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Bottlenecks in Operations

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Operation and Maintenance Modelling for Multi Rotor Systems: Bottlenecks in Operations

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Abstract. As the installed capacity of individual turbines increases, as does costs associated with manufacture and maintenance. One proposed solution to this problem is the Multi-Rotor System (MRS) which utilises many small rotors to yield the same energy capture as a sing large turbine. The operational advantage of the MRS is the built in redundancy between rotors on the same structure. However, despite this advantage, an increase in number of components is likely to result in an increase in transfers. This work examines the balance between additional crew and vessel requirements for such a structure against the expected savings in downtime due to redundancy and small rotor power rating. Three scenarios are analysed to determine the distribution of the failures which contribute to downtime. The study aims to find the optimal vessel fleet which limits downtime without drastically increasing direct operational expenditure (OpEx). As site size increases, the impact of global failures, which shut down the whole asset, as lessened. However, there is a significant increase in the number of vessels required to reduce downtime to <10% of the total OpEx. While a large fleet can offer significant downtime savings, there are practical limitations and challenges which must be acknowledged.

1. Introduction

The UK has committed to 40GW of installed capacity in offshore wind by 2030 and achieving carbon net-zero by 2050 [1]. Offshore wind is expected to be one of the key areas to achieving these ambitious targets. Initial capital cost (CapEx) has seen steady reductions in offshore wind; however, the operations and maintenance (O&M) costs remain high - currently, up to a third of the cost of energy (CoE) can be attributed to maintenance cost [2].

The cost of components in the latest generation of offshore wind turbines are becoming more expensive and heavier as turbines increase in size [3]. This poses serious challenges for farm developers to maintain a competitive levelised cost of energy (LCoE) due to the substantial self-loads of larger structures [3,4]. In addition, the increase in size of components puts additional pressure on the supply chain to accommodate such vast structures and components. As the supply chain is squeezed, savings must be found elsewhere. Any failures to the main components of 20MW+ turbines will result in a lengthy downtime and expensive repair due to the cost of the components, loss of earnings, and the requirement for a heavy-lift vessel (HLV).

The Multi Rotor System (MRS) presents itself as the solution to this problem. As the size of turbine blades increase, the benefit of energy capture is outweighed by the increase in mass and manufacturing cost [4]. Energy uplift is determined by the square of the area, whereas volume (weight) scales on a cubed basis. The MRS makes use of this disadvantage 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. All rotors are equally weighted in their contribution to overall energy capture and operate somewhat independently. Therefore, the system has built in redundancy where the failure of a single rotor is not detrimental to the overall operation of the system.

One of the main operational challenges associated with the MRS is the volume of components, which leads to the assumption of an increased number of failures, despite the redundancy advantage. To the authors knowledge, this operational issue has only been considered once before in the Innwind project

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[5]. Understanding of the operational challenges and operational expenditure (OpEx) breakdown are vital for determining the validity of such a concept.

The aim of this work is to model the MRS system in an O&M context as the scale of the project increases. Due to the expected increase in transfers, there will be an increase in the resources required. The key element in this work is the identification of the bottlenecks in the system and their direct, and indirect, impact on OpEx. Section 2 provides an overview of the MRS and the components modelled. Section 3 details the O&M model used, and the assumptions made regarding the O&M strategy. Section 4 details the overall methodology and simulation set up. Section 5 provides the results and analysis, and finally, section 6 provides an overview of the analysis and makes recommendations for areas of future study.

2. The Multi-Rotor System

The concept of the MRS was first proposed in 1926 [6], however, since then there has yet to be an agreed upon standardized design or the implementation of an operational concept. One of the most common designs, and that considered within this work, is the 45 rotor system explored by Peter Jamieson [7]. This design consists of 45 individual 455 kW rotors arranged in a hexagonal configuration. This is the design which was also considered within the EU funded Innwind project which considered O&M advantages of the MRS [5]. The concept design is shown in Figure 1.

Within this study, each MRS consists of 45 500kW Double Fed Induction Generators (DFIG). Each turbine power train includes: 3 stage gearbox, a DFIG, and a DFIG power converter. The power curve for each individual rotor is shown in Figure 2.

The key advantage of the MRS system is the built in redundancy. It is assumed that for the majority of components, a failure in one system will not impact the other operational rotors. However, there are certain component failures which will result in a failure of the whole asset. Failures within this work fall into one of the following two categories:

1) *Local failure*: the failure of these components will shut down the associated rotor. However, it will have no impact on the operation of other rotors on the same structure
2) *Global failure*: the failure of these components will result in the failure/shut down of the whole MRS

The components/failure considered within this work are shown in Table 1 with details regarding the impact of the failure as local or global. Failure data, including repair cost and repair time, for such components are taken from Carroll et al. [8] and Van Bussel et al [9].

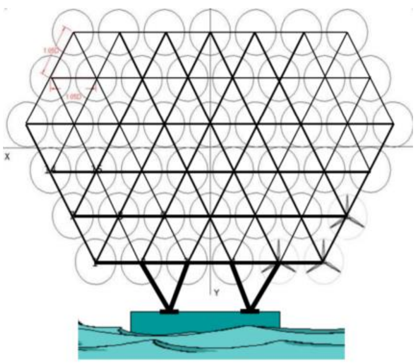

Figure 1. 45 x 445 kW rotor MRS concept [7]

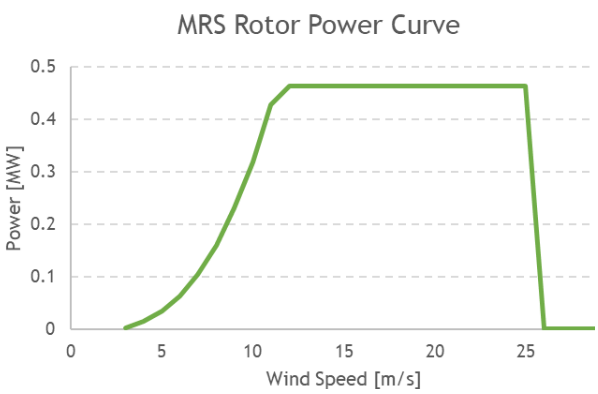

Figure 2. Power curve of individual 445 kW rotor

Table 1. Failure category for all components in each MRS rotor

Component	Failure Category	
	Local	**Global**
Pitch		✓
Electrical (power supply/converter)		✓
Blade	✓	
Other	✓	
Gearbox	✓	
Generator	✓	

2.1. Operational Advantages and Challenges

OpEx is typically split into direct and indirect costs. Direct costs include fixed costs, transport costs, staff cost and cost of repair. Indirect costs include loss of earnings, often referred to as downtime. This makes up a significant part of the overall total OpEx. This is an opportunity cost which has been lost due to the failure of an asset and is equal to the revenue which would have been generated, had the turbine been operational. As turbines scale to 20MW, and beyond, downtime is expected to increase. The MRS advantage of smaller installed capacity per rotor leads to a smaller loss in earnings during periods of rotor downtime. Figure 3 shows a downtime comparison of a 20MW machine and a single MRS rotor based on the current Round 3 UK CfD strike price of £39.65 [11].

This is based on the assumption that a single failure does not impact the operation of the remaining operational rotors. While global failures will result in the shutdown of the whole asset, the majority of failures are categorized as local and therefore, it is expected that for the majority of time, downtime will be minimal. . The latest ScotWind allocated zones have an average distance of 70 km. Based on a CTV travelling 20 knots, this will take upwards of 2 hours to reach the site before maintenance can be performed, highlighting the high potential losses associated with a failure of a high MW machine.

Due to the small cost of downtime, the urgency to repair immediately is decreased. This opens new opportunities such as grouped maintenance which would require an analysis of the balance between the cost of downtime and the cost of repair.

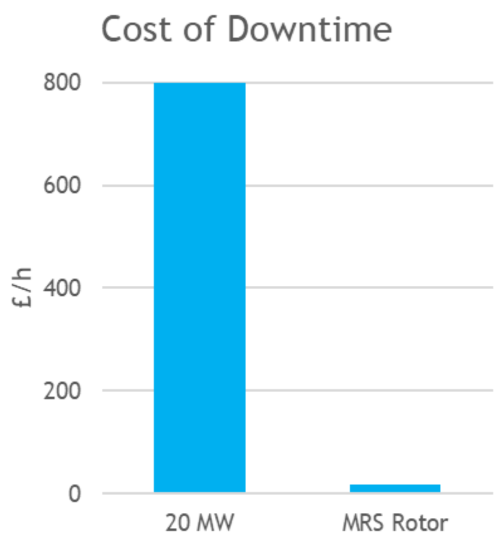

Figure 3. Cost of downtime is £/hour for a single 20MW turbine and a rotor of an MRS

3. O&M Strategy

The O&M process was modelled and simulated using the Strathclyde OpEx model [12]. The Strathclyde University offshore wind OpEx model utilises a time domain Monte-Carlo simulation approach. The focus of this model is detailed analysis of the O&M fleet. This model has been previously validated for its intended use [13] and has been used to assist with commercial operational projects. Details of the model and its inputs are summarised in Figure 4.

As this model was originally developed for traditional offshore wind turbines, there were some adaptations needed for MRS simulation. Each individual rotor was modelled as a single wind turbine. Each set of 45 rotors were then assigned the same location to form a MRS. The failure categories considered were that of Table 1.

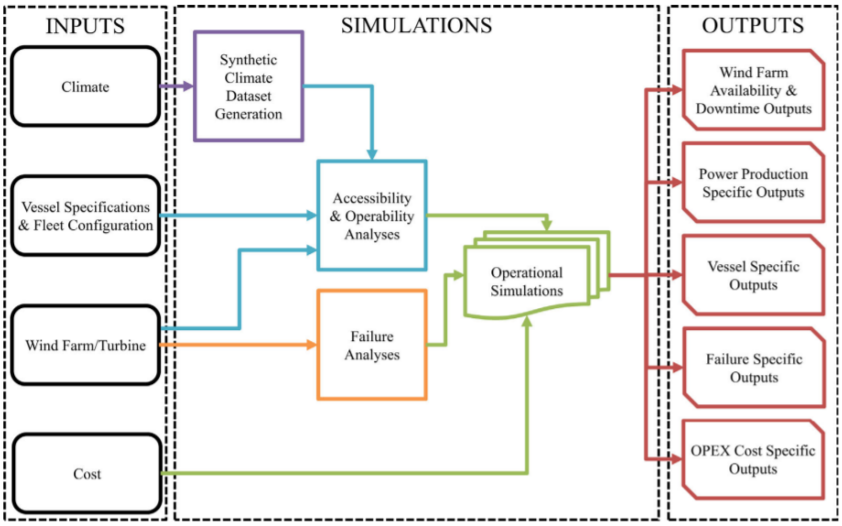

Figure 4. Strathclyde University O&M model summary showing inputs and outputs [12].

3.1. Met Ocean and Site Conditions

The modelling is based on a fictitious site 45 km from shore. The weather conditions across the site are summarised in Table 2. Weather data is taken from [14]. Operations are limited to a 1.5m Hs limit to ensure the safety of technicians during transfer.

Each set of 45 rotors are modelled in the same location in order to simulate a full MRS.

Table 2. Summary of climate data for modelled site

Number of years of data	5
Average Significant Wave Height (Hs)	1.51m
Average Wind Speed (U)	10.36 m/s
Average Peak Wave Period (Tp)	7.21s

3.2. Vessels and Personnel

All maintenance activities will be conducted by a CTV due to the distance to shore [15]. Due to the size of components, a larger CTV is utilised due to the requirement for increased deck space of replacement of rotor components. This is included in the model through a 10% increase in the cost of charter of a "typical" CTV used in industry. Significant wave height limit is 2 m/s for safe transfer and repair. Workability is not limited by daylight and therefore maintenance can be performed at any time, given safe working weather conditions. No HLV due to the reduced size of the components and the assumption that the structure is fitted with an onsite crane for lifting operations. This assumption is in line with the analysis in [5].

Each CTV is able to accommodate 12 technicians. Each repair required a minimum of 2 crew due to safety requirements surrounding lone working offshore. As the number of vessels are increased throughout the simulations as is the number of technicians. It is assumed that there is no waiting time, and all parts are readily available.

3.3. Types of Maintenance

The focus of this work is on unscheduled minor repairs only. The lifecycle of all sites is 20 years.

4. Methodology

The modelling explores how the resource need of the O&M operation changes as the site scales from a single MRS to a full wind farm with installed capacity similar to current operational sites. A total of 3 scenarios are modelled featuring 1, 10 and 40 deployed MRSs. The details of each scenario is detailed in Table 3.

For each of the three scenarios with increased scale of operation, the number of vessels is varied from 1 CTV to 10 CTVs total. Each vessel has an associated crew of 12 technicians.

Table 3. Description of modelled scenarios with details of MRS set up

Scenario	1	2	3
Total Number of Rotors Across the Site	45	450	1800
Number of MRS	1	10	40
Total Installed Capacity (MW)	20.9	208.7	834.8

5. Results and Summary

This section discusses the key findings from the simulations for the three scenarios described in Table 2. The areas of focus are failure specific contribution to downtime, resource utilisation and optimal fleet selection.

5.1. Contribution to Downtime

As discussed in Section 2.1 and illustrated in Figure 3, the small cost of downtime associated with each rotor is one of the key advantages of the MRS from an operational perspective. However, while there is a degree of redundancy amongst the individual rotors, there are still components which impact the downtime of the whole asset such as pitch and electrical configuration. The contribution to downtime can be broken down into local and global for the three scenarios as shown in Figure 5.

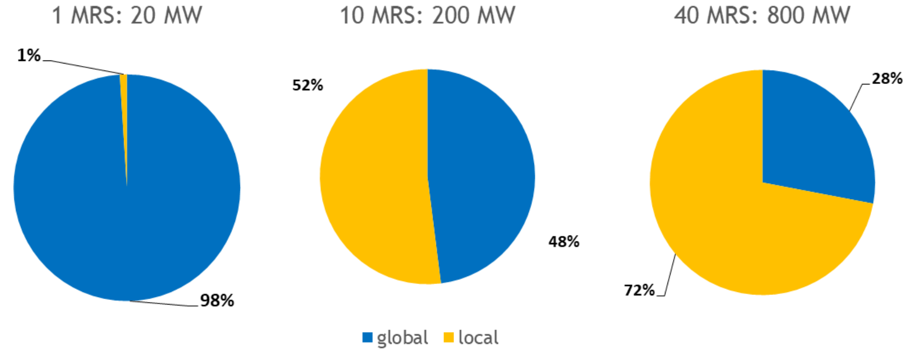

Figure 5. Contribution to downtime from global and local failures for scenarios 1-3.

While global failures have the highest “loss” associated due to the shut-down of the whole asset, they occur much less frequently than that of a local failure, which impacts it’s associated rotor in isolation. Figure 5 shows how the breakdown of downtime contribution between global and local failures changes as installed capacity of the site increases. It can be seen that from 20MW-200MW, the downtime total is dominated by the impact of global failures. This is due to the impact of a failure on the overall site, where a single global failure results in the shutdown of 10-100% of the total site. However, as the total capacity of the site decreases, as does the impact of the complete shutdown of a single MRS on the farm revenue, as illustrated in the middle and right charts of Figure 5.

5.2. Vessel Utilisation

The number of vessels for each site was varied from 1-14 where each vessel had a crew of 12 technicians. Tables 4-6 show the utilisation of each individual vessel, as the total number of vessels available within the fleet were increased through a sensitivity analysis. The tables also show the associated contribution to total OpEx from Downtime as a percentage.

Table 4. Scenario 1: vessel utilisation and corresponding downtime contribution to total OpEx

		vessel number					Downtime
		1	2	3	4	5	% total OpEx
total # of vessels	1	0.74					4%
	2	0.64	0.18				2%
	3	0.61	0.14	0.1			2%
	4	0.59	0.12	0.08	0.06		2%
	5	0.59	0.11	0.06	0.06	0.05	2%

Table 5. Scenario 2: vessel utilisation and corresponding downtime contribution to total OpEx

		vessel number								Downtime
		1	2	3	4	5	6	7	8	% total OpEx
total # of vessels	1	1								98%
	2	1	0.99							53%
	3	1	0.91	0.79						23%
	4	0.99	0.87	0.71	0.62					13%
	5	0.99	0.85	0.67	0.58	0.54				10%
	6	0.99	0.84	0.64	0.55	0.5	0.48			9%
	7	0.99	0.84	0.64	0.54	0.49	0.46	0.45		7%
	8	0.99	0.83	0.63	0.52	0.47	0.44	0.42	0.4	7%

Table 6. Scenario 3: vessel utilisation and corresponding downtime contribution to total OpEx

		vessel number												**Downtime**
		1	2	3	4	5	6	7	8	9	10	12	14	**% total OpEx**
total # vessels	3	1	0.99	0.98										36%
	4	1	0.97	0.89	0.83									24%
	5	1	0.96	0.84	0.75	0.71								16%
	6	1	0.95	0.81	0.7	0.64	0.61							12%
	7	1	0.95	0.81	0.69	0.64	0.61	0.59						11%
	8	1	0.95	0.81	0.68	0.64	0.61	0.56	0.5					10%
	9	1	0.94	0.8	0.68	0.64	0.61	0.55	0.48	0.48				8%
	10	1	0.94	0.78	0.68	0.64	0.61	0.5	0.48	0.48	0.47			7%
	12	1	0.94	0.78	0.68	0.64	0.6	0.5	0.47	0.48	0.46	0.45		7%
	14	0.99	0.94	0.78	0.68	0.64	0.59	0.47	0.47	0.46	0.46	0.42	0.42	7%

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The results indicate that the number of vessels, and available technicians, is a significant bottleneck in operations due to a high utilisation of a small number of vessels resulting in an increased contribution from downtime to OpEx. By increasing the number of vessels, the overall downtime contribution decreased steadily across all of the scenarios.

5.3. *Operational Expenditure Breakdown*

As shown in section 5.2, there is a clear and direct link between the number of vessels within the fleet and the overall cost of downtime. However, the addition of a new vessel comes with added costs such as charter, fuel, and staff costs. This section explores the changes in direct and indirect OpEx and how this varies as both installed capacity and number of vessels increases. Figures 7-9 show the total OpEx (£/MWh) and the total downtime/lost revenue for each scenario as the number of vessels increases.

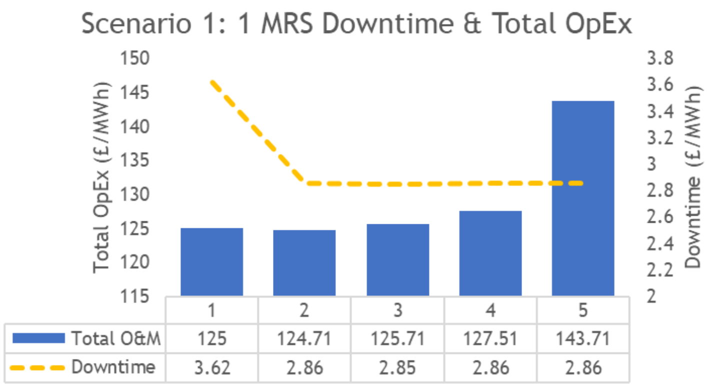

Figure 6. Scenario 1: sensitivity anaylsis of total OpEx and downtime/lost revenue as number of vessels/crew increases

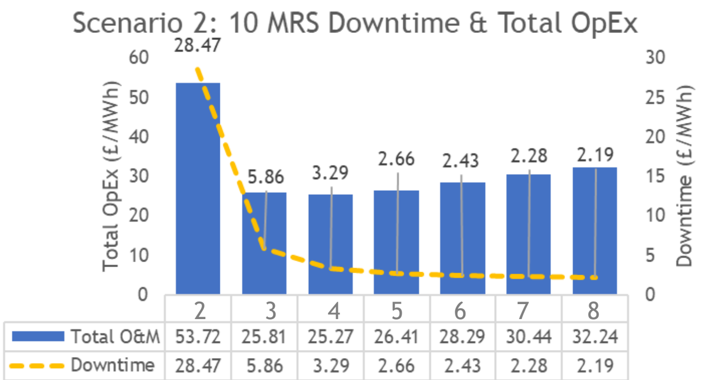

Figure 7. Scenario 2: sensitivity anaylsis of total OpEx and downtime/lost revenue as number of vessels/crew increases

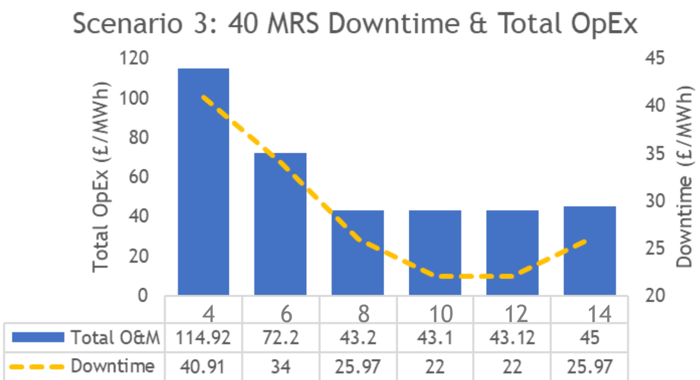

Figure 8. Scenario 3: sensitivity anaylsis of total OpEx and downtime/lost revenue as number of vessels/crew increases

For scenario 1, when the number of vessels reaches 2, there is a clear levelling out of the downtime cost. As the number of vessels increases, as does the total OpEx, however, this is insignificant until a 5 level fleet is used. This also corresponds to the output from Table 5, which saw the vessels 3, 4 and 5 only being utilised >10%. The optimal operating conditions for scenario 2 is a fleet consisting of 4 vessels. While having a 5 vessel fleet results in the lowest downtime cost, the additional costs of vessel and personnel results in a higher OpEx. Scenario 3 selects a 10 vessel fleet for optimised O&M practices. This configuration had both the lowest OpEx and downtime cost.

6. Discussion and Conclusion

Further work on this study would include the addition of safety limitations for technicians in regarding working on rotors while others remain operational. A shut down of the whole asset would result in the same downtime of a conventional turbine, however, this would only be during the period of active repair. Other additional considerations include introduction of major repairs and replacements, vessel optimisation and calculation of LCOE for the whole structure. A CapEx vs OpEx study would quantify the benefit of installing a crane on site (additional CapEx) due to the benefit of OpEx savings.

It was found that at installed capacity increases, the global failures become less prominent in their contribution to downtime. Due to the small installed capacity of each rotor, and subsequent downtime, group maintenance could be explored as a maintenance strategy. This would require a cost benefit analysis and optimisation of cost of repair vs cost of downtime. Benefits of such a strategy would include the sharing of resources and therefore would likely reduce the size of fleet required.

Vessel utilisation upwards of 45% indicate that the vessel is being of use and the additional contribution to direct OpEx is often outweighed by the savings in downtime cost. Overall, it is more beneficial to overestimate the needed resources than underestimate as the cost of downtime due to resource availability severely outweighs the additional staff and transportation costs.

Scenario 3 with an 800 MW installed capacity required a fleet of 10 vessels and a staff upwards of 120 personnel. As installed capacity increases, the trend indicates that the vessels required will also increase for profitable operation. While the increase in vessel and staff costs were outweighed by the savings in lost production, physical constraints such as port facilities, capabilities, and infrastructure will dramatically limit the number of vessels permitted. Therefore, the proposal of group maintenance strategies is encouraged to make efficient use of realistic available resources.

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