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A review of operations and maintenance modelling with considerations for novel wind turbine concepts

Jade McMorland [b,*], Callum Flannigan [a], James Carroll [a], Maurizio Collu [b], David McMillan [a], William Leithead [a], Andrea Coraddu [c]

[a] Electronic and Electrical Engineering, University of Strathclyde, Glasgow, United Kingdom
[b] Naval Architecture Ocean and Marine Engineering, University of Strathclyde, Glasgow, United Kingdom
[c] Maritime and Transport Technology, Delft University of Technology, Delft, the Netherlands

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ABSTRACT

New wind turbine technologies and designs are being explored in order to reduce the cost of energy from offshore wind farms. Two potential routes to a lower cost of energy are the X- Rotor Concept (XRC) and Multi-Rotor System (MRS) turbines. A key cost saving for both Novel concepts included in this paper is operation and maintenance (O&M) costs savings. The major component replacement cost for conventional horizontal axis, XRC and MRS turbines are examined and the benefits of the concepts are provided in this paper. A review on existing decision support systems for offshore wind farm O&M planning is presented with a focus on how applicable these previous models are to novel turbine concepts, along with analysis of how the influential factors can be modified to effectively model XRC and MRS.

1. Introduction

Ambitious climate change targets have become law globally following the 2015 Paris agreement. Since then, the UK has committed to a target of 40 GW of installed capacity of offshore wind by 2030 and achieving carbon net-zero by 2050 [1]. However, despite the considerable market growth and success of offshore wind, the levelised cost of energy (LCoE) of the technology is still high in comparison with conventional generation. Initial capital expenditure (CapEx) has seen steady reductions; however, operational expenditure (OpEx) remains high - currently, up to a third of the cost of energy can be attributed to maintenance cost [2]. Future offshore wind farms are also expected to face new challenges of increased distance to shore, more remote locations, and higher installed capacity.

Based on expert opinion and assuming all variables are equal, OpEx typically halves on a per MW basis as capacity doubles. While this seems advantageous, it does not consider practical limitations such as increased supply chain competition and increase in opportunity cost/downtime. Opportunity cost is defined, in industry, as lost revenue which occurs during failure. It is the revenue which could have been generated, had the turbine been operational. Therefore, as turbine, and site, capacity increases, as does the potential revenue loss. The balance between expected OpEx savings and potential opportunity cost is shown in Fig. 1. Opportunity cost is calculated using a value of £47.38/MWh based on the assumption of 2% indexing for the 2012 strike price of £39.65/MWh as provided in the Round 3 CfD Crown Estate (2019) and operating at full capacity during the downtime period.

O&M is a key area of interest with a number of reviews within the literature on O&M modelling and OpEx [3,4]. Seyr and Muskulus [5] break the O&M model into key elements: weather/met-ocean; failure and degradation; transportation and vessel routing; vessel, personnel and spare part logistics; and economic parameters and cost estimation. More recent reviews, such as [6–8], analyse current and future O&M modelling techniques and limitations in research and industry shortcomings. Shafiee [7] divides the literature into long-term, medium-term, and short-term decision support models for all industries. Shafiee et al. build upon this work in Ref. [9] where the authors present a preview of optimisation and inspection planning for offshore wind farms. Rinaldi et al. [8] review and examine future technologies such as artificial intelligence and drones within the industry and how this may benefit O&M practises in the future.

However, these works fail to address the growing concern regarding the increasing size of turbines within the industry. Increasing scale can result in manufacturing and cost concerns. In this work, we introduce

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* Corresponding author.
E-mail addresses: jade.mcmorland@strath.ac.uk (J. McMorland), callum.flannigan@strath.ac.uk (C. Flannigan).

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two novel turbine concepts which overcome these issues and discuss the O&M implications of these concepts: the X-Rotor offshore wind turbine concept (XRC) [10] and the multi-rotor system (MRS) [11–13]. The novel contributions and focus of this paper are to review, summarise, and identify opportunities in the past literature for the areas of O&M cost modelling of novel offshore wind turbine concepts; and to outline the changes required to the inputs of current offshore decision support models to allow for modelling of future concepts. The key motivation for this paper is to allow OpEx cost estimation and operations strategy to progress alongside and, importantly, influence the design of these novel concepts.

In Section 2, the XRC and MRS concepts are introduced along with the main design opportunities of each that could be utilised to make O&M tasks easier and less expensive in Section 2.3. In Section 3, the factors that influence decisions are discussed with a key focus on the extent to which the modelling of these parameters will need to change in order to accommodate new concepts. A table is presented in Section 3.5.1 directly comparing costs of components for a 5 MW version of these concepts and a direct-drive and a 3-stage geared conventional horizontal axis wind tur-bine (HAWT). These cost considerations will be important inputs for O&M cost modelling. The maintenance strategy and different types of maintenance are discussed in Section 4, focusing on the new challenges that are present with the XRC and MRS. Finally, a summary and conclusion are given in Section 5.

2. Novel concepts

The cost of components in the latest generation of offshore wind turbines are becoming more expensive and heavy as the size of the turbines increases [14]. The GE Halliade-X has blades of length 107 m, weighing 55 t each. This poses serious challenges for developers to maintain a competitive LCoE due to the substantial self loads of this structure [14,15]. Any failures to the main components of this turbine will result in a lengthy downtime and expensive repair due to the cost of the components and the requirement for a heavy-lift vessel (HLV). Further increasing the size of conventional wind turbines will further amplify this concern. For this reason, both the wind energy industry and academia are developing alternative options for turbines with a higher power rating and a lower LCoE. In this study, two promising concepts are presented.

2.1. X-Rotor Concept (XRC)

The X-Rotor concept (XRC) offshore wind turbine is the subject of a €4 m EU H2020 project being conducted from 2021 to 2023 called “X-shaped Radical Offshore wind Turbine concept for Overall cost of energy Reduction” (XROTOR) [16]. The XRC is a radical rethink of a vertical axis wind turbine (VAWT) that directly addresses its disadvantages [10]. Fig. 2(a) shows an illustration of the proposed concept. The VAWT part has conventional blades angled both up and down in an ‘X’ shape from the ends of a short cross-arm. The role of the lower half of the XRC is to reduce overturning moment on the main bearing and support the secondary horizontal rotors. The role of the secondary rotors is to provide power take-off (PTO). One of the fundamental issues with VAWTs is PTO due to low rotational speed and high torque. This design removes the PTO from the vertical rotor and in turn reduces the cost vs a conventional VAWT. The rotation round the vertical axis provides the HAWTs with an increased wind speed - leading to increased energy capture for the size of HAWT - and gives a rotational symmetry that removes the requirement for yaw for the turbines. There is a large increase in the rotor speed of the HAWTs with this arrangement; this allows the drivetrain to be a direct-drive system without the need for a multipole generator. Similarly, the torque on the PTO systems is lower for the XRC than for a conventional VAWT.

The O&M costs for this turbine are expected to be reduced due to the being situated closer to sea level. The main benefit from this would be that almost all repair and maintenance could be completed without the need for a heavy lift vessel (HLV), which accounts for 50% vessel charter costs for conventional wind farms [17]. There is also the opportunity for the secondary rotors to be designed as modular systems which can be replaced and maintained onshore, with each secondary rotor module weighing under 10 tonnes. The XRC will also be able to operate with reduced capacity if one of the secondary rotors fails. The turbine will have to switch to a different operational strategy for this.

The XRC has an interesting scaling solution. It is proposed that to increase the rated power of this turbine, additional secondary rotors are added to the lower half of the X, with each secondary rotor having a rated power of 2.5 MW. Another option is to have three primary rotor blades, separated by 120°.

2.2. Multi-rotor systems (MRS)

A Multi-rotor System (MRS) is defined as a HAWT where two or more rotors are placed on a single turbine. A typical MRS configuration and turbine topology is shown in Fig. 2(b). Typically, the rotors are arranged hexagonally to keep loading symmetrical. The first MRS system was built in 1930 by Honnef [19]. Despite the long history of the technology, there is not yet an agreed upon standard design.

The MRS presents itself as the solution to offshore wind’s increasing weight problem. As the size of turbine blades increase even more, the benefit of energy capture is outweighed by the increase in mass and cost [15]. Energy uplift is determined by the square of the area, whereas volume (weight) scales on a cubed basis. The MRS makes use of this dis-advantage by exploiting rotors with a small volume to determine high energy yield over the same area, with a fraction of the weight due to the reduced blade size. This saving in mass, and materials, has a positive

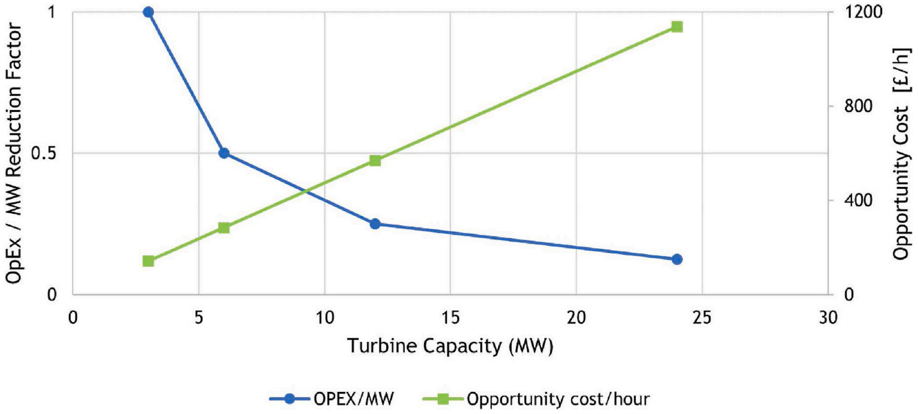

Fig. 1. Predicted reduction in OpEx (£/MW) and calculated opportunity cost based on UK Crown Estate CfD Round 4 price.

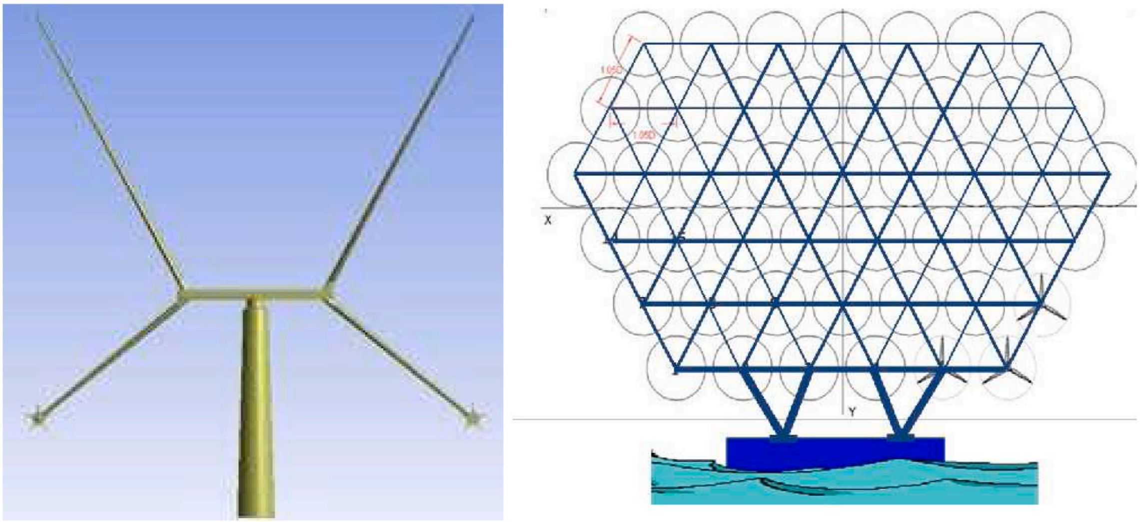

Fig. 2. Images of the novel wind turbine concepts discussed in this paper; (a) an artists impression of a 5 MW X-rotor (XRC) concept (not design drawings) designed by Leithead et al. [10] and (b) the 20 MW Multi-rotor System (MRS) designed by Jamieson and Branney [11,15,18] consisting of 45 × 444 kW turbines. Both images used with permission from original author.

impact on the overall LCoE.

Within the context of this paper, all MRS rotors act as secondary rotors. They are all equally weighted in their contribution to energy capture and probability of failure. The conformity of the rotors will lead to standardisation of components leading to potential cost reduction, reduced system loads and the potential of a modular based approach for assembly, operation and maintenance [15]. While the MRS will require an additional support system for the structure to hold the rotors, this cost is compensated by the cost reduction of blades and drive-train [19].

The main issue surrounding MRS is the increase in the components with some designs having upwards of 45 rotors [11]. An increase in components implies an increase in the overall number of failures. However, unlike with a conventional single rotor machine, a failure does not mean the whole system is required to shut down. A single failure no longer has a detrimental impact on the downtime of the whole system. This allows new maintenance strategies to determined based on a cost/benefit analysis between loss of earning due to single rotor failure vs cost to repair. This approach removes the urgency of finding a suitable weather window and therefore could allow for a safer transfer.

The MRS concept is gaining credibility within industry with both MHI Vestas and Siemens Gamesa building concept demonstrator MRS projects in recent years. The MHI Vestas concept design comprised of four refurbished V29-225 kW nacelles mounted on a single support structure [20]. The project saw technical benefits including a power gain of 1.5% in annual energy production [21] in comparison with a standard HAWT turbine with the same rating. However, as of present there is not a commercial model available.

2.3. Novel concept OpEx reduction opportunities

For both concepts discussed, there is no final standardised design. This allows the concepts to be developed with O&M challenges considered. 2.9 GW of offshore wind was installed in Europe in 2020, bringing the total to GW [22]. Siemens Gamesa and MHI Vestas dominated the market with 63% and 33% of installations by capacity in 2020, respectively. Currently, the technology used in these OEMs (original equipment manufacturer) varies: Siemens Gamesa offshore products are direct-drive turbines [23], and MHI Vestas offshore products are geared permanent magnet synchronous generator turbines [24]. All of these configurations have very little redundancy in the system. Therefore, it is very unlikely to be cost-effective to batch fix failures that have resulted in a non-operational turbine. Similarly, due to large size of each component in the drivetrain, it is difficult to construct the turbine with interchangeable modules. The XRC and MRS can be designed in a way to utilise opportunities such as these. The question of whether the added CapEx for efficient module replacement is worth the reduction in OpEx will be deter-mined by cost models and design research.

In XRC, the power converter will be housed within a central module within the tower that has better accessibility. In a fault-free environment, the rotational speed of the HAWTs will be controlled independently due to the different instantaneous rotational speed required for each. However, if one of the power converters were to fail, they could be controlled together through the remaining, functioning, power converter. This would be less efficient but would increase availability and not require hasty maintenance. For MRS, power converters could be cross-connected and achieve several levels of redundancy with different designs for this. Pirrie et al. [13] present eight electrical topologies for grid connection and analysis of capital cost, mass, and reliability. Some of the configurations in the study rely on components that are not yet commercially available. There is also the possibility of cross linking power converters within MRS.

Due to the nature of having multiple PTOs on one support structure for both XRC and MRS, the systems will have option to operate at reduced capacity with some failed rotors. For example, a 20 MW MRS made up of 45 × 444 kW machines, if one turbine fails, the capacity will only drop to 97.8%. Therefore, the operator could wait until there is a full day of maintenance tasks before chartering a vehicle. Bakir et al. [26] present a multicomponent model to minimise O&M costs which includes batching or repairs based on the prediction of the useful life of the remaining components. Therefore, there could be other criteria in the threshold for when to repair, such as if capacity of the farm drops to a certain percentage.

The design of nacelles for these systems as modules will have a significant impact on OpEx. The modules place replaced and the turbine operation restored quickly with maintenance then carried out onshore. This requires less equipment shipped to the site, tasks become easier to plan, weather windows required are shorter, and training for offshore technicians is less complex. A schematic or repair timeline for a module replacement is shown in Fig. 3. Typical minor repair times are detailed in Carroll et al. [25] for traditional offshore turbines at site. Repair times range from 2 to 10 h, depending on component. This highlights the impact that reduced repair time can have on the overall timeline of the repair task. This also has implications on the maintenance strategy, i.e. corrective, preventative, or predictive maintenance.

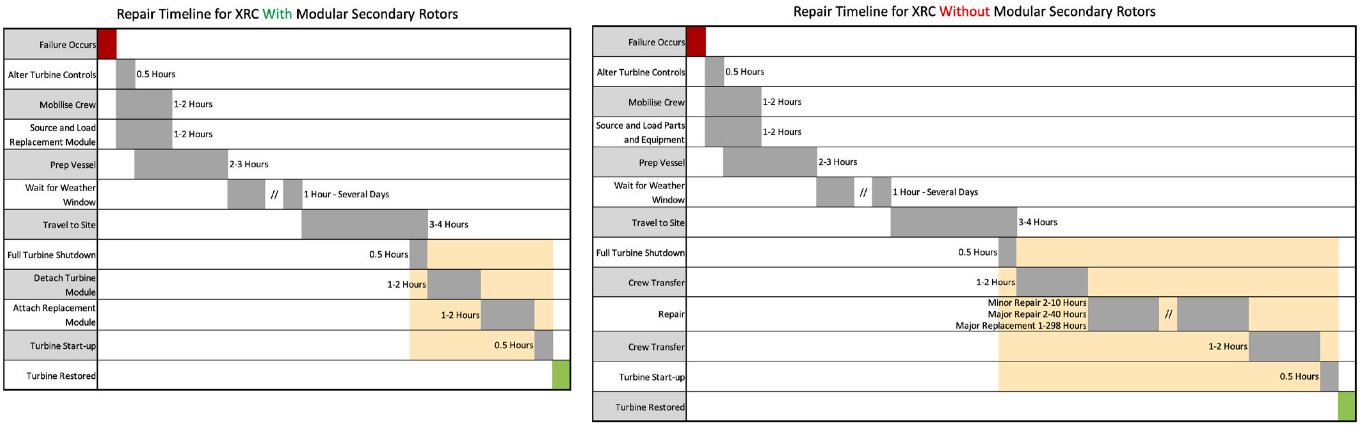

Fig. 3. Diagram of timeline for a repair task for an X-rotor turbine (a) with a modular secondary rotor design; and (b) without. The time estimations for each part are based on discussions with a commercial CTV charter company and other researchers. The repair times in (b) for minor/major/replacement are taken from Carroll et al. [25]. The "//" indicated the time axis is cut in this period. The yellow shaded areas indicated the time where the modular rotor will have influence on the repair time.

The design opportunities described here give increased flexibility in strategy and planning. Cost models will have be flexible to variable design input and changes in optimisation criteria to determine which methods and designs add value to operators by increasing availability and decreasing OpEx costs.

3. Influential factors in O&M costs and how they will change for novel concepts

Maintenance scheduling for offshore wind farms is a multi-factor problem, with the majority of those being variable some stochastic. There has been extensive research in this field to capture the influence of each factor on the overall LCoE with a goal of determining where innovation must occur in order to reduce LCoE further. Fig. 4 shows a breakdown of OpEx costs into the four main categories: staff, lost production, repair and transport. Many of the factors presented in Fig. 4 feature in more than one category because they have an impact on the costs in each category. For example, an increase in the wind farm distance from shore will increase the staff cost to complete that task, the size of the weather window required hence the downtime, and the quantity of fuel used to complete the task. This section discusses the key influential factors identified by Seyr and Muskulus [5] and how these factors will need to be adapted for the novel concepts.

3.1. Weather and sea state modelling

Accessibility to site is a growing concern as sites move further from shore. Access/No Access decisions are based weather operational limitations of the chosen transport/vessel. At present, the key input parameters for O&M modelling of conventional turbines are significant

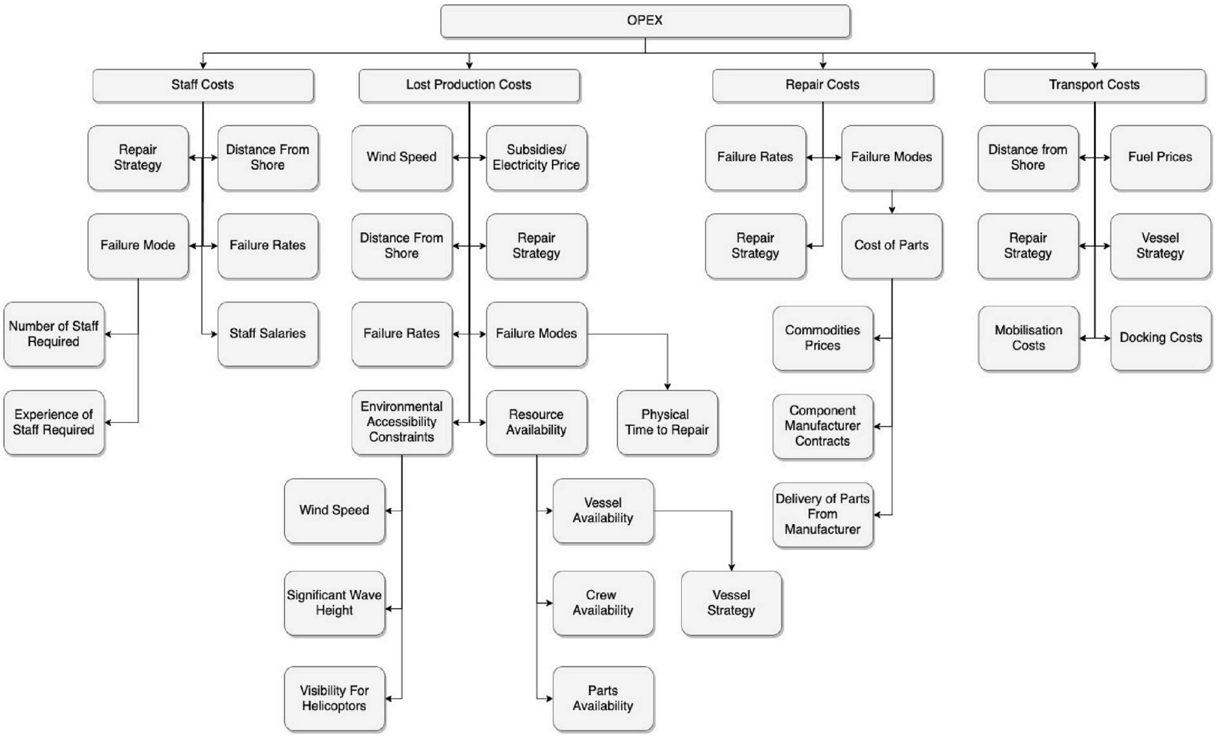

Fig. 4. Breakdown of operations and maintenance costs for an offshore wind farm.

wave height (Hs) and mean wind speed. Hs is defined as the mean of the highest one-third (33%) of waves (measured from trough to crest) that occur in a given period [27]. Wind speed limits both vessel safety and type of maintenance activity. Other transport options, such as helicopters, require additional weather inputs such as visibility. In addition to the direct impact of weather conditions on accessibility, met-ocean conditions can have significant impacts on a number of aspects of the O&M modelling process as shown in Fig. 5. Each met ocean parameter has its own direct and indirect impact on the different areas of the modelling process and the key performance indicator (KPI) as highlighted in Table 1.

Wind speed is one of the most important parameters. It directly determines accessibility, maintenance activity, power output and site revenue. To accurately measure power production, the wind speed at hub height for the specific site is used in partnership with the turbine specific power curve, typically found in the manufacturers data sheet. This informs capacity factor, power generated and therefore income. Wind speed also limits activities that typically involve crane operation, such as blade maintenance, which is limited to 12.5 m/s [28]. Vessels are typically limited by 20 m/s [29,30] for safe transfer. However, in most cases Hs is viewed as the limiting factor for transfer, as vessel limits are often included in charter contracts. In order for maintenance to be carried out, a suitable weather window must be available. A weather window is defined as the total length of time needed for a maintenance operation to be completed, including time-to-repair (TTR), vessel mobilisation, and travel time. This requires that all inputs from the met ocean model be within safe operational limits.

Met-ocean inputs to O&M models can be collected/generated through the use of hindcast models. Hindcast models are the most common substitutes to measured data [31], typically used in the planning stage of a site with on-site measurements to determine the available resource [32,33]. Alternatively, probabilistic models can be used to model wind variations and sea state. The frequency distribution of wind speeds at most sites are typically represented by the two parameter Weibull distribution as used in Ref. [34]. Wind speed and Hs show a strong correlation; hence, Weibull distributions can also be used to determine the sea state of a site [35]. A sea state is defined as the state of the surface of the water at a given location at a given time. It is defined by 3 parameters: Hs, mean zero crossing period (Tz), and wave spectrum type. It is assumed that the sea state is constant for 1–3 h. Each sea state has a corresponding wave spectrum [36]. Markov theory is another method of modelling environmental conditions and is used extensively within existing work to determine wind speed across a site. Weather and sea state are often regarded as a stationary first-order Markov process [37], using historical weather data to determine a Markov matrix. [38–40] all use a variety of Markovian methods to simulate the inputs.

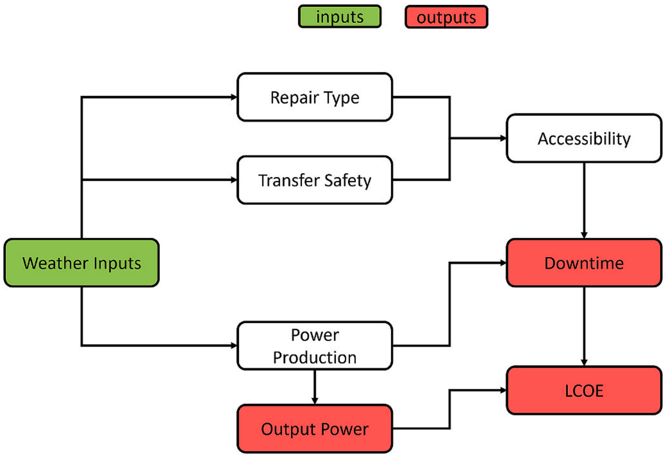

Fig. 5. Areas of impact of weather modelling.

Table 1
Offshore wind O&M weather modelling inputs and their impacts.

Met-Ocean Parameter	Format	Direct impact	Indirect Impact
Wind Speed	Meters Per Second (ms^{-1}) in Hourly Time-steps	Type of Maintenance Vessel Access Lost Power	Accessibility Availability Capacity Factor LCoE
Significant Wave Height	Meters	Vessel Accessibility	Accessibility Downtime LCoE
Visibility	Statute Miles	Helicopter Accessibility	Accessibility Downtime LCoE
Wind/Wave Direction	Degrees	Vessels Ability to Push on Safely (Failed Transfer)	Accessibility Downtime LCoE
Tide	Meters	Ability for Vessels to Leave Port	Accessibility Downtime LCoE

Other methods include auto-regression techniques (AR). AR techniques can be used to determine both wind speed and wave height. Generally, an AR of order 2 is sufficient for wind and an AR model of order 19–20 is required for Hs [41–43]. There is also data transformations required for AR use, such as removal of the monthly mean and diurnal variations.

A number of publications [41,44] make use of historical data such as the CEFAS wavenet open source data for wave parameters. Although there are some key adaptations needed to met-ocean parameters for the O&M processes for the MRS and XRC, the general inputs will remain the same. The type of maintenance activity and vessel transfer will continue to be limited by Hs and mean wind speed. However, the specific limits may change. Challenges regarding the reduced weight of components for these concepts and the overall height of the structures will impact the wind speed lifting limit. Hs limitations will continue to be based on the selected vessel strategy. The overall modelling and collection of these inputs will also remain unchanged.

However, for conventional modelling mean wind speed measurements are taken at hub height (typically ≈100 m for modern traditional turbines) as this is the area where the energy is converted. However, in order to gain an accurate production value for the XRC and MRS this may need to be modified as the rotors at the top of the system will experience a different wind speed to those at the bottom due to wind shear. It is not known at this time how much of an impact this will have on overall modelling.

The MRS may require more detailed wind direction data. This is dependent on the pitching mechanism employed and will vary depending on individual rotor pitch or whole system pitch design. The same consideration will not be needed for the XRC due to the rotational symmetry about the vertical axis.

3.2. Failure and degradation modelling

A failure in the context of a wind turbine can be defined as an abrupt cessation of a component’s design functions whilst under the designated operating and environmental conditions [45]. The occurrence of failures directly cause maintenance actions hence research into probability of failures for wind turbine components has been extensive. The reliability of each component is becoming increasingly significant as wind farm sites move further from shore and maintenance actions become more difficult to complete. Modelling of failures is usually performed in one of two ways: deterministically, using a mean time between failures (MTBF) derived from observed failures; and probabilistically, using a probability density function (PDF) of time to failure derived from historical data; the model then draws random numbers to determine when failures occur. The probability density of failures in components generally resemble a bathtub curve. There are three contributing factors for each component: infant mortality (wear-in), normal lifetime and wear-out, that make up the bathtub curve. However, there are reports in the literature that this is not necessarily the case for offshore wind turbines [25], this paper shows empirical failure data for wind farms per year of operation from year 1–8, where all years of operation have similar statistics and no clear trend can be drawn. There is not sufficient data to observe a wear-out as turbines are expected to last 20 years. Faulstich et al. [46] break failure contributing factors into five categories: early, random, ageing, overload, and components specific behaviours. The first three are in line with the bathtub curve contributors. Overload failures are caused by operating the component out of the designed conditions arising from strong mechanical forces, extreme temperatures, or unexpected high voltages. Component-specific failures models additional effects such as lightning strikes, earthquakes or bird strikes.

There are several methods of modelling the probability distributions in the literature, outlined in detail by Seyr and Muskulus [5]. Popular methods include: Weibull distributions, Poisson processes, Gamma processes, and Bernoulli processes. Weibull distributions contain a shape factor which is different for each failure curve. The superposition of the three distributions gives the overall failure PDF. Poisson processes can be homogeneous (constant failure rate, λ) or inhomogeneous (failure rate is time dependent, (t)). Examples of usage of these methods in the literature can be found here (in order of publication): Weibull [17,34,38,41,47–51], Poisson [38,39,41,47–49,52–55], Gamma [52,56], Bernoulli [40,57].

Even though XRC and MRS are wholly immature technologies, there are some advantages to modelling these systems over modelling future conventional HAWTs. An advantage is the quantity of data available for the reliability components. For example, with the simple scaling properties of these turbines, the reliability of drivetrain components is inherently transferable when upscaling, contrary to conventional HAWTs. This is due to the same turbine being utilised instead of new technology for larger turbines. For an equivalent installed capacity of 20 MW, for a MRS you will have 45 × 444 kW rotors, against the 2 rotors of a 10 MW wind turbine. Therefore, the rate at which reliability data can be collected is (nominally) 45/2 times faster. Basically, what we will learn in terms of reliability data for a 10 MW wind turbine in 25 years will be learned in ≈1.2 years for the MRS system. This is also applicable to XRC but the increase in learning rate will not be as significant (8 secondary rotors in 20 MW). This will increase the accuracy of the probability density functions derived to model the failures in these turbines. Similarly, the sensitivity of failure rate modelling will be better for XRC and MRS as energy production can continue to a certain degree with some failed turbines. When comparing this with a conventional direct drive HAWT, the PDF of failure of the generator for a 5 MW machine will not be identical to a 10 MW. As a generator failure will result in complete system shutdown and likely require a very costly repair, the accuracy of the failure probability density is much more important to obtain an accurate lifetime O&M cost estimation. Additionally, the opportunity of including redundancy present within XRC and MRS leads to a greater reliability of the turbine as a whole. The laws for combining reliability of individual components are straightforward and easy to implement into the models. This is described in Yang [45] and can be used to include redundancy and similarly combine the reliabilities of components within a modular rotor to decrease complexity when using these within the model.

There are, however, some challenges for modelling failures in XRC. Firstly, there is very limited data for operational VAWTs. The XRC does not have a power take-off system (PTO) on the vertical axis but there is the main bearing and the loading implications on the tower to consider. There will also be the impact of leading-edge erosion for the HAWT rotors to consider. As the rotational speed of these blades is much faster than conventional HAWTs and the tip-speed ratio will be ≈ 15, as opposed to ≈8 for conventional HAWTs.

Full failure data is generally hard to obtain, as manufacturers do not want the reliability their products to be public as they see this knowledge as their competitive advantage and may also have concerns about reputation damage. Similarly, in the authors' experience, wind farm operators usually do not store complete historical data due to the added expense of data storage. Therefore, most of the failure data available is an anonymous amalgamation of different technologies from different sites, sometimes a mix of offshore and onshore turbines. This is good for obtaining generic reliability data on each component for cost models, but it would be preferred to form a failure PDF from as specific a data set as possible. Therefore, using onshore data to generate PDFs for offshore turbines is not the best practise because there are different types of turbines offshore due to the harsher weather conditions having a detrimental impact on the lifetime of components. This leads to increased degradation of components and a variation in the dominance of causes and failure modes. Data from onshore wind farms reported for use in offshore cost models are [58–63]. Offshore wind farm data is reported in Refs. [2,25,64–66]. Feng et al. [2] give an in-depth account of availability and capacity factor analysis for four UK offshore wind farms. This is appropriate for calculating lost production cost but not for in-depth Monte Carlo life-cycle cost modelling. NoordzeeWind produced an annual report from 2007 to 2009 [64–66] which provides information on thirteen failure modes. An account of lost production in MWhr, number of failures and total downtime is provided for each failure mode. Carroll et al. [25] provide failure rates for 19 turbine components and three types of maintenance: minor repair (<e1000), major (e1000-10000) and major replacement (>e10000). This includes failures/turbine/year for several components, with breakdowns of the most common failure modes for generators and gearboxes, individually quoted over a number of years. There are also average repair costs, required technicians, and repair time for each type of maintenance. This data can be used to generate robust failure PDFs for different components. The data is compared to reference data for O&M model verification based on expert opinion [67]. Pfaffel et al. and Cevasco et al. present reviews of performance and reliability of wind turbines [68,69]. These reviews outline the different initiatives formed to gather and present data on reliability and failure rates of wind turbines and make an effort to compare what can be compared between the 23 initiatives. Generalised availability, failure rates, mean down time, and share of downtime per component are presented in Pfaffel et al. The review by Cevasco et al. goes on to identify trends in wind turbine reliability.

It will be a challenge to generate PDFs for components in XRC and MRS turbines from the available data due to the radical differences in topology. The data available for equivalent drivetrains in these turbines will primarily be onshore and potentially outdated. There is also no suitable data for operational VAWTs present in the literature. How-ever, future HAWTs have challenges. Manufactures are moving towards medium-speed and direct-drive generators, which will have different statistics to the data available and the sensitivity of the PDFs of these components are going to be of much greater importance than for XRC and MRS.

Data regarding individual component failure rates that are comparable to XRC and MRS may be available within the literature, coming from older publications (pre 2003). Van Bussel and Schöntag (1997) [70] offers failure rates for 500 kW turbines based on a case study of operational 500 kW turbines off the German coast. Within their study they provide MTBF and failures/year/component. Vachon (2002) [71] provides MTBF for individual components of turbines ranging in 600 kW - 3 MW rated power. The work by Carroll et al. [25] is widely used within the literature. However, the data set is based on 3 MW machines which are now considered out-dated. This data-set may more closely resemble that of the smaller capacity MRS and XRC individual rotors, than that of newer technology turbines. Data previously considered obsolete due to the current scale of rated power amongst modern turbines may be revived by the need of data for small-scale turbines for MRS and XRC applications. It should also be noted, that several other factors, apart from turbine size, will impact the overall reliability of the system. It is expected that there will be an additional increase in the reliability of the references to "older" technologies [70,71] due to the maturity of the technology and the experience of manufacturing larger-scale turbines for current offshore wind projects.

3.3. Vessel, personnel and spare parts logistics

In order to complete the repair, resources such as transportation, crew, and spare parts are required. The chosen transportation is influenced by distance to shore, size of site, water depth, weather conditions and type of maintenance operation [72]. Main strategies currently used within industry include: helicopter, crew transfer vessels (CTV), ser-vice operations vessels (SOV) and jack-up vessel (JUV). Each transport has a maximum passenger limit as well as type specific access restrictions, travel times and mobilisation cost. Full details of the strategies, their limitations, capacity and cost are summarised in Table 2.

Typically, working limits for CTV and SOV are based on significant wave height and mean wind speed, with Hs being the priority. It is widely accepted that the typical Hs limit for a CTV is 1.5 m [73,74] and a SOV can range from 2.5 to 3.5 m [72,75]. However, the day rate of an SOV is approximately 8–10 times that of a CTV [75]. It is generally agreed that the use of CTVs are restricted to a 50 nautical miles limit from shore [76]. CTVs are small vessels that make single trips to site to perform maintenance before returning to port. They are advantageous due to low charter fees and relative speed. However, there use far from shore is limited due to lengthy travel time and the requirement of the HSE to be within 2 h of a place of safety [77].

SOVs are becoming more popular within the UK due to their higher crew capacity, the potential to store spare parts board, and ability to stay at site for long periods of time. An SOV typically stays at sea (within the wind farm) for weeks before returning to port, restaffing, refuelling and replenishing supplies, acting as an "offshore hotel" where it performs the same duties as a permanent offshore base [78,79], without the requirement for a large capital investment, making it a comfortable choice for sites far from shore. The SOV can act as a mothership with supporting small CTV vessels. The significant advantage of an SOV is its high transfer limit, of up to 4 m Hs [72,75]. However, due to the increase in capability, comes with an increase in price.

JUVs are traditionally used during the installation process within offshore wind. However, the need for JUVs in-crease as assets age and major repairs and replacement of components is required. As the pipeline for offshore wind increases globally, it is predicted that the increase in demand and lack of supply will considerably increase the cost of these vessels.

Spare parts provision is included in Refs. [41,47,48,80,81]. The provision of spare parts is typically modelled as a component lead time. Spare parts are typically stored at the O&M base on shore, or depending on size and weight, some specific parts may be stored on board an SOV. Due to the uncertainty in availability, works such as [40,55], assume spare parts are always available.

The chosen MRS and XRC maintenance strategy will be dependent on the use of smaller systems and/or modular systems. When using modular systems, the maintenance vessel will require: sufficient weight capacity (10 tonne for XRC and 13 tonne for MRS), deck space, and potentially a crane. A crane would be required to reach over 150 m above sea level for the MRS but only 25 m above sea level for the XRC. Although Hs is still a limitation for the maintenance of novel turbines, it is expected that the time at sea will be reduced as modular systems are removed and returned to shore for maintenance. This removed the repair time from the total repair timeline (see Fig. 3). This should reduce the length of access (weather window) required for safe maintenance. If modular systems are not used and individual parts are replaced then a smaller, less robust vessel can be used as the limit of weight is removed from the vessel selection criteria. To improve OpEx, it is recommended that each MRS and XRC would have a dedicated crane on site to eliminate the need for an expensive JUV. However, this would require a significant CapEx increase.

Table 2
Summary of offshore wind transportation options and their characteristics based on authors experience.

Characteristic	CTV	SOV	JUV	Helicopter
Hs Limit (m)	1.5	2.5–4	2.5	Vessel Dependent
Wind Speed Limit (ms^{-1})	10–12	20–25	15.3	12–15
Crew Capacity	12–14	60	30	2–3
Fuel Consumption (Mt/hr)	0.24	0.2	0.55	0.4
Charter Cost (£1000s/day)	3–4	30–40	200–300	£2500/hr[a]
Speed (Knots)	25	15	10	140

[a] Helicopter charter is typically based on number of flight hours and therefore charter cost is given in £/hour.

Due to the predicted increase in the transfers required, fuel consumption may become an increasing concern. Reducing carbon emissions of offshore maintenance vessels is becoming more of a priority for operators. The Carbon Trust has included reducing emissions and fuel consumption in offshore wind vessels as part of the "low emission vessels competition" within the offshore wind accelerator project [82]. At present, the battery systems used for electric vessels are limited to 30 min of operation. Current battery technology is relatively heavy, resulting in hybrid systems burning more fuel as a result of the additional weight. However, studies of vessels such as Edda Passat have found savings of 21% on fuel costs through the use of variable speed engine systems with a DC grid [83].

The advantages of XRC and MRS comes from the potential to eliminate the use of JUV as part of O&M practices. It is expected that novel turbines maintenance strategy will be based on the current options available. As technology progresses, and the industry becomes more established, it is likely that purpose-built vessels with the capacity to carry multiple of individual modular rotor systems will be commissioned.

Spare parts and stock inventory is also an area of interest with regards to novel turbines. One proposed maintenance solution is that the rotor module will be removed, replaced and then the faulty module repaired at shore. This should, in theory, decrease the inventory needs due to the "swap in, swap out" strategy. The size of components should also allow stock to be kept on site (at port), or on board (dependent on vessel capabilities) which would reduce the lead time for components, which would reduce the overall downtime. However, vessels are bounded by budget and size constraints that limit having excess supplies/parts on board [84]. However, previous work [84] has determined that vessel resupply can significantly reduce overall downtime. Although downtime of individual rotors is not as catastrophic for novel concepts as a traditional turbine, significant benefits are found through its reduction.

3.4. Transport fleet and maintenance strategy

Due to the increase in the number of components, the number of transfers is expected to be higher for novel turbines than for conventional HAWTs. This increase in visits will have a high influence over the vessel selection, due to charter cost and fuel consumption. Often, sites will use a fleet of vessels of different types to deal with the complexities of different maintenance scenarios. The overall vessel selection and chosen maintenance strategy is site dependent, as shown by Dewan and Asgarpour [72] through their baseline scenarios for five difference scenarios at different locations and distances to shore.

Both [85,86] provide fleet selection for a single type of vessel strategy. Lazakis et al. [85] provide an optimisation framework (OptiRoute) for scheduling vessels activities using a SOV to carry out the offshore wind turbines maintenance tasks, which acts as a servicing station having required technicians and daughter crafts (CTV) onboard to facilitate on-time and on-demand servicing of wind turbine. Dalgic et al. [86] explore the optimal selection of the CTV fleet with the aim to decide the specification of CTVs which will bring the optimum financial benefit, considering both the enhancement of the offshore wind farm power generation as well as the minimisation of the total O&M cost. It was found that more advanced CTV vessels increased key KPIs such as availability and decreases overall cost, despite the increase in charter cost.

Rinaldi et al. [49] model an accommodation vessel (SOV) and a CTV. Scheu et al. [39] describe two vessel types within their work. The first being "an ordinary maintenance vessel" such as a CTV and the second a crane vessel, similar to a JUV, for major repair. [49,67,87] all model CTVs and SOVs with the inclusion of a helicopter option in their work. Whereas [81] only includes CTVs and helicopters. The use of helicopters within the UK for mainte-nance is limited as they are restricted by wind speed and the Hs limit of their associated rescue vessel (typically a CTV).

Halvorsen-Weare et al. [88] performed a fleet optimisation using a wide variety of transport options: CTVs and supply vessels (of varying sizes), two helicopters, a JUV and a multipurpose vessel for all maintenance activities across the site (preventive and corrective). As scale of site increases, as does the configuration of the optimal fleet. However, a CTV was included in all optimal configurations.

Sperstad et al. [89] utilised a ranking approach to determine the optimal fleet of vessels, but compared a mathemat-ical optimisation tool and an analytic spreadsheet-based tool using the reference case study from Ref. [67]. In general, tools showed agreement in vessel selection. It was found that vessel selection was highly sensitive to Hs access limitations in comparison to other vessel inputs such as speed and vessel day rates, highlighting that optimum selection is highly dependent on the location/conditions of the site.

The expected need for more transfers also may encourage operators to explore new charter agreements. Dalgic et al. [79] explore the differentiation of charter rates associated with charter periods and vessel capabilities. It was found that using vessels developed for the oil and gas industry were inefficient. Therefore, it may be beneficial for novel turbine operators to explore purpose-built vessels for their specific needs rather than using existing vessels that have been created specifically for fixed HAWT specifications. For instance, for XRC and MRS farms, there will be large quantities of small nacelles. It may be beneficial to use vessels have large deck space to crew ratio and can travel at fast pace. There would not be many technicians required to remove a XRC secondary rotor, but a CTV could not hold a spare secondary rotor module. Currently, an SOV would be the best option due to deck facilities.

In addition to capacity, port facilities and maintenance needs, UK sites must also factor "local content" into their vessel fleet selection criteria. Based on the UK's Offshore Wind Sector Deal, the offshore wind industry is "committing to increase UK content to 60% by 2030" [90]. One way of achieving this ambition is by utilising a number of small work boats instead of a larger vessel for maintenance activities. However, it is unknown how many CTVs would be required, are therefore may raise practical issues regarding local ports ability to support a large fleet. Dalgic et al. [87] and Rinaldi et al. [49] explore the optimal number of vessels for a conventional site with one rotor. However, XRC and MRS have multiple rotors. This raises the question of whether the optimal vessel selection should be based on the number of systems or number of rotors.

However, the need to urgent repair of failures is overcome by the redundancy of the MRS and XRC. Most maintenance models assume that immediate repair is required for turbines. However, Nielsen and Sørensen [91] considered three separate repair timelines. The first being immediate repair through the use of vessels only, the second immediate repair with all available maintenance options (including the use of helicopters), and the third being a risk-based approach to determine an alternative maintenance effort. Potential solutions for novel turbines with redundancy are summarised in Fig. 6.

An "ASAP" approach follows the same process as the first maintenance strategy of [91]. Upon failure there is an immediate effort made to repair as soon as a suitable weather window occurs. For a power threshold approach the operator waits until the power of the asset decreases to a predetermined power output before attempting repair. The two remaining options wait until a predetermined number of failures occur before completing maintenance. Maintenance activities can be grouped based on TTR, parts needed, specialist vessel requirement or the need for a specialist technician to repair. Finally, for a scheduled based approach, all maintenance is carried out across the site during set times throughout the year, regardless of when failure occurs.

The concept of batch repairs is already operational within the wind industry, specifically for JUV charter, as explored in Ref. [41] where four JUV strategies are considered: fix on fail, batch repair, annual charter, and purchase. Due to the high cost of the JUV, and limited available time with the asset, it is vital to utilise it effectively. Fleets/vessels where charter time is limited can benefit from such an approach [57] This methodology could be applied to the day-to-day O&M repairs associated with MRS and/or XRC and may introduce the opportunity to use the day-to-day fleet in the same way as JUV, where they are only chartered for periods where batched repairs are required.

3.5. *Economic parameters and cost estimation*

The goal of the O&M strategy is to maximise the profit for the operator. Economic parameters such as electricity ice (through means of contract for difference, prepayment agreement or variable electricity market price), cost of aff, parts and vessels are important parameters that also require modelling.

Most modelling techniques for these parameters are simple. Vessel charter costs and technicians salaries are usu-fixed [41,81,86]. Similarly, lost production was previously calculated by the turbine rating multiplied by the capacity factor and the mean TTR [41]. However, more recently, models have started using a wind speed time series to determine the lost revenue from the turbine power curve [41].

In Douard et al. [38] cost estimation contains both deterministic and probabilistic components. Probabilistic es-timation is more complex and generally more accurate but is more computationally expensive. The costs of capital, operational costs for fixed and preventative maintenance are in reality typically pre-determined, making it reasonable to model these deterministically. The probabilistic components include direct and indirect costs. Direct costs are directly paid for such as labour, transports, and spare parts.

Similarly to failure and reliability data, cost data for spare parts,

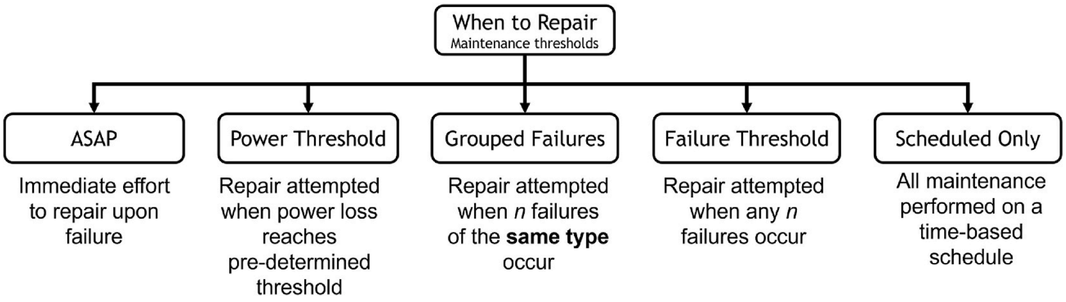

Fig. 6. Definition of potential maintenance strategies available for MRS and XRC.

technician salaries and vessel charter rates are not easily obtained. Dalgic et al. [86] consider fuel consumption, vessel speed and daily charter for two types of CTV, and also staff costs. Besnard et al. [81] estimates annual CTV costs, number of CTVs and annual cost of technicians based on fixed charter costs and salary predictions provided by expert opinion. Shafiee et al. [80] present equations for the estimation of the lifetime cost for all aspects of a wind farm where the total maintenance cost is divided by direct and indirect, where some parameters are assumed to be fixed and some variable.

It is expected that the modelling and categories of direct costs will not require any changes for novel concepts. wever, indirect costs, such as downtime/lost revenue are determines probabilistically as they are dependent on the maintenance duration and accessibility due to weather. This method will require adaptation due to the redundancy of the XRC and MRS. Therefore, it is suggested that downtime be split into three categories: primary downtime, secondary downtime, and repair downtime.

- Primary: failures, such as primary yaw failure or tower issues, which will result in the downtime of the whole system. This will be modelled the same way as conventional HAWTs.
- Secondary: failures which result in downtime of a single rotor. Lost revenue is based on projected output of the failed rotor during its period of in-operation from initial failure till the maintenance crew reach the asset.
- Repair: due to safety concerns, the whole structure may be shut down during active repair. This will be modelled in the same way as primary downtime, however over a much shorter time period.

3.5.1. *Comparison of replacement costs for novel concepts*

A 3-stage geared conventional HAWT (Geared HAWT), a direct drive conventional HAWT (DD HAWT), a XRC, a 3-stage geared MRS, and a DD-MRS, all rated at 5 MW, were compared in terms of component costs, which significantly contributes to repair costs. The Geared HAWT used for the comparison is the NREL 5 MW Reference Turbine [92]. The DD HAWT is by Slot et al. [93] which was specifically designed to be the DD equivalent of [92]. The goal is to establish a one-to-one conversion of the existing reference turbine, which makes the developed model suitable for comparing structural loads for the two design concepts, even though the 5 MW reference turbine may not necessarily reflect the design of modern utility turbines [93]. The XRC used is the basic design consisting of two blade pairs with a single 2.5 MW HAWT on each of the lower blades [10] as described in Section 2.1. The MRS used consisted of 12 × 444 kW turbines arranged in rows of 3-4-3-2 from top to bottom based on the 20 MW design by Jamieson and Branney [11,12,18] which consists of 45 × 444 kW turbines arranged in rows of 7-8-9-8-7-6 from top to bottom. Therefore, to scale down to 5 MW the number of turbines was reduced in order to keep the design of each rotor consistent with the literature. In Table 3, the MRS is described as having no primary rotor and 12 secondary rotors. This is to aid in comparison as these rotors are more similar to the secondary rotors on the XRC in terms of O&M considerations. Both geared and DD drivetrains for this MRS structure were considered.

The mass and cost of components of all turbines were derived from Ref. [94]. Some of the empirical equations within this scaling tool have large y-axis intercepts, hence, do not perform well for small turbines. For these components, such as hub mass, nose cone and pitch system mass, explicit data is shown; however, these factor into the rotor mass. The rotor mass for the XRC and MRS is presented in the table with an asterisk (*) to indicate this is underestimated as those components are not

Table 3

Table comparing components size and cost for different turbine technologies for a 5 MW turbine. Table data was populated using empirical equations for turbine scaling provided by Fingersh et al. [94].

	Components	Geared HAWT	DD HAWT	XRC	Geared MRS	DD MRS
Primary Rotor	Arrangement	3 Blade	3 Blade	2 Upper 2 Lower	*No Primary Rotor*	*No Primary Rotor*
	Blade Size (m)	61.5	61.5	Upper = 100 Lower 65.3		
	Blade Mass (t)	17.7	17.7	Upper = 40.5[b] Lower = 23.4[b]		
	Blade Cost ($1000s)	473	473	Upper = 775 Lower = 485		
	Total Mass (t)	110	110	128[b]		
	Total Cost ($1000s)	1735	1735	2519		
Secondary Rotors	Arrangement	*No Secondary Rotors*	*No Secondary Rotors*	2 Rotors 5 Blades	12 Rotors 3 Blades	12 Rotors 3 Blades
	Blade Size (m)			4.7	19	19
	Blade Mass (t)			25	968	968
	Blade Cost ($1000s)			0.3	17	17
	Total Mass (t)			180[a]	6000[a]	6000[a]
	Total Cost ($1000s)			1.5	2904	2904
Tower	Height (m)	87.6	87.6	≈40	42	42
	Mass (t)	296	296	135	169	169
	Cost ($1000s)	444	444	170	253	253
Gearbox	Mass (t)	38	*No Gearbox*	*No Gearbox*	2.5	*No Gearbox*
	Cost ($1000s)	686			33	
Generator	Type	5 MW PMSG	5 MW DD	2.5 MW Synchronous	444 kW PMSG	444 kW DD
	Mass (t)	17	100	8	2	11
	Cost ($1000s)	325	1096	163	29	97
	Total cost for 5 MW ($1000s)	325	1096	326	1305	4265
Power Converter	Cost ($1000s)	395	395	198	35	35
Yaw System	Mass (t)	13	13	*No Yaw System*	18	18
	Cost ($1000s)	114	114		150	150
Nacelle	Elevation (m)	87.6	87.6	<30	42-78-144-151	42-78-144-151
	Mass (t)	200	227	9	13	20
	Cost ($1000s)	2928	2994	168	136	107

[a] Some sub-components of the rotor are not included in the total due to large y-axis intercepts of the empirical equations.

[b] Data taken explicitly from turbine design rather than calculated using the scaling equations in Ref. [94].

included in the total. The mass and cost of the primary rotor for the Geared HAWT and DD HAWT are the sum of the components within the rotors, including the ones not listed. In the NREL publication that outlines the properties of the 5 MW Reference turbine [92], the mass of the rotor is quoted as 110 t, hence the derived mass of the subcomponents is consistent with the reference design. Where mass data is provided explicitly for the XRC in Ref. [10], marked with a dagger (†), this is used instead of the scaling equations. The cost is then calculated using the scaling equations. The tower height of the Geared HAWT and DD HAWT are from Refs. [92,93], respectively. XRC tower height was determined from the coning angle and nacelle height quoted in Leithead et al. [10]. MRS nacelle heights were determined using the convention of a 22 m ground clearance requirement for the blades [95] and that the vertical spacing between rotor centres is 0.909 diameters [11–13]. There is an option to have the tower at a range of heights on the grid of rotors. The space frame was chosen to attach to the tower at the centre rotor in the bottom row, hence 42 m. This calculation does not include the mass of the space frame for the MRS. The cost of the tower for all turbines was determined using the linear equation between tower mass and the cost of steel from Fingersh et al. [94]. The mass and cost of gearboxes and DD generators depend on the low-speed shaft torque. This was calculated from the rated power divided by the rated rotor speed, hence, no shaft damping or electrical losses were considered. Therefore, the data for the gearboxes and DD generators is marginally underestimated. The generator for the XRC is lighter and cheaper than conventional HAWTs as the low-speed shaft torque is low; due to the increased rotational speed of the secondary rotors. There is no equation provided by Fingersh et al. for estimating the mass of the power converter. There is no yaw system present in the XRC in either the primary or secondary rotors. For MRSs, the yaw system is in the central tower and yaws all turbines collectively. The mass and cost of the yaw system is dependent on the radius of the rotor. To amend this for the MRS, the total swept area for the 12 rotors is scaled to an equivalent single rotor radius. The nacelle mass is the total of the rotor mass, the gearbox (if applicable), the yaw system mass (if applicable), and the generator, plus some other minor components such as the mainframe and nacelle cover that are not listed explicitly.

The benefits of the XRC are clear to see. The nacelle mass is under 10 t and is less than 30 m from sea level. This has great implications for O&M. A vessel with a crane suitable to support 10 t and a deck suitable to support 20 t will.

be sufficient for the majority of maintenance tasks if the nacelle was designed as a replaceable module. The cost of the turbine is also less than a conventional HAWT. The MRS has similar benefits to the nacelle mass totalling 13 t and 20 t for the geared and direct-drive designs, respectively. However, the elevation of the nacelles suggests a modular nacelle would not have as significant a benefit as the XRC. The top row is over 150 m above sea level, meaning a JUV or onsite crane would be required. Given the high charter costs of these vessels, it would not be cost effective unless the nacelles were replaced and serviced in large batches. In this turbine, the elevation of the top row would be over 220 m above sea level, and hence an even more specialist task to remove the nacelles. There are construction helicopters that have external load capabilities up to 20 t [96] but these are not commonly used in the offshore wind industry.

4. Maintenance strategy

Maintenance strategy can be simply divided into scheduled and unscheduled. Corrective maintenance (unscheduled) is when components are repaired upon fault with no attempt to preempt failure. This constitutes the majority of maintenance actions for all wind farms. However, as distance to shore increases, this approach becomes increasingly challenging. Preventive maintenance (scheduled) is performed proactively to inspect and repair degrading components at fixed time intervals in an attempt to reduce unexpected downtime [91]. This can include scheduled annual servicing or condition-based monitoring (CBM), where maintenance is carried out depending on the condition of the component, hence specialist condition-monitoring equipment is necessary. This can provide an optimised maintenance schedule that prevents failures without resorting to over-maintenance [18,97]. Artigao et al. [98] provides a review of the state of the art condition monitoring techniques.

Models typically include a mixture of strategies [38–41,87]. This is important to allow for flexibility in the cost model analysis, especially for new technologies. Dalgic et al. [87] present three different strategies with increasing importance of preventive maintenance with respect to corrective maintenance. Preventative maintenance can occur to a varying degree of frequency, but it should be noted that the achieving the highest availability leads to large direct costs. CBM has a high initial cost for the system, and itself will require maintenance, but can theoretically yield the least expensive proactive maintenance schedule. Most models that consider CBM usually do so independently of other techniques [99–102].

Future sites are facing increasing challenges due to the expected move to more challenging locations. To over-come these challenges, flexible, cost-effective maintenance strategies must be exploited. One such strategy, which has been gaining traction in recent years, is opportunistic maintenance (OM). This strategy was first proposed in 2009 by Besnard et al. [103]. This strategy typically, involves performing non-critical maintenance actions (such as inspections/preventive maintenance) during author-defined “opportunities”. Opportunities can be: during low wind speed [103], performing scheduled maintenance during unscheduled trips [104] and group based maintenance [105]. There is increasing interest in multilevel decision-making and strategy by introducing opportunistic thresholds based on age [106–110], locational clustering [111], and condition [112]. Due to the redundant nature of failures for MRS and XRC, these technologies are in a position to benefit from this strategy.

The optimum maintenance strategy for XRC and MRS will be different to conventional HAWTs. Corrective maintenance will be less problematic due to the lower downtime cost per failure. Preventative maintenance actions are likely to be more expensive per turbine as there are more components to replace/repair. Similarly, CBM systems will have a higher initial cost than for a conventional HAWT because there will need to be a separate measurement system for each component monitored. Therefore, operating with failed rotors and batching corrective maintenance actions is likely to be a cost-effective option for wind farm operators with XRC and MRS turbines. Modules can be replaced and fully serviced onshore which could be carried out proactively or correctively. Therefore, models will be required to be flexible to this. A cost-benefit analysis is needed to determine the effectiveness of a purely scheduled maintenance schedule due to the decreased impact of downtime.

There are concerns regarding the maintainability of turbine components. For secondary rotors, there is the possibility of replacing the entire rotor, returning to port and repairing the failed rotor. This introduced “onsite” maintenance into the repair programme.

5. Conclusions

Details of two novel concepts, X-rotor (XRC) and multi-rotor (MRS), have been presented with regards to issues pertaining conventional HAWTs. HAWTs will struggle to maintain the consistent reduction trend in LCoE as turbines increase in size towards 20 MW [14,15]. The unique scaling mechanisms of XRC and MRS provide a solution to this problem - along with several other benefits that are likely to make them a competitive option for future manufacturers and operators. Table 3 provides a detailed outline of the replacement component costs expected for 5 MW turbines using consistent scaling equations. The component replacement costs are clear for the novel concepts.

MRS and XRC design opportunities such as modular rotors will have great maintenance benefits for the operators, but are likely to increase the CapEx costs of the turbines. Analysis of the benefits of this could influence the design of these turbines to decrease the lifetime cost. The other main design opportunity discussed was the ability for these turbines to continue operating at reduced capacity with failed secondary rotors.

Based on the influential factors highlighted by Seyr and Muskulus [5], key changes needed for O&M adaptations are summarised. In general, the inputs to O&M modelling will remain relatively unchanged - wind speed, Hs, failure rates, resource inputs, cost estimated. Based on the literature and discussion throughout the paper, the following areas have been identified as key areas when modelling MRS and/or XRC O&M procedures:

- ***Weather***: Hs and wind speed will continue to be the main inputs. Mean wind speed should not be solely based on the wind speed at "hub" height. Power production has a high influence on OpEx and revenue, and therefore it must be recognised that there will be differences in output from all rotors in the system
- ***Failure and degradation***: It can be expected that operation/reliability data will be acquired more rapidly due to the high number of rotors. However, it is expected that the novel technologies will face the same challenges as current projects such as "secrecy" surrounding such data. Sensitivity of LCoE on reliability of specific components will be better due to the turbines continuing to operate at reduced capacity with failed secondary rotors
- ***Vessels and transport***: The proposed modular system of technologies allows the failed rotor to be replaced on site and repaired on shore. However, due to the size of the components, sufficient deck space will be required. However, the reduced component size may allow larger vessels to stock spare parts on board. Therefore, vessel selection and JUV elimination will be determined by a CapEx vs OpEx study determining the advantages of an onsite crane.
- ***Transport fleet and maintenance strategy***: It is expected that an SOV will be the primary strategy, potentially with larger deck space CTVs. However, it is unknown if the number of structures or the total number of rotors will be the main driver for the optimisation of the vessel fleets.
- ***Cost estimation***: due to the economies of scale and the existing supply chain to support the offshore wind industry, it is expected that the cost of components will see a decrease at a quicker rate as the deployment of the technology increases. However, there will be additional economic parameters to consider for the new concepts if they are to have modular rotors that can be maintained onshore.
- ***Maintenance strategy***: The redundancy of the technologies decreases the dependence on corrective maintenance activities, which should result in a safer, less critical maintenance strategy

While XRC and MRS O&M models will require the same inputs as a conventional turbine, it is important to be aware of the additional factors related to redundancy and downtime. Accurate O&M modelling and planning of these systems is vital to reducing LCoE and allowing the technologies to compete in the current market against conventional fixed HAWT turbines.

Credit author statement

Callum Flannigan, PhD Candidate: Conceptualization, Formal analysis, Writing - original draft, Visualization, Investigation. Jade McMorland, PhD Candidate:Formal analysis, Writing - original draft, Visualization, Investigation. James Carroll, Senior Lecturer: Supervision, Validation, Writing - Review & editing, Funding acquisition. Maurizio Collu, Professor: Supervision, Writing - Review & editing. David McMillan, Reader: Supervision, Writing - Review & editing. William Leithead, Professor: Supervision, Funding acquisition, Validation. Andrea Coraddu, Professor (Assistant): Supervision.

Declaration of competing interest

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