j=1}^{n} \lambda_j x_j \leq x_0 \tag{17}$$

$$\sum_{j=1}^{n} \lambda_j y \geq \varphi y_0 \tag{18}$$

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{19}$$

$$\varphi\ , \lambda_j\ \geq 0, j \neq 0 \tag{20}$$

2.5 DEA Case application

Although the DEA methodology has its roots in economics and production theory, it has been used extensively within the realm of operations management for benchmarking the performance of decision making units. In this domain, instead of forming a production frontier, the efficient DMUs form a best practice frontier [41]. In the remainder of this section, the rationalization behind the selection of the inputs and outputs of the DEA model developed in this chapter is presented.

2.5.1 Selection of inputs and outputs

For the classification of inputs and outputs, it is suggested that if the underlying problem represents a form of production process, then the selected inputs are usually the resources used or required, and the outputs are the outcome of the process. However, if the problem refers to a benchmarking problem, then the inputs may be selected based on the assumption of "the less the better" and the outputs may be selected based on the assumption of "the more the better" [49]. For this analysis, DEA is employed as a multiple criteria decision making tool where the DMUs are alternatives and the inputs and outputs are two sets of performance criteria where the input is to be minimized and the output to be maximized [49]. The problem of efficiency assessment of offshore wind farms can therefore be classified as a benchmarking problem as it does not only consider the production of electricity given a number of resources, but it assesses the offshore wind farms including other factors including the social impact, cost, and the connectivity to population centres. While it can never be guaranteed that the chosen set of inputs and outputs that perfectly reflect the process under study are included in the DEA analysis, every attempt should be made to ensure that the selected measures reflect the process under study in as detailed a way as possible. In the next section a description and justification for selection is provided for each of the inputs and outputs used in this study. The main categories of the inputs and outputs are defined as:

a. *Economic* criteria including the cost, and the amount of produced electricity
b. *Technical* criteria including the number of turbines, and water depth,
c. *Social* criteria including the distance to shore and connectivity to population centres
d. *Environmental* criteria including the area of the offshore wind farm.

2.5.1.1 Inputs

The description of the four inputs including the number of turbines, cost, distance to shore and the area of the wind farm is provided below:

1) Number of turbines: the number of turbines has been selected as an input since it corresponds to the capacity of the wind farm, and also affects the construction, and operation and maintenance of the wind farm. The number of turbines has a direct impact on the cost of the wind farm, particularly the operation and maintenance cost, and also the amount of area that the wind farm occupies in the sea, which is a factor which affects its environmental impact. Therefore, this parameter has been chosen as an input since the best output performance from as few a number of turbines is desirable.
2) Cost: amongst the most important parameters with which offshore wind projects are assessed is the cost of the project. Distance from the shore, water depth, the technology used and many other factors can have an impact on the cost of the wind farm. For this analysis the cost component comprises of the construction and operation and maintenance costs (CapEx plus OpEx) of the wind farm throughout its entire life cycle and the data for the cost of wind farms has been retrieved from publically available sources [50] including company reports. This parameter has been chosen as an input since a best output performance at a lower cost is desirable. The cost data for the wind farms [51] has been inflation adjusted based on their year of commissioning up to the end of year 2018.
3) Distance to shore: the distance to shore is included as it relates to the sea scape, landscape and visual impact of the wind farm. While offshore wind farms are subjected to the NIMBY effect (not in my back yard) less than that of onshore wind turbines, there are still issues associated with their visual impact, and the impact they could have on the local industries of the region such as tourism. An example of this case is the rejected Navitus Bay wind farm that was planned to be built in the South of England.

Amongst the important reasons for the rejection of this project was that the scale and location of the project would affect areas of outstanding beauty over a widespread area of coastline. The wind farm would be visible from vantage points along a 30 km section of the eastern edge of the World Heritage site with the closest point lying on the shore approximately 15 km from the edge of the wind turbine layout [16]. It is therefore desired that the wind farms are built at a distance from the shore to lower their negative social impact, which is better. Certainly, this can lead to a trade-off between the cost and social impact inputs that forms part of the intrinsic reasoning of the DEA analysis. Table 1 presents the figures used for calculating the impact of the distance to shore of the windfarms. The visual impact of the wind farms is characterized as very low to very high, and the score is allocated accordingly ranging from 1-5.This means the impact score of a wind farm with very low visual impact is 1, and a windfarm with very high visual impact has a score of 5.

4) Offshore wind farm area: this input is related to the marine footprint of the offshore wind farm. Although offshore wind farms are under less space restriction compared to on-land wind farms, they are still in competition with other sea-users in terms of the space that can be allocated to them. However, some studies suggest the positive effect of the construction of offshore wind farms for the marine environment. This is due to the fact that the construction of the offshore wind farms have contributed to the recovery of vulnerable species due to those areas being closed to beam trawl fisheries [52].

   However, the overall impact of the offshore wind farm area is such that it can be considered as an input, since best output performance from a smaller area is desirable for the wind farms. This is particularly true of the crowded maritime spaces in North West Europe where the wind farms considered in this study are located. Hence, in this study the negative impacts of the offshore wind farm area have been considered and this parameter is used as an input (i.e. the lower the better). The area that the offshore wind occupies in the sea is important due to the following reasons [53]:

- The larger the area, the larger the marine footprint which may lead to marine life interruptions, fishing industry prohibitions, and leisure industry limitations.
- The larger area of the wind farms could lead to marine transportation disruptions, since the offshore wind industry competes with other industries such as container shipping, bulk shipping, defence vessel movements, and passenger ferry line alterations.
- The larger area of wind farm may be due to greater number of turbines employed or larger spacing between turbines, which could lead to higher installation, O&M and decommissioning costs. Therefore, it may be desirable to increase the capacity of the wind turbines rather than the number of turbines.

Distance from shore (km)	Visual impact	Impact score
1-10	very high	5
10- 20	high	4
20-30	moderate	3
30-40	low	2
Distance>40	very low	1

Table 1: Distance from shore impact score

The inclusion of all the aforementioned inputs will help in capturing different aspects of an offshore wind farm. However, some level of correlation exist between some of the inputs which may result in over optimistic DEA results and low variation among DMUs. For example, the number of turbines may be correlated with the offshore wind farm area, i.e. the larger the area, the greater number of turbines. But this is not the case in all wind farms, since some wind farms occupy a very large area but have fewer turbines with a higher capacity. Therefore, we argue that although correlation exists in some instances, inclusion of both criteria is necessary since the number of turbines is related to the amount of energy and efficiency of the wind farm, while the area occupied by the wind farm has an impact on the environmental footprint of the wind farm.

2.5.1.2 Outputs

Three outputs, namely the connectivity to population centres, produced electricity and the water depth have been selected for the DEA model as described below:

1) Connectivity to population centres: the connectivity and proximity of the wind farm to the population centres is an important parameter since this will allow a lower strain in terms of grid accessibility and logistics. This output is calculated as the distance of the wind farm to nearest medium sized city within 250 km with a population density above 1000 person/ km^2. It is desired that the connectivity is maximised and therefore this parameter has been inverted and used as an output of the model.
2) Electricity produced: this parameter measures the amount of estimated theoretical annual electricity produced by the wind farm using the average wind speed data for each location. Based on the Betz momentum theory the amount of mechanical energy that can be extracted from a free stream airflow by an energy convertor is limited to around 59% of E using the equation below:

$$E = \left(\frac{1}{2}\right) A\rho v^3 t \tag{21}$$

   Where A designates the swept area of the rotor ($A = \pi r^2$), ρ represents the air density, v is the average wind speed, and t is the time.
   Since an important goal of the wind farm is to maximize its electricity production, this parameter is chosen as an output.

3) Water depth: In order to take better advantage of energy resources at sea, the offshore wind industry is developing wind turbine concepts for deployments in deeper waters. Some offshore wind projects are now planned for instalment in water depths up to 50 m, which require a shift from the monopile foundation (which are used in about 96% of the presently commissioned wind farms) to novel foundation types such as floating structures [54]. The ability to produce energy efficiently at greater water depths is seen as a positive development and this parameter is therefore used in this analysis as an output.

The suitable number of inputs and outputs with relation to the number of DMUs is amongst the debated topics within the DEA literature. Banker et al. [45] suggest that the number of DMUs should be at least three times the number of inputs and outputs while [55] suggest that the number of DMUs should be two times greater the combined number of inputs and outputs, however this rule may not be imperative [49]. They point out that while in statistical regression analysis, the sample size can be a critical issue as it tries to estimate the average behaviour of a set of DMUs, DEA focuses on individual DMU performance. In that sense the number of DMUs under evaluation may be immaterial. For this analysis a combined number of 7 inputs and outputs and 70 DMUs are considered, which comfortably meets the suggested rules of [45] and [55].

2.5.2 Data description

It is suggested that for the DEA analysis a mixture of raw data (e.g. revenue, number of employees) and percentile/ratio data (e.g. returns on investment, profit per employee) can be used simultaneously [49]. The type of data used for this DEA analysis is raw data and none of the inputs or outputs have an equal value across all DMUs. The data related to the inputs and outputs has been retrieved from the literature [56], [31], and publically available data sources including online resources [50],[57] and company reports. The sample consists of 70 operational and in construction offshore wind farms and excludes any demonstration wind farms. The statistical description of the input and output data used for this analysis is described below in Table 2.

Parameters		Median	Min	Max	Standard deviation
x_1	Number of turbines	60	6	175	37
x_2	Cost(£ million/MW)	5.96	2.77	11.44	1.79
x_3	Distance to shore (1-5)	3.00	1	5	1.44
x_4	Area(km^2)	33.00	2	407	59.55
y_1	Connectivity(km)	80.25	6.45	250	66.77
y_2	Generated electricity (GWh)	977.67	48.12	5289	943.036
y_3	Water Depth(m)	19	2.5	42.5	10.006

Table 2: Data description

2.5.3 DEA Analysis result

Table 3 shows the DEA efficiency estimation results for 70 offshore wind farms across Europe Using the CRS, VRS, Scale efficiency, SBM and super efficiency methods. While the first four methods provide a relative efficiency score of the offshore wind farms, the super efficiency method provides a ranking of the DMUs via allowing the efficiency scores to exceed 1, and therefore allowing discrimination between the efficient units.

Code	**Offshore wind farm**	**CRS**	**VRS (input oriented)**	**VRS (output oriented)**	**Scale efficiency (output oriented)**	**SBM**	**Super efficiency**
OW_01	Scroby Sands	84.37	100	100	84.37	100	84.37
OW_02	North Hoyle	88.7	100	100	88.7	100	88.7
OW_03	Kentish Flats	100	100	100	100	100	152.02
OW_04	Burbo Bank	100	100	100	100	100	146.25
OW_05	Burbo bank extension	100	100	100	100	100	122.78
OW_06	Beatrice	88.68	100	100	88.68	100	88.68
OW_07	Hornsea project 1	100	100	100	100	100	199.65
OW_08	East Anglia 1	100	100	100	100	100	112.73
OW_09	Dudgeon	78.09	78.73	85.93	90.88	74.08	78.09
OW_10	Rampion	83.38	100	100	83.38	100	83.38
OW_11	Galloper	90.15	91.76	93.12	96.81	69.32	90.15
OW_12	Walney extension	100	100	100	100	100	194.92
OW_13	Walney Phase 1	82.77	83.06	88.97	93.03	70.98	82.77
OW_14	Walney Phase 2	78.54	84.6	94.97	82.7	74.88	78.54
OW_15	Race bank	100	100	100	100	100	100.95
OW_16	Lincs	66.55	72.79	67.34	98.83	64.24	66.55
OW_17	London array	99.26	100	100	99.26	100	99.26
OW_18	Lynn	65.31	89.22	70.68	92.41	78.85	65.31
OW_19	Teeside	84.58	99.92	99.75	84.79	83.71	84.58
OW_20	Thanet	74.03	76.79	82.41	89.83	68.2	74.03
OW_21	Sheringham shoal	77.1	80.95	79.02	97.57	69.88	77.1
OW_22	Rhyl flats	75.41	96.99	88.28	85.42	92.58	75.41
OW_23	Robin Rigg	62.17	87.33	65.75	94.56	79.79	62.17
OW_24	Ormonde	100	100	100	100	100	104.23
OW_25	Westermost rough	88.07	88.81	94.53	93.16	74.63	88.07
OW_26	West of duddon sands	79.46	82.12	95.7	83.03	77.14	79.46
OW_27	Gwynt y mor	92.77	92.97	94.81	97.85	72.49	92.77
OW_28	Gunfleet sands	66.22	84.88	70.41	94.05	76.09	66.22
OW_29	Greater Gabbard	73.45	75.13	75.42	97.38	66.17	73.45
OW_30	Humber gateway	79.9	82.57	81.33	98.25	66.93	79.9
OW_31	Barrow	100	100	100	100	100	111.26
OW_32	Amrumbank west	90.34	100	90.34	100	83.89	90.34

OW_33	Bard offshore	100	100	100	100	100	100.08
OW_34	Butendiek	80.8	83.24	81.11	99.62	67.02	80.8
OW_35	EN BW Baltic 1	80.91	92.65	81.38	99.42	75.47	80.91
OW_36	EN BW Baltic 2	92.19	92.6	93.34	98.77	71.93	92.19
OW_37	Dantysk	81.07	100	81.07	100	76.17	81.07
OW_38	Global tech 1	100	100	100	100	100	101.57
OW_39	Riffgat	100	100	100	100	100	101.47
OW_40	Sand bank	86.49	100	86.49	100	79.16	86.49
OW_41	Trianel windpark borkum	100	100	100	100	100	113.59
OW_42	Arkona	100	100	100	100	100	101.86
OW_43	Borkum riffgrunde 1	90.81	100	90.81	100	84.69	90.81
OW_44	Borkum Riffgrund 2	100	100	100	100	100	123.59
OW_45	Merkur	91.97	100	91.97	100	87.6	91.97
OW_46	Nordergrunde	83.82	100	100	83.82	100	83.82
OW_47	Wikinger	100	100	100	100	100	109.5
OW_48	Veja mate	100	100	100	100	100	118.19
OW_49	Alpha ventus	100	100	100	100	100	192.34
OW_50	Nordsee One	100	100	100	100	100	101.83
OW_51	Meerwind sud/ost	88.34	100	88.34	100	81.08	88.34
OW_52	Belwind	100	100	100	100	100	109.88
OW_53	Nobelwind offshore wind farm	100	100	100	100	100	109.61
OW_54	North wind offshore wind farm	100	100	100	100	100	105.63
OW_55	Thornton Bank 1	100	100	100	100	100	127.86
OW_56	Thonton bank 2	86.85	100	100	86.85	100	86.85
OW_57	Thornton Bank 3	85.75	93.31	87.71	97.77	72.15	85.75
OW_58	Rentel	100	100	100	100	100	112.92
OW_59	Norther	83.7	90.45	83.9	99.76	82.41	83.7
OW_60	Egmond aan Zee	87.44	100	100	87.44	100	87.44
OW_61	Eneco Luchterduinen	95.16	95.3	96.66	98.45	84.87	95.16
OW_62	Gemini	100	100	100	100	100	138.93
OW_63	Prinses Amalia	93.73	97.69	98.53	95.13	68.57	93.73
OW_64	Westermeerwind	73.01	96.53	85.61	85.28	94.03	73.01
OW_65	Anholt	71.31	75.06	71.39	99.89	64.83	71.31
OW_66	Rodsand 2	100	100	100	100	100	101.52

OW_67	Horns Rev 3	90	100	100	90	100	90
OW_68	Horns Rev 1	100	100	100	100	100	110.79
OW_69	Nysted	47.57	72.38	47.76	99.59	67.28	47.57
OW_70	Horns Rev2	100	100	100	100	100	105.07
Average efficiency score (%)		89.15	94.83	92.64	96.24	88.59	98.16

Table 3: DEA results

2.6 Statistical analysis

Based on the results reported in Table 3, the average efficiency of wind farms for all the methods ranges from 88.6% to 98.16%. In order to interpret the DEA efficiency estimation results on a country level, it is important to determine whether the median efficiency rating of the offshore wind farms located in different countries is significantly different. For this, the Kruskal Wallis test, which is a non-parametric statistical test that evaluates if two or more samples are drawn from the same distribution is conducted. In order to conduct the test, three groups are created such that the wind farms located in Netherlands and Belgium form Group 1 [OW52-OW64], Germany and Denmark form Group 2 [OW32-OW51 and [OW65-OW68] and the wind farms located in the UK form Group 3 [OW1-OW31]. This categorization is done primarily because the number of wind farms in Netherlands, Belgium and Denmark are not large enough to be presented as an individual group for the Kruskal Wallis H test (as the number of observations should be more than 5). Hence these countries are grouped together based on the geographical proximity and similarity, to form a group which is suitable for the statistical analysis using non-parametric tests [58]. In order to understand the distribution of the data, the Anderson-Darling test is conducted for the CRS, VRS (input and output oriented) the super efficiency, and SBM DEA (Figure 3-7), which shows that the data is not normally distributed.

The Kruskal-Wallis H test determines if the median efficiency score of the countries are statistically significantly different from one another (i.e. whether the medians of two or more groups differ) [59]. The p-value is a probability that measures the evidence against the null hypothesis (i.e. the population medians are all equal) and lower probabilities provide stronger evidence against the null hypothesis. The DF (Degree of Freedom) is equal to n-1, where n represents the number of data groups, and the z-value indicates how the average rank for each group compares to the average rank of all observations, and the higher the absolute value, the further a group's average rank is from the overall average rank. The AD value (Anderson Darling goodness of fit statistic) measures the area between the fitted line and the empirical distribution function which is based on the data points. The Anderson Darling statistics is a squared distance that is weighted more heavily in the tails of the distribution.

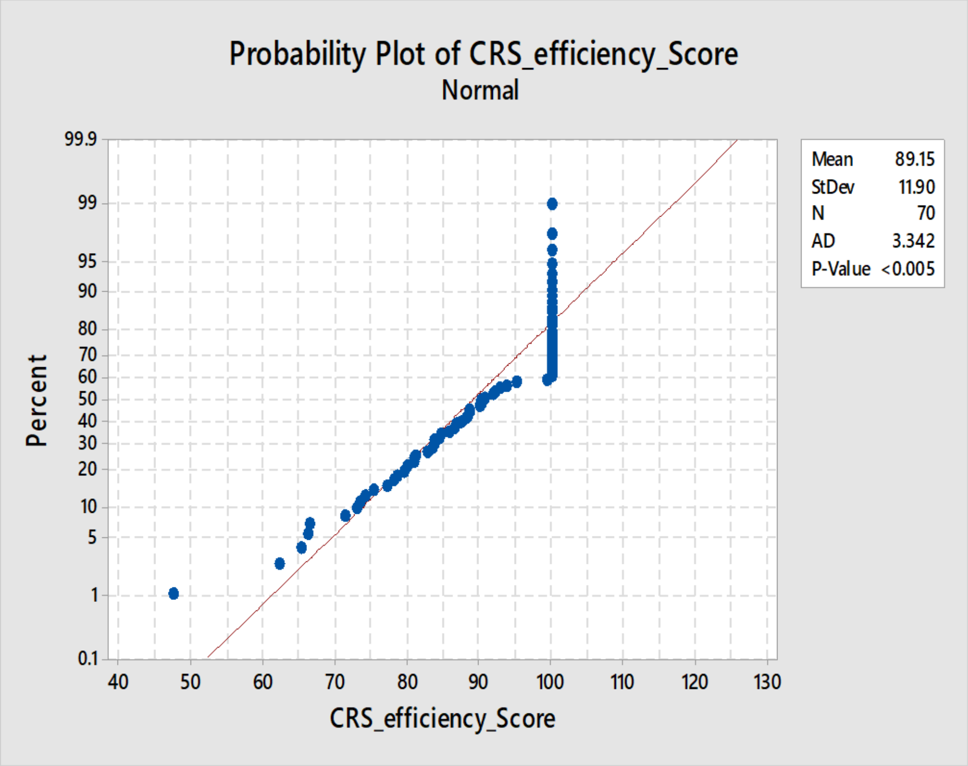

Figure 3:Anderson-Darling test for the CRS model

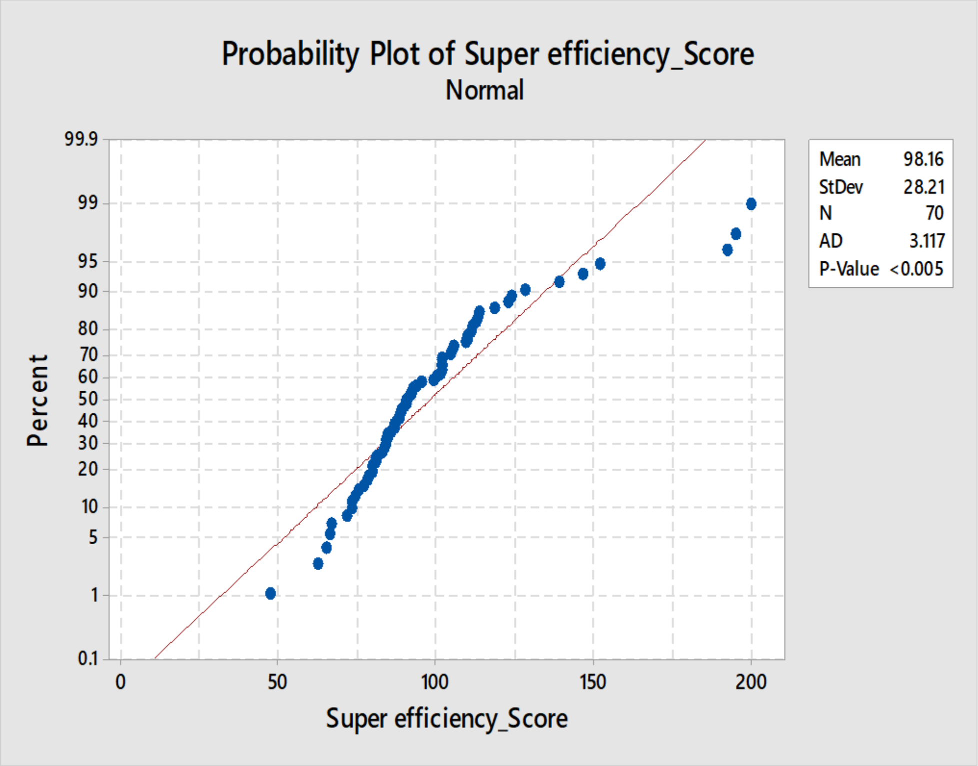

Figure 4:Anderson-Darling test for the Super efficiency model

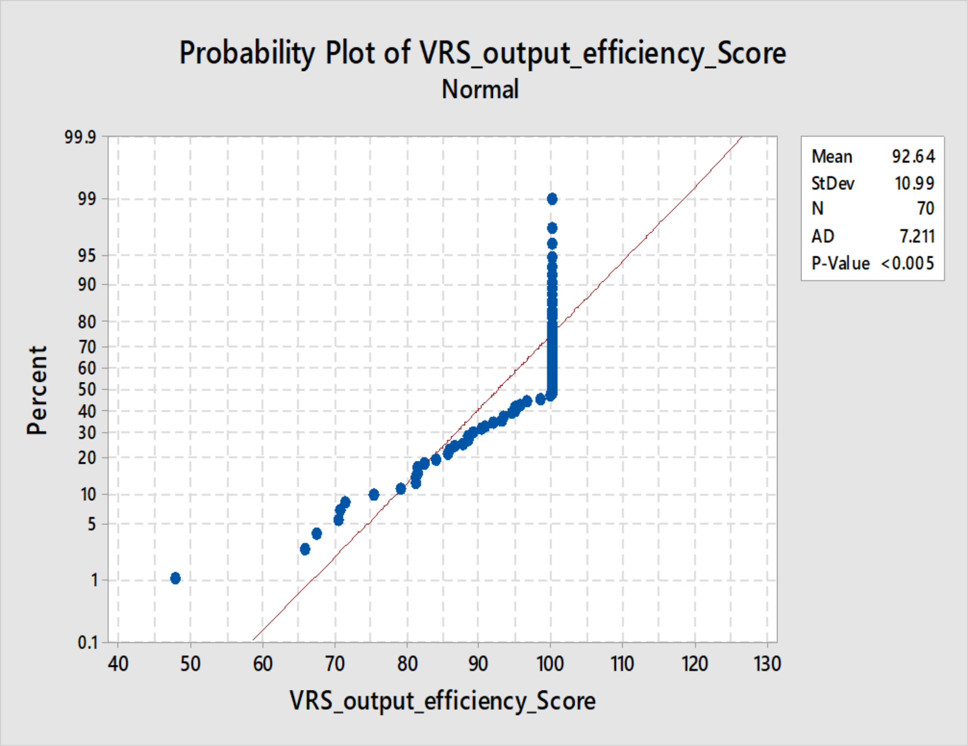

Figure 5: Anderson-Darling test for the VRS output oriented model

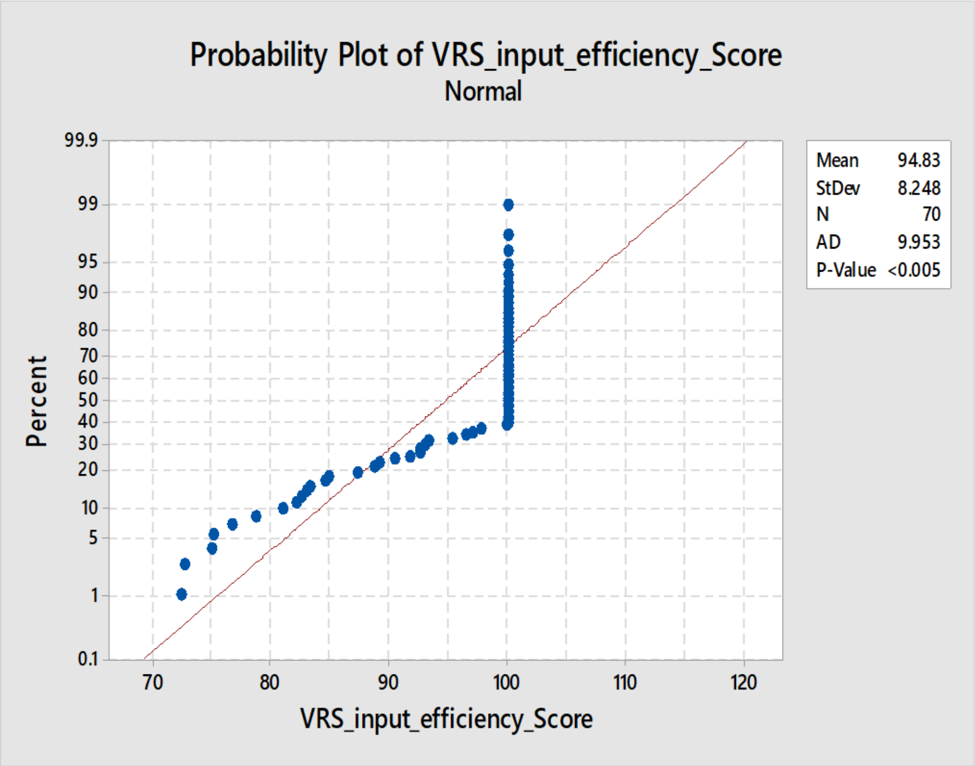

Figure 6:Anderson-Darling test for the VRS input oriented model

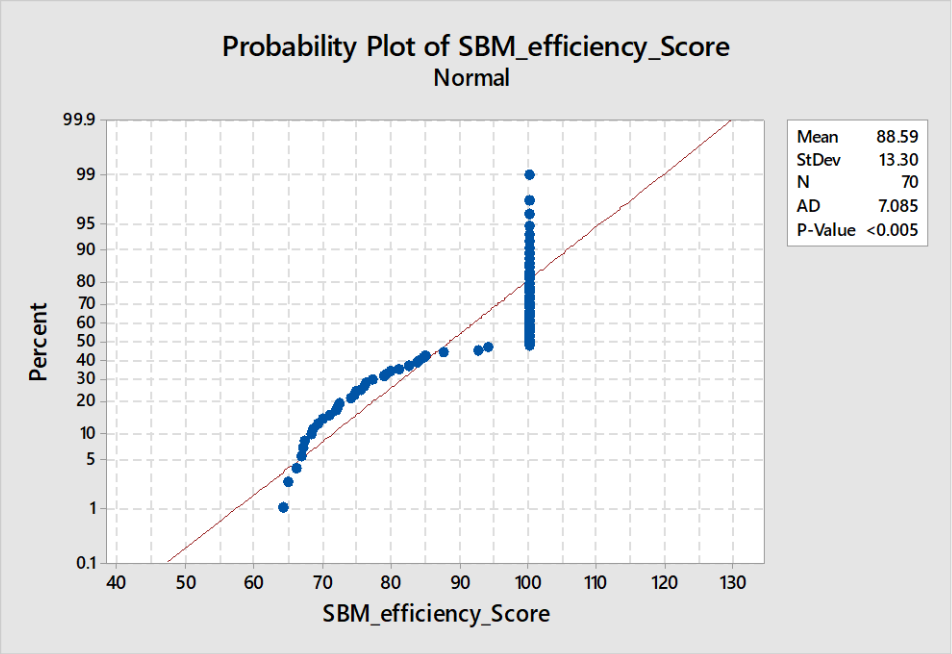

Figure 7: Anderson-Darling test for the SBM model

Country	N	Median	Average rank	Z
Germany-Denmark	26	100	36.5	0.33
Netherlands-Belgium	13	100	32.5	-1.08
UK	31	95.7	32.5	-1.08
Overall	70		35.5	
H=1.75 DF=2 P=0.417 (adjusted for ties)				

Table 4: VRS output oriented model

Country	N	Median	Average rank	Z
Germany-Denmark	26	100	41.7	1.94
Netherlands-Belgium	13	100	38.8	0.64
UK	31	96.99	3229	-2.39
Overall	70		35.5	
H=7.69 DF=2 P=0.021 (adjusted for ties)				

Table 5: VRS input oriented model

Country	N	Median	Average rank	Z
Germany-Denmark	26	96.13	38.7	1.00
Netherlands-Belgium	13	95.16	41.4	1.16
UK	31	84.58	30.4	-1.87
Overall	70			
H=3.67				

DF=2 P=0.16 (adjusted for ties)

Table 6: Super Efficiency results

Country	N	Median	Average rank	Z
Germany-Denmark	26	96.09	40.4	1.54
Netherlands-Belgium	13	95.16	40.6	1.00
UK	31	84.58	29.3	-2.28
Overall	70		35.5	
H=5.56 DF=2 P=0.062 (adjusted for ties)				

Table 7: CRS efficiency results

Country	N	Median	Average rank	Z
Germany-Denmark	26	100	37.7	0.68
Netherlands-Belgium	13	100	40.5	0.97
UK	31	83.71	31.6	-1.42
Overall	70			
H=2.57 DF=2 P=0.276 (adjusted for ties)				

Table 8: SBM efficiency results

The results in Table 5 for the VRS input oriented model reveals that the median efficiency of the UK group is statistically lower compared to that of the other two groups. The results in Tables 4,6,7,8 show that there are no significant differences between the median efficiency scores of the three country groups in the VRS out-put oriented, Super efficiency, CRS and SBM models with p-values of 0.417 , 0.16 , 0.062, 0.276 respectively.

Given the super efficiency results in Table 3, it can be seen the highest ranking offshore wind farms are the Hornsea 1 and the Walney Extension projects located in the UK. Additionally, it is noted that the UK offshore wind farms tend to be larger than their continental counterparts, which may be a factor that could give a potential efficiency advantage. However, DEA is a relative rather than an absolute efficiency measurement technique, and hence concentrates on the level of output achieved (including electricity generated) per unit of input (including turbines and area). This effect could potentially diminish the role of an absolute measure of the size of the wind farm (e.g in GW) when determining efficiency. One possible hypothesis for the median efficiency score of UK being slightly lower than that of the Germany-Denmark group in VRS input oriented model, is found in [60] which gives the location of the component manufacturers for North West European offshore wind farms as principally located in Germany and Denmark, with consequent longer and more complex supply chains to offshore wind farms in the UK. Although proving this hypothesis is beyond the scope of the DEA analysis in this chapter, it is a plausible argument and in line with the DEA results that the longer UK supply chains are causing the slightly lower levels of efficiency at UK offshore wind farms.

2.7 Sensitivity analysis

A sensitivity analysis is conducted to determine the effects of the elimination of inputs $(x_1, \dots, x_4)$and outputs $(y_1, \dots, y_3)$ on the DEA efficiency scores for the CRS, VRS (input and output oriented) and the super efficiency methods. The efficiency scores are reported in Tables 9,10,11,12 where Y = the variable is included, and N=the variable is removed from the model. In each table, in the models 1,2,3 and 4 one of the input variables has been removed, and in models 5,6,7 one of the output variables has been removed at a time.

In all the DEA variants, the average efficiency score of the original model including all the inputs and output variables is higher compared to the other models . This is to be expected as allowing the units more dimensions by which they can gain their efficiency, normally, results in a higher efficiency score, conversely removing a measure can result in a lower efficiency score. The results of the sensitivity analysis shows that all the inputs and outputs, and especially the cost and the water depth have an effect on the efficiency score of the wind farms in all the DEA variants applied in this study.

Criteria	Original model	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
x_1=No. of turbines	Y	N	Y	Y	Y	Y	Y	Y
x_2=Distance to shore	Y	Y	N	Y	Y	Y	Y	Y
x_3=Cost	Y	Y	Y	N	Y	Y	Y	Y
x_4=Area	Y	Y	Y	Y	N	Y	Y	Y
y_1=Electricity production	Y	Y	Y	Y	Y	N	Y	Y
y_2=Connectivity	Y	Y	Y	Y	Y	Y	N	Y
y_3=Water depth	Y	Y	Y	Y	Y	Y	Y	N
Average CRS efficiency score	0.87	0.85	0.85	0.75	0.8	0.74	0.79	0.64

Table 9: Sensitivity analysis for the CRS model

Criteria	Original model	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
x_1=No. of turbines	Y	N	Y	Y	Y	Y	Y	Y
x_2=Distance to shore	Y	Y	N	Y	Y	Y	Y	Y
x_3=Cost	Y	Y	Y	N	Y	Y	Y	Y
x_4=Area	Y	Y	Y	Y	N	Y	Y	Y
y_1=Electricity production	Y	Y	Y	Y	Y	N	Y	Y
y_2=Connectivity	Y	Y	Y	Y	Y	Y	N	Y
y_3=Water depth	Y	Y	Y	Y	Y	Y	Y	N
Average VRS input oriented model efficiency score	94.82	93.54	92.14	88.9	90.71	89.04	93.47	92.62

Table 10: Sensitivity analysis for the VRS-input oriented model

Criteria	Original model	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
x_1=No. of turbines	Y	N	Y	Y	Y	Y	Y	Y

x_2=Distance to shore	Y	Y	N	Y	Y	Y	Y	Y
x_3=Cost	Y	Y	Y	N	Y	Y	Y	Y
x_4=Area	Y	Y	Y	Y	N	Y	Y	Y
y_1=Electricity production	Y	Y	Y	Y	Y	N	Y	Y
y_2=Connectivity	Y	Y	Y	Y	Y	Y	N	Y
y_3=Water depth	Y	Y	Y	Y	Y	Y	Y	N
Average VRS output oriented efficiency score	92.64	91.39	90.96	87.97	88.79	85.51	87.72	87.51

Table 11: Sensitivity analysis for the VRS-output oriented model

Criteria	Original model	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
x_1=No. of turbines	Y	N	Y	Y	Y	Y	Y	Y
x_2=Distance to shore	Y	Y	N	Y	Y	Y	Y	Y
x_3=Cost	Y	Y	Y	N	Y	Y	Y	Y
x_4=Area	Y	Y	Y	Y	N	Y	Y	Y
y_1=Electricity production	Y	Y	Y	Y	Y	N	Y	Y
y_2=Connectivity	Y	Y	Y	Y	Y	Y	N	Y
y_3=Water depth	Y	Y	Y	Y	Y	Y	Y	N
Average super efficiency score	98.16	93.8	92.13	89.5	87.53	84.47	86.22	87.93

Table 12: Sensitivity analysis for the Super efficiency model

2.8 Conclusions

In this chapter the efficiency of 70 offshore wind farms across five north western European countries including Germany, United Kingdom, Netherlands, Belgium and Denmark has been assessed using five different DEA methods including the CCR, BCC (input and output oriented), Slack based measure(SBM) and the super efficiency. This study fills the gap in i) utilising and comparing the different DEA methodologies for the offshore wind sector and interpreting the results on a country level, ii) providing a ranking of the offshore wind farms using the super efficiency DEA method and iii) including a large offshore wind dataset, which could be considered as benchmark for the industry.

This cross European analysis is useful to understand the current state of the industry and shall provide a benchmark for future analysis as well as providing further insight on the factors affecting the efficiency of wind farms as shown by the sensitivity analysis. Further investigation of the properties of the highly efficient wind farms is recommended on a case by case basis in order that the logistical and operational factors where good practice can be replicated are distinguished from non-replicable factors that are specific to those sites.

The slightly higher, although not statistically significant, efficiency and high reference levels of the German wind farms is in part due to the relative input-output basis of the DEA analysis, but also has other potential underlying causes. This chapter highlights one potential cause, the length and complexity of the component supply chains from the German-Danish base to the UK offshore wind farms. This applies to both the construction phases of future and the operational phase of current and future wind farms. At the time of writing, there is significant political uncertainty between the UK and the European Union that may affect future supply chains and hence the efficiency of future UK wind farms. Therefore, it is recommended that this aspect is monitored and mitigated as possible as political developments unfold. The general relationship between length of supply chains and efficiency of offshore wind farms is worthy of further investigation in other geographical regions, particularly where there exists a long distance between the component manufacturing base and the offshore wind farm locations. However, transferal to onshore wind farms is not possible due to the different operating conditions giving rise to some new inputs or outputs and removal of others.

The results of the DEA analysis show that the efficiency score is not evenly spread across the countries, however, the result of the statistical analysis shows that except for the BCC-input oriented model, the median efficiency scores of the wind farms in different groups are not statistically different from one another. The average efficiency score of the offshore wind farms in all the models ranges between 88% to 98%, which signals the high efficiency of this sector.

The offshore wind industry is an attractive and rapidly growing marine renewable energy technology and there is a need to assess the performance of this technology on a broad scale i.e. assessing as many decision making units as possible. This chapter offers a practical and holistic performance assessment to the offshore wind stakeholders and policy makers by including economic, environmental, technical and social inputs and outputs in the analysis.

2.8.1 Limitations and future research

The DEA method is a descriptive analytical technique that allows decision makers to understand the relative level of efficiency of a set of units rather than providing prescriptive decision making suggestions. Although the super efficiency method has provided a ranking for the DMU via further discrimination of the efficient units, but the method is not suggested as a prescriptive analytical tool. The purpose of this chapter is to provide a comparison of the efficiency of the wind farms in different countries and show their relative efficiency. Whilst understanding the relative efficiency of offshore wind values is valuable, future research may focus on employing other descriptive methods, and furthermore providing recommendations on the prescriptive improvement actions to increase the efficiency of inefficient wind farms with other multi-criteria decision making methods.

Part II

Chapter 3

Multi-Criteria decision analysis for the logistics of offshore wind industry [*]

3.1 Introduction

In the previous section, a descriptive analysis on the efficiency of offshore wind farms across Europe provides an understanding of the relative efficiency of the sector and shows that in general the sector has a high efficiency. In this chapter we utilise a prescriptive decision making tool for the assessment of logistics capability of ports to support the construction and operations and maintenance of the wind farms. The North Sea accommodates almost 70% of the total installed capacity of offshore wind farms, followed by the Irish Sea, The Baltic Sea and the Atlantic Ocean. The sea transport of wind turbine

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[*] This Chapter has been published as a journal article and a book chapter in:

61. Akbari, N., et al., *A multi-criteria port suitability assessment for developments in the offshore wind industry*. Renewable Energy, 2017. **102**: p. 118-133.

62. Akbarin, N., et al., *The role of ports in the offshore wind industry* Port Management: Cases in Port Geography, Operations and Policy, ed. S. Pettit and A. Beresford. 2018, London: Kogan Page.

components can take place between any of the bordering countries and the offshore wind project. Ports play a significant role in the development of offshore wind energy and there has been major investments in European ports to expand and diversify their current operations into the offshore renewable energy sector. The ports in the North Sea coast have different capabilities therefore multi-port strategies, in which certain activities take place in different ports with the most suitable facilities are possible.

The current trend of offshore wind farm construction involves the onsite manufacturing or delivery of the components to an installation port where they are assembled and loaded on the installation vessels to be taken offshore. In order to (i) accelerate the expensive offshore installation, (ii) effectively use the limited weather windows, and (iii) reduce the number of required offshore lifts, construction companies tend to minimise the work done offshore by assembling as much of the turbine onshore (at ports) as possible [63].

For the operations and maintenance (O&M) phase, the ports serve as a base from which the offshore wind farms are routinely serviced. Different requirements are placed on the ports' technical and logistical capabilities based on the role that the port plays in the installation and O&M phases of the offshore wind farm [64]. These requirements are numerous and include different criteria. For instance, installation ports preferably must be deep sea ports with a large land area sufficient for the storage and assembly of offshore wind components, whereas O&M ports must be located preferably within 200 km of the site in order to provide a fast and reliable service to the wind farm [65] & [66].

Therefore, it is envisaged that a port's suitability can have an impact on the offshore wind farm's project cost, since a suitable port that optimally meets the requirements can facilitate the installation and O&M process whereas a sub-optimal port will incur extra costs and/or delays for the developers. Given the remarkable growth in the offshore wind industry, suitable ports and onshore infrastructure are in demand in order to meet the future capacity targets of the industry [67] [64].

3.2 Contributions

The principal objective in this chapter is to address the following questions:

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

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

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

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

As the offshore wind industry expands in Europe and worldwide, the ports and onshore bases become strategic hubs in the supply chain from which all the operations of the wind farms are supported. Therefore, the selection of logistically suitable ports, for supporting this operation becomes an important issue. Given the relative immaturity of the offshore wind industry, there is a dearth in the scientific literature concerning decision support models for port selection.

In this chapter, a detailed overview of the most critical logistical criteria for offshore wind ports is provided. Using pairwise comparisons of the criteria, a multi-criteria decision support model for port selection in the offshore wind sector by adopting the analytical hierarchy process (AHP) methodology is developed. The port selection model can be viewed as a generic model and is applicable for the suitability assessment of ports for any offshore wind project.

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

3.3 Literature Review

This section presents an overview of the application of Multi-criteria decision making (MCDM) in the offshore wind industry as well as a literature review on container port selection using MCDM. Although container ports differ from the offshore wind ports, there may be some commonality in methodology that could be exploited.

3.3.1 MCDM in the offshore wind industry

Scholars have used MCDM for a variety of problems in the offshore wind sector. Lozano-Miguez *et al.* [68] propose a method for the systematic assessment of the selection of the most preferable support structures for offshore wind turbines. The approach uses the TOPSIS multi-criteria decision-making method (Technique for Order Preference by Similarity to Ideal Solution) for the benchmarking of candidate options. In this study, a monopile, a tripod and a jacket for a reference 5.5 MW wind turbine and a reference depth of 40 metres are compared by taking into account multiple engineering, economic and environmental attributes.

Fetanat *et al.* [69] propose a hybrid multi-criteria decision approach for offshore wind farm site selection based on the fuzzy Analytic Network Process (FANP), fuzzy decision-making trail, evaluation laboratory and fuzzy ELECTRE (Elimination and Choice Expressing Reality). This paper aims to find the best site selection of an offshore wind farm in Bandar Deylam, located in the southwest of Iran. There are six criteria considered which are the depth and height, environmental issues, proximity to facilities, economic aspects, technical resources and levels, and culture.

Jones and Wall [70] implement an extended goal-programming model for demonstrating the multi-criteria, multi-stakeholder nature of decision-making in the field of offshore wind farm site selection based on the United Kingdom future round three sites. Moreover, they discuss the strategic importance of offshore shore wind farms and the use of multi-objective modelling methodologies for the offshore wind farm sector.

Shafiee [71] studies a FANP model for selecting the most appropriate strategy for mitigating the risk associated with offshore wind farms. The model comprises four criteria/attributes namely safety, added value, cost and feasibility. The model is applied to select a suitable risk mitigation strategy with four possible alternatives (variation of the offshore site layout, improvement of maintenance services, upgrading the monitoring systems, and modification in design of the wind turbines) for an offshore wind farm consisting of thirty 2MW wind turbines.

The logistics of offshore renewable energies (wind, wave and tidal) have been considered in the literature as well. MacDougall [72] considers the uncertainty related to infrastructure and supply chains as well as government policy, financing and environmental impacts as factors causing delays in tidal energy developments in the Bay of Fundy, Canada. It is suggested that for development of this industry, such uncertainties must be reduced via investments in infrastructure and governmental support.

Cradden *et al.* [65] conduct a multi-criteria site selection for combined offshore wind and wave platforms considering two selection criteria groups. The primary selection criteria includes minimum wind speed, minimum wave power density, depth range and minimum distance to shore. The secondary criteria group includes logistics, shipping traffic, electricity networks and environmental protection. Their analysis shows that sites in the north-west, off the coasts of Scotland and Ireland, appear to be the most favourable for the combined platform, however logistics issues related to the ports for construction and O&M of such platforms could be significant limiting factors. For example, when considering potential construction ports (with a draft of 9.4m and a large shipyard) within 200km distance of suitable sites, 70-90% of potential sites for such platforms are eliminated due to the unsuitability of the ports in that area.

3.3.2 Container port selection

In the container port selection literature, the use of MCDM is widely recognised and therefore the literature analysis is conducted in this domain to find transferable commonalities with the offshore wind sector. Ugboma *et al.* [73] use AHP to determine the service characteristics that shippers consider important when selecting a container port. The results of their study suggest that shippers place a high importance on efficiency, frequency of ship visits and adequate infrastructure while quick response to port users' needs was less significant to them. Port managers were interested in the results since the study provided essential information on the key factors that port users consider in their decision-making processes.

Based on the combined importance of quality of infrastructure, cost, service and geographical location, Guy&Urli [74] study whether the accepted rationale of port selection by shipping lines can effectively assess the selection behaviour observed in the Northeast of North America, in particular given the recent arrival of new global carriers in Montreal. They combine a multi-criteria approach with scenarios where the relative significance given to selection criteria and the performance of ports are both varied across a wide range. This approach enables the authors to assess how changes in both the criteria weight (expressing selection rationale) and evaluation (expressing relative port performance) affects port preference. Based on the common selection rationale, their findings suggest that New York is the preferred choice for shipping lines, however if the selection criteria change, then the preferred port also changes from New York to Montreal.

Chou [75] uses a fuzzy MCDM method for tackling the marine transhipment container port selection, applying the method to a number of ports in Taiwan. His findings suggest that when choosing a port, decision makers are more concerned about the volume of import/export/ transhipment containers than cost, port efficiency, port's physical attributes and port's location respectively. He recommends the port managers to increase the volume of import/export/transhipment containers and reduce their charges to be become a more attractive choice. Lee *et al.* [76] implements the AHP and proposes a decision support system (DSS) for port selection in container shipping, considering the three criteria of port infrastructure, port charge and container traffic. Their model enables port managers to obtain a detailed understanding of the criteria and address the port selection problem utilising multi criteria analysis.

Zavadskas Kazimieras *et al.* [77] investigate the combination of AHP and fuzzy ratio assessment to tackle the issue of finding a deep water sea port in the Klaipeda region in Baltic Sea in order to satisfy economic needs. Asgari *et al.* [78] study the sustainability performance of five major UK ports. The AHP method is implemented in order to rank the ports using the collected data based on a set of economic and environmental criteria. Sensitivity analysis on the obtained data is also presented in order to verify the consistency of the outcomes. In Table 13, a list of studies in which MCDM methods have been used for the port selection problem is presented. This survey shows that AHP is one of the most common methodologies in this area.

3.3.3 Analysis of Literature

After reviewing the literature, it becomes apparent that much of the work related to the use of MCDM methods in the offshore wind is related to offshore wind site selection. Furthermore, although MCDM has been applied to different container port selection models, it has not been used to date in the context of offshore wind port selection; therefore a gap is identified in the literature related to the assessment of onshore infrastructure and port suitability for the offshore wind industry. In this study, the use of AHP as a multi-criteria decision making model for the assessment of port suitability is proposed. The AHP has been applied in a various decision making scenarios including prioritisation/evaluation, choice, resource allocation, benchmarking of processes, and quality management [79]. Its ease of use for preferential information elicitation from subject experts has made it amongst the most widely used MCDM techniques.

Among the advantages of AHP is that it structures the criteria into a hierarchy allowing for a better focus when allocating the weights. Also, the pairwise comparison of the criteria allows the decision maker to consider just two criteria simultaneously, which is argued to be an easier and more accurate way to express one’s opinion rather than simultaneous assessment of all the criteria [80]. Another strength of the method is that it is able to evaluate quantitative and qualitative criteria on the same preference scale. Furthermore, the AHP provides a measure of consistency of decision making that is lacking in some of its competitor techniques [80].

Despite the wide application of AHP in various domains, the method has been subject to criticism. Perhaps the most debated of them is the rank reversal problem first appeared in the work of Belton and Gear [81]. In many instances, the rankings of alternatives obtained by the AHP may change when a new alternative is added. Also, the preference scale and the absence of zero in the scale has been criticized by [82] & [83]. However, with reference to the key criteria of ease of usage by the decision maker, proven decision support ability in the maritime sector, and the measurement of consistency outlined above, the AHP is chosen as the most suitable methodology to capture and analyse expert opinion in this chapter.

Author	Article	Methodology
Lirn *et al*. [84]	An Application of AHP on transhipment Port Selection: A Global Perspective	AHP
Ugboma *et al*. [73]	An Analytical Hierarchy Process (AHP) Approach to Port Selection Decisions-Empirical evidence from Nigerian ports	AHP
Guy and Urli [74].	Port Selection and multi-criteria analysis: An application to the Montreal-New York alternative	AHP
Chou. [75]	A fuzzy MCDM method for solving marine transhipment container port selection problems	Fuzzy-MCDM
Chou. [85]	AHP model for the container port choice in the multiple-ports region	AHP
Onut *et al*. [86]	Selecting container port via fuzzy ANP-based approach: A case study in the Marmara Region	Fuzzy-ANP
Ka [87]	Application of fuzzy AHP and ELECTRE to China dry port location selection	Fuzzy AHP and ELECTRE
Lee and Dai.[76]	A decision support system for port selection	AHP
Wang *et al*. [88]	Selecting a cruise port of call location using the fuzzy-AHP method: a case study in East ASIA	Fuzzy AHP
Zavadskas Kazimieras *et al*. [77]	Multi-criteria selection of a deep water-port in the Eastern Baltic Sea	Fuzzy-AHP
Sayareh and Rezaee Alizmini [89]	A hybrid decision-making model for selecting container seaport in the Persian Gulf	TOPSIS and AHP

Table 13: Summary of the literature

3.4 Methodology

Decision makers frequently have to make decisions in the presence of multiple, conflicting criteria [90]. In order to evaluate these choices and to make the best decision, scholars in the area of decision sciences offer several methodologies including MCDM. MCDM includes methods such as, the AHP, ANP, Fuzzy set theory based decision making, Goal Programming, ELECTRE, and Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE). MCDM has seen a significant amount of use over the last several decades and its role in different applications has increased significantly, especially as new methods develop and old ones improve[91] .

In the remainder of this section, a description of MCDM methods, and the main steps of formulating this research is provided.

3.4.1 MCDM

MCDM comprises of a set of methods for making choices in the presence of a set of relevant criteria. These methods can be classified into two different categories namely multi-objective decision-making (MODM) and multi-attribute decision-making (MADM)[92] . MODM problems involve finding the best from a large (potentially infinite) number of potential solutions given a set of conflicting objectives.

For example, offshore wind developers may wish to minimize the turbine installation time while minimizing the installation cost at the same time. These two objectives may conflict, hence a multi-objective decision making method is proposed to find the optimal solution [93]. For example in Northern Europe, to minimise the installation cost, the installation of the turbines has to wait until the Summer when the weather is relatively calm, otherwise in Autumn or Spring the installation time of a turbine will incur more disruption due to variable weather conditions which results in an increased installation cost. Multiple Attribute Decision-making (MADM) refers to making preference decisions (e.g., evaluation, prioritization, selection) over a discrete set of available alternatives that are characterized by multiple, usually conflicting, attributes [94]. Methodologies such as AHP, ANP, TOPSIS, ELECTRE, and PROMETHEE are classified under this category. MADM ranks alternatives based on a set of discrete criteria and produces discrete solutions [95].

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

$$\text{Optimize} \qquad Z_i = f(x_1, x_2, \dots, x_n) \quad \forall i = 1, \dots, k \tag{22}$$

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

$$Z = \sum_{i=1}^{k} w_i Z_i \tag{23}$$

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

3.4.2 AHP

In order to identify the most suitable ports for each phase of the offshore wind farm, the AHP methodology is applied. The AHP introduced by Saaty is a theory of measurement through pairwise comparison that relies on the judgements of experts in order to derive priority scales [96]. These comparisons may be taken from actual measurements or from a fundamental scale, which reflects the relative strength of preferences and feelings. The decision problem is structured in a hierarchical form with the goal of the decision at the top level, followed by the factors affecting the decision in gradual steps from the general, at the upper levels of the hierarchy, to the particular at the lower levels. When constructing hierarchies, enough detail to represent the problem as thoroughly as possible must be included. However, it is important not to include so many details that the sensitivity of the model to variation of the elements is negatively impacted. Although in practice it is difficult for researchers to clearly justify their choice of one method over the other [97], the AHP has been selected because of its practicality, ability to provide a framework for group participation in decision-making or problem solving, ease of use for stakeholders, and successful track record of use for analysing similar problems (Table 13). While in outranking methods such as ELECTRE, the process and outcome can be difficult to explain in layman's terms [91] , the AHP's output is easily understood and makes intuitive sense [98]. Furthermore, whilst some MCDM methods such as PROMETHEE do not provide a clear method by which to assign weights, the AHP clearly addresses the process[91] . Furthermore, AHP has gained remarkable success as decision making tool and it shows flexibility in dealing with both the qualitative and quantitative factors of a multi-criteria evaluation problem [99].

The main steps of this research are as follows:

a. Identify the main objective:

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

b. Identify criteria/attributes:

A set of criteria/attributes along with their sub-criteria related to port selection for the installation and O&M phases need to be determined. Interviews with offshore wind developers, stakeholders and port authorities were conducted to elaborate the criteria.

c. Score the weight of each criterion:

The experts compare criteria i with j in the corresponding level with respect to the goal, and calibrate them on the numerical scale (Table 14). This requires $n(n-1)/2$ comparisons for each criteria level given the consideration that diagonal elements are equal or 1, and the other elements are the reciprocals of the earlier comparisons [100]. A matrix is then formed for each criteria level using these comparisons, denoted as matrix A where a_{ij} is the comparison between criteria i and j.

$$A = \begin{bmatrix} 1 & a_{ij} & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & 1 \end{bmatrix} \tag{24}$$

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 14: Saaty's numerical scale

d. Calculate the weight of criteria

The largest eigenvalue problem is then solved to find the unique normalized vector of weights that reflect the relative importance of the attributes in each level of the hierarchy. The normalized weights of all hierarchy levels are then combined in order to determine the unique normalized weights corresponding to the final level. These relative weights are then used to accomplish the stated objective of the problem [101].

e. Determine the consistency of the judgements

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

$$CR = \frac{CI}{RI} \tag{25}$$

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

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{26}$$

Where λ_{max} is the largest eigenvalue of the matrix A and n is the dimension of the matrix. RI is the random index (i.e. the average CI of 500 randomly filled matrices). Other researchers have run simulations with different number of matrices [102]. Their derived RIs are different but close to that of Saaty's [80]. Saaty [103] has provided average consistencies (RI values) of randomly generated matrices (up to size of 11×11) for a sample size of 500. In general, a CR value of 10% or less is acceptable [103].

f. Select a set of potential alternatives:

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

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

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

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

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

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

In this section, hierarchical structures for the port selection model are developed which include the criteria and sub-criteria for the installation and O&M ports. The weight of each criterion and sub-criterion is also derived based on the experts' judgements who were chosen from different organisations related to offshore wind port logistics. The AHP hierarchies were sent to the experts electronically and they were asked to give their opinion on the suitability and the relevance of the criteria that was chosen for the installation and O&M ports. Furthermore, the AHP method and how it should be used to give scores was described to them. The experts were given two weeks to respond to the questionnaires. The response times were variable; expert 5 completed the questionnaire within a day, experts 2, 3 and 4 completed the questionnaires within 2 days, and expert 1 returned the completed the questionnaire within 6 days. The information regarding the experts, and the questionnaires are presented in Table 15 and the appendix.

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

Table 15: Experts' information

3.6 Hierarchy structures for the port selection model

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

For each phase of the offshore wind lifecycle a separate hierarchy was developed, as each phase requires different criteria within the port and also because even the common criteria could have different weights depending on the type of operations carried out in that port. For both phases of installation and O&M, three groups of criteria were identified:

Port's physical characteristics, including:

a. **Port's depth**: this parameter relates to the ability of the port to accommodate large vessels with deep drafts. Most of the offshore wind construction and O&M vessels have a draft of over 8 meters. Therefore, suitable ports must have adequate depth for such vessels. For the O&M phase, small workboats may also be used with a shallow draft. In addition, the port's depth is an important consideration for the manufacture of substructures such as the Gravity Based Foundations (GBFs) at the port. For example for the manufacture of a GBF for a water depth of 25m, the port depth should be a minimum of 7.5m [104].

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

c. **Quay loadbearing capacity**: the bearing capacity is defined as the ability of the ground surface to support the weight of a specific component. The soil bearing capacity is the maximum bearing pressure that soil can support before failure occurs. A ground bearing capacity of 15 - 20 tonnes /m^2 is identified as suitable by the industry [64] [105].

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

e. **Component handling equipment** (Ro-Ro, Lo-Lo, heavy lifting equipment i.e. cranes): ports need to have sufficient equipment to handle components such as nacelles, blades and towers. While some of these components are loaded using lift-on lift-off (Lo-Lo) or roll on-roll off (Ro-Ro) type of vessels, the availability of heavy lifting cranes is also needed at the ports [105].

Port's connectivity, including:

a. **Distance from the wind farm**: this parameter is associated with the distance from the port to the given wind farm, since it has a direct effect on the time and cost of the installation and O&M phases.
b. **Distance from the key component suppliers**: large offshore wind components have to be taken from their place of manufacture to the installation ports, where they are stored or assembled prior to offshore installation. Furthermore, fixed offshore wind foundations such as the Gravity Base Foundations are preferably fabricated at the ports, and floating offshore wind platforms, can be built at large shipyards [65]. The Port's distance from the manufacturers' and suppliers could affect the cost of transportation.
c. **Distance from road networks**: for transportation of some of the turbine components, the ports must have access to road networks. Components such as blades have been transported via roads from their place of manufacture in some offshore wind projects. Vehicles such as trucks, SMPTs and low-loader trailers are used for transporting the components and subassemblies [106]. For a reference turbine of 3MW, the road running lane width on straight roads must be a minimum of 5.5 m. The horizontal clearance around the access and site roads must be increased from 5.5m to 11m when a crawler crane is used.
d. **Distance from heliports**: This parameter is considered only for the O&M phase. Helicopters are used to service the turbines during certain types of

inclement weather conditions as they provide fast access compared to the workboat solution [107].

Port's layout, including:

a. **Storage space availability**: components delivered to the port need to be stored for later assembly. In order to support the routine inventory at the port, a large storage area is required. The port's layout should be in a way that the storage area is in direct connection with the pier front area in order not to transport the components too far or for too long during storage, preassembly or loading [108] . The storage area criteria also includes the sub-criteria of open storage area, covered storage area and storage load bearing capacity.

b. **Component manufacturing facility availability**: this parameter is considered only for the installation ports. In order to reduce the component transportation cost, and avoid multiple loading/unloading, locating turbine manufacturing facilities at the installation ports is proposed where the components can be shipped to the site directly from the ports. Some existing European ports including Bremerhaven and Cuxhaven in Germany have adopted this strategy and they have established turbine manufacturing facilities located at the port. This is also taking place at a number of the UK ports such as the Greenport Hull project, which are in the development stage of building turbine manufacturing facilities within the port [109].

c. **Component laydown (staging) area availability**: this parameter is considered only for the installation ports. This area is particularly important at installation ports, since some components that are delivered to the port need to be assembled prior to the installation phase, e.g. towers could be delivered to port in two pieces, but they might be assembled and loaded on the installation vessel as one single piece. This criterion includes the sub-criteria of lay down area and laydown's area access to quayside.

d. **Workshop area**: This parameter is considered only for the O&M ports. The workshop area is the area in the O&M ports in which repairing of broken or faulty components take place.
e. **Office facilities**: This parameter is considered only for the O&M ports. Office facilities must be available at O&M ports, since these ports are responsible for daily operations and maintenance activities of the wind farm and the human resource and control rooms are based at the O&M ports.
f. **Potential for expansion**: selecting and investing in a port facility is a long term strategic decision for offshore wind developers and ports that offer the potential for expansion are considered more desirable as opposed to ports with restricted growth potential.

Figure 8 presents the hierarchy structures for the installation port. The model consists of 3 levels where

a. Level 1 includes three criteria namely the port’s physical characteristics, the port’s connectivity, and the port’s layout.
b. Level 2 is divided into three levels (Level 2A, Level 2B, and Level 2C). Level 2A contains the sub-criteria of port’s physical characteristics including quay length, port depth, seabed suitability, quay load bearing capacity, and component handling equipment. Level 2B contains the sub-criteria of port’s connectivity, which comprises of the distance from wind farm, distance from road networks, and distance from key component supplier and level 2C comprises of the sub-criteria of port’s layout, which consists of storage area, manufacturing facility, component laydown area, and potential for expansion.
c. Level 3 is divided into three levels (Level 3A, 3B and 3C). Level 3A comprises of the sub-criteria of component handling equipment and comprises Ro-Ro, Lo-Lo, and heavy cranes. Level 3B comprises of the sub-criteria of storage area, which includes covered storage, open storage, and storage load bearing capacity. Level 3C comprises of the sub-criteria

of laydown area availability and includes the sub-criteria of laydown area and laydown area’s access to quayside.

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

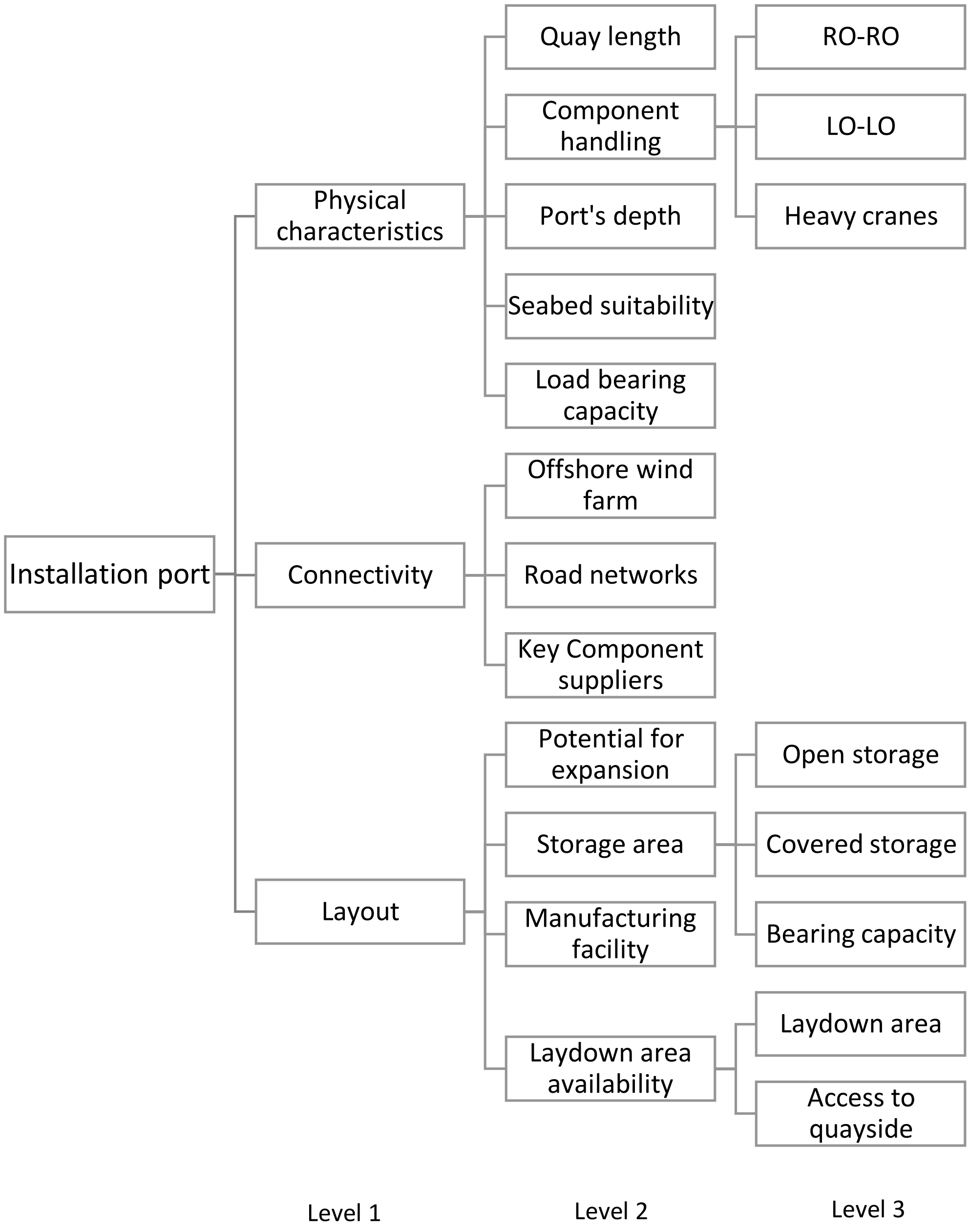


Figure 8: Hierarchical structure for Installation port

Figure 9 shows the hierarchical structures for the O&M port. The hierarchical structures for an O&M port are similar to those for installation port except that there are additional criteria in some levels. In Level 2B, a sub-criterion, distance from heli-ports, is added and Level 2C now includes storage area, workshop area, office facilities and potential for expansion. In the case study, four O&M ports are assessed which either have been involved in servicing the offshore wind farms or offer their services to the sector. These ports include Port of Lowestoft involved in Greater Gabbard project; Port of Ramsgate, involved in Thanet, Kentish Flats Extensions, and London Array projects; Grimsby-ABP involved in Humber Gateway project; and Port of Sheerness, which offers development land for offshore wind use.

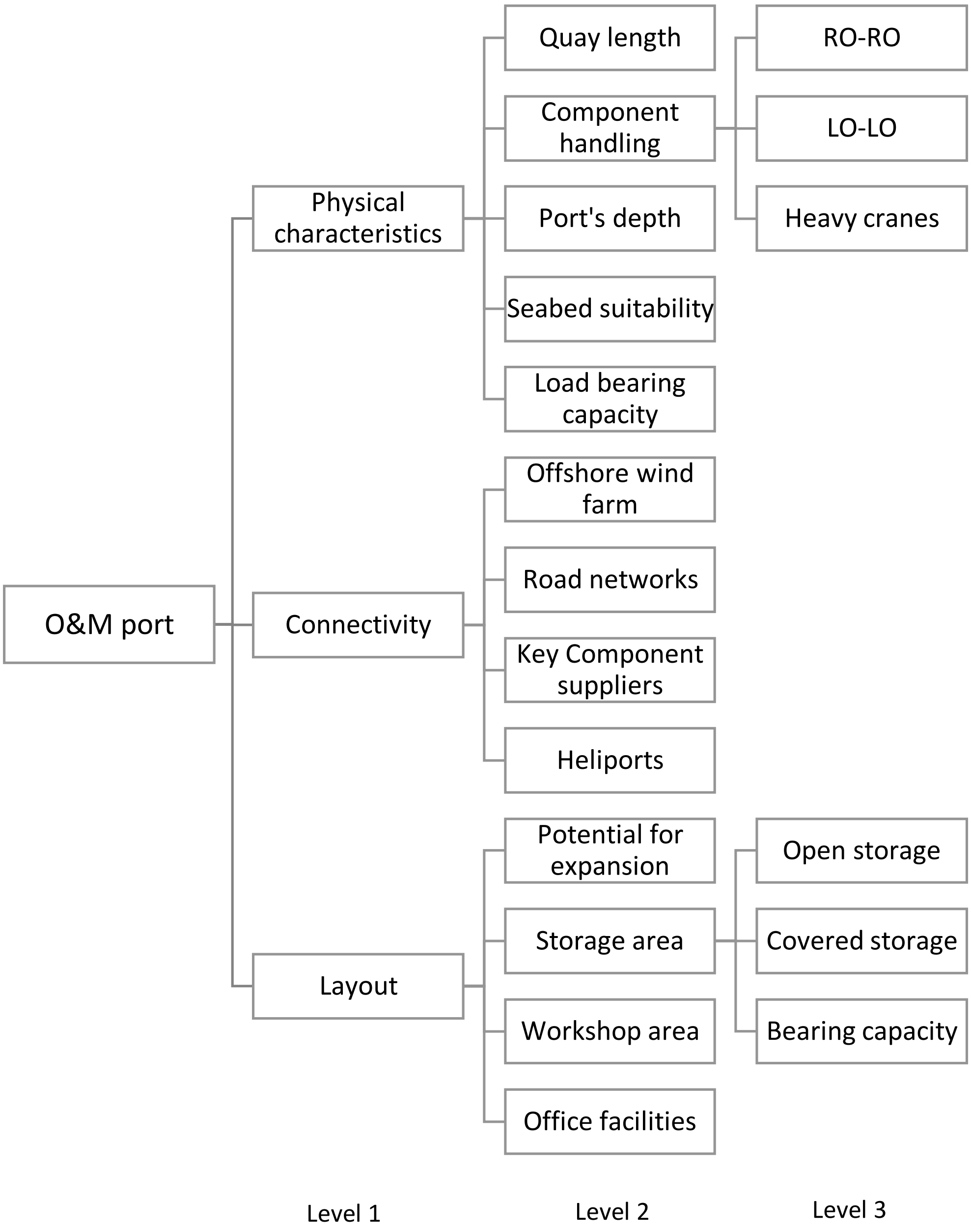


Figure 9: Hierarchical structure for O&M port

3.6.1 The weight of the port criteria

In this subsection, the weight of port criteria based on the judgement of the experts are presented. The pairwise comparison of the port criteria is used to calculate the weight based. The AHP can be effectively applied within a group, where sharing opinions and insight often results in a more complete representation and understanding of the problem, which may not be fully attained when involving a single decision maker [103]. The use of questionnaires has also been suggested as a means of taking individual opinion, the method that is used for this study. For this study, five respondents are chosen, all of which holding senior positions in their respective organisations. The experts are chosen from a range of industries including offshore wind port management, renewable energy consulting, offshore wind O&M consulting, offshore wind turbine manufacturing, and offshore wind farm development (including installation and O&M). In order to conduct the pairwise comparison of criteria, a questionnaire containing all the pairwise comparisons were sent to all five experts. The experts were asked to conduct the pairwise comparisons and give a score based on the values in Table 14. The final values of the questionnaires are derived from the geometric mean of the judgements, e.g. the geometric mean of 1,3,9 is 3; meaning that the first criterion is weakly more important than the second one, according to the AHP comparison scale (Table 14). Adopting the geometric mean method is recommended [110] and based on the scale provided in Table 13, the value 1 implies the equal importance of criteria i and j, and 9 implies extreme preference of criteria i against criteria j. All the values in between are equally spread between these two extremes. Based on the AHP review paper by [80], the 1-9 scale is based on psychological observations by Stevens [111] and its use by far dominates all the other scaling methods. The choice of "best" scale however is a debated topic among scientists, and other scales such as quadratic and root square scale [112] , geometric scale [113], balanced scale where the local weights are evenly dispersed over the weight range(0.1,0.9) [114] have been proposed in the literature.

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

3.6.1.1 Installation port

In most offshore wind projects, the components cannot be directly shipped from the manufacturing facility to the offshore site. Instead, they are first delivered to an installation port where the components are pre-assembled and stored, before loading onto the vessel and transferral to the offshore wind farm site [109]. 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 [115] Therefore, the installation ports play a key role in the development of offshore wind farms. Table 16 shows the obtained weight of the criteria for an installation port.

Criteria			**Weight**		
Port's physical characteristics			0.483		
	Seabed suitability			0.201	
	Component handling			0.130	
		Lo-Lo capability			0.596
		Ro-Ro capability			0.102
		Heavy cranes			0.302

	Quay length			0.145	
	Quay load bearing capacity			0.287	
	Port's depth			0.236	
Port’s Connectivity			0.275		
	Distance to offshore site			0.706	
	Distance to key component supplier			0.186	
	Distance to road			0.109	
Port’s layout			0.242		
	Potential for expansion			0.257	
	Component laydown area			0.334	
		Component laydown area			0.654
		Laydown area access to quay side			0.346
	Storage			0.289	
		Storage load bearing capacity			0.599
		Open storage area			0.300
		Covered storage area			0.101
	Component fabrication facility			0.121	

Table 16: Criteria weight for installation port

The values in Table 16 suggest that for an installation port the port’s physical characteristics with weight 0.483 are more important than the port’s connectivity (0.275) and the port’s layout (0.242). For the port’s physical characteristics, quay load bearing capacity is the most important sub-criterion, having a score of 0.287. The distance to the offshore site and the component laydown area availability are found to be the most important factors for the port’s connectivity and port’s layout criterion respectively.

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

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

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

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

Table 17 shows the consistency ratio (CR) of each criteria level of the installation port. On average, the CR value is within the limits suggested by Saaty [103] which is 10%. However, in Level 1, it is above the recommended limit, although not at a level that invalidates the analysis. Table 18 and Figure 10 present the final weight of each sub-criterion. The additive value function approach has been assumed to derive the final priority weights reported in Table 18 and 21. The most significant sub-criterion is the port's distance from the offshore site (0.193). This result suggests that the port's distance to the wind farm is a significant factor in the decision-making process, since the ports located closer to the wind farm allow weather windows to be exploited more efficiently and the transportation time and cost will hence be reduced. Ro-Ro capability in the ports has been ranked the least significant factor and this could be due to the fact that in the installation process, typically heavy lifting vessels (HLV) are used. The bar charts in Figures 10 and 11 provide a clear visual representation of the ratio of the weight values in Tables 18 and 21.

Level	Consistency Ratio (%)
1	16.3
2A	1.7
2B	0.2
2C	2.1
3A	7.7

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

Table 17: Consistency ratio of each criteria level for installation port

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

Table 18: Final weight of the sub-criteria for installation port

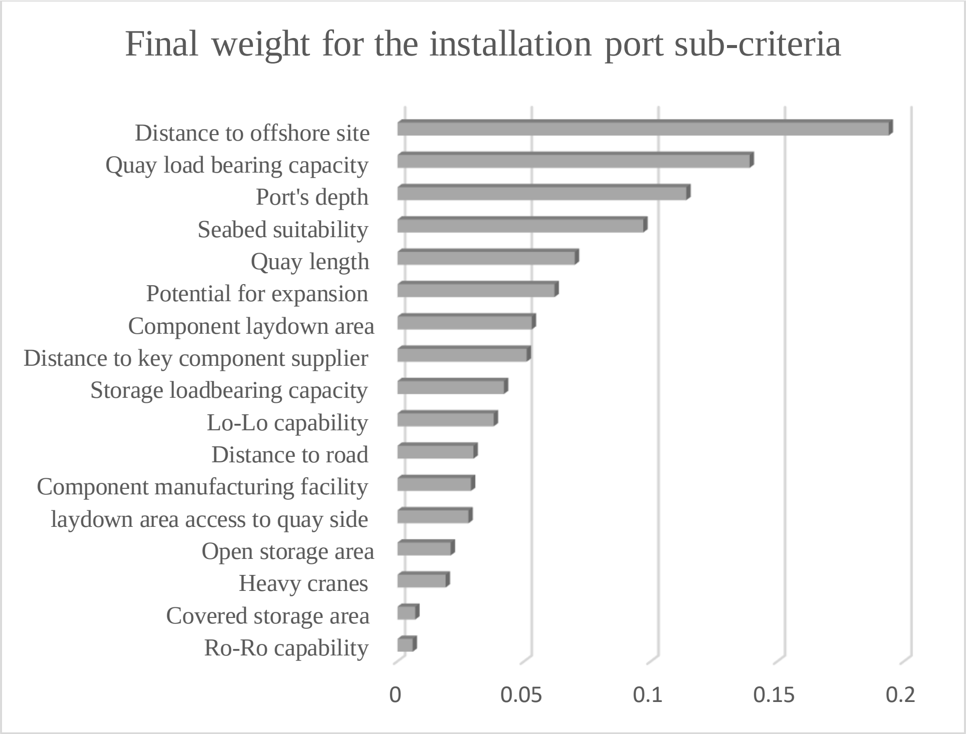


Figure 10: Final weight for the installation port sub-criteria

3.6.1.2 Operations and maintenance (O&M) port

Operations and maintenance of the wind farm is the longest of all the phases as the wind farm needs servicing during its entire design life. Developers normally look for ports that are willing to commit to this long period and provide regular service to the wind farm. Operations consists of activities such as remote monitoring, control, electricity sales, coordination, and back office administration of the wind farm operations which represents a small share of O&M expenditure. On the other hand, maintenance activities including the upkeep and repair of the physical plant and system has the largest share in the overall cost, risk and effort of the O&M phase [107]. Table 19 shows the weight of the criteria for an O&M port. For the O&M port, the port's connectivity was ranked the highest in terms of significance, followed by the port's physical characteristics and lastly the port's layout.

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

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

	Potential for expansion		0.145	
	Office facilities		0.339	

Table 19: O&M port criteria weight

In the port’s physical characteristics category, the port’s quay load bearing capacity was ranked the most important, followed by the component handling capabilities, quay length, port’s depth, and seabed suitability for jack-up vessels. In the port’s connectivity category, the port’s distance to the wind farm was ranked significantly higher than the port’s distance to a heliport, distance to key component suppliers and distance to road network, which are the second, third and fourth respectively in terms of importance. For the port’s layout category, the availability of office facilities was ranked the highest, followed by the storage capacity, workshop area for component repair and potential expansion opportunities at the port. In level 3B, the covered storage area ranked the highest followed by the open storage area and the load bearing capacity.

Table 20 presents the consistency ratio (CR) value of each criteria level for an O&M port which is within the recommended limit. Table 21 and Figure 11 provide the final weight of each sub-criterion for the O&M port.

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

Table 20: Consistency ratio of each criteria level for O&M port

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

Table 21: Final weight of the sub-criteria for O&M port

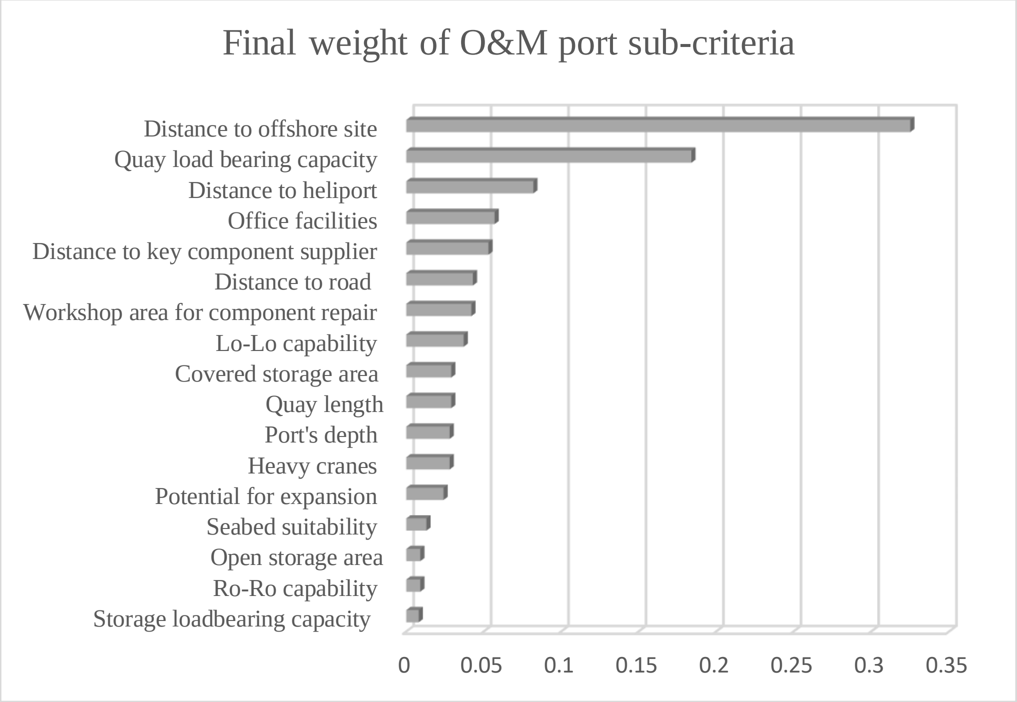


Figure 11: Final weight for the O&M port sub-criteria

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

3.7 Case application

Figure 12 shows the offshore wind farms located the UK waters that are either in the pre-planning stage, consented, under construction, constructed or in operation. As shown, there is a high concentration of wind farms in the southern part of the North Sea.

3.7.1 Problem definition

For this case application, we define the problem as the decision maker’s choice of selecting the most suitable port for a specific offshore wind farm, namely the West Gabbard wind farm located in southern part of the North Sea (details of the wind farm are presented in Table 22). For this example, as shown in Figure 13 the candidate ports for the installation phase include the port of Oostende, Harwich Navyard port, the port of Great Yarmouth, the port of Hull-ABP and ABLE UK-Humber port. The candidate ports for the O&M phase include the port of Sheerness, the port of Lowestoft, the port of Grimsby and the port of Ramsgate. The application of the methodology developed in previous section aids the decision maker to select the most suitable port from a number of ports with potentially similar attributes.

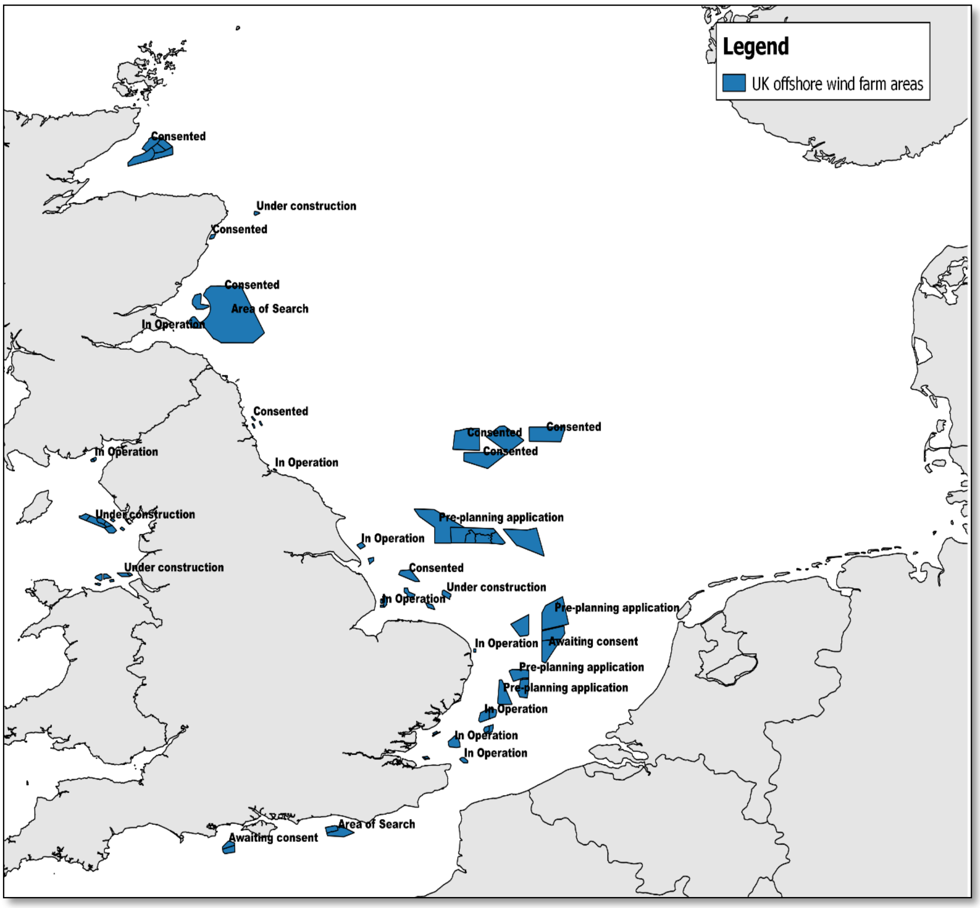


Figure 12: Map of UK offshore wind farms[61]

3.7.1.1 Data

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

a. The port's proximity to the site: All the ports selected for this example are within 300 km from the offshore wind farm based on the expert opinions and Cradden, et al. [65] , and Furthermore,

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

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

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

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

e. For normalising the data the unity-based normalisation has been used to bring all the values in the range [0,1].such that:

$$X = \frac{X - x_{min}}{x_{max} - x_{min}}$$

Figure 13 shows the location of wind farm site and the potential ports (both the installation and O&M ports) which are selected in this study. The data for the ports related to the port criteria is collected from publicly available data. The main resources are the 4C offshore database, UK Port Directory, and the World's Port Index (WPI) [50] [116] [117].

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

Table 22: West Gabbard specification

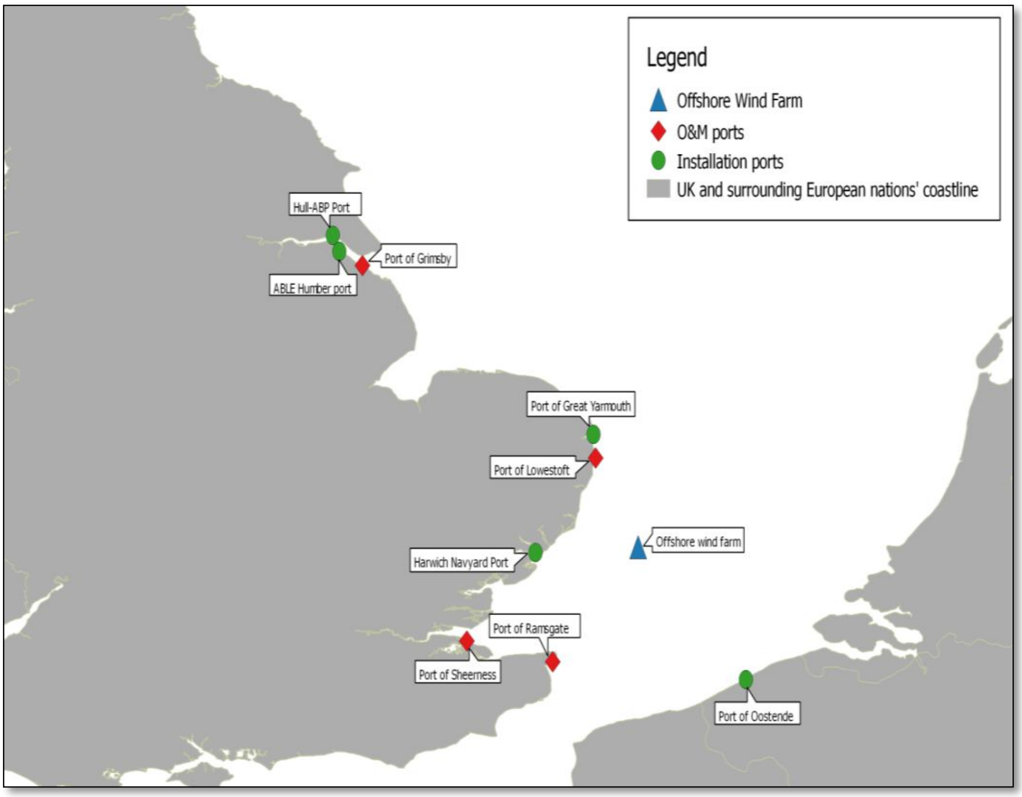


Figure 13: The location of the wind farm site and potential ports

3.7.2 Results

Each port has been assessed based on a number of criteria discussed in the previous sections. As each port is different in terms of these criteria, each port can have some advantages over the other, while lagging in other factors; however, the final results enable the decision makers to select the port which has the highest overall score as the most suitable port for their wind farm(Tables 23, 24).

3.7.2.1 Installation port

Table 23 presents the final score of each installation port based on the collected data. In the table, the first column is the list of sub-criteria considered for selecting the installation port and in the second column, the weight of the sub-criteria is given . Columns 3 to 7 provide the normalised data which are adjusted values measured on different scales to a notionally common scale, for each installation port responding to the sub-criteria. In Columns 8 to 12, the final score of each installation port is presented. As previously shown in for installation ports, the physical characteristics of the port dominates the ports' connectivity and ports' layout in the decision-making process.

The results of the analysis suggest that the most suitable installation base for this wind farm is the Port of Oostende. The port of Hull is ranked second, followed by Able UK, Harwich Navyard Port, and the port of Great Yarmouth. The port of Oostende, which has the highest suitability ranking, is one of the major European ports in the offshore wind sector with dedicated offshore wind terminal and foundation manufacturing facilities. The Port of Hull and Able UK, as part of the Humber Enterprise Zone are also among the Humber area energy ports that are developing facilities to serve the offshore wind sector. Siemens, together with Associated British Ports (ABP) has invested in building a blade manufacturing facility as part of the Green Port Hull project. The Able Marine Energy Park (AMEP) will provide a facility for the manufacture, storage, assembly and deployment of the next generation of offshore wind turbines. This is estimated to create 4100 jobs when complete [118]. The port of Harwich, operated by Harwich Haven Authority, is a multi-purpose port that has served as the installation base for the Gunfleet Sand and Greater Gabbard projects. The port of Great Yarmouth, owned by the Peel Port Group, is strategically located to serve the planned offshore wind farms on the East coast of the UK, however, as yet, it does not offer component manufacturing facilities [117] .

3.7.2.2 Operations and maintenance port

Table 24 shows the final score of each O&M port where the first two columns show the sub-criteria and their ranking. Columns 3 to 6 show the normalised data for four O&M ports while in columns 7 to 10, the final score for each

O&M port is given. For the O&M port, the port's connectivity and specifically the port's distance from the farm are the dominating factors in the decision making process. The results of the analysis suggest that the Port of Sheerness has the highest suitability ranking for the O&M base for the wind farm, followed by the Port of Lowestoft, the Port of Ramsgate and the Port of Grimsby. The port of Sheerness, as part of the Peel Port Group, offers services and development land for the renewable energy sector. The port of Lowestoft, part of the ABP Group, offers services to the offshore wind sector and serves as the O&M base for Round 2 offshore wind projects such as the Greater Gabbard wind farm. The port of Ramsgate, owned and operated by Thanet District Council, serves as the O&M base for the Thanet and London Array wind farm and offers extensive services to the offshore wind sector [117]. The port of Grimsby, owned by ABP, is one of the established centres for the offshore wind sector and serves as the O&M base for a number of Round 1&2 offshore wind projects, however the considerable distance from the West Gabbard wind farm makes it the least suitable port.

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

Component manufacturing facility	0.029204786	0.136661	0.767396	0.767396	0.767396	0.136661	0.003991	0.022412	0.022412	0.022412	0.003991
Total							0.49935	**0.631048**	0.590605	0.571384	0.402547
Rank							4	**1**	2	3	5

Table 23: Final score for each installation port

Criteria	**Priority Weight**	**Alternatives weight**				**Final Score = Priority weight * Alternatives weight**			
		Grimsby	Sheerness	Lowestoft	Ramsgate	Grimsby	Sheerness	Lowestoft	Ramsgate
Seabed suitability	0.012778818	1	1	1	1	0.012779	0.012779	0.012779	0.012779
Quay length	0.028981505	0.410167	0.926964	0.34134	0.206787	0.011887	0.026865	0.009893	0.005993
Lo-Lo capability	0.037407015	0.308538	0.933193	0.308538	0.308538	0.011541	0.034908	0.011541	0.011541
Ro-Ro capability	0.008692965	1	1	1	1	0.008693	0.008693	0.008693	0.008693
Heavy cranes	0.028367065	0	0	0	0	0	0	0	0
Quay load bearing capacity	0.183909433	0.199635	0.869473	0.199635	0.712925	0.036715	0.159904	0.036715	0.131114
Port's depth	0.02821776	0.25066	0.92861	0.273105	0.42479	0.007073	0.026203	0.007706	0.011987
Distance to offshore site	0.324803959	0.109407	0.416613	0.879178	0.606177	0.035536	0.135317	0.28556	0.196889
Distance to key component supplier	0.052933117	0.312767	0.24805	0.93098	0.376582	0.016556	0.01313	0.04928	0.019934
Distance to road	0.043448349	0.729535	0.839997	0.111235	0.349797	0.031697	0.036496	0.004833	0.015198
Distance to heliport	0.082064742	0.196851	0.189692	0.806748	0.806748	0.016155	0.015567	0.066206	0.066206
Storage loadbearing capacity	0.007977375	1	1	1	1	0.007977	0.007977	0.007977	0.007977
Open storage area	0.008523493	0.155119	0.632409	0.286467	0.892552	0.001322	0.00539	0.002442	0.007608

Covered storage area	0.028867234	0.303888	0.932293	0.354473	0.272069	0.008772	0.026913	0.010233	0.007854
Workshop area for component repair	0.041505152	1	1	1	1	0.041505	0.041505	0.041505	0.041505
Potential for expansion	0.024465917	0.278988	0.932826	0.324317	0.324317	0.006826	0.022822	0.007935	0.007935
Office facilities	0.057054778	1	1	1	1	0.057055	0.057055	0.057055	0.057055
Total						0.312089	**0.631526**	0.620352	0.610266
Rank						4	1	2	3

Table 24: Final score for each O&M port

3.8 Discussion and conclusion

Offshore wind is a growing industry globally and particularly in North western European countries. Therefore, managerial tools, which can enable decision makers to make supported optimal choices, are needed. The main contribution of this chapter is the application of a methodology that uses industry expert judgments for determining the relative significance of different port criteria for port selection.

For conducting this research, industry experts in the ports logistics of the offshore wind sector were contacted and their judgments were collected via questionnaires containing the pairwise comparison of criteria. These questionnaires were processed and the final weight value of the criteria were obtained which were then used for assessing the suitability of a number of ports(as an example). The author has gathered publicly available information about the ports and used the AHP model to rank the suitability. It should be noted that while every effort has been made to gather most accurate port data, due to the nature of the data(a mix of qualitative and quantitive) and the fact that they are gathered only using publicly available sources, inconsistencies may exist. The results show that the most significant sub-criterion for the installation port is the port's distance from the offshore site followed closely by the port's quay loadbearing capacity and the port's depth. This result suggests that the port's distance to the wind farm is an influential factor in the decision-making process, since the ports located closer to the wind farm allow for weather windows to be exploited more efficiently and the transportation time and cost will hence be reduced. In addition, since large offshore wind components are assembled at the installation port, the port must have adequate quay loadbearing capacity to support the heavy load of the component. Furthermore, deep-water ports are preferred to accommodate the large draft vessels required. Ro-Ro capability in the port is ranked the least significant factor and this could be due to the fact that for the installation process, typically heavy lifting vessels (HLV) are used.

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

In addition to providing a port selection decision-making model, this research provides insight for port owners/operators wishing to pursue a sustainable future for their port. The emergence of offshore renewable energy projects (wind, wave, tidal) provides an opportunity for ports to diversify or expand their activities into undertaking the installation and O&M of offshore wind technology. For example, the decline in the fishing industry in some regions could make diversification into offshore wind industry an attractive option for ports and can provide job opportunities and boost the local economy as evidenced by the case of UK Humber region ports [118]. In order to support the decision-making for such diversifications, this study provides an overview of the necessary requirements for offshore wind ports and their relative importance in order to provide a clear understanding for the decision makers.

3.8.1 Limitations and future research

The focus of this study has been on the port’s requirements from a logistical perspective and the factor of cost has not been explicitly included in the decision-making strategy reported in this study. The future research could also include the cost as a direct factor and assess the ports based on cost and other requirements. Furthermore, our model made no account for existing operations at a port facility. For instance, a firm that had existing operations at a particular port might select that port even if the model shows it to be suboptimal because very little additional investment may be needed. A further model could be developed to take into account these situations, which will occur more often as the industry continues to develop.

Part III

Chapter 4

Goal Programming models with interval coefficients for the selection of marine renewable energies in the UK

4.1 Introduction

In the first two chapters of this research, development of decision making models and their application to the offshore wind sector is considered. In this chapter the attention is focused on providing a prescriptive tool to help decision makers in determining how a number of projects can be selected given the different goals and objectives. In addition to offshore wind, two other marine renewable energy types, namely the tidal and wave technologies are considered, and we will look at the problem of how a portfolio of projects can be selected given uncertain data and will demonstrate this model on a case of marine renewable energy selection in the UK. This problem is particularly important due to the fact that decision makers in this sector face uncertainties in the data and the goals. For example, the amount of energy production may not be captured by a single point due to the inherent fluctuations in the wind and may be better reflected using an interval of upper and lower bounds.

4.2 Contributions

In this chapter, a strategic decision making model for the development of marine renewable energy in the UK is proposed. As an island nation, the UK benefits from significant marine energy potential which could be a substantial addition to the UK renewable energy portfolio. The chapter investigates the question of how could a decision maker (developer / government body that issues planning permit) reach a decision on what types of marine renewable energy to be selected given that strategic energy planning is often subject to a number of uncertain parameters.

In this context, the contribution of this chapter lies in the intersection of renewable energy portfolio selection and the application of multi-objective methods. We demonstrate how existing goal programming models can be transformed to interval models to address the impreciseness and uncertainty associated with the goals and coefficients of the models.

4.3 Literature review

In the remainder of this section, a review on the past work in the application of MCDM in the renewable energy selection problems is provided, followed by the identified research gaps in the literature.

Multi-criteria decision making methods have gained acceptance in the appraisal and assessment of energy technologies and policies for a range of energy planning problems at different decision levels (strategic, tactical and operational) and time frames. These methodological frameworks allow for the incorporation of decision makers' preferences, consideration of numerous objectives and provide robust recommendations [27]. The problem of determining the energy mix has been an important topic within the realm of energy management and significant literature is devoted to this topic and different methods have been applied.

Pratama et al [119] apply a deterministic multi-objective optimization method for the development of power generation mix of Indonesia based on sustainability indexes and developing policy scenarios for different regions within the country. Similarly, regionalised multi-objective approaches are adopted in [120] [121] . Deterministic optimization has been applied for efficient resource planning of the wind, solar and biomass in a Greek Island taking into account environmental impacts, energy demand, energy cost, and resource availability. The solution allow decision makers to choose between different scenarios[122]. Arnette and Zobel [123] , develop a multiobjective binary model for determining the mix of renewable energies for solar, wind and biomass using the cost and greenhouse gas minimization as the objectives. Goal Programming has been used to determine the optimal mix and location of wind, solar, hydraulic and biomass power plants in Spain [124]. The criteria used were CO2 emissions, cost, distance between power plants, energy generation, employment and social acceptance factor. Chang [125] expands the model suggested by [19] and applies a multi-choice goal programming method for avoiding the underestimation of aspiration levels. More recently, Mytilinou and Kolios [126] link life cycle cost analysis to genetic algorithm optimisation to determine the optimal layout, location, number of turbines and turbine size for the UK’s round three offshore wind farms which are larger developments compared to round one and two, with up to 33 GW capacity . Mardani et al. [127] present a review on the MCDMs used for energy policy planning from the period of 1995 to 2015 and state that AHP is the second most used method after hybrid MCDM methods.

Non-deterministic methods have also been applied in this domain, Kaya [128] presents a comprehensive review on the application of fuzzy Multi-criteria decision making methods for energy policy making. The main methods considered in their research is fuzzy AHP, ANP, TOPSIS, DEMATEL, ELECTRE, VIKOR, PROMETHEE and suggests that fuzzy AHP method and type-1 fuzzy sets are the most preferred type of fuzzy MCDMs used in the studies reviewed.

A robust formulation is applied to address uncertainties in parameters such as interest rate, technology lifetime, cost of investment, and resource for strategic energy planning by [129] which demonstrates that robust investment strategies are on average marginally more expensive than the deterministic solution, but are more reliable over time. Soroudi and Afrasiab [43] propose a stochastic dynamic multi-objective method for the integration of DG in electricity distribution networks. The uncertainties of load, electricity price and wind power generation are taken into account using scenarios and a fuzzy satisfying method is applied to select the best solution given the DM's preference.

Hocine et al. [130] apply a multi-segment fuzzy goal programming for optimizing the renewable energy portfolio in Italy comprising of wind, solar, Hydro, geothermal and bio energy. The evaluation criteria in their study is the investment cost, O&M cost, primary energy saving, realization time, sustainability of climate change, and job creation In a goal programming context, Multi segment method proposed by Liao [131] is applied for the problems with multi-aspiration segment levels (i.e. decision variable coefficients) and constraints. The proposed method allows the decision maker to minimize the deviations between the achievement of goals and their aspiration levels of decision variable coefficient. To avoid under estimations, in the multi-segment GP method the decision maker (DM) could set multiple segments for each decision variable

The fuzzy method is used to deal with the imprecise parameters such as the coefficient related to each criteria. Ervural et al. [132] apply a combined approach, consisting of fuzzy TOPSIS and weighted goal programming to evaluate the renewable energy investment and planning of Turkey using budget, energy generation, social acceptance factor, and the energy potential for the wind, solar, biomass, geothermal, and hydraulic energy. A fuzzy approach has been used by [133] for portfolio optimization for renewable energy in China, using AHP fuzzy method to determine the weight of the criteria and the Non-Sorting Genetic Algorithm to solve a binary programming model for the approximation of the Pareto optimal set of projects given the environmental, economic and social objectives. Furthermore, each goal of the multiple objective problem can be divided to multiple aspiration levels to better suit management requirements (e.g. "the more(less) the better"). The criteria used in their study is the generated power, the investment cost, the avoided emission, jobs created, operation and maintenance cost, the distance between plants, and social acceptance.

Weiss et al. [10] used the suitability index method and have used a number of criteria including resource assessment, structural survivability, logistics infrastructure, distance to consumer centers and estimated extractable power of the identified potential zones for determining the best locations for the offshore wind and wave energy globally. In this study, the targets used for this study are the electricity generation, connectivity, distance from shore, CO2 emission reduction, cost, employment, and social impact.

The gaps in the current literature are identified as the paucity of studies on the application of non-deterministic MCDMs for emerging marine renewable energies. As a growing source of renewable energy, marine renewable energies are becoming increasingly important for the renewable energy portfolio of countries with marine resources and therefore suitable decision making methods should be developed that could effectively assess these technologies. Furthermore, non-deterministic approaches may be more suitable due to the fact that the relevant data is inexistent, difficult to obtain or estimate.

Methodology		Author	Application area
Deterministic methods	Goal programming	[124]	Optimal mix and location of solar, wind, hydro, biomass in Spain
		[134]	Optimal mix of renewables in Greece
	Multi-choice GP	[125]	Wind energy project selection in Thaiwan
	Meta GP	[135]	Location selection for wind farms in Algeria
	Extended GP	[70]	Offshore wind in UK location
	Multi-objective optimization	[120]	Renewable project selection in china
		[126]	Optimal layout, location, turbines size of offshore wind in UK
		[123]	Renewable energy mix for solar, wind and biomass
		[121]	Renewable energy mix in China
		[119]	Power generation mix in Indonesia
	Multisegment fuzzy GP	[130]	Renewable energy planning in Italy
	Fuzzy GP	[136]	Sustainable development in India
	Fuzzy multi-objective	[137]	Renewable energy mix in China (Hydro, wind, solar, biomass)
	Other methods		
	Suitability Index method	[10]	Global offshore wind and wave potential assessment
	Fuzzy linguistic terms	[138]	Wind, solar, biomass, hydro in Turkey
	Fuzzy AHP	[139]	Energy policy in Turkey

	Promothee and scenario planning	[140]	Energy planning in Germany

Table 25: Summary of the literature

4.4 Methodology

Multi-objective optimization involves the simultaneous optimisation of number of (conflicting) objectives. Distance metric based techniques are a subset of multi-objective methods where the distance between the ideal and the desired solution and solutions that are achievable in practice is minimised. Goal programming(GP) is one of the multi-objective methodologies that can assist decision makers for obtaining solutions that satisfy multiple conflicting goals [141]. Initially developed by Charnes and Cooper in 1961 [142], GP is devised to address decision making problems where targets have been assigned to all the attributes and where the decision maker is interested in minimising the non-achievement of the corresponding goals [143]. A key element of a GP model is the achievement function that represents a mathematical expression of the unwanted deviation variables. The generic algebraic form of the goal programming model is as following:

$$Min\, z = h(d_i^-, d_i^+)\, , i = 1,2, \dots, n \tag{27}$$

$$f_i(x) + d_i^- - d_i^+ = g_i, i = 1,2, \dots, n \tag{28}$$

$$x \in F, d_i^-, d_i^+ \geq 0 \tag{29}$$

Where $h(d_i^-, d_i^+)$ contains a number of unwanted deviational variables and its exact number depends on the number of goals to be formulated. g_i is the target level for the ith goal, d_i^- and d_i^+ are the negative and positive deviations from the target value of the ith goal. x is the vector of decision variables and F is an optional set of constraints. Three of the most common GP models are:

I. Weighted goal programming (Archimedean GP) : the objective function of the WGP lists the unwanted deviation variables, each weighted according to its relative importance.

II. Lexicographic goal programming (non-archimedean, preemptive GP): the achievement function of the LGP model is made up of an ordered vector whose dimension coincides with the Q number of priority levels established in the model. Each component in this vector represents the unwanted deviation variables of the goals placed in the corresponding priority level.

III. MINMAX GP (Chebyshev GP): The achievement function of the this model implies the minimisation of the maximum unwanted normalised deviation from any single goal.

In the conventional GP variants such as the ones introduced above, every goal is formulated in a precise way with crisp number coefficients. However, it should be noted that using conventional MODM techniques, which require complete and exact information on the criteria and goals, may limit the practicality of the models in real world applications where there are impreciseness and uncertainty associated with the data.

In general uncertainty falls within two main categories of aleatory uncertainty, and epistemic uncertainty. Aleatory uncertainty, also called natural variability, random uncertainty, stochastic uncertainty, is derived from the natural variability of the physical world and reflects the inherent randomness in events such as flipping a coin, in which the results cannot be predicted regardless of the number of experiments [144] . On the other hand, Epistemic uncertainty, also called knowledge uncertainty, subjective uncertainty, or incompleteness, stems from human’s lack of ability of measuring and modelling the physical world precisely. However, unlike the aleatory uncertainty, it is reducible given more knowledge of the problem and proper methods.

In this chapter, the problem of evaluation and selection of MRE projects is subject to epistemic uncertainty, where the values of the parameters are not exactly known due to limited information of decision makers and incompleteness of data.

To overcome this limitation, theories such as fuzzy sets, probabilistic (stochastic), and interval analysis are introduced [130], each method tackling a certain type of uncertainty. While probabilistic methods such as Bayesian network and Monte-Carlo simulation are mainly used to deal with Aleatory uncertainty, fuzzy methods and interval methods are introduced to capture the epistemic uncertainty. Fuzzy logic, introduced by [145] is a powerful tool for the representation of imprecise, ambiguous and vague phenomena that are expressed in linguistic terms rather than numerical form. For example, a continuous variable such as temperature which is expressed as cold, warm or hot. In such cases fuzzy methods enable effective quantification of imprecise information, and are extremely useful since they eliminate the burden of quantifying a linguistic term[144] .

Figure 14 shows a classification of the methods that deal with uncertainty based on the review by [144] .

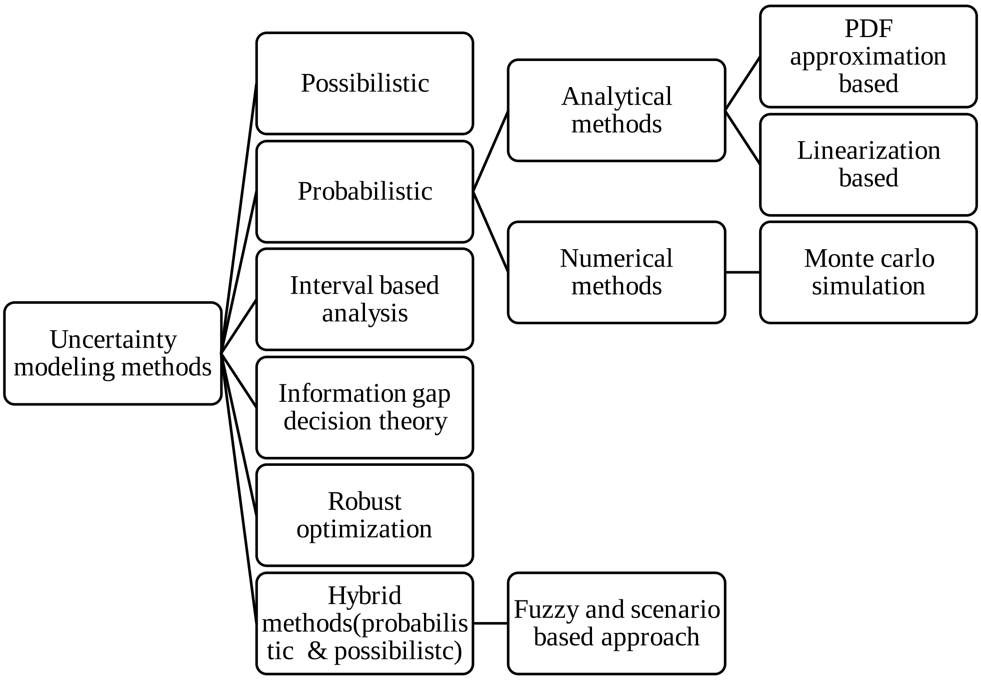


Figure 14: Methods for modelling uncertainty

4.4.1 GP using interval coefficients and targets

In mathematical programming problems, parameters such as coefficients and right-hand side values of constraints have been assumed to be given as exact figures . Nonetheless, in some real-world problems those parameters cannot be given precisely due to lack of knowledge or the uncertain nature of the coefficients. Examples of such uncertainties are rate of return in investment, demands for products, or time for a manual operations [146]. In stochastic programming, such uncertain parameters are treated as random variables. To formulate a stochastic model, a proper probability distribution should be estimated, however, that may not always be possible due to the fact that i) historical data of some parameters cannot be obtained easily, and ii) subjective probabilities cannot be easily specified when many parameters exists. Furthermore, even if a probability distribution can be estimated from the historical data, there is no guarantee that the current parameters obey the predefined distribution [146]. However, it is often possible to estimate the possible range of the uncertain parameters through the use of upper and lower bounds. In some problems, the coefficient impreciseness is not related to the linguistic nature of the variable, rather different data points are used to reflect a range of variation of parameters.

The uncertain parameters can be categorized in three groups including those with known probability density functions, those with possibilistic distributions and those without either possibilistic or probabilistic distributions but with interval properties. For dealing with the latter class of problems, mathematical programming with interval coefficients is proposed. The interval coefficients on the left hand side, are regarded as regions the coefficients can possibly take and the right hand side represented by convex sets have been regarded as regions within which the decision maker can be satisfied [147]. Therefore, interval programming is proposed since it does not require the specification or the assumption of probabilistic distribution (as in stochastic programming) or possibilistic distribution (as in fuzzy programming). This is of practical interest since in many instances it is difficult to determine precisely the coefficients of the objective function, and furthermore, it is more convenient for decision makers to define intervals of uncertain parameters instead of specifying their probability distribution [148]. The following linear programming problem with an interval objective function can be considered as:

$$\max Z(x) = cx \tag{30}$$

$$Ax \leq b \tag{31}$$

$$x \geq 0 \tag{32}$$

Where c is an interval vector, with the generic elements $c_j \in \left[c_j^L, c_j^U\right], j = 1, \dots, n,$ and A is an $m \times n$ matrix, b is an $m \times 1$ vector, x is an $n \times 1$ vector and the superscripts L and U represent lower and upper bounds of the coefficients, respectively. The following GP problem can therefore be stated as:

$$\sum_{j=1}^{n} c_{kj}x_j = t_k, \qquad k = 1, \dots, p \tag{33}$$

Subject to:

$$Ax \leq b \tag{34}$$

$$x \geq 0 \tag{35}$$

Where $c_{kj} \in C_{kj}\ (K = 1, \dots, P), (j = 1, \dots, n)$ is a closed interval $\left[c_{kj}^{L}, c_{kj}^{U}\right]$, and $t_k \in T_k\ (K = 1, \dots, P)$ is a closed interval $[t_k^L, t_k^U]$.

In conventional GP, the regret function is defined by the weighted sum of deviations (weighted GP) or the maximal deviation (minmax GP). In interval programming, the regret function is defined by a convex combination of the weighted sum of deviations and the maximal deviations Eq. 36 shows how the deviations are penalised in the interval goal programming model and the goal programming problem become minimizing $D(x)$, such that:

$$\min D(x) = [d^L(x), d^U(x)] = [\lambda \textstyle\sum_{k=1}^{p} \gamma_k (d_k^{L-} + d_k^{U+}) + (1-\lambda) \bigvee_{k=1}^{p} (d_k^{L-} + d_k^{U+}), \lambda \textstyle\sum_{k=1}^{p} \gamma_k (d_k^{L+} \vee d_k^{U-}) + (1-\lambda) \bigvee_{k=1}^{p} (d_k^{L+} \vee d_k^{U-})] \tag{36}$$

$$0 \leq \lambda \leq 1, \gamma_k \geq 0 \ and \ \sum_{k=1}^{p} \gamma_k = 1 \tag{37}$$

Extending the interval method suggested by [147] and [149] , the immediate point where $c_k^L < c_k^M < c_k^U$, $d_k^L < d_k^M < d_k^U$, $t_k^L < t_k^M < t_k^U$ are also added to the formulation such that the deviational variables, $d_k^{L-}, d_k^{L+}, d_k^{M-}, d_k^{M+}, d_k^{U-}, d_k^{U+}$, are defined as:

$$\sum_{j=1}^{n} c_{kj}^{U} x_j + d_k^{L-} - d_k^{L+} = t_k^{L} \leftrightarrow t_k^{L} - \sum_{j=1}^{n} c_{kj}^{U} x_j = d_k^{L-} - d_k^{L+};\ d_k^{L-} - d_k^{L+} = d_k^{L}; \tag{38}$$

$$\sum_{j=1}^{n} c_{kj}^{L} x_j + d_k^{U-} - d_k^{U+} = t_k^{U} \leftrightarrow t_k^{U} - \sum_{j=1}^{n} c_{kj}^{L} x_j = d_k^{U-} - d_k^{U+};\ d_k^{U-} - d_k^{U+} = d_k^{U}; \tag{39}$$

$$\sum_{j=1}^{n} c_{kj}^{M} x_j + d_k^{M-} - d_k^{M+} = t_k^{M} \leftrightarrow t_k^{M} - \sum_{j=1}^{n} c_{kj}^{M} x_j = d_k^{M-} - d_k^{M+};\ d_k^{M-} - d_k^{M+} = d_k^{M} \tag{40}$$

$$D_k = \left|[d_k^{L}, d_k^{M}, d_k^{U}]\right|;\ d_k^{L-}.\,d_k^{L+} = 0;\ d_k^{U-}.\,d_k^{U+} = 0\ ;\ d_k^{M-}.\,d_k^{M+} = 0 \tag{41}$$

Where, $a \vee b = \max(a, b)$, d_k^{L-} ,d_k^{M},d_k^{U+} are the deviational variables, $t_k^{L}, t_k^{M}, t_k^{U}$ are the targets (goals), and $c_{kj}^{L}, c_{kj}^{M}, c_{kj}^{U}$ are the criteria for the lower bound, midpoint and upper bound respectively. $\sum_{k=1}^{p} \gamma_k (d_k^{L-} + d_k^{U+})$ is the weighted sum of deviations($\gamma_k$represent the weights), and $\vee(d_k^{L-} + d_k^{U+})$ is the maximal deviation. λ weights the importance attached to the minimisation of the weighted sum of unwanted deviation variables. If $\lambda = 0$, a MINMAX(Chebyshev) GP model is formed, and if $\lambda = 1$, an Archimedean GP model is derived. $\lambda \in (0,1)$ results in intermediate solutions between the aforementioned solutions. The underlying Chebyshev (L_∞) distance metric has the effect of ensuring a balance between the satisfaction of the goals rather than just concentrating on optimization [141].

Given the regret function, two kinds of deviational intervals from the target interval can be derived namely the optimistic and pessimistic procedures. In the optimistic formulation, the deviations from the lower bound of the regret interval is minimised, whereas in the pessimistic formulation, the deviation from upper bound of the regret interval is minimised. If the DM follows a possible optimistic procedure, then the GP formulation can be written as follows where v^L and v^U represent the maximum deviations from the lower bound and upper bound respectively.

$$\min \lambda \sum_{k=1}^{p} \gamma_k (d_k^{L-} + d_k^{M-} + d_k^{M+} + d_k^{U+}) + (1-\lambda) v^L \tag{42}$$

s.t.

$$\sum_{j=1}^{n} c_{kj}^{U} x_j + d_k^{L-} - d_k^{L+} = t_k^L \ (k = 1, \dots, p) \tag{43}$$

$$\sum_{j=1}^{n} c_{kj}^{M} x_j + d_k^{M-} - d_k^{M+} = t_k^M \ (k = 1, \dots, p) \tag{44}$$

$$\sum_{j=1}^{n} c_{kj}^{L} x_j + d_k^{U-} - d_k^{U+} = t_k^U \ (k = 1, \dots, p) \tag{45}$$

$$\sum_{j=1}^{n} a_{ij} x_j \le b_i \ \ i = (1, \dots, m) \tag{46}$$

$$d_k^{L-} + d_k^{M+} + d_k^{M-} + d_k^{U+} \le v^L \ (k = 1, \dots, p) \tag{47}$$

$$0 \le \lambda \le 1 \tag{48}$$

$$\sum_{k=1}^{p} \gamma_k = 1 \tag{49}$$

$$x_j \ge 0, \gamma_k \ge 0 \tag{50}$$

A pessimistic possible regret interval approach can be written as follows:

$$min\lambda \sum_{k=1}^{p} \gamma_k v_k + (1-\lambda)\, v^U \tag{51}$$

$$\sum_{j=1}^{n} c_{kj}^{U} x_j + d_k^{L-} - d_k^{L+} = t_k^L \; (k=1,\dots,p) \tag{52}$$

$$\sum_{j=1}^{n} c_{kj}^{M} x_j + d_k^{M-} - d_k^{M+} = t_k^M \; (k=1,\dots,p) \tag{53}$$

$$\sum_{j=1}^{n} c_{kj}^{L} x_j + d_k^{U-} - d_k^{U+} = t_k^U \; (k=1,\dots,p) \tag{54}$$

$$\sum_{j=1}^{n} a_{ij} x_j \le b_i \;\; i=(1,\dots,m) \tag{55}$$

$$d_k^{L+} \le v_k (k=1,\dots,p) \tag{56}$$

$$d_k^{M-}, d_k^{M+} \le v_k (k=1,\dots,p) \tag{57}$$

$$d_k^{U-} \le v_k (k=1,\dots,p) \tag{58}$$

$$v_k \le v^U \; (k=1,\dots,p) \tag{59}$$

$$0 \le \lambda \le 1 \tag{60}$$

$$\sum_{k=1}^{p} \gamma_k = 1 \tag{61}$$

$$\gamma_k \ge 0\,, x_j \ge 0 \tag{62}$$

A set of candidate projects ($x_i = 1, .. n$) are considered, and the aim of this model is to provide decision support tool that can identify a subset of projects to be called the project portfolio given a number of predefined goals g_i. The decision variable $x_i = 1$ if the project is included in the portfolio and 0 otherwise.

4.5 Interval Goal Programming Model for UK marine renewable energy

Using the possible regret interval method presented in the previous section, a goal programming formulation for the selection of marine renewable energy projects in the United Kingdom can be derived in which both the coefficients and the goals can take imprecise values. This is particularly useful for problems that are by nature characterized by uncertainty in the data. The model presented in this section is applied to determine the MRE mix for the United Kingdom. For this analysis 43 planned MREs are selected including 11 offshore wind farms, 16 wave and 16 tidal projects these projects are in the consent and planning phase. The offshore wind project capacity range between 448 MW to 1500 MW, the tidal energy projects range between 0.03 MW to 312 MW and the wave energy projects range between 0.02MW to 9.74 MW. The question is that how the decision maker can select a number of marine renewable energy projects given multiple goals and objectives. In this problem, the decision maker may refer to the organisations and stakeholders that determine the renewable energy strategy on a local or national level. This problem is also interesting given the spread of the marine renewables across the UK.

In the first step, we use a clustering method to determine the diffusion of the projects around the UK.

4.5.1 Clustering analysis

In order to determine the optimal mix of future marine renewable energy in the United Kingdom, a regionalised approach is adopted. Renewable energy projects are spread across different regions within United Kingdom and a clustering approach is required to determine where are these clusters based[†].

[†] In the remainder of this research, the terms “clusters” and “zones” may be used interchangeably.

Following the identification of clusters, the decision makers can then determine how many projects are chosen from each cluster using the suggested goal programming model. In the remainder of this section, the clustering approach is explained followed by the implementation of the goal programming model.

One of the main methods in dealing with data is to classify them into a set of categories and clusters. In order to understand a new phenomenon or learn a new object, its describing features are identified and compared with other known objects, based on the similarity or dissimilarity, generalized as proximity, according to certain standards or rules [150]. In cluster analysis, a group of objects are split up into a number of more or less homogenous subgroups on the basis of an often subjectively chosen measure of similarity between objects. The similarity between objects within a subgroup is larger than the similarity between objects belonging to different subgroup, however, both similarity and non-similarity should be examinable in a clear and meaningful way [151]. The two main frequently used clustering approaches are hierarchical and partitional. In the hierarchical approach, successive level of clusters by iterative fusions or divisions are obtained. The partitional approach assigns a set of objects into K clusters without a hierarchical structure. In principle, the optimal partition based on some specific criterion can be found by enumerating all possibilities, however, due to the large number of possible solutions, heuristics have been developed to approximate the solutions. For the problem of clustering the marine renewable energy projects in the UK, the K-means partitional algorithm is suggested. The K-means algorithm is the best known squares error-based clustering algorithm and has been used for solving practical problems. The pseudo code is as following:

```
1) Initialize a K-partition randomly or based on some prior knowledge.
   Calculate the cluster prototype matrix $M = [m_1, \dots, m_K]$.
2) Assign each object in the data set to the nearest cluster $C_w$, i.e.
```

$$x_j \in C_w, if \ |x_j - m_w| < |x_j - m_i| \tag{63}$$

$$for \ j = 1, \dots, N \ \ i \neq w \ and \ i = 1, \dots, K \tag{64}$$

3) Recalculate the cluster prototype matrix based on the current partition.
4) Repeat steps 2-3 until there is no change for each cluster.

4.5.2 Marine Renewable Energy projects clusters

For determining a meaningful number of clusters (k), the procedure starts with a set of n clusters (each cluster containing one sample) and the clusters are successively combined through $(n-1)$ fusion steps to ultimately obtain one large clusters with n samples. Since the main purpose of the clusters analysis is to define categories, there is little meaning in considering the starting point (n clusters) or the finishing point (1 cluster). Therefore, this procedure should be stopped at some point in the analysis in order to obtain a meaningful number of clusters (k) [152].

Figure 15 shows the number of clusters, in which the horizontal axis (k) shows the number of clusters and the vertical axes shows the ratio of With-in Sum of Square over Between sum of squares. The optimal number of clusters for the dataset related to 43 marine renewable energy projects spread across the UK in this study is 4 clusters, which is a meaningful number when assessing the clusters geographically and on the UK's map. Figure 16 shows the concentration of these clusters and Figure 17 shows the geographical location of these projects in the UK. By using the results of clustering, the decision maker could determine the number of chosen projects in each region and set different targets for each region.

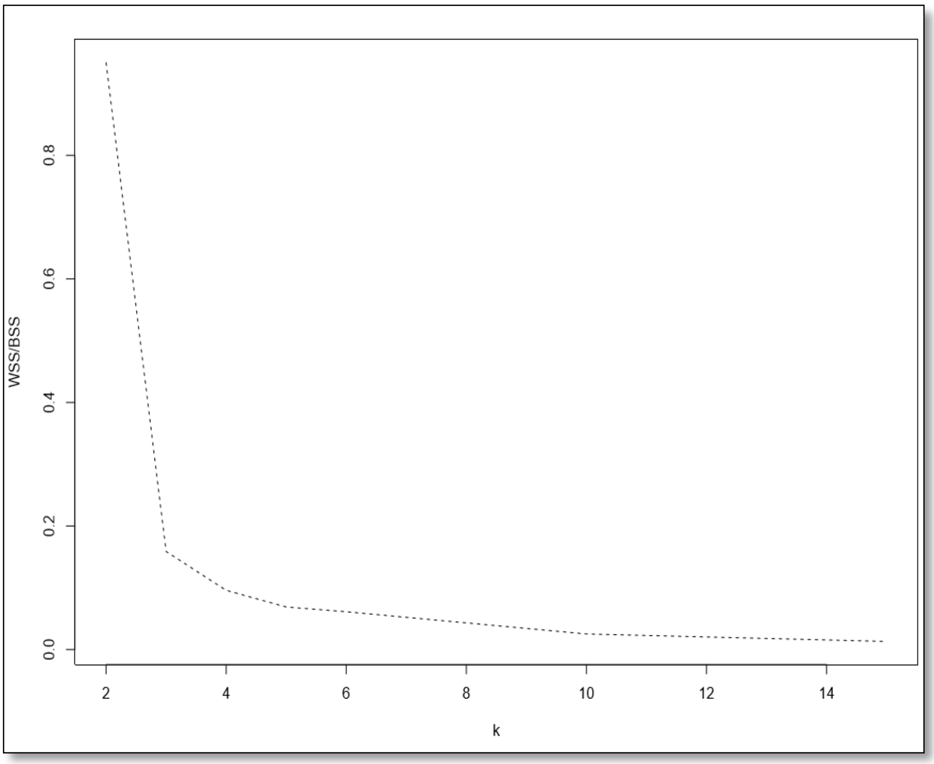


Figure 15: Analysis of number of clusters

4.5.2.1 Plot of the clusters

The cluster plot shown in Figure 16 indicates the spread of the projects based on their geographical latitude and longitude. The plot shows that the center of the clusters lies in 4 different regions

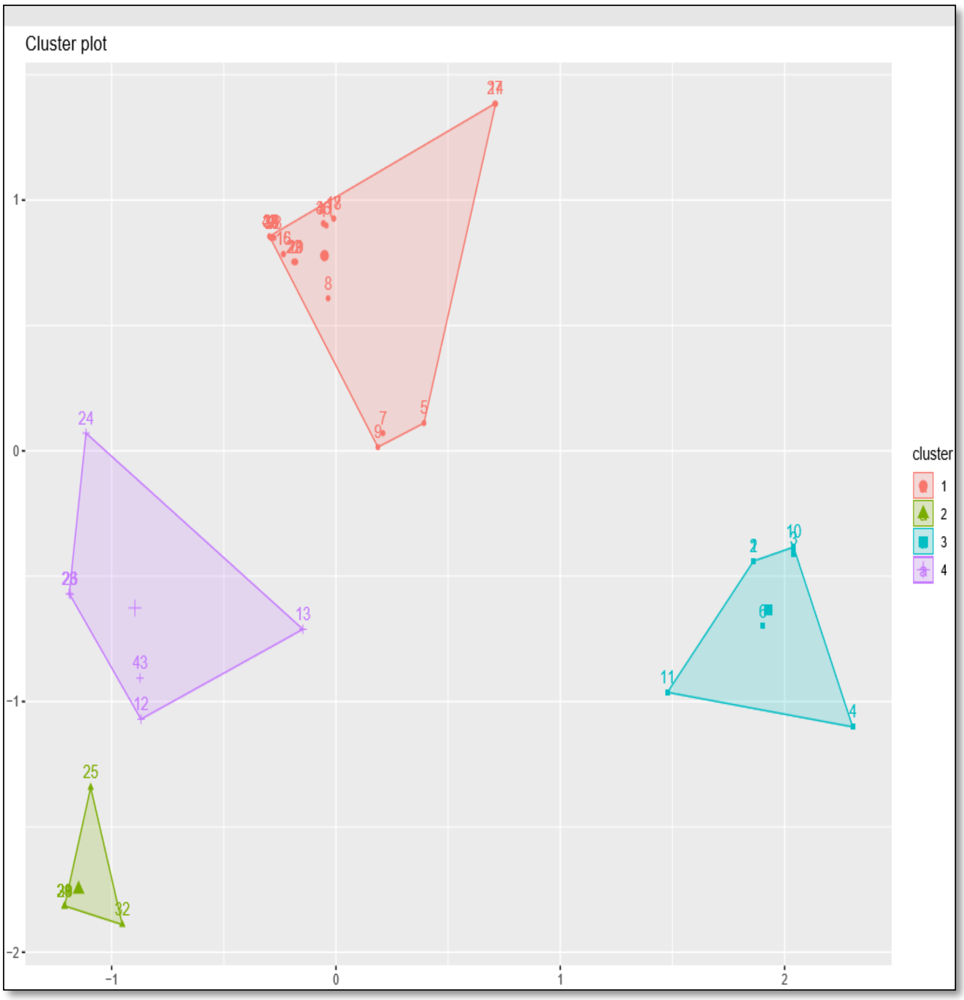
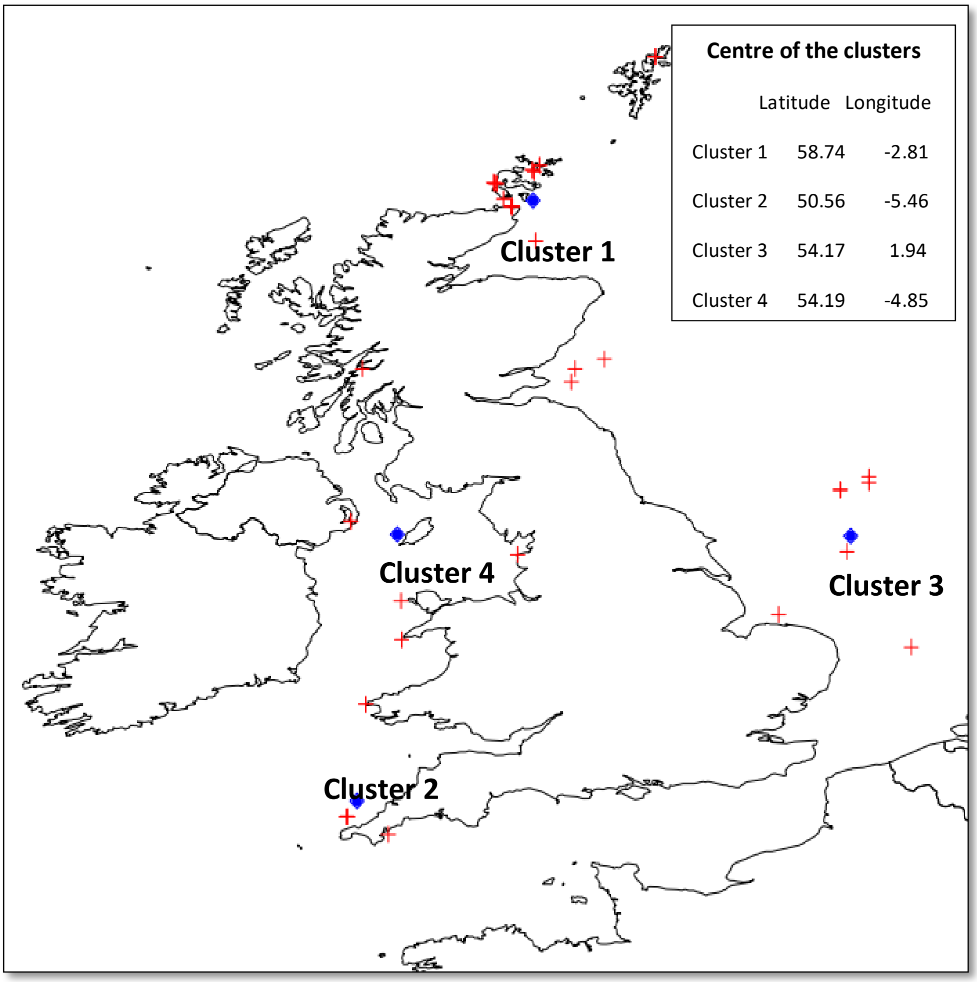


Figure 16: Cluster plot

Figure 17, presents the location of the center of the cluster on the UK map. Cluster 1 is located on the North East, Cluster 2 is based on South West, Cluster 3 is based on East and cluster 4 is based on West of UK. The center of the clusters is shown in blue dots and their latitude and longitude is presented in the map’s legend. Table 26 shows that 24 projects belong to cluster 1, 6 projects belong to cluster2, 7 projects belong to cluster 3 and 6 projects belong to cluster 4.

	Name	Capacity	Type	membership
1	Dogger bank Creyke beck A	1200	Offshore wind	3
2	Dogger bank Creyke beck B	1200	Offshore wind	3
3	Dogger bank Teesside A	1200	Offshore wind	3
4	East Anglia three	1400	Offshore wind	3
5	Firth of forth1(Alpha and bravo)	1500	Offshore wind	1
6	Hornsea project 2	1386	Offshore wind	3
7	Inch Cape	700	Offshore wind	1
8	Moray firth western	800	Offshore wind	1
9	Neart na gaoithe	448	Offshore wind	1
10	Sofia	1400	Offshore wind	3
11	Triton Knoll	860	Offshore wind	3
12	Ardsey Sound Tidal Array	3	Tidal	4
13	Wyre Estuary Tidal Barrage	160	Tidal	4
14	Bluemull Sound	0.03	Tidal	1
15	Brims Tidal Array Phase 1	30	Tidal	1
16	Brims Tidal Array Phase 2	170	Tidal	1
17	Lashy Sound Phase 1	10	Tidal	1
18	Lashy Sound Phase 2	20	Tidal	1
19	MeyGen Pentland Firth Phase 1a	6	Tidal	1
20	MeyGen Pentland Firth Phase 1b	6	Tidal	1
21	MeyGen Pentland Firth Phase 1c	73.5	Tidal	1
22	MeyGen Pentland Firth Phase 2	312	Tidal	1
23	Minesto Strangford Lough	0.03	Tidal	4
24	PLAT-I Floating Tidal Energy Platform	0.28	Tidal	4
25	Ramsey Sound	0.4	Tidal	2
26	Seagen Strangford Lough	1.2	Tidal	4
27	Shetland Tidal Array Phase 1	0.3	Tidal	1
28	Wave Hub CETO 6 Phase 1	1	Wave	2
29	Wave Hub CETO 6 Phase 2	1	Wave	2
30	Wave Hub Seatricity Phase 1	0.16	Wave	2
31	Wave Hub Seatricity Phase 2	9.74	Wave	2
32	FaBTest WaveSub	0.25	Wave	2
33	EMEC Aquamarine Power Phase 2	0.8	Wave	1
34	EMEC Clean Energy From Ocean Waves Phase 1	1	Wave	1
35	EMEC Laminaria	0.2	Wave	1
36	EMEC OpenHydro	0.25	Wave	1
37	EMEC Scotrenewables SR2000	2	Wave	1
38	EMEC ScottishPower Renewables Pelamis P2	0.75	Wave	1
39	EMEC Seatricity	0.02	Wave	1
40	EMEC Sustainable Marine Energy	1	Wave	1
41	EMEC Tocardo Phase 2	1.75	Wave	1
42	EMEC Wello Oy	0.5	Wave	1
43	Holyhead Deep - Phase 1	0.5	Wave	4

Table 26: MRE projects



Centre of the clusters

	Latitude	Longitude
Cluster 1	58.74	-2.81
Cluster 2	50.56	-5.46
Cluster 3	54.17	1.94
Cluster 4	54.19	-4.85

Figure 17: UK map representing MRE projects

4.5.3 Description of criteria

Energy sustainability can be represented through five core dimensions of social, economic and environmental technical and institutional factors, and the concept of sustainable development can be viewed as an approach which aims to achieve the desired balance between these competing factors within a society [42]. In a review study by [153], the environmental factors consist of climate change, resources and ecotoxicity and the social aspect consist of creation of employment, beneficiary population and expected mortality in an accident. For the economic aspect, the cost of operations and maintenance, cost of capital and energy cost are considered and the technical aspect covers the availability of resources (distance, weight, nominal power and height).

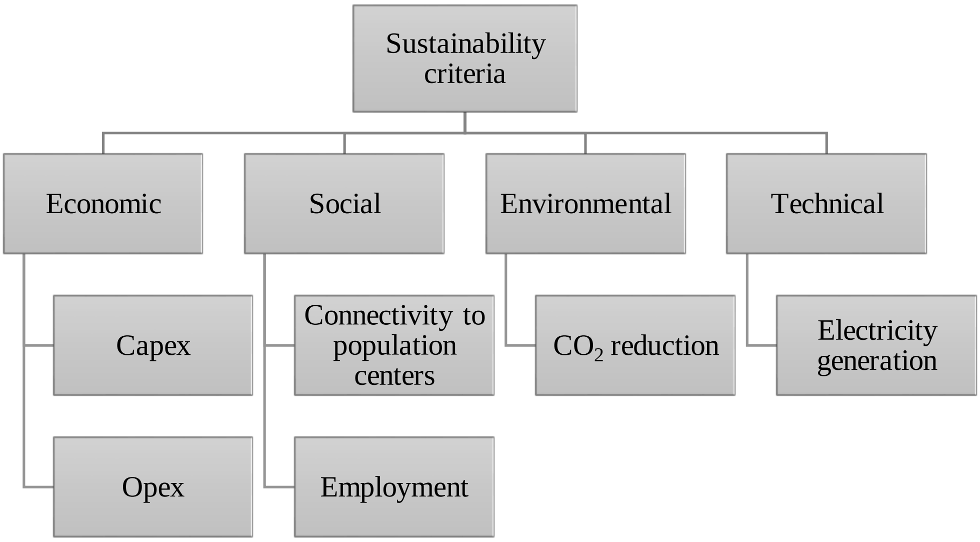


Figure 18: Sustainability criteria and goals

Based on the aforementioned sustainability categorisation, the goals and criteria of the interval goal programming model in this chapter are categorised in four main echelons namely Economic, Environmental, and Social and Technical goals as presented in the Figure 18. The Capex, Opex and belong to the economic category, the electricity generation belongs to the technical. The CO_2 reduction belongs to the environmental category and the connectivity to population centers and the employment belong to the social category. The value and threshold of each goal is ideally determined by the decision maker (e.g. Energy developer, energy policy makers) and will be implemented in the goal programming model. These criteria tend to capture a wide range of aspects associated with the development of MREs and are in line with the criteria presented in the literature in [119] [124] [134]. A description of the criteria is presented below:

Capex: The capital cost (CAPEX) includes the cost during the development and consenting production and acquisition, installation and commissioning

[126]. The factors affecting CAPEX are the average depth, distance to shore, the technology and foundation type, and the capacity [21].

Opex: The operational cost (OPEX) includes the operational and maintenance costs including the vessel and technician cost during the operational lifetime of the devices [126].

Co2 reduction: This criterion is related to the amount of CO2 that would be reduced if the source of energy is wind energy rather than fossil fuels (combined cycle gas). The approximated amount is 0.45 tonnes of CO_2 reduction per MWh [154].

Connectivity to population centers: The connectivity to population centers is an important factor for decision making since marine renewable resource generators are often placed in remote areas where the conditions are more optimal for energy generation, however that could impose higher transmission cost due to the generators being placed in further distance from the end users. For example, the cost of maintaining transmission infrastructure in the Western Isles of Scotland could be in excess of five times more than that of a generator in Northern Scotland [155]. In this study, the connectivity to population centers is calculated as the Euclidean distance between the selected farms and the nearest city within 100 km.

Energy production: The annual energy production (AEP) is an estimation of the electric energy that is produced at the site and is calculated using the formula below.

Wind Energy:

$$E = \left(\frac{1}{2}\right) A \rho v^3 t \tag{65}$$

Where A designates the swept area of the rotor ($A = \pi r^2$), ρ represents the air density, v is the average wind speed, and t is the time

Wave energy:

$$p = \left(\frac{KW}{2\,m^3.s}\right) * H_{m0}^2 T_e \tag{66}$$

Where H_{m0} is the significant wave height, T_e is the wave energy period

Tidal energy convertors:

$$AEP = N_h C_{ava} \sum_{i=1}^{Nb} P_i f_i \tag{67}$$

Where N_h are the hours available within a year, $C_{ava}$is the availability rate of the tidal energy convertor during the year ($C_{ava} = 1$ corresponds to 100% availability during the N_h hours). P_i is the power generated at the mean velocity $U_{\infty,\mathrm{i}}$ ($U_{\infty,\mathrm{i}}$ is the inflow velocity for upstream [m/s])in a velocity bin i of the velocity distribution, where f_i is the frequency of $U_{\infty,\mathrm{i}}$ [156].

The capacity factor of the turbines may theoretically vary from 0-100%, however the Betz limit sets an upper limit for the power production by turbines expressed as a maximum power coefficient of approximately 59%(16/27). This figure ranges from 31% to 56% in United Kingdom, Germany and Denmark for offshore wind [56]. The wave energy device capacity factors are generally well below the assumed value of 30%+- 5% , and tidal turbines are reported to reach 59% capacity factors especially tidal turbines located in channels [157].

Employments: The regional opportunities from the installation and maintenance of MREs exist and employment of between 22.9 - 35.3 fulltime equivalent jobs per MW for tidal energy and 26.4 - 32.3 per MW for wave energy [19]. Values for job creation for the offshore wind sector are usually higher which may be explained by the more complex supply chain and the estimated direct jobs are 44.8 jobs per MW in a year [158].

4.5.3.1 Description of data and constraints

Index/set

$i \in I$ Technology Type $(i = 1, \dots, m)$

$j \in J$ Marine renewable energy project $(j = 1, \dots, n)$

$c \in C$ Criteria $(k = 1, \dots, r)$

EG = Electricity generation

CP = Connectivity to population centres

CO= CO_2 reduction

CAPEX= Capital Expenditure

OPEX= Operating Expenditure

Emp = employment (jobs) created per MWh

Criteria $c_{ijk} \in C_{ijk}(i = 1, \dots, m \quad j = 1, \dots, n \quad k = 1, \dots, r)$

Technology $t_{ij} \in T_{ij}(i = 1, \dots, m \quad j = 1, \dots, n)$

Expected goals $g_p \in G_p$ $(p = 1, \dots, r)$

Non-negative variables:

d^{L-}= Negative deviation from the lower bound

d^{L+}= Positive deviation from the lower bound

d^{M-}=Negative deviation from the mid-point

d^{M+}=Positive deviation from the mid-point

d^{U-}=Negative deviation from the upper bound

d^{U+} =Positive deviation from the upper bound

Goal programming deviational variables:

Deviational variables from Electricity generation goal:

$d_{EG}^{L-}, d_{EG}^{L+}, d_{EG}^{M-}, d_{EG}^{M+}, d_{EG}^{U-}, d_{EG}^{U+}$

Deviational variables from connectivity to population center goal:

$d_{CP}^{L-}, d_{CP}^{L+}, d_{CP}^{M-}, d_{CP}^{M+}, d_{CP}^{U-}, d_{CP}^{U+}$

Deviational variables from CO_2 emission goal:

$d_{CO}^{L-}, d_{CO}^{L+}, d_{CO}^{M-}, d_{CO}^{M+}, d_{CO}^{U-}, d_{CO}^{U+}$

Deviational variables from operating cost goal:

$d_{OPEX}^{L-}, d_{OPEX}^{L+}, d_{OPEX}^{M-}, d_{OPEX}^{M+}, d_{OPEX}^{U-}, d_{OPEX}^{U+}$

Deviational variables from capital cost goal:

$d_{CAPEX}^{L-}, d_{CAPEX}^{L+}, d_{CAPEX}^{M-}, d_{CAPEX}^{M+}, d_{CAPEX}^{U-}, d_{CAPEX}^{U+}$

Deviational variables from Job creation (employment) goal:

$d_{EMP}^{L-}, d_{EMP}^{L+}, d_{EMP}^{M-}, d_{EMP}^{M+}, d_{EMP}^{U-}, d_{EMP}^{U+}$

Weights:

w_E= weight assigned to the Economic category

w_S= weight assigned to the Social category

w_T= weight assigned to the Technical category

w_{En}= weight assigned to the Environmental category

Each sustainability category (i.e. Environmental, technical, Economic and Social) contains different criteria, therefore in order to be more concise in the formulation, the weights are assigned to the category level rather than criteria level.

Binary Variables

X_{ij}= 1 , if the project is selected,

X_{ij}= 0 , otherwise

The objective function for this problem consists of the goals presented in Table 27 such that the negative deviations for Electricity generation, CO2 reductions, and Employment goals must be penalised, and the positive deviations for the connectivity to population centers (distance to population center), Opex and Capex must be penalised. For the optimistic scenario, the following objective function can be written as:

$$Minz = \frac{W_E}{8} * \left(\frac{d_{CAPEX}^{U+} + d_{CAPEX}^{M+}}{G_{capex}} + \frac{d_{OPEX}^{U+} + d_{OPEX}^{M+}}{G_{opex}}\right) + \frac{W_{En}}{4} * \left(\frac{d_{CO}^{L-} + d_{CO}^{M-}}{G_{CO}}\right) + \frac{W_S}{8} * \left(\frac{d_{EMP}^{L-} + d_{EMP}^{M-}}{G_{emp}} + \frac{d_{CP}^{U+} + d_{CP}^{M+}}{G_{CP}}\right) + \frac{W_T}{4} * \left(\frac{d_{EG}^{L-} + d_{EG}^{M-}}{G_{EG}}\right) + 1/2(v^L) \tag{68}$$

The following constraints show the goals related to the renewable energy projects.

$$\sum_{i,j} EGU_i * X_{ij} + d_{EG}^{L-} - d_{EG}^{L+} = G_{EGL} \tag{69}$$

$$\sum_{i,j} EGL_i * X_{ij} + d_{EG}^{U-} - d_{EG}^{U+} = G_{EGU} \tag{70}$$

$$\sum_{i,j} COU_i * X_{ij} + d_{CO}^{L-} - d_{CO}^{L+} = G_{COL} \tag{71}$$

$$\sum_{i,j} COL_i * X_{ij} + d_{CO}^{U-} - d_{CO}^{U+} = G_{COU} \tag{72}$$

$$\sum_{i,j} EMPU_i * X_{ij} + d_{EMP}^{L-} - d_{EMP}^{L+} = G_{EMPL} \tag{73}$$

$$\sum_{i,j} EMPL_i * X_{ij} + d_{EMP}^{U-} - d_{EMP}^{U+} = G_{EMPU} \tag{74}$$

$$\sum_{i,j} OPEXU_i * X_{ij} + d_{OPEX}^{L-} - d_{OPEX}^{L+} = G_{OPEXL} \tag{75}$$

$$\sum_{i,j} OPEXL_i * X_{ij} + d_{OPEX}^{U-} - d_{OPEX}^{U+} = G_{OPEXU} \tag{76}$$

$$\sum_{i,j} CAPEXU_i * X_{ij} + d_{CAPEX}^{L-} - d_{CAPEX}^{L+} = G_{CAPEXL} \tag{77}$$

$$\sum_{i,j} CAPEXL_i * X_{ij} + d_{CAPEX}^{U-} - d_{CAPEX}^{U+} = G_{CAPEXU} \tag{78}$$

$$\sum_{i,j} CPU_i * X_{ij} + d_{CP}^{L-} - d_{CP}^{L+} = G_{CPL} \tag{79}$$

$$\sum_{i,j} CPL_i * X_{ij} + d_{CP}^{U-} - d_{CP}^{U+} = G_{CPU} \tag{80}$$

$$\sum_{i,j} EGM_i * X_{ij} + d_{EG}^{M-} - d_{EG}^{M+} = G_{EGM} \tag{81}$$

$$\sum_{i,j} COM_i * X_{ij} + d_{CO}^{M-} - d_{CO}^{M+} = G_{COM} \tag{82}$$

$$\sum_{i,j} EMPM_i * X_{ij} + d_{EMP}^{M-} - d_{EMP}^{M+} = G_{EMPM} \tag{83}$$

$$\sum_{i,j} CAPEXM_i * X_{ij} + d_{CAPEX}^{M-} - d_{CAPEX}^{M+} = G_{CAPEXM} \tag{84}$$

$$\sum_{i,j} OPEXM_i * X_{ij} + d_{OPEX}^{M-} - d_{OPEX}^{M+} = G_{OPEXM} \tag{85}$$

$$\sum_{i,j} CPM_i * X_{ij} + d_{CP}^{M-} - d_{CP}^{M+} = G_{CPM} \tag{86}$$

$$d_I^{L-} + d_I^{U+} + d_I^{M-} + d_I^{M+} \leq v^L \tag{87}$$

Constraints (69-70) model the electricity generation goal, constraints (71-72) model the Co2 reduction, constraints (73-74) model the goal related to job creation and employment, constraints (75-76) model the goal related to operational cost, and constraints (77-78) model the goals for capital cost and constraints (79-80) model the goal for connectivity to population centers. In the case where the midpoints are added to the formulation, constraints 81 to 86 are also added to the formulation.

In the pessimistic scenario the objective function is written as:

$$Min\ \ {}^{1}\!/_{12}\,(v_1 + v_2 + v_3 + v_4 + v_5 + v_6) + {}^{1}\!/_{2}\ (v^U) \qquad (88)$$

$$\sum_{i,j} EGU_i * X_{ij} + d_{EG}^{L-} - d_{EG}^{L+} = G_{EGL} \qquad (89)$$

$$\sum_{i,j} EGL_i * X_{ij} + d_{EG}^{U-} - d_{EG}^{U+} = G_{EGU} \qquad (90)$$

$$\sum_{i,j} COU_i * X_{ij} + d_{CO}^{L-} - d_{CO}^{L+} = G_{COL} \qquad (91)$$

$$\sum_{i,j} COL_i * X_{ij} + d_{CO}^{U-} - d_{CO}^{U+} = G_{COU} \qquad (92)$$

$$\sum_{i,j} CPU_i * X_{ij} + d_{CP}^{L-} - d_{CP}^{L+} = G_{CPL} \qquad (93)$$

$$\sum_{i,j} CPL_i * X_{ij} + d_{CP}^{U-} - d_{CP}^{U+} = G_{CPU} \qquad (94)$$

$$\sum_{i,j} EMPU_i * X_{ij} + d_{EMP}^{L-} - d_{EMP}^{L+} = G_{EMPL} \qquad (95)$$

$$\sum_{i,j} EMPL_i * X_{ij} + d_{EMP}^{U-} - d_{EMP}^{U+} = G_{EMPU} \qquad (96)$$

$$\sum_{i,j} OPEXU_i * X_{ij} + d_{OPEX}^{L-} - d_{OPEX}^{L+} = G_{OPEXL} \qquad (97)$$

$$\sum_{i,j} OPEXL_i * X_{ij} + d_{OPEX}^{U-} - d_{OPEX}^{U+} = G_{OPEXU} \qquad (98)$$

$$\sum_{i,j} CAPEXU_i * X_{ij} + d_{CAPEX}^{L-} - d_{CAPEX}^{L+} = G_{CAPEXL} \tag{99}$$

$$\sum_{i,j} CAPEXL_i * X_{ij} + d_{CAPEX}^{U-} - d_{CAPEX}^{U+} = G_{CAPEXU} \tag{100}$$

$$\sum_{i,j} EGM_i * X_{ij} + d_{EG}^{M-} - d_{EG}^{M+} = G_{EGM} \tag{101}$$

$$\sum_{i,j} COM_i * X_{ij} + d_{CO}^{M-} - d_{CO}^{M+} = G_{COM} \tag{102}$$

$$\sum_{i,j} PPM_i * X_{ij} + d_{CO}^{M-} - d_{CO}^{M+} = G_{COM} \tag{103}$$

$$\sum_{i,j} EMPM_i * X_{ij} + d_{EMP}^{M-} - d_{EMP}^{M+} = G_{EMPM} \tag{104}$$

$$\sum_{i,j} CAPEXM_i * X_{ij} + d_{CAPEX}^{M-} - d_{CAPEX}^{M+} = G_{CAPEXM} \tag{105}$$

$$\sum_{i,j} OPEXM_i * X_{ij} + d_{OPEX}^{M-} - d_{OPEX}^{M+} = G_{OPEXM} \tag{106}$$

$$d_{CAPEX}^{L+} \Big/ G_{CAPEXL} \leq v_1 \tag{107}$$

$$d_{CAPEX}^{U-} \Big/ G_{CAPEXU} \leq v_1 \tag{108}$$

$$d_{CO}^{L+} \Big/ G_{COL} \leq v_2 \tag{109}$$

$$d_{CO}^{U-} \Big/ G_{COU} \leq v_2 \tag{110}$$

$$d_{OPEX}^{L+} \Big/ G_{OPEXL} \leq v_3 \tag{111}$$

$$d_{OPEX}^{U-} \Big/ G_{OPEXU} \leq v_3 \tag{112}$$

$$d_{EMP}^{L+} \Big/ G_{EMPL} \leq v_4 \tag{113}$$

$$d_{EMP}^{U-} \Big/ G_{EMPU} \leq v_4 \tag{114}$$

$$d_{EG}^{L+} \Big/ G_{EGL} \leq v_5 \tag{115}$$

$$d_{EG}^{U-}\Big/G_{EGU} \leq v_5 \tag{116}$$

$$d_{CP}^{L+}\Big/G_{CPL} \leq v_6 \tag{117}$$

$$d_{CP}^{U-}\Big/G_{CPU} \leq v_6 \tag{118}$$

$$v_1 \leq v^U \tag{119}$$

$$v_2 \leq v^U \tag{120}$$

$$v_3 \leq v^U \tag{121}$$

$$v_4 \leq v^U \tag{122}$$

$$v_5 \leq v^U \tag{123}$$

$$v_6 \leq v^U \tag{124}$$

$$x_{ij} \geq 0, (j = 1, \dots, 43) \tag{125}$$

Constraints (89-90) model the electricity generation goal, constraint (91-92) model the Co2 reduction, constraints (93-94) model the connectivity to population centers, constraints (95-96) model the goal related to employment, and constraints (97-98) model the goals for operating cost and constraints (99-100) model the goal for capital cost. In the case that the midpoints are added to the formulation, constraints (101-106) are also added to the formulation.

Criteria	**Technology type**			**Goals** g_k	**Inequality direction**
	Offshore wind	**Tidal Energy**	**Wave energy**		
Electricity Generation	$[\boldsymbol{C}_{111}^{L}, \boldsymbol{C}_{111}^{M}, \boldsymbol{C}_{11}^{U}$	$[\boldsymbol{C}_{211}^{L}, \boldsymbol{C}_{111}^{M}, \boldsymbol{C}_{21}^{U}$	$[\boldsymbol{C}_{311}^{L}, \boldsymbol{C}_{311}^{M}, \boldsymbol{C}_{31}^{U}$	$[\boldsymbol{G}_{EG}^{L}, \boldsymbol{G}_{EG}^{M}, \boldsymbol{G}_{EG}^{U}]$	≥
Connectivity (distance) to populatio	$[\boldsymbol{C}_{112}^{L}, \boldsymbol{C}_{112}^{M}, \boldsymbol{C}_{11}^{U}$	$[\boldsymbol{C}_{212}^{L}, \boldsymbol{C}_{212}^{M}, \boldsymbol{C}_{21}^{U}$	$[\boldsymbol{C}_{312}^{L}, \boldsymbol{C}_{312}^{M}, \boldsymbol{C}_{31}^{U}$	$[\boldsymbol{G}_{CP}^{L}, \boldsymbol{G}_{CP}^{M}, \boldsymbol{G}_{CP}^{U}]$	≤

n centres					
CO2 reduction	$[C_{113}^{L}, C_{113}^{M}, C_{11}^{U}$	$[C_{213}^{L}, C_{213}^{M}, C_{21}^{U}$	$[C_{313}^{L}, C_{313}^{M}, C_{31}^{U}$	$[G_{CO}^{L}, G_{CO}^{M}, G_{CO}^{U}]$	$\geq$
Employment	$[C_{114}^{L}, C_{114}^{M}, C_{11}^{U}$	$[C_{214}^{L}, C_{214}^{M}, C_{21}^{U}$	$[C_{314}^{L}, C_{314}^{M}, C_{31}^{U}$	$[G_{EMP}^{L}, G_{EMP}^{M}, G_{EMP}^{U}]$	$\geq$
Operating cost (OPEX)	$[C_{115}^{L}, C_{115}^{M}, C_{11}^{U}$	$[C_{215}^{L}, C_{215}^{M}, C_{21}^{U}$	$[C_{315}^{L}, C_{315}^{M}, C_{31}^{U}$	$[G_{\mathrm{OPEX}}^{L}, G_{\mathrm{OPEX}}^{M}, G_{\mathrm{OPEX}}^{U}]$	$\leq$
Capital cost (CAPEX)	$[C_{116}^{L}, C_{116}^{M}, C_{11}^{U}$	$[C_{216}^{L}, C_{216}^{M}, C_{21}^{U}$	$[C_{316}^{L}, C_{316}^{M}, C_{31}^{U}$	$[G_{CAPEX}^{L}, G_{CAPEX}^{M}, G_{CA}^{U}$	$\leq$

Table 27: Data description for interval coefficient model

4.5.4 Weight sensitivity

Solving a multi-objective goal programming requires a process of weight assignments that must be obtained via expert judgments or assumed by the modeller. In this model, *a priori* expert judgments are not used, and the basic starting assumption is the equal decision maker's preference for all the objectives, hence the assignment of equal weights. However, that does not reflect all the possible weight combinations that could beneficial in the process of decision making. On the other hand, exploring the entire weight space and all the combinations may not be appropriate, due to the large number of produced solutions that are not useful for the decision maker. Based on the method proposed by Jones [159], in order to avoid extreme and unbalanced solutions, in the objective function, a specific weight is assigned to each criterion $(0.1 \leq w_i \leq 0.7)$ leading to a total number of 15 solutions for the four economic, technical, social and environmental criteria shown in Table 28.

Therefore, possible weight combinations of the interval coefficient GP model for the optimistic and pessimistic scenario is reported in which each combination gives different weight value to the criteria.

Combinations	Weights			
	$w_{economic}$	$w_{environmental}$	w_{soical}	$w_{technical}$
1	0.25	0.25	0.25	0.25
2	0.7	0.1	0.1	0.1
3	0.1	0.7	0.1	0.1
4	0.1	0.1	0.7	0.1
5	0.1	0.1	0.1	0.7
6	0.4	0.4	0.1	0.1
7	0.1	0.4	0.4	0.1
8	0.1	0.1	0.4	0.4
9	0.1	0.4	0.1	0.4
10	0.4	0.1	0.4	0.1
11	0.4	0.1	0.1	0.4
12	0.3	0.3	0.3	0.1
13	0.1	0.3	0.3	0.3
14	0.3	0.1	0.3	0.3
15	0.3	0.3	0.1	0.3

Table 28: Weight combinations

4.5.5 Data

In order to demonstrate the model, the data set is acquired from a number of proposed marine renewable projects within the UK and the data is obtained via the literature, open access online sources, and reports [50] [160]. In our dataset, the upper and lower limits are within 20% of the central values. In the following results section, we report the results for 43 marine renewable energy projects comprising of 11 offshore wind, 16 tidal projects and 16 wave energy projects using the interval GP method. The code is written in Lingo v.18, and experiments were run on a PC with an Intel Core i5-4590 CPU @3.3GHz, 3301 Mhz, 4 Cores, 4 Logical Processors under Windows 10.

4.6 Results

The results for the two main variants of the interval coefficient goal programming model are reported here. The first variant of the model includes the three points (a_l, a_m, a_u) which is referred to as problem 1 (problem 1a will refers to the optimistic formulation and problem 1b refers to the pessimistic formulation). The second variant of the model, which includes two points (a_l, a_u) i.e. the lower and upper bounds, is referred to as problem 2, (problem 2a will refer to the optimistic formulation and problem 2b will refer to the pessimistic formulation).

4.6.1 Results for Problem 1

In this section, we report the results of problem 1, in which adding a midpoint to the formulations adds more certainty to the formulation and therefore the results, by encouraging the solutions that are away from the bounds of the interval closer to the midpoint of the interval. Table 29 and 30 represent the solutions for all different weight combinations for the optimistic and pessimistic scenario respectively given the three point interval developed in this section. As reported for each weight combination a different set of projects are selected which allows the decision maker to examine the effects of criteria weights in different scenarios.

Criteria (Optimistic LMU)		Weights	Offshore wind [1-11]	tidal [12-27]	wave [28-43]
1	Economic	0.25	1,2,5,6,7,10	13,14,15,18	
	Environmental	0.25			
	Social	0.25			
	Technical	0.25			
2	Economic	0.7	1,2,6,7,10	13,27	32,35,38
	Environmental	0.1			
	Social	0.1			
	Technical	0.1			
3	Economic	0.1	1,6,7,10	13,15,18,20,25	38
	Environmental	0.7			
	Social	0.1			
	Technical	0.1			
4	Economic	0.1	1,6,7,10	13,15,20,25,27	35
	Environmental	0.1			
	Social	0.7			
	Technical	0.1			
5	Economic	0.1	1,2,6,7,10	13,14,15,18	43
	Environmental	0.1			
	Social	0.1			
	Technical	0.7			
6	Economic	0.4	1,6,7,10	13,15,18,20,27	32
	Environmental	0.4			
	Social	0.1			
	Technical	0.1			
7	Economic	0.1	1,2,3,4,6,7,10	13,15	43
	Environmental	0.4			
	Social	0.4			
	Technical	0.1			
8	Economic	0.1	1,6,7,9,10	13	32,35,38,43
	Environmental	0.1			
	Social	0.4			
	Technical	0.4			
9	Economic	0.4	1,2,3,6,7	13,15,18	42,43
	Environmental	0.1			

	Social	0.1			
	Technical	0.4			
10	Economic	0.1	1,2,3,6,7,10	13,15,18	41
	Environmental	0.4			
	Social	0.1			
	Technical	0.4			
11	Economic	0.4	1,6,7,10	13,15,18,20,25,27	
	Environmental	0.1			
	Social	0.4			
	Technical	0.1			
12	Economic	0.3	1,2,3,6,7,10	13,18	35,38
	Environmental	0.3			
	Social	0.3			
	Technical	0.1			
13	Economic	0.1	1,2,6,7,9,10	13	38,41,43
	Environmental	0.3			
	Social	0.3			
	Technical	0.3			
14	Economic	0.3	1,2,3,4,6,7,10	13	29,32
	Environmental	0.1			
	Social	0.3			
	Technical	0.3			
15	Economic	0.3	1,2,3,4,6,7,10	13	29,32
	Environmental	0.3			
	Social	0.1			
	Technical	0.3			

Table 29: Problem 1a

Figure 19 shows the frequency of the selected projects in problem 1a. As it can be seen in the bar chart, a total of 20 different projects were chosen (each project selected in at least one weighting combinations) and a number of projects appear more frequently in the different weighting combinations; for example projects 1,6,7,13 appear in all weighting combination which could signal their potential suitability.

In terms of the clusters, 47% of the selected projects belong to Cluster 1, 32% belong to Cluster 3, 11% to Cluster 4 and 10% to Cluster 2. This signals the potential attractiveness of Cluster 1, since the majority of the selected projects belong to this cluster.

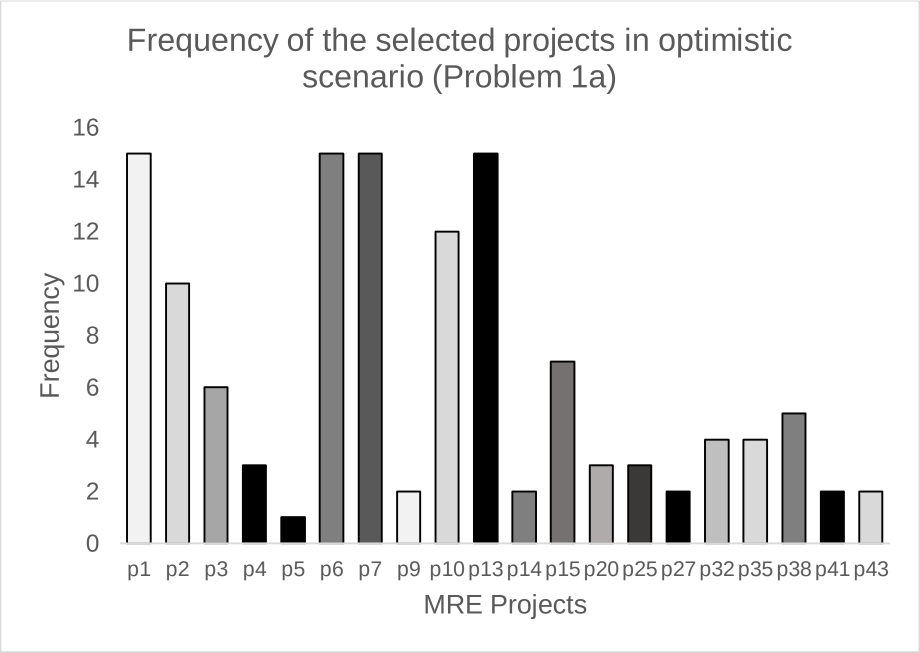


Figure 19: Frequency of selected projects Problem 1a

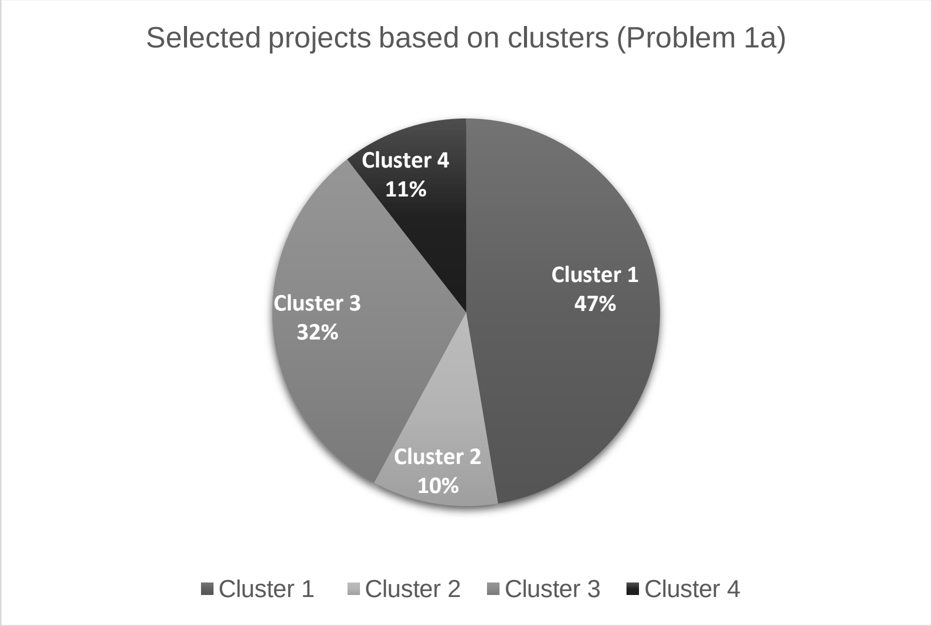


Figure 20: Selected projects based on clusters (Problem 1a)

Table 30 presents the results for the pessimistic scenario in problem 1b.

Criteria(Pessimistic LMU)		**Weights**	**Offshore wind [1-11]**	**tidal [12-27]**	**wave [28-43]**
1	Economic	0.25	1,2,3,8,11	12,16,19	28,30
	Environmental	0.25			
	Social	0.25			
	Technical	0.25			
2	Economic	0.7	1,5,6,10	13,16,18,20,22,24	
	Environmental	0.1			
	Social	0.1			
	Technical	0.1			
3	Economic	0.1	1,2,3,8,11	12,16,19	28,30
	Environmental	0.7			
	Social	0.1			
	Technical	0.1			
4	Economic	0.1	1,2,3,8,11	12,16,19	28,30
	Environmental	0.1			
	Social	0.7			
	Technical	0.1			
5	Economic	0.1	1,2,3,8,11	12,16,19	28,30
	Environmental	0.1			
	Social	0.1			
	Technical	0.7			
6	Economic	0.4	1,2,3,8,11	12,16,19	28,30
	Environmental	0.4			
	Social	0.1			
	Technical	0.1			
7	Economic	0.1	1,2,3,8,11	12,16,19	28,30
	Environmental	0.4			
	Social	0.4			
	Technical	0.1			
8	Economic	0.1	1,2,3,8,11	12,16,19	28,30
	Environmental	0.1			
	Social	0.4			
	Technical	0.4			
9	Economic	0.4	1,2,3,8,11	12,16,19	28,30
	Environmental	0.1			
	Social	0.1			

	Technical	0.4			
10	Economic	0.1	1,2,3,8,11	12,16,19	28,30
	Environmental	0.4			
	Social	0.1			
	Technical	0.4			
11	Economic	0.4	1,2,3,8,11	12,16,19	28,30
	Environmental	0.1			
	Social	0.4			
	Technical	0.1			
12	Economic	0.3	1,2,3,8,11	12,16,19	28,30
	Environmental	0.3			
	Social	0.3			
	Technical	0.1			
13	Economic	0.1	1,2,3,8,11	12,16,19	28,30
	Environmental	0.3			
	Social	0.3			
	Technical	0.3			
14	Economic	0.3	1,2,3,8,11	12,16,19	28,30
	Environmental	0.1			
	Social	0.3			
	Technical	0.3			
15	Economic	0.3	1,2,3,8,11	12,16,19	28,30
	Environmental	0.3			
	Social	0.1			
	Technical	0.3			

Table 30: Problem 1b

Figure 21 shows the frequency of the selected projects in problem 1b. A total of 17 different projects were chosen (each project chosen in at least one weighting combination) and a number of projects appear more frequently in the different weighting combinations. Furthermore, some of these projects are different from the optimistic scenario. For example, projects 8,12,16,19 have not been selected at all in the optimistic scenario model. Considering the clusters, Figure 22 shows that the 41% of the selected projects belong to cluster 1, followed by Cluster 3 (29%), Cluster 4 (18%) and Cluster 2 (12%).

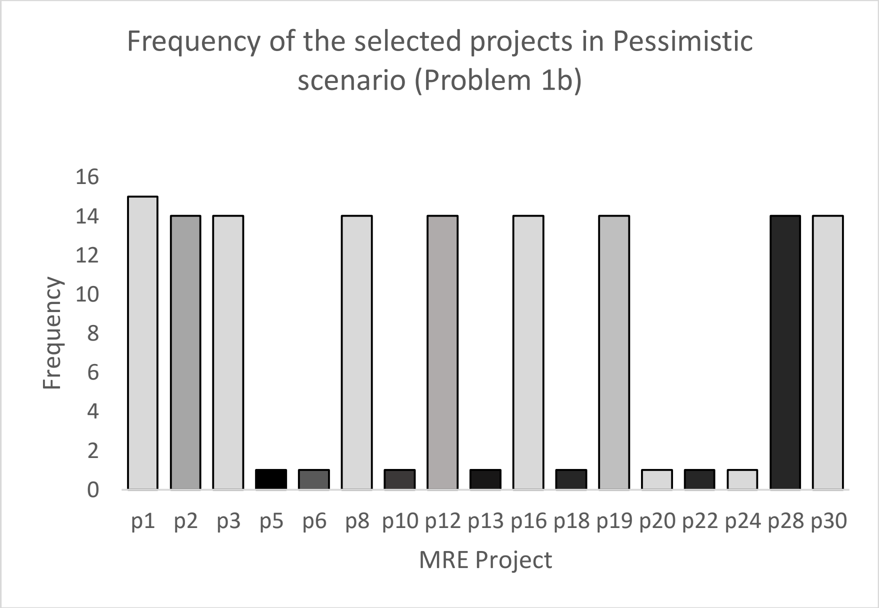


Figure 21: Frequency of selected projects Problem 1b

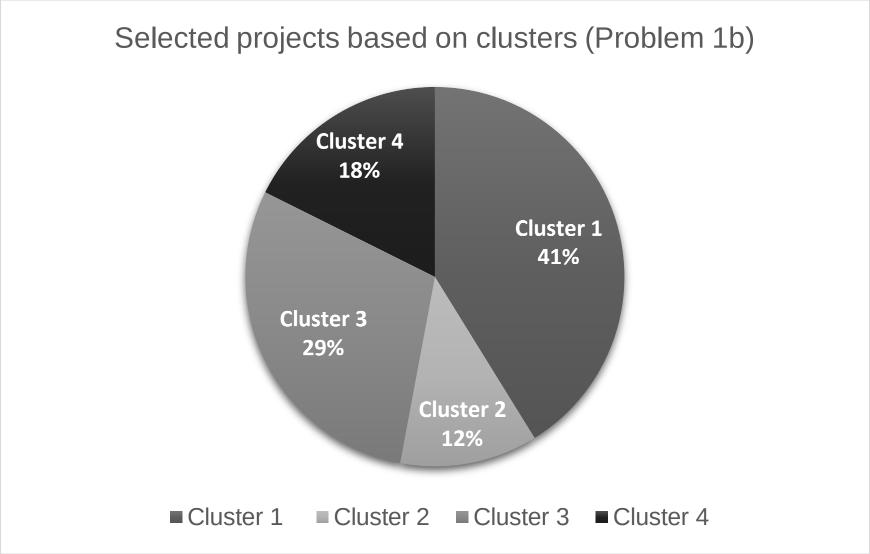


Figure 22: Selected projects based on clusters (Problem 1b)

4.6.2 Results for Problem 2 (Inuiguchi method)

In this section, the results obtained by using the method introduced in Inuiguchi and Kume [147] are reported, in which the interval only has the lower and upper bounds(problem 2a & 2b). Tables 31 and 32, present the optimistic and pessimistic scenario result using Inuiguchi method.

Criteria-Opt-UL		**Weights**	**Offshore wind [1-11]**	**tidal [12-27]**	**wave [28-43]**
1	Economic	0.25	1,4,8,11	13,15,20,22,23	43
	Environmental	0.25			
	Social	0.25			
	Technical	0.25			
2	Economic	0.7	1,4,5,6,8,11	13,15,23	43
	Environmental	0.1			
	Social	0.1			
	Technical	0.1			
3	Economic	0.1	1,4,5,8,11	13,15,20,23	43
	Environmental	0.7			
	Social	0.1			
	Technical	0.1			
4	Economic	0.1	1,4,8,11	13,15,20,23,25	43
	Environmental	0.1			
	Social	0.7			
	Technical	0.1			
5	Economic	0.1	1,4,5,8,11	13,15,20,23,25,26	43
	Environmental	0.1			
	Social	0.1			
	Technical	0.7			
6	Economic	0.4	1,3,4,5,7,8,11	13,15,20	
	Environmental	0.4			
	Social	0.1			
	Technical	0.1			
7	Economic	0.1	1,4,5,8,11	13,15,20,23,25,26	43
	Environmental	0.4			
	Social	0.4			
	Technical	0.1			
8	Economic	0.1	1,4,5,8,11	13,15,20,23	43
	Environmental	0.1			
	Social	0.4			
	Technical	0.4			
9	Economic	0.4	1,4,5,6,8,9,11	13,23	43
	Environmental	0.1			
	Social	0.1			
	Technical	0.4			
10	Economic	0.1	1,4,5,8,11	13,15,20,23,25	
	Environmental	0.4			

	Social	0.1			
	Technical	0.4			
11	Economic	0.4	1,4,5,8,11	13,15,20,23	43
	Environmental	0.1			
	Social	0.4			
	Technical	0.1			
12	Economic	0.3	1,4,7,8,9	13,20	39,40,43
	Environmental	0.3			
	Social	0.3			
	Technical	0.1			
13	Economic	0.1	1,4,5,8,11	13,15,20,23,25,26	43
	Environmental	0.3			
	Social	0.3			
	Technical	0.3			
14	Economic	0.3	1,3,4,7,8,11	13,15,20,25	43
	Environmental	0.1			
	Social	0.3			
	Technical	0.3			
15	Economic	0.3	1,4,5,7,8,11	15,20,23	43
	Environmental	0.3			
	Social	0.1			
	Technical	0.3			

Table 31: Problem 2a

Figure 23 shows the selected projects in problem 2a. A total of 19 projects have been selected and projects 1,4,8 are selected in all 15 weighting combinations. As shown in Figure 24, the majority of the selected projects belong to Cluster 1, followed by Clusters 3, 4 and 2. The three projects which are frequently selected are Dogger Bank Creyke A, East Anglia 3 and Moray Firth Western. Their inclusion in all scenarios could be explained by their high technical performance in terms of producing electricity, higher number of jobs provided, and better environmental performance in terms of CO2 reduction.

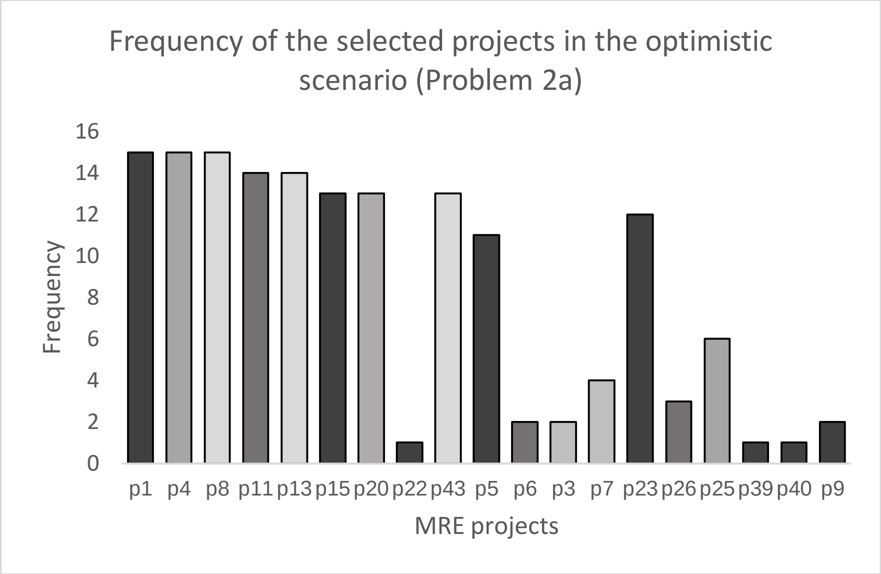


Figure 23: Frequency of the selected projects (Problem 2a)

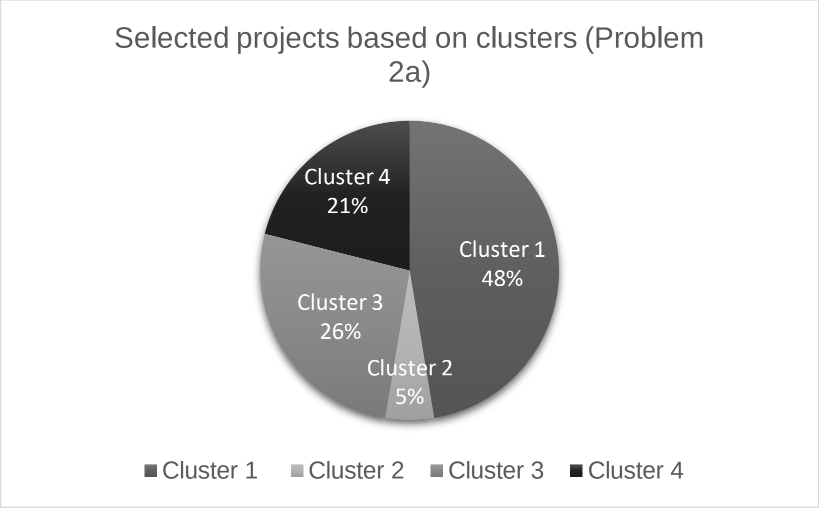


Figure 24: Selected projects based on clusters (Problem 2a)

Table 32 shows the results for different weighting combination in problem 2b.

Criteria-Pess-UL		Weights	Offshore wind [1-11]	tidal [12-27]	wave [28-43]
1	Economic	0.25	1,3,4,5,8,9,11	13,15,17	
	Environmental	0.25			
	Social	0.25			
	Technical	0.25			
2	Economic	0.7	1,3,4,5,8,9,11	13,15,17	
	Environmental	0.1			
	Social	0.1			
	Technical	0.1			
3	Economic	0.1	1,3,4,5,8,9,11	13,15,17	
	Environmental	0.7			
	Social	0.1			
	Technical	0.1			
4	Economic	0.1	1,3,4,5,8,9,11	13,15,17	
	Environmental	0.1			
	Social	0.7			
	Technical	0.1			
5	Economic	0.1	1,3,4,5,8,9,11	13,15,17	
	Environmental	0.1			
	Social	0.1			
	Technical	0.7			
6	Economic	0.4	1,3,4,5,8,9,11	13,15,17	
	Environmental	0.4			
	Social	0.1			
	Technical	0.1			
7	Economic	0.1	1,3,4,5,8,9,11	13,15,17	
	Environmental	0.4			
	Social	0.4			
	Technical	0.1			
8	Economic	0.1	1,3,4,5,8,9,11	13,15,17	
	Environmental	0.1			
	Social	0.4			
	Technical	0.4			
9	Economic	0.4	1,3,4,5,8,9,11	13,15,17	
	Environmental	0.1			
	Social	0.1			
	Technical	0.4			
10	Economic	0.1	1,3,4,5,8,9,11	13,15,17	
	Environmental	0.4			

	Social	0.1			
	Technical	0.4			
11	Economic	0.4	1,3,4,5,8,9,11	13,15,17	
	Environmental	0.1			
	Social	0.4			
	Technical	0.1			
12	Economic	0.3	1,3,4,5,8,9,11	13,15,17	
	Environmental	0.3			
	Social	0.3			
	Technical	0.1			
13	Economic	0.1	1,3,4,5,8,9,11	13,15,17	
	Environmental	0.3			
	Social	0.3			
	Technical	0.3			
14	Economic	0.3	1,3,4,5,8,9,11	13,15,17	
	Environmental	0.1			
	Social	0.3			
	Technical	0.3			
15	Economic	0.3	1,3,4,5,8,9,11	13,15,17	
	Environmental	0.3			
	Social	0.1			
	Technical	0.3			

Table 32: Problem 2b

Figure 25 shows the selected projects using the method in problem 2b. A total number of 10 projects are chosen which is less than the projects selected in problem 1b (17 projects). Furthermore, no variation in the results can be seen and the same projects are chosen in all the weighting combinations. As shown in Figure 26, Cluster 2 has not been chosen in any of the weighting combinations and Cluster 1 appears to be chosen more compared to other two Clusters.

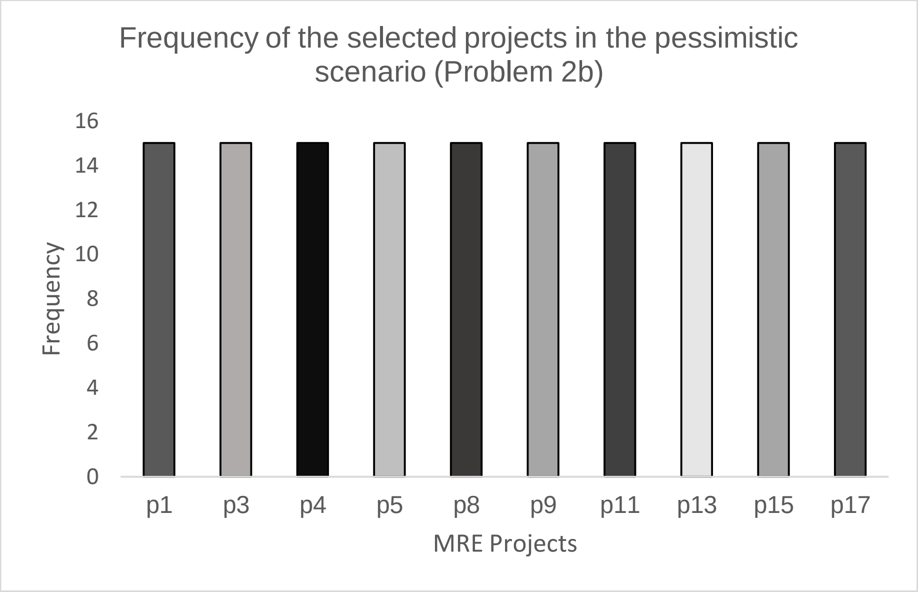


Figure 25: Frequency of the selected projects (Problem 2b)

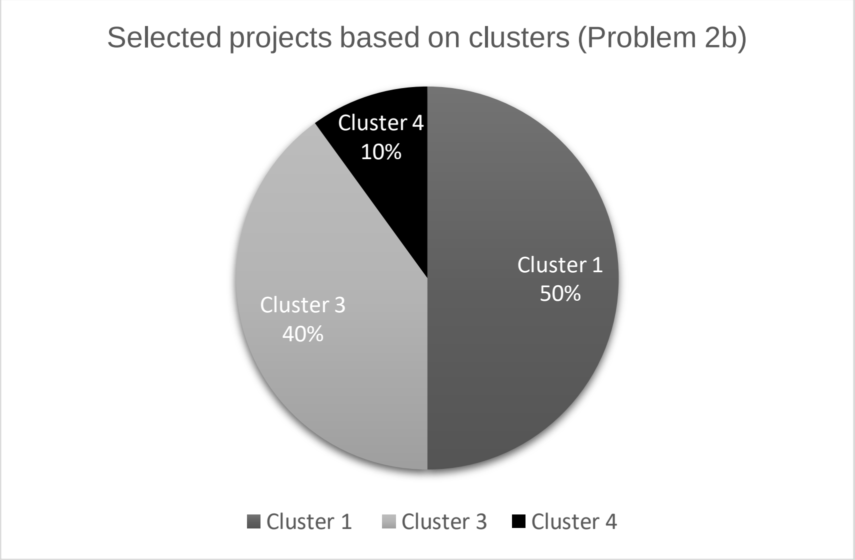


Figure 26: Selected projects based on clusters (problem 2b)

4.6.3 Discussion of the results

The results in Table 29 reflect that under the optimistic procedure and considering the midpoint, a variety of projects are being chosen for tidal, wave and offshore wind energy. Interpreting the results from the decision makers' perspective, it can be observed that in the weight combination 1, in which equal weights are given to all the criteria, no wave energy project has been selected. This could be due to the fact that wave projects have not gained the economies of scale of offshore wind and tidal projects which directly affects the technical, environmental and social goals, and hence they are dominated by offshore wind and tidal projects. Weight combination 2, in which the economic objective has the highest weight, choses a number of projects for all three technologies. This could be due to the fact that the tidal and wave technologies have a lower Capex and Opex compared to offshore wind and can hence easily meet the decision makers' economic objectives. On the other hand, if decision maker assigns the highest weight to the technical factor (i.e. electricity generation), a higher number of offshore wind projects, and lower number of wave and tidal technologies are selected, which could be due to the fact that offshore wind projects generated significantly higher electricity compared to tidal and wave projects. For the pessimistic scenario (Table 30), a different set of projects are chosen, with no variation in different weight combinations except for weight combination 2 in which the economic factor has the highest weight value compared to the other 3 criteria.

Considering the Inuiguchi method in which only the upper and lower bounds are used in the formulation, the results in Table 31(Problem 2a) reveal that under the optimistic scenario, in each weight combination, there is a variation in the selected projects however the number of selected projects in this method is lower compared to the three point method (problem 1a).

The results in Table 32(Problem 2b) show that in the pessimistic approach, no wave energy project is selected under any weight combinations, and also there is no variation in the results in different weight combinations. Furthermore, fewer projects were selected in this scenario compared to the problem 1b method.

Based on these results, both pessimistic scenarios (1b and 2b), produce less variations in the selected projects compared to the optimisitic scenario (1a and 2a) which could imply that in the pessimistic scenario a set of projects that meet the basic level of utility are chosen.

4.6.4 Analysis of results based on the clusters

The categorisation of selected projects based on their clusters, allows the identification of potentially attractive zones for the development of marine energies which is an important aspect in renewable energy decision making. The clustering analysis will help the decision maker to have a better spatial and geographical map of the potential MRE zones and will also help in more refined decision making by creating zones of MRE across the country.

For the optimistic formulation, Table 33 presents the projects that have been commonly selected in both scenarios (1a and 2a). Based on the clustering analysis defined in Section 4.5.1, Cluster 3, which is located on the East coast of UK, has been repeatedly selected in all 15 weight combinations with a minimum of 1 and maximum of 2 projects selected for each weight combination. The second most frequent cluster is cluster 4, located on the west coast of the UK, that appears in 14 weight combinations with a minimum of 1 and maximum of 2 selected projects. Cluster 1, located on the North East of the UK, appears in 11 weight combinations with a minimum of 1 and maximum of 3 projects. The least chosen cluster is cluster 2, in the UK's South West coast , which appears in only one of the weight combinations with 1 project selected.

Based on the results in Table 33, cluster 3 appears to be the most attractive zone since it has been selected in all possible weight combinations in both the methods (1a and 2a). On the other hand, cluster 2, located on the South West coast of UK offers the least number of selected projects and only appears to be selected when the weight priority is given to the social category. Perhaps the presence of touristic and/or natural beauty sites, lower level of supply chain integration, geographical isolation and the paucity of tidal and wind farms in that location could partly explain why this cluster has not been selected in more combinations.

Marine renewable energy projects				Clusters			
Weight combination	Wind	Tidal	Wave	1	2	3	4
1	1	13,15	43	15		1	13,43
2	1,6	13				1,6	13
3	1	13,15,20		15,20		1	13
4	1	13,15,20,25		15,20	25	1	13
5	1	13,15	43	15		1	13,43
6	1,7	13,15,20		15,20,7		1	13
7	1,4	13,15	43	15		1,4	13,43
8	1	13	43			1	13,43
9	1,6	13	43			1,3	13,43
10	1	13,15		15		1	13
11	1	13,20		20		1	13
12	1,7	13		7		1	13
13	1	13	43			1	13,43
14	1,3,4,7	13		7		1,4	13
15	1,4,7			7		1,4	
Frequency of clusters in all 15 combinations				11	1	15	14
Percentage of the frequency of clusters in all combinations				73%	6%	100%	93%

Table 33: Commonly selected projects for the optimistic scenario (Problem 1a&2a)

Figure 27 shows the break down of the projects which were selected commonly in both optimistic scenarios(problem 1a & 2a) and their frequency. The three most frequently selected projects are projects 1, 13, and 15. It can be seen that the offshore wind farm project Dogger bank Creyke A (project number 1) which belongs to cluster 3 has been frequently selected in all 15 weighting combinations. The second most frequently selected project is the Tidal energy project Wyre estuary Tidal Barrage which belongs to cluster 4 which has been selected in 14 out of 15 weighting combinations, followed by project 15 which is the Brims tidal array phase 1 belonging to cluster 1 which has been selected in 7 different weighting combinations. From a decision making standpoint, this chart shows the most frequently selected projects which can be identified as potentially suitable projects for development.

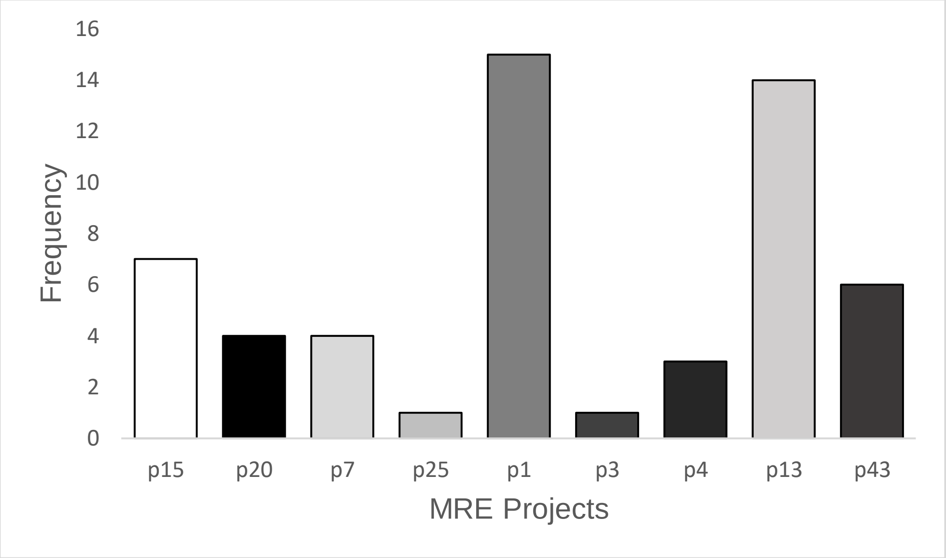


Figure 27: Frequency of commonly selected projects in Problem 1a&2a

For the pessimistic formulation, Table 34 presents the projects that have been commonly selected in both pessimistic scenarios (1b and 2b). The results in Table 34 show that cluster 3, has been repeatedly chosen in all 15 weight combinations with a minimum of 1 and maximum of 3 projects. The second most repeated cluster, selected in 14 combinations, is cluster 1, with one project selected. Cluster 4 has only been selected in one weight combination and cluster 2 has not been selected in any weight combination. The results for the pessimistic scenario also reveal the attractiveness of zones 1 and 3 for the proposed MRE projects.

Marine renewable energy projects				Clusters			
Weight combination	Wind	Tidal	Wave	1	2	3	4
1	1,3,8,11			8		1,3,11	
2	1	13				1	13
3	1,3,8,11			8		1,3,11	
4	1,3,8,11			8		1,3,11	
5	1,3,8,11			8		1,3,11	
6	1,3,8,11			8		1,3,11	
7	1,3,8,11			8		1,3,11	
8	1,3,8,11			8		1,3,11	
9	1,3,8,11			8		1,3,11	
10	1,3,8,11			8		1,3,11	
11	1,3,8,11			8		1,3,11	
12	1,3,8,11			8		1,3,11	
13	1,3,8,11			8		1,3,11	
14	1,3,8,11			8		1,3,11	
15	1,3,8,11			8		1,3,11	
Frequency of clusters in all 15 combinations				14		15	1
Percentage of the frequency of clusters in all combinations				93%	-	100%	6%

Table 34: Commonly selected projects for the pessimistic scenario (Problem 1b&2b)

Figure 28 shows the breakdown of the projects which were selected commonly in both pessimistic scenarios (problem 1b & 2b) and their frequency. Fewer optimal projects are chosen in the pessimistic case compared to the optimistic case. The most frequent project are, the offshore wind farms Dogger Bank Creyke Beck A (Project 1) which has been selected frequently in all cases followed by the Moray Firth Western (Project 8), which belongs to Cluster 1, Dogger Bank Teesside A (Project 3) belonging to cluster 3, and Project Triton Knoll belonging to Cluster 3. From a decision making standpoint, this chart shows the most frequently selected projects which can be identified as potentially attractive for development.

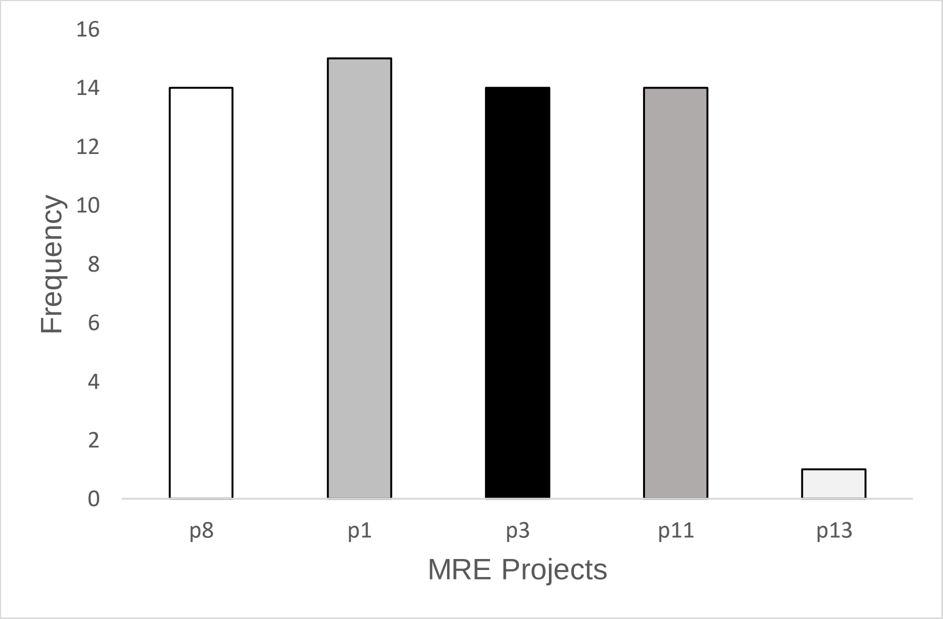


Figure 28: Frequency of commonly selected projects in Problem 1b&2b

It should be noted that although there are 43 installations possible within the region, the inability of some of the projects to meet the decision maker's goals negate their possible inclusion in the portfolio. From the 43 possible project that were initially considered in the model, almost 30% of the projects, where not selected under any of the scenarios, which could be due to suboptimal level of the projects with respect to the criteria considered. These criteria were selected following an extensive literature review and the GP model is designed as a proof of concept to show how a potential decision making tool can be useful the decision making process. The results produced by the model are in line with current industry practice were large offshore wind farms are being constructed. However, it would be critical that in a real decision making scenario these models must be validated through industrial partners to ensure their effectiveness and accuracy.

4.7 Conclusions

The ocean and seawaters offer great potential for low carbon energies including offshore wind, wave and tidal energies. However, marine renewable energy investments are challenging due to the complexity and conflicting nature of the different criteria to be examined in the process of decision making. Energy planning scenarios based on sustainability indicators including economic, environmental, social and technical aspects require decision making methods that can simultaneously take into account multiple objectives. Furthermore, policy makers need to be able to assess such investments taking into account the impreciseness and uncertainties in the data as well as different (often conflicting) objectives.

In this chapter an Interval coefficient goal programming model is developed which can offer a decision making tool for selecting marine renewable energy projects in United Kingdom, by using six main criteria including the capital cost, operating cost, generated electricity, connectivity to population centers, employment and the CO_2 reduction. Furthermore, by using the clustering methodology, these projects have been categorized in four distinct zones across the UK and upon the identification of projects, attractive zones for the development of MREs are also identified. Therefore, the decision makers can clearly recognize how the projects are spread across the UK, and which zones offer better potential for the development of MREs.

The interval GP method has been initially developed in the work of Inuiguchi and Kume [147], and the main methodological contribution of this chapter is the proposition of an intermediate point in the original formulation of [147], and also incorporating the penalisation of the associated deviations of the goals in the objective functions such that the one sided goals can be clearly incorporated in the regret function. Furthermore, to the knowledge of the author, this model had not been applied in an MRE project selection application and one of the contributions of this study is on the application of the model in a new application area and also inclusion of the midpoint in the model and comparing the results with the original model.

Our results show that incorporating the mid-point to the interval method adds more certainty and modelling control to GP solution and produces more varied results, in comparison to only using the lower and upper bounds in the formulation.

This model has been applied to the case of marine renewable energy mix in the UK considering 43 projects including offshore wind, tidal and wave technology. The model applies the interval goal programming methodology to provide a set of solutions which could help decision makers in the identification of portfolio of MRE projects based on the DM's different weighting preferences.

The results of this analysis suggest that in optimistic scenario, the majority of the selected project belong to zone 3, located on the East coast of the UK, followed closely by Zones 1 in North East and 4 in west of the UK. Based on our current data and solution, south west coast of the UK (zone 2) has been hardly identified as an attractive zone, and this could imply that this area will require an extra level of investment if MREs are to be developed in this region.

In the pessimistic scenario, the majority of the selected project belong to zone 3, located on the East coast of the UK, followed closely by Zones 1 in North East. However in this scenario Zones 4 and 2 are much less attractive as they are not selected .

Further experimentation on the European level could be conducted to produce more comprehensive results, however this model provides a proof of concept and offers a decision making tool to the policy makers within the realm of marine renewable energy planning in the UK . Through the use of Interval methodology and goal programming, a practical and flexible decision making tool is provided which could offer prescriptive recommendations for the regionalized renewable energy mix problems.

Chapter 5

Conclusions

The work presented in this thesis is a set of decision analytical tools for the development of marine renewable energies based on sustainability criteria. Strategies are proposed for the efficiency assessment, evaluation and selection of a set of marine renewable projects, and case applications are presented for each method.

5.1 Original research contributions

In the first part of this thesis (Chapter 2), the DEA efficiency assessment method is applied for the evaluation of the offshore wind industry across North Western Europe. The findings show that there are no statistically significant difference in terms of median efficiency scores between the offshore wind farms except in one of the variants of the model (the Variable Return to Scale) in which the average efficiency of UK wind farms is slightly lower compared to the other offshore wind farms across Europe. The results of the statistical analysis show that although the median efficiency of the wind farms are different on a country level, it does not distinguish them in terms of efficiency level since the difference in average efficiency levels are not statistically significant. The contribution of this chapter is providing a benchmark study for the European offshore wind sector via taking into account economic, technical, social and environmental criteria, through the application and comparison of the results of several DEA variant models. Additionally, with the application of the super efficiency DEA method, a ranking of the offshore wind farms are provided and efficient wind farms are discriminated based on their efficiency score.

In Chapter 3, the Analytical Hierarchy process (AHP) method is proposed as a practical decision making tool for the selection and evaluation of the infrastructure for the logistics of offshore wind energy. The AHP method is developed via pairwise comparison of the criteria using the expert judgements for deriving the weights. Engaging with the stakeholders has been a positive outcome in this chapter as it reflects that such evaluation models are in demand by the industry and prove to be useful for tackling decision-making problems. A case application of an offshore wind farm located on the East coast of the UK is considered, and the AHP method has been used for the selection of a port for the construction and operations of the wind farms. Selecting the suitable port for supporting the developments of an offshore wind farm through different phases of its lifecycle is one of the strategic choices for the decision makers in the offshore wind sector. Different logistics requirements are taken into account and practical managerial tools to shortlist and select suitable ports are valuable tools for decision support.

In Chapter 4, a multi-objective problem in the context of marine renewable project selection is considered. The problem concerns that how a set of marine renewable energy projects can be chosen given the sustainability indicators including economic, environmental, technical and social. By using a goal programming model with interval coefficients, a non-determinitic approach has been adopted and the proposed model can incorporate the uncertainties associated with the estimation of criteria and goals via setting intervals for the coefficients and goals in the model. For demonstrating the model, a numerical example of a set of proposed MRE projects in the UK are taken into account and the model enables the decision maker to select the optimal projects by using the goal programming model based on different weighting preferences. The model prioritises projects that meet the decision makers’ goals in the best possible way. For example, the most frequently selected projects are all projects that have received consent and are moving towards the construction phase since year 2020. This result shows the model’s capability in selecting optimal/desirable projects. The design of the portfolio of technologies for electricity generation is an important subject in the context of energy and environmental planning which involves not only the production cost but also other factors such as efficiency, and the social and environmental impacts [161]. The proposed GP model in this chapter can broaden the perspective in decision making since decisions are based on interval analysis. Furthermore, the clustering analysis allows the decision makers to understand which regions within the country offer a better potential for future development of MREs. The results of this chapter show that all three technology types i.e. offshore wind, tidal and wave energy can be selected for the UK’s marine renewable energy portfolio, although wave energy project are less competitive with the other two technologies. Furthermore, the clustering analysis reveals that the North East of the UK offers significant development potential for MREs. The originality of this chapter lies in the development of the methodology and the application in the marine renewable energy domain in which such models have not been used before.

5.2 Research limitations and future avenues

For moving towards sustainable renewable energy systems and a low carbon economy, decision support tools are required in order to improve the accuracy of the policy makers /developers choices. One of the limitations of the presented research, is the assumption of one group of decision makers (namely the developers) in the decision making process. This assumption may be limiting since, in some cases, several stakeholders may be involved with different (conflicting) perspectives. In order to implement this model in a real world case, successful and continuous stakeholder participation is important in improving the decision making process. Future research may focus on incorporating several stakeholders with different view points in the decision making to avoid the dominance of one group of stakeholders and include as many dimensions as possible in the decision making model. For example, the fishing industry or other marine users such as container shipping may be opposed to the development of such projects which could affect the decision process. Future research may focus on the development of models given a network of decision makers with conflicting interests and may consider a broader range of criteria for decision making.

The contribution of this study lies in the development of set of decision support models, which provide practical managerial tools for guiding policy makers on their mission for renewable energy developments. Marine renewable energies are a growing sector around the world, and many countries are discovering the vast sustainable and clean energy potential that these sources offer. Coastal countries in particular, can directly take advantage of such sources for tackling greenhouse gas emissions, climate change and protect national energy security. The presented decision support models in this thesis may have applications in any region opting for further investments in this sector.

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Appendix

Chapter 2 : Data related to the DEA analysis

		Inputs				Outputs		
	Offshore wind farms	No.turbine	Social Impact	Area km^2	combined(million £ /MW)	annual energy production (GWh)	Connectivity	Water depth
1	Scroby Sands	30	5	4	3.25	142.4326	0.030186	5
2	North Hoyle	30	4	10	3.29	164.8836	0.033063	8.5
3	Kentish Flats	30	5	10	2.77	180.2663	0.049661	3.5
4	Burbo Bank	25	4	10	3.52	212.3322	0.063561	2.5
5	burbo bank extension	32	4	40	6.00	1166.521	0.04894	8.5
6	Beatrice	84	4	131	5.95	1477.845	0.007617	42.5
7	Hornsea project 1	174	1	407	5.40	5289.842	0.006887	30.5
8	East Anglia 1	102	1	205	6.20	3005.043	0.010766	35.5
9	Dudgeon	67	2	55	6.45	1798.595	0.014147	18
10	Rampion	116	4	79	6.24	1966.147	0.029577	29
11	Galloper	56	2	113	7.44	1855.832	0.010544	27
12	Walney extension	87	3	149	3.58	1530.626	0.019795	37
13	Walney Phase 1	51	4	28	6.49	793.8238	0.02503	21
14	Walney Phase 2	51	3	45	7.08	998.4333	0.02106	27
15	Race bank	91	2	62	5.54	2371.951	0.012837	15
16	Lincs	75	5	41	6.70	1202.676	0.01215	12

17	London array	175	3	122	6.86	3596.732	0.020775	11.5
18	Lynn	27	5	10	3.14	256.0966	0.012524	9
19	Teeside	27	5	4	6.20	281.0292	0.020247	12
20	Thanet	100	4	35	4.72	600.8877	0.023836	18.5
21	Sheringham shoal	88	3	35	5.61	1125.632	0.017536	18.5
22	Rhyl flats	25	4	10	4.14	237.1265	0.022961	7.5
23	Robin Rigg	58	4	18	3.77	348.5148	0.01348	6
24	Ormonde	30	4	10	5.93	647.5133	0.025062	19
25	Westermost rough	35	4	35	5.65	933.457	0.031868	17
26	West of duddon sands	108	3	67	6.76	2114.329	0.029766	19
27	Gwynt y mor	160	4	68	4.91	1688.189	0.025198	22.5
28	Gunfleet sands	48	5	16	4.48	439.0244	0.0191	6.5
29	Greater Gabbard	140	2	146	5.98	2239.777	0.011171	20.5
30	Humber gateway	73	5	27	6.44	1029.778	0.023769	13.5
31	Barrow	30	5	10	3.56	265.3192	0.038863	14
32	Amrumbank west	80	1	33	6.51	1561.375	0.005701	22.5
33	Bard offshore	80	1	59	10.29	1735.606	0.00429	40
34	Butendiek	80	2	33	7.89	1566.17	0.004597	19.5
35	EN BW Baltic 1	21	4	7	6.22	134.739	0.014989	17.5

36	EN BW Baltic 2	80	2	30	6.84	1149.14	0.008387	31
37	Dantysk	80	1	66	7.15	1654.155	0.003985	25
38	Global tech 1	80	1	42	6.98	1583.224	0.004443	39.5
39	Riffgat	30	1	6	8.07	601.8295	0.005943	20.5
40	Sand bank	72	1	47	8.06	1811.052	0.003742	27.5
41	trianel windpark borkum	40	1	23	4.96	399.2861	0.00532	30
42	Arkona	60	2	39	4.14	1055.604	0.00669	24.5
43	borkum riffgrunde 1	78	1	36	6.27	1588.658	0.00562	26
44	Borkum Riffgrund 2	56	1	36	5.76	2130.341	0.005534	27
45	Merkur	66	1	39	5.73	1101.627	0.005476	30
46	Nordergrunde	18	4	3	6.04	407.8694	0.010706	7
47	wikinger	70	1	34	5.96	1175.707	0.006682	38
48	Veja mate	67	1	51	8.33	2329.999	0.00423	40
49	Alpha ventus	12	1	4	6.74	200.5886	0.005626	29
50	Nordsee One	54	1	35	5.21	1205.254	0.006043	28.5
51	Meerwind sud/ost	80	1	40	6.88	1561.375	0.006161	25.5
52	Belwind	55	1	13	5.71	676.9664	0.010679	16
53	nobelwind offshore wind farm	50	1	22	6.24	730.95	0.010817	26.5

54	North wind offshore wind farm	72	2	14	7.53	1392.785	0.007758	19
55	Thornton Bank 1	6	3	2	7.89	146.8953	0.012967	20
56	Thonton bank 2	30	3	12	4.56	734.4764	0.012997	13
57	Thornton Bank 3	18	3	7	9.88	333.3458	0.012885	16
58	Rentel	42	2	23	4.53	738.9227	0.012399	29
59	Norther	44	3	38	4.52	774.1095	0.013955	19.5
60	Egmond aan Zee	36	4	24	5.08	278.2169	0.042655	16.5
61	Eneco Luchterduinen	43	3	16	4.83	400.1407	0.02845	20
62	Gemini	150	1	70	7.54	3640.003	0.006981	33
63	Prinses Amalia	60	3	17	11.44	558.3359	0.027681	21.5
64	Westermeerwind	48	3	16	3.63	414	0.017857	5
65	Anholt	111	3	116	5.00	1589.021	0.012744	15.5
66	Middlegrunden	20	1	10	10.63	48.12018	0.154921	4.5
67	Rodsand 2	90	1	34	3.60	577.453	0.007085	9
68	Horns Rev 3	49	3	144	3.47	977.6694	0.006063	15.5
69	Horns Rev 1	80	1	21	3.16	379.8203	0.006031	8.5
70	Nysted	72	5	26	5.02	359.1439	0.007334	7.5
71	Horns Rev2	91	1	33	3.43	583.8692	0.005709	13

Table 35:Data related to DEA analysis

Type	Description	Depth
Monopile	This foundation consists of a sylindrcal steel tube supporting the tower and is fixed into the seabed. Currently this is the most common foundation used for offshore wind	0-30
Jacket/	Jacket foundation consists of corner piles interconnected and fixed into the soil	25-50
Tripod	Tripods consist of three diagonal braces	25-50

	anchored to the seabed with piles	
Tension Leg Platform (TLPs)	In TLPs tendons anchor the floating structure on the sea bottom	50-120
Semi submersibles(floating)	In floating platforms a floating barge is anchored into the seabed	>120
Spar (Floating)	The Spar foundation is a ballasted vertical tube that floats upright	>120

Table 36: Offshore wind foundation types

Chapter 3: Offshore wind port suitability Questionnaire

Participant Name:

Position:

Company:

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

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with I	A reasonable assumption

1.1-1.9	If the activities are very close	May be difficult to assign the best value but when compare with other contrasting activities the size of small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Table 37:AHP scale

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

Example: If you were to compare these two criteria in terms of importance, e.g. Port's physical characteristics Versus Port's connectivity, which score you would give to the first criteria VS the second one?

If your answer is 1, it means that these two criteria are **equally important.**

….

if your answer is 5 it means that the first criteria is **strongly more important** compared to the second one

…..

If your answer is 9 it means that the first criteria is **extremely more important** compared to the second one.

*Please note: if you think that the second criteria is more important, then your answer should be the reciprocal of the above.

For example: if you think that the port's connectivity extremely more important than the port's physical characteristics, then your answer should be 1/9.

Installation port:

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

18	Distance to offshore site VS distance to road networks	
19	Distance to key component supplier VS distance to road networks	
20	Potential for expansion VS component laydown area	
21	Potential for expansion VS storage capacity	
22	Potential for expansion VS component fabrication facility	
23	Component laydown area VS storage capacity	
24	Component laydown area VS component fabrication facility	
25	Storage Capacity VS fabrication facility	
26	Component laydown area VS laydown's area access to quayside	
27	Storage load bearing capacity VS open storage area	
28	Storage load bearing capacity VS covered storage area	
29	Open storage area VS covered storage area	

Table 38: Pairwise comparison questionnaire for installation port

O&M Port:

	Pairwise comparisons	Score

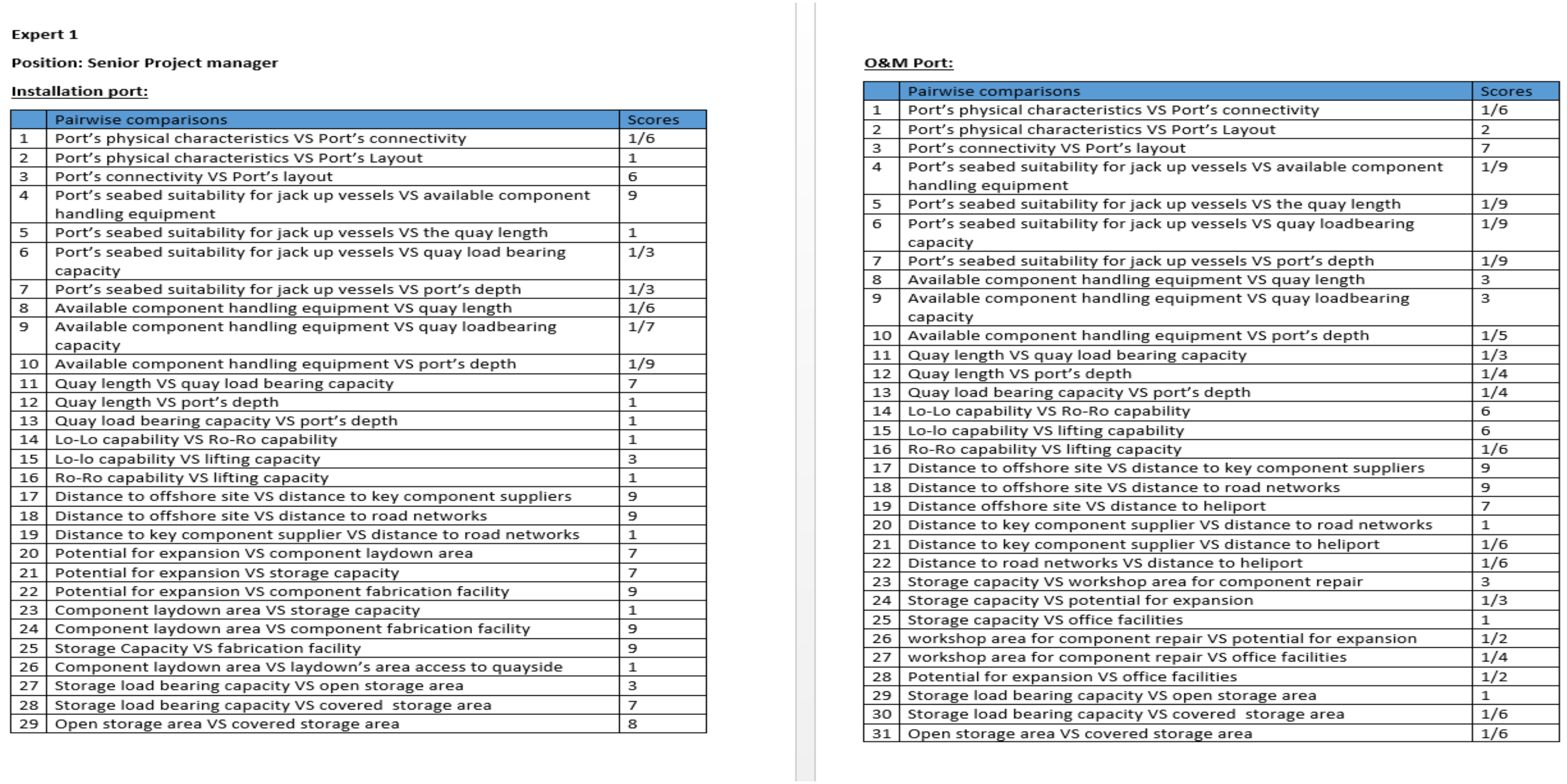
1	Port’s physical characteristics VS Port’s connectivity	
2	Port’s physical characteristics VS Port’s Layout	
3	Port’s connectivity VS Port’s layout	
4	Port’s seabed suitability for jack up vessels VS available component handling equipment	
5	Port’s seabed suitability for jack up vessels VS the quay length	
6	Port’s seabed suitability for jack up vessels VS quay loadbearing capacity	
7	Port’s seabed suitability for jack up vessels VS port’s depth	
8	Available component handling equipment VS quay length	
9	Available component handling equipment VS quay loadbearing capacity	
10	Available component handling equipment VS port’s depth	
11	Quay length VS quay load bearing capacity	
12	Quay length VS port’s depth	
13	Quay load bearing capacity VS port’s depth	
14	Lo-Lo capability VS Ro-Ro capability	
15	Lo-lo capability VS lifting capability	
16	Ro-Ro capability VS lifting capacity	
17	Distance to offshore site VS distance to key component suppliers	
18	Distance to offshore site VS distance to road networks	
19	Distance offshore site VS distance to heliport	
20	Distance to key component supplier VS distance to road networks	

21	Distance to key component supplier VS distance to heliport	
22	Distance to road networks VS distance to heliport	
23	Storage capacity VS workshop area for component repair	
24	Storage capacity VS potential for expansion	
25	Storage capacity VS office facilities	
26	workshop area for component repair VS potential for expansion	
27	workshop area for component repair VS office facilities	
28	Potential for expansion VS office facilities	
29	Storage load bearing capacity VS open storage area	
30	Storage load bearing capacity VS covered storage area	
31	Open storage area VS covered storage area	

Table 39:Pairwise comparison questionnaire for O&M port

Questionnaires completed by experts:

Expert 1



Expert 1

Position: Senior Project manager

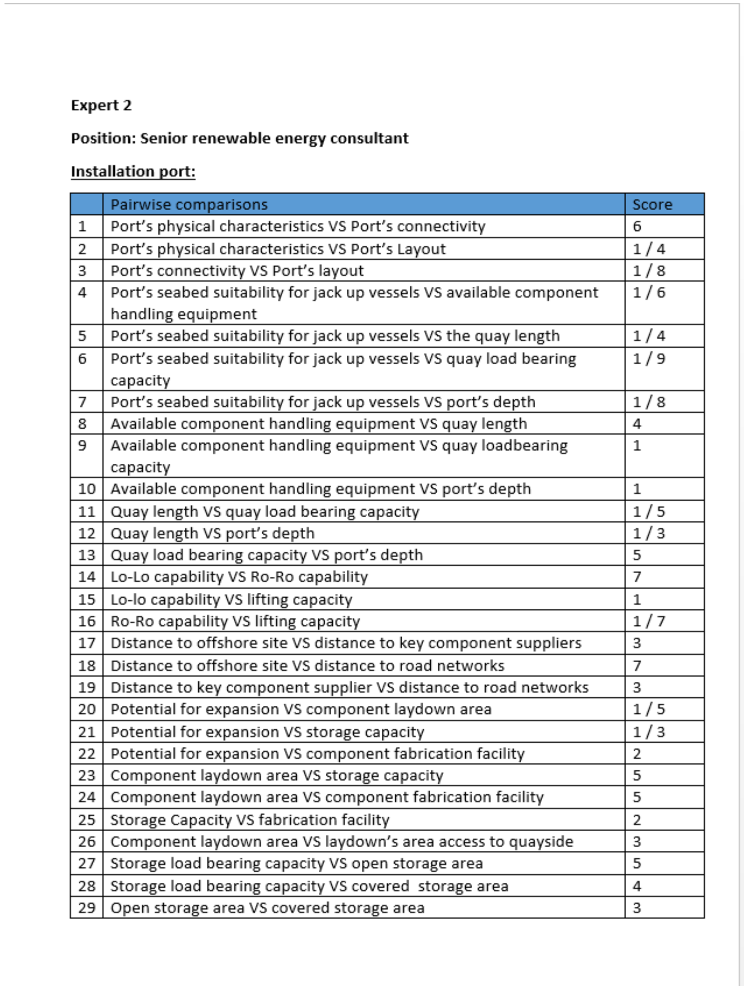
Installation port:

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

O&M Port:

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

Expert 2

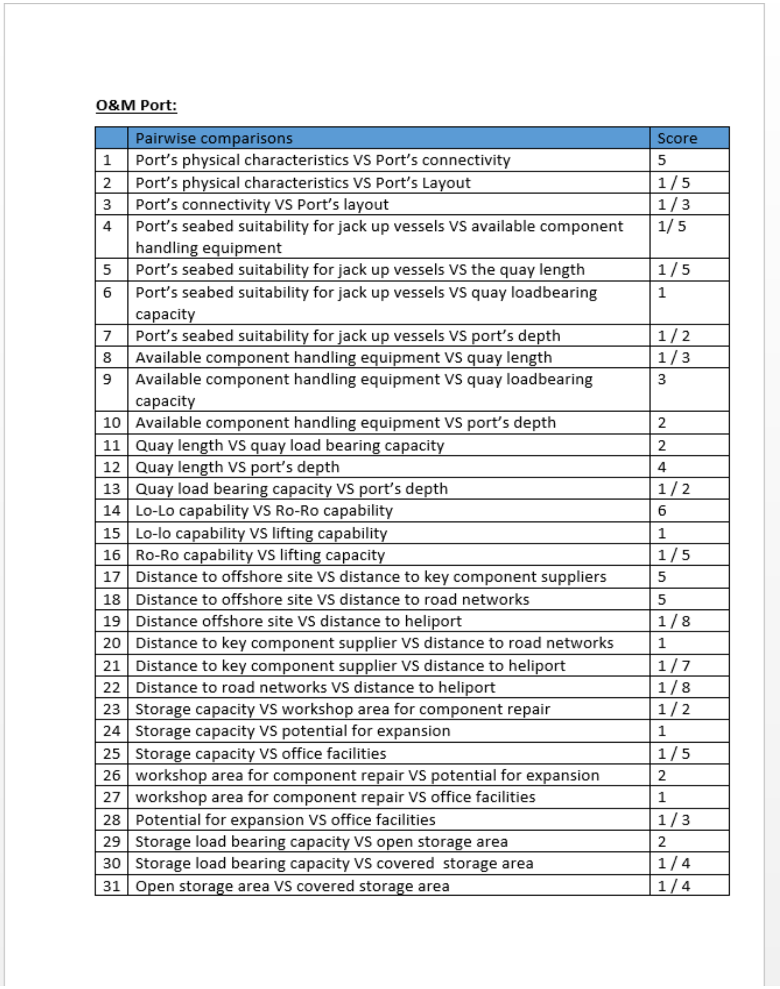


Expert 2

Position: Senior renewable energy consultant

Installation port:

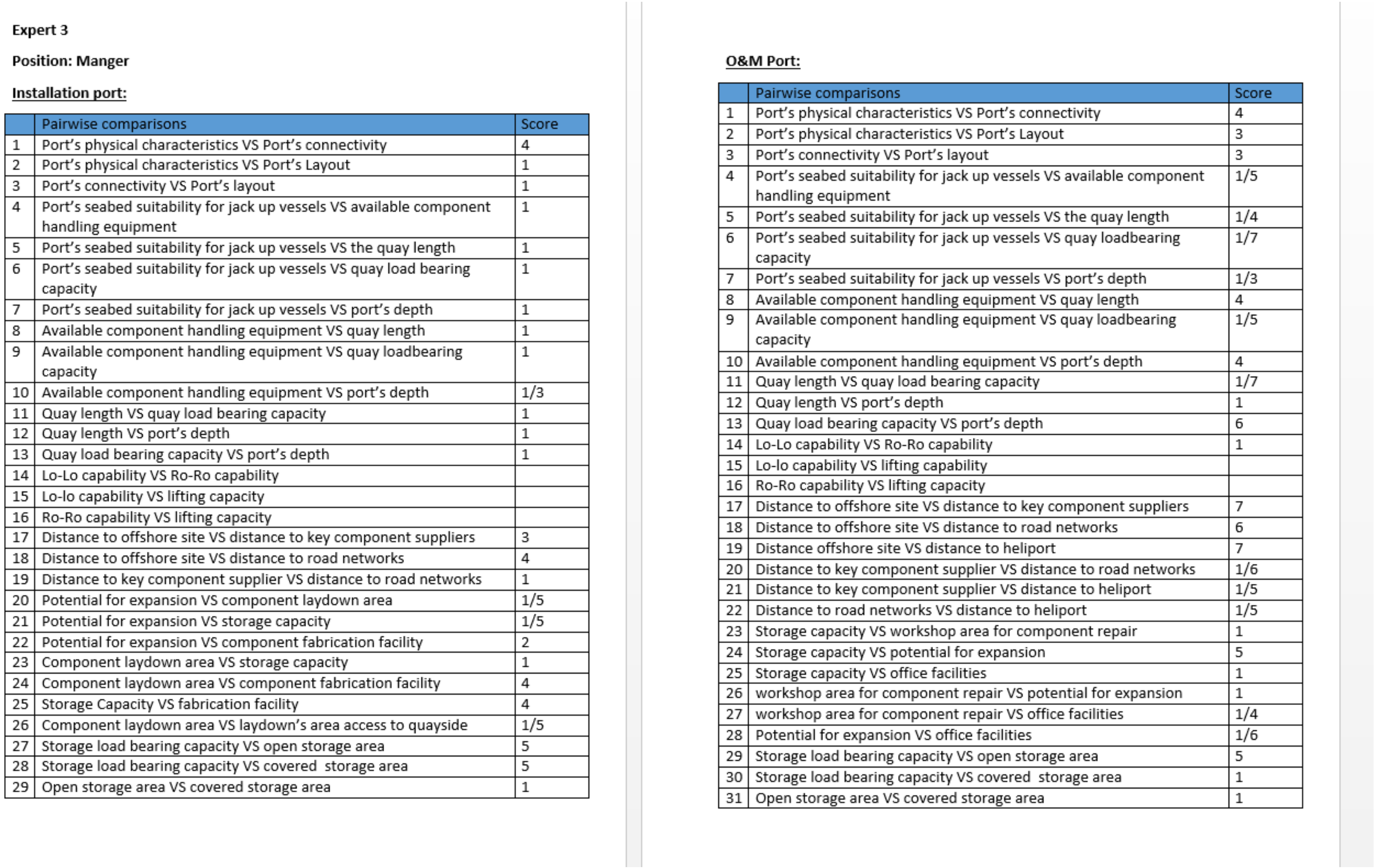
	Pairwise comparisons	Score
1	Port’s physical characteristics VS Port’s connectivity	6
2	Port’s physical characteristics VS Port’s Layout	1 / 4
3	Port’s connectivity VS Port’s layout	1 / 8
4	Port’s seabed suitability for jack up vessels VS available component handling equipment	1 / 6
5	Port’s seabed suitability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



O&M Port:

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

Expert 3



Expert 3

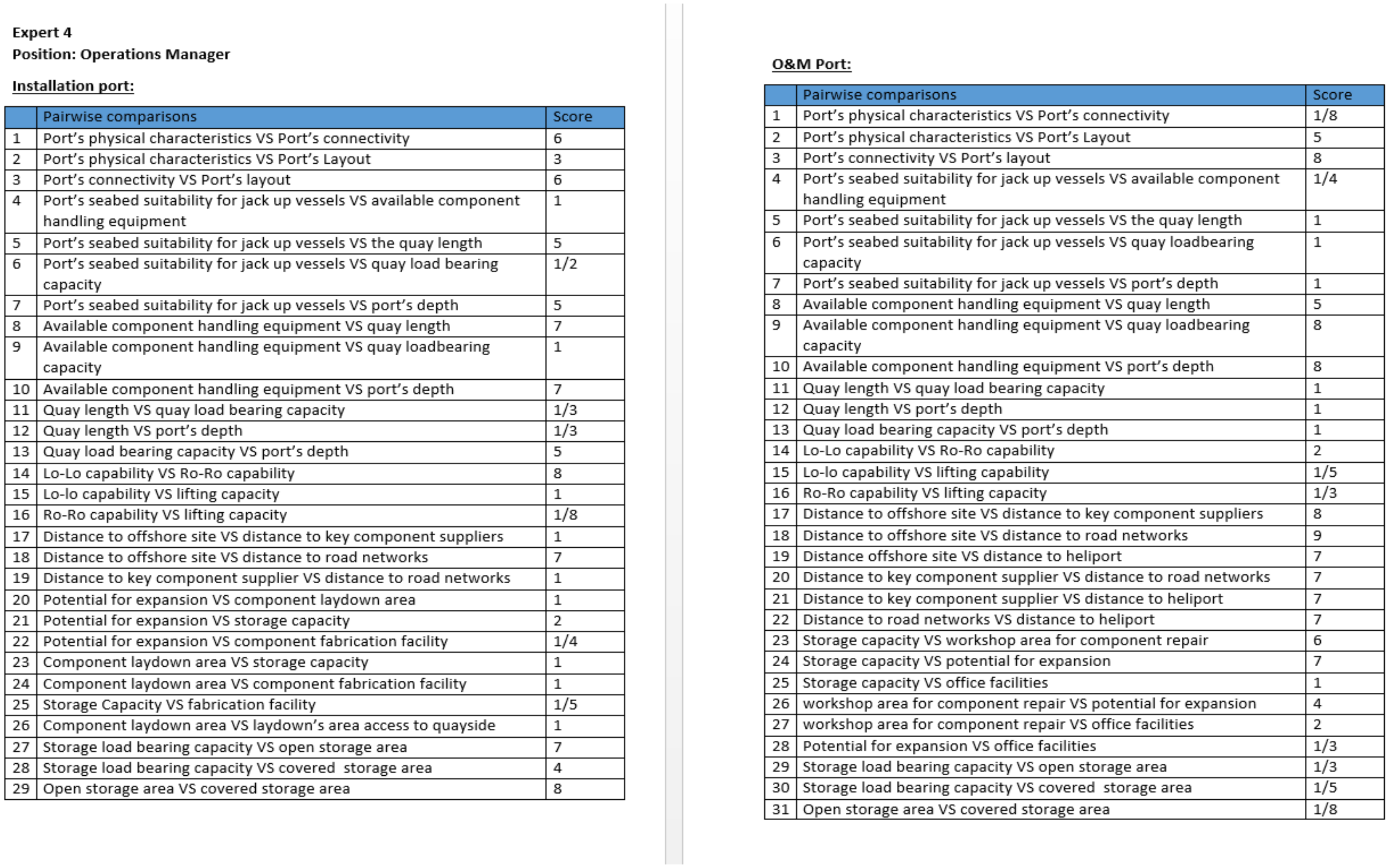
Position: Manger

Installation port:

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

O&M Port:

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



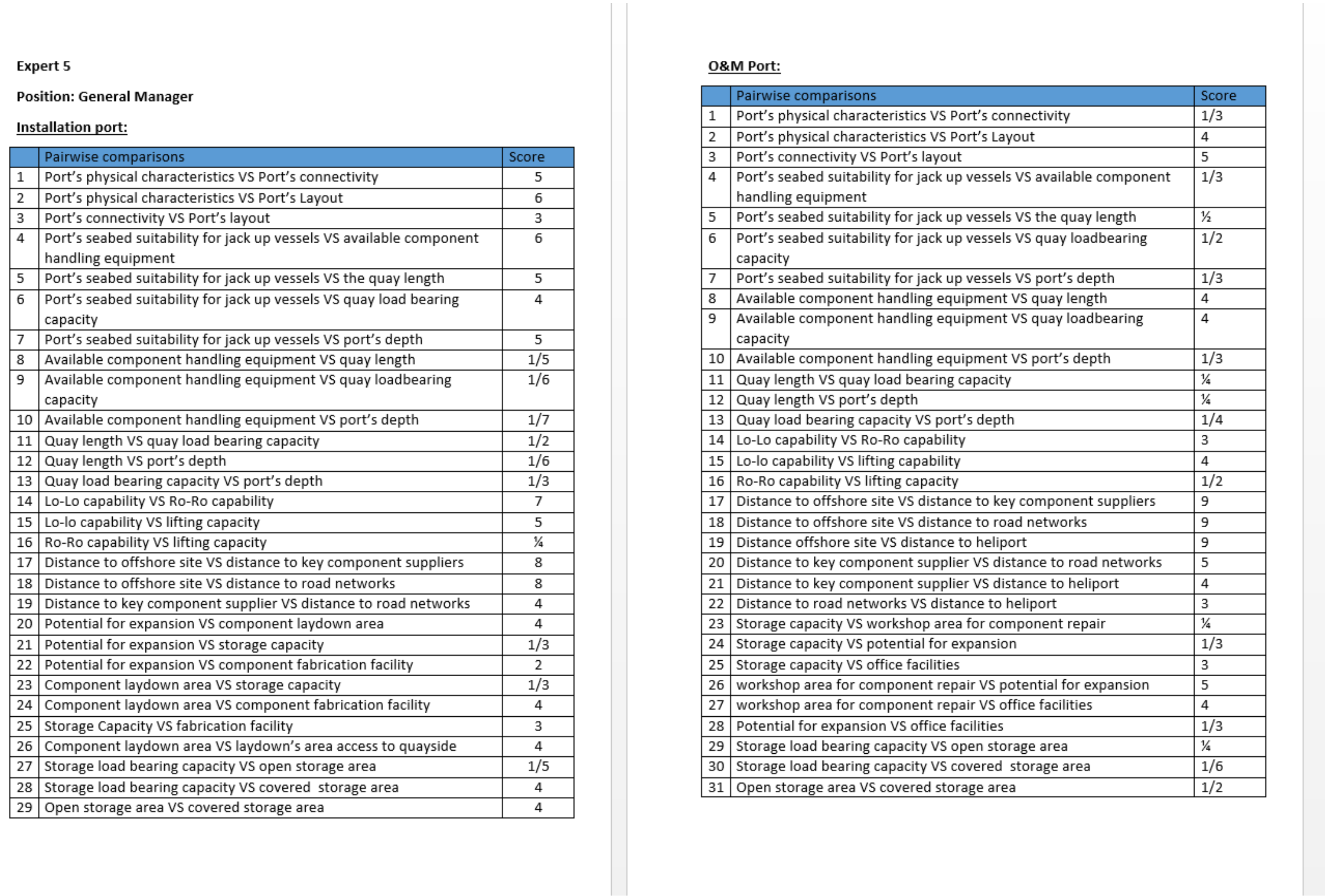
Expert 4
Position: Operations Manager

Installation port:

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

O&M Port:

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



Expert 5

Position: General Manager

Installation port:

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

O&M Port:

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

Appendix

Port Data:

Port's Name	Country	Port depth(m)	Quay length	Draught(m)	Seabed suitability	distance to helipad(km)	distance to international airport(km)	Distance to offshore site(km)	Distance to nearest rail network	distance to nearest road network	no. Crane	Quay length(m)	Quay loading capacity(tonnes/m^2)	Storage space available(Hectars)	development land availbale(Hectars)
Great yarmouth	UK	9	220	10	1	6.4	36.8	74	3	133	3	1400	3	2	12
Grimsby	UK	5.8	145	5.8	1	30	30	270	2	0.1	6	145	5	2	1
Harvich Navyard	UK	8.5	175	8.5	1	96	96	56	0	80	1	175	1	2	4
Hull	UK	11.3	215	10.4	1	21	21	270	4	30	5	5069	40	23	50
Humberport	UK	17.5	1389	17.5	1	14.5	14.5	270	0	30	4	1279	20	60	10
Lowesttoft-ABP	UK	6	125	6	1	0	52	61	0	128	0	2100	5	1	3
Oostend	Bel	13	250	8	1	0	6.5	101	0	2	3	1500	20	127	15
Ramsgate	UK	7.2	180	6.5	1	5	5	101	3	37	2	80		10	10
Sheerness	UK	12	230	12	1	100	100	101	0	17	12	330	40	80	85

Table 40: Port data for AHP

Chapter 4: Data related to Marine renewable energy projects

	MRE project	CAPEX (m£/100)			OPEX(m£)			Co2 reduction			Emplyoment(EMP)			Annual energy production (GWh)(PP)			connectivity to poplulation centers (CP)		
1	dogger bank Creyke beck A	2861385600	3576732000	4292078400	171,683,136	214,603,920.00	257,524,704.00	1,475,884.80	1844856	2213827.20	33600.00	42,000.00	50,400.00	3,279,744.00	4,099,680.00	4,919,616.00	104.80	131.00	157.20
2	dogger bank Creyke beck B	2861385600	3576732000	4292078400	171,683,136	214,603,920.00	257,524,704.00	1,475,884.80	1844856	2213827.20	33600.00	42,000.00	50,400.00	3,279,744.00	4,099,680.00	4,919,616.00	104.80	131.00	157.20
3	dogger bank Teesside A	2861385600	3576732000	4292078400	171,683,136	214,603,920.00	257,524,704.00	1,475,884.80	1844856	2213827.20	33600.00	42,000.00	50,400.00	3,279,744.00	4,099,680.00	4,919,616.00	156.80	196.00	235.20
4	East Anglia three	3338283200	4172854000	5007424800	200,296,992	250,371,240.00	300,445,488.00	1,721,865.60	2152332	2582798.40	39200.00	49000.00	58,800.00	3,826,368.00	4,782,960.00	5,739,552.00	59.20	74.00	88.80
5	firth of forth1(Alpha and bravo)	3576732000	4470915000	5365098000	214,603,920	268,254,900.00	321,905,880.00	1,844,856.00	2306070	2767284.00	42000.00	52500.00	63,000.00	4,099,680.00	5,124,600.00	6,149,520.00	21.60	27.00	32.40
6	Hornsea project 2	3304900368	4131125460	4957350552	198,294,022	247,867,527.60	297,441,033.12	1,704,646.94	2130808.68	2556970.42	38808.00	48510.00	58,212.00	3,788,104.32	4735130.40	5,682,156.48	96.80	121.00	145.20
7	Inch Cape	1669141600	2086427000	2503712400	100,148,496	125,185,620.00	150,222,744.00	860,932.80	1076166	1291399.20	19600.00	24500.00	29,400.00	1,913,184.00	2391480.00	2,869,776.00	12.00	15.00	18.00
8	Moray firth western	1907590400	2384488000	2861385600	114,455,424	143,069,280.00	171,683,136.00	983,923.20	1229904	1475884.80	22400.00	28000.00	33,600.00	2,186,496.00	2733120.00	3,279,744.00	18.00	22.50	27.00
9	Neart na gaoithe	1068250624	1335313280	1602375936	64,095,037	80,118,796.80	96,142,556.16	550,996.99	688746.24	826495.49	12544.00	15680.00	18,816.00	1,224,437.76	1530547.20	1,836,656.64	12.40	15.50	18.60
10	Sofia	3338283200	4172854000	5007424800	200,296,992	250,371,240.00	300,445,488.00	1,721,865.60	2152332	2582798.40	39200.00	49000.00	58,800.00	3,826,368.00	4782960.00	5,739,552.00	132.00	165.00	198.00

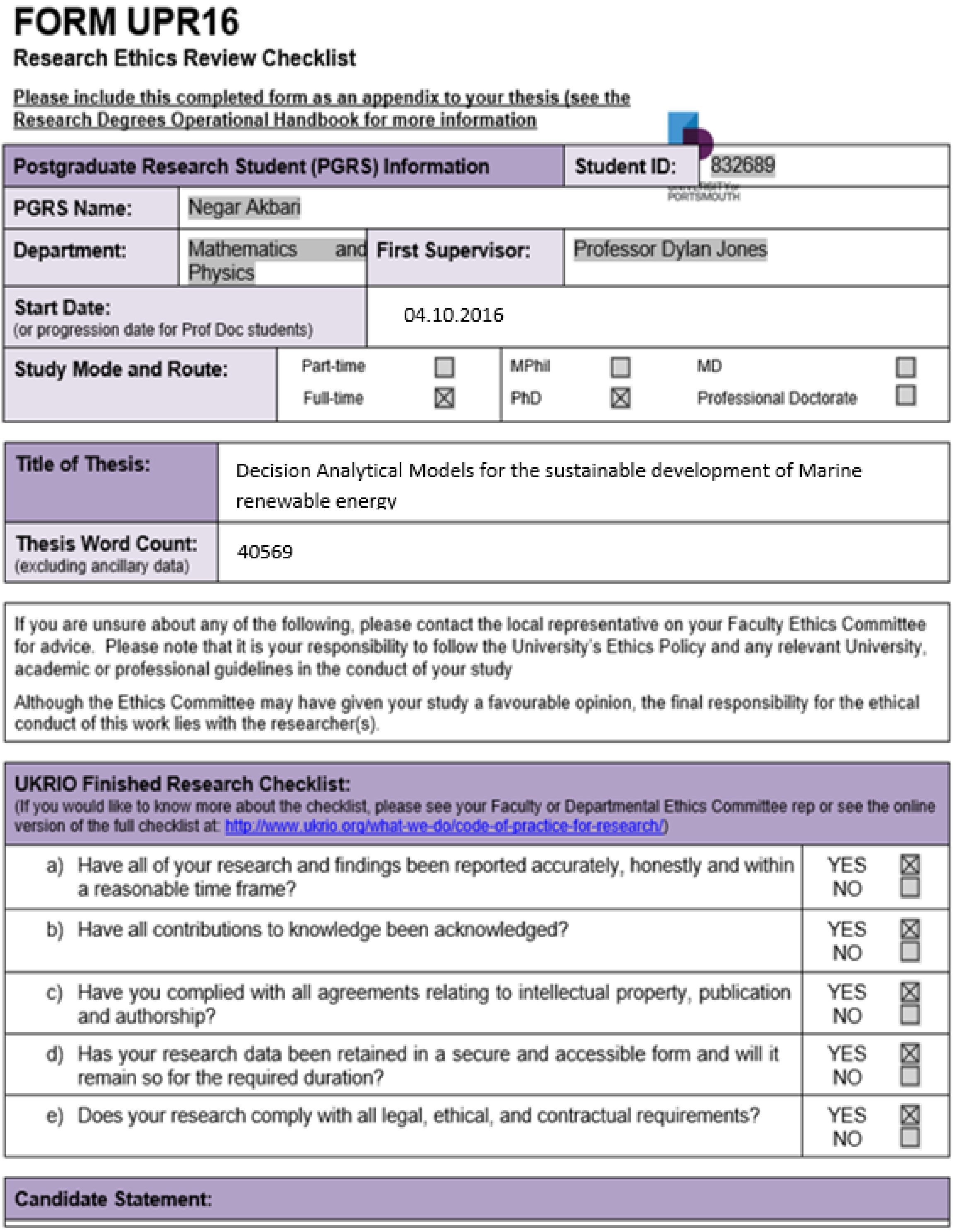
Appendix

11	Triton Knoll	2050659680	2563324600	3075989520	123,039,581	153,799,476.00	184,559,371.20	1,057,717.44	1322146.8	1586576.16	24080.00	30100.00	36,120.00	2,350,483.20	2938104.00	3,525,724.80	26.40	33.00	39.60
12	ardsey Sound Tidal Array	17760000	22200000	26640000	744,000	930,000.00	1,116,000.00	3,689.71	4612.14	5534.57	68.40	85.50	102.60	8,199.36	10249.20	12,299.04	49.64	62.04	74.45
13	Wyre Estuary Tidal Barrage	588800000	736000000	883200000	21,760,000.000	27,200,000.00	32,640,000.00	-		0.00	3648.00	4560.00	5,472.00	437,299.20	546624.00	655,948.80	9.14	11.43	13.71
14	Bluemull Sound	1130400	1413000	1695600	45,120.000	56,400.00	67,680.00	36.90	46.1214	55.35	0.68	0.86	1.03	81.99	102.49	122.99	33.82	42.27	50.73
15	Brims Tidal Array Phase 1	120000000	150000000	180000000	4,080,000.000	5,100,000.00	6,120,000.00	36,897.12	46121.4	55345.68	684.00	855.00	1,026.00	81,993.60	102,492.00	122,990.40	17.99	22.49	26.99
16	Brims Tidal Array Phase 2	625600000	782000000	938400000	23,120,000.000	28,900,000.00	34,680,000.00	209,083.68	261354.6	313625.52	3876.00	4,845.00	5,814.00	464,630.40	580,788.00	696,945.60	17.99	22.49	26.99
17	Lashy Sound Phase 1	38400000	48000000	57600000	2,560,000.000	3,200,000.00	3,840,000.00	12,299.04	15373.8	18448.56	228.00	285.00	342.00	27,331.20	34,164.00	40,996.80	23.92	29.90	35.88
18	Lashy Sound Phase 2	76800000	96,000,000	115200000	5,120,000.000	6,400,000.00	7,680,000.00	24,598.08	30747.6	36897.12	456.00	570.00	684.00	54,662.40	68,328.00	81,993.60	23.98	29.98	35.98
19	MeyGen Pentland Firth Phase 1a	23040000	28,800,000	34560000	1,536,000.000	1,920,000.00	2,304,000.00	7,379.42	9224.28	11069.14	136.80	171.00	205.20	16,398.72	20,498.40	24,598.08	20.53	25.66	30.80
20	MeyGen Pentland Firth Phase 1b	23040000	28,800,000	34560000	1,536,000.000	1,920,000.00	2,304,000.00	7,379.42	9224.28	11069.14	136.80	171.00	205.20	16,398.72	20,498.40	24,598.08	20.53	25.66	30.80
21	MeyGen Pentland Firth Phase 1c	294000000	367,500,000	441000000	9,996,000.000	12,495,000.00	14,994,000.00	90,397.94	112997.43	135596.92	1675.80	2,094.75	2,513.70	200,884.32	251,105.40	301,326.48	20.53	25.66	30.80
22	MeyGen Pentland Firth Phase 2	1148160000	1,435,200,000	1722240000	42,432,000.000	53,040,000.00	63,648,000.00	383,730.05	479662.56	575595.07	7113.60	8,892.00	10,670.40	852,733.44	1,065,916.80	1,279,100.16	20.63	25.79	30.95
23	Minesto Strangford Lough	1130400	1,413,000	1695600	712,800.000	891,000.00	1,069,200.00	36.90	46.1214	55.35	0.68	0.86	1.03	81.99	102.49	122.99	58.03	72.54	87.04
24	PLAT-I Floating Tidal	7168000	8,960,000	10752000	421,120.000	526,400.00	631,680.00	344.37	430.4664	516.56	6.38	7.98	9.58	765.27	956.59	1,147.91	30.52	38.15	45.78

	Energy Platform																		
25	Ramsey Sound	9504000	11,880,000	14256000	2,256,000.000	2,820,000.00	3,384,000.00	491.96	614.952	737.94	9.12	11.40	13.68	1,093.25	1,366.56	1,639.87	1.78	2.22	2.67
26	Seagen Strangford Lough	8064000	10,080,000	12096000	8,064,000.000	10,080,000.00	12,096,000.00	1,475.88	1844.856	2213.83	27.36	34.20	41.04	3,279.74	4,099.68	4,919.62	57.36	71.70	86.03
27	Shetland Tidal Array Phase 1	7680000	9,600,000	11520000	7,128,000.000	8,910,000.00	10,692,000.00	368.97	461.214	553.46	6.84	8.55	10.26	819.94	1,024.92	1,229.90	33.68	42.10	50.52
28	Wave Hub CETO 6 Phase 1	6880000	8,600,000	10320000	176,000.000	220,000.00	264,000.00	1,229.90	1537.38	1844.86	23.48	29.35	35.22	2,733.12	3,416.40	4,099.68	55.98	69.98	83.97
29	Wave Hub CETO 6 Phase 2	6880000	8,600,000	10320000	176,000.000	220,000.00	264,000.00	1,229.90	1537.38	1844.86	23.48	29.35	35.22	2,733.12	3,416.40	4,099.68	55.98	69.98	83.97
30	Wave Hub Seatricity Phase 1	3289600	4,112,000	4934400	28,160.000	35,200.00	42,240.00	196.78	245.9808	295.18	3.76	4.70	5.64	437.30	546.62	655.95	55.98	69.98	83.97
31	Wave Hub Seatricity Phase 2	28830400	36,038,000	43245600	1,714,240.000	2,142,800.00	2,571,360.00	11,979.26	14974.0812	17968.90	228.70	285.87	343.04	26,620.59	33,275.74	39,930.88	55.98	69.98	83.97
32	FaBTest WaveSub	5140000	6,425,000	7710000	44,000.000	55,000.00	66,000.00	307.48	384.345	461.21	5.87	7.34	8.81	683.28	854.10	1,024.92	39.68	49.60	59.52
33	EMEC Aquamarine Power Phase 2	12992000	16,240,000	19488000	140,800.000	176,000.00	211,200.00	983.92	1229.904	1475.88	18.78	23.48	28.18	2,186.50	2,733.12	3,279.74	7.39	9.23	11.08
34	EMEC Clean Energy From Ocean Waves (CEFOW) Phase 1	6880000	8600000	10320000	176,000.000	220,000.00	264,000.00	1,229.90	1537.38	1844.86	23.48	29.35	35.22	2,733.12	3,416.40	4,099.68	9.34	11.67	14.00
35	EMEC Laminaria	4112000	5140000	6168000	35,200.000	44,000.00	52,800.00	245.98	307.476	368.97	4.70	5.87	7.04	546.62	683.28	819.94	9.34	11.67	14.00
36	EMEC OpenHydro	5140000	6425000	7710000	44,000.000	55,000.00	66,000.00	307.48	384.345	461.21	5.87	7.34	8.81	683.28	854.10	1,024.92	17.07	21.34	25.60

37	EMEC Scotrenewables SR2000	13760000	17200000	20640000	352,000.000	440,000.00	528,000.00	2,459.81	3074.76	3689.71	46.96	58.70	70.44	5,466.24	6,832.80	8,199.36	9.34	11.67	14.00
38	EMEC ScottishPower Renewables Pelamis P2	12180000	15225000	18270000	132,000.000	165,000.00	198,000.00	922.43	1153.035	1383.64	17.61	22.01	26.42	2,049.84	2,562.30	3,074.76	8.89	11.11	13.33
39	EMEC Seatricity	1315200	1644000	1972800	3,520.000	4,400.00	5,280.00	24.60	30.7476	36.90	0.47	0.59	0.70	54.66	68.33	81.99	8.75	10.94	13.13
40	EMEC Sustainable Marine Energy	6880000	8600000	10320000	176,000.000	220,000.00	264,000.00	1,229.90	1537.38	1844.86	23.48	29.35	35.22	2,733.12	3,416.40	4,099.68	16.24	20.30	24.36
41	EMEC Tocardo Phase 2	12040000	15050000	18060000	308,000.000	385,000.00	462,000.00	2,152.33	2690.415	3228.50	41.09	51.36	61.64	4,782.96	5,978.70	7,174.44	15.21	19.01	22.81
42	EMEC Wello Oy	8120000	10150000	12180000	88,000.000	110,000.00	132,000.00	614.95	768.69	922.43	11.74	14.68	17.61	1,366.56	1,708.20	2,049.84	9.98	12.48	14.98
43	Holyhead Deep - Phase 1	8120000	10150000	12180000	88,000.000	110,000.00	132,000.00	614.95	768.69	922.43	11.74	14.68	17.61	1,366.56	1,708.20	2,049.84	9.20	11.51	13.81

Table 41: Data related to MRE projects



FORM UPR16

Research Ethics Review Checklist

Please include this completed form as an appendix to your thesis (see the Research Degrees Operational Handbook for more information

Postgraduate Research Student (PGRS) Information		**Student ID:**	832689
PGRS Name:	Negar Akbari		
Department:	Mathematics and Physics	**First Supervisor:**	Professor Dylan Jones
Start Date: (or progression date for Prof Doc students)		04.10.2016	
Study Mode and Route:	Part-time ☐ Full-time ☒	MPhil ☐ PhD ☒	MD ☐ Professional Doctorate ☐

Title of Thesis:	Decision Analytical Models for the sustainable development of Marine renewable energy
Thesis Word Count: (excluding ancillary data)	40569

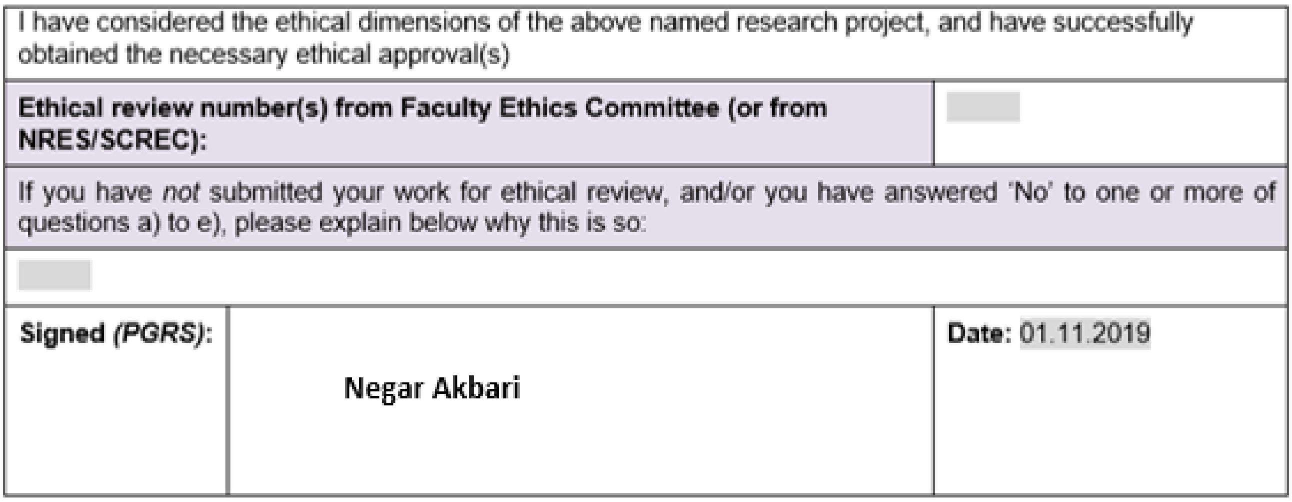
If you are unsure about any of the following, please contact the local representative on your Faculty Ethics Committee for advice. Please note that it is your responsibility to follow the University's Ethics Policy and any relevant University, academic or professional guidelines in the conduct of your study

Although the Ethics Committee may have given your study a favourable opinion, the final responsibility for the ethical conduct of this work lies with the researcher(s).

UKRIO Finished Research Checklist:
(If you would like to know more about the checklist, please see your Faculty or Departmental Ethics Committee rep or see the online version of the full checklist at: http://www.ukrio.org/what-we-do/code-of-practice-for-research/)

a) Have all of your research and findings been reported accurately, honestly and within a reasonable time frame?	YES ☒ NO ☐
b) Have all contributions to knowledge been acknowledged?	YES ☒ NO ☐
c) Have you complied with all agreements relating to intellectual property, publication and authorship?	YES ☒ NO ☐
d) Has your research data been retained in a secure and accessible form and will it remain so for the required duration?	YES ☒ NO ☐
e) Does your research comply with all legal, ethical, and contractual requirements?	YES ☒ NO ☐

Candidate Statement:



I have considered the ethical dimensions of the above named research project, and have successfully obtained the necessary ethical approval(s)		
Ethical review number(s) from Faculty Ethics Committee (or from NRES/SCREC):		
If you have *not* submitted your work for ethical review, and/or you have answered 'No' to one or more of questions a) to e), please explain below why this is so:		
Signed ***(PGRS)***:	Negar Akbari	**Date:** 01.11.2019