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Estimating the major replacement rates in next-generation offshore wind turbines using structured expert elicitation.

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Abstract. With offshore wind turbines continuing to increase in size and move further offshore and into harsher environments, the complexity of carrying out the major replacement of large components is expected to pose a significant challenge for future offshore wind farms. However, the rate of major replacement operations that will be required in these next generation offshore wind turbines is currently unknown. Using a structured expert elicitation method, based on the Classical Model and implemented using EFSA guidance for the practical application of structured expert elicitation, major replacement rates of large components (generator, gearbox, and rotor) were systematically estimated for four next generation offshore wind turbine configurations, based on the knowledge of six wind energy experts. The results presented in this paper are based on an equal-weighting aggregation approach. The major replacement rate values found using this approach are presented and compared between different turbine configurations. Based on these results, it is expected that a larger number of major replacement operations are more likely to be required in medium-speed turbine configurations, in comparison to direct-drive, and in floating turbines, in comparison to fixed-foundation turbines.

1. Introduction

The installed capacity of offshore wind has increased significantly over the last decade, with installed capacity of offshore wind turbines in Europe reaching over 22GW in 2019, from less than 5GW in 2009 [1]. Not only have more turbines been installed over this period, but the turbines themselves have also changed. Offshore wind turbines have become increasingly larger, with turbines of rated power up to 9.5MW currently being installed [2]. This is a significant increase in comparison to the first-generation of offshore turbines with rated power around 2MW to 3MW. The generator and drive-train configuration of turbines offshore have also changed over this time, with the move to direct-drive and medium-speed permanent magnet configurations [3], and developers have also begun to target deeper waters using floating foundations [4]. These trends are expected to continue, with 15MW turbines expected in the middle of the decade [5].

With turbines of this scale, the major replacement of large components that typically require the use of a heavy lift vessel, for example the electrical generator, gearbox, and rotor, will become an increasingly complex operation. There is a very limited number of heavy lift vessels with the required crane height to carry out the replacement of these components offshore [6], and in floating wind farms, where the water depth is likely to be beyond the operational range of a jack-up vessel, the optimum strategy for carrying out these replacements is still uncertain. Therefore, the replacement of these components should be given consideration at the early stages of an offshore wind project.

However, the rate at which these major replacements will be required in the next-generation of offshore wind turbines is currently unknown. It may be possible to make predictions of this based on available operational failure rate data for past and current generation offshore turbines, however offshore wind turbine failure rate data is currently extremely limited. To the author's knowledge, the only publicly available source of data on the rate of major replacements of large offshore wind turbine components was published by Carroll et al. [7]. For confidentiality reasons, the exact details of these turbines are not given, but it is stated that the analysis is based on around 350 fixed-foundation offshore wind turbines of the same model with a rated power between 2-4MW with 3-stage gearboxes and induction generators. It has already been highlighted that there have been significant developments in offshore turbine technology since these first-generation turbines, and therefore these published values may no longer be representative of the next generation of offshore wind turbines.

In situations when no representative data is available, yet decisions still have to be made, the judgement of subject matter experts is often used as a best alternative. Expert elicitation methods have previously been used in the area of wind energy to estimate the future costs of offshore wind [8], [9], and has been applied for decades in a wide range of other areas [10], [11]. Structured expert elicitation methods provide a framework to capture expert knowledge, represent their uncertainty in the values they provide, and reduce the impacts of the various cognitive biases and heuristics that may impact the results [12], [13].

The objective of this work is to estimate the major replacement rate of large components in four next-generation offshore wind turbine configurations using a structured expert elicitation approach. The next-generation wind turbine configurations considered for this work are,

- 15MW fixed-foundation direct-drive turbine,
- 15MW fixed-foundation medium-speed turbine,
- 15MW semi-submersible foundation direct-drive turbine, and
- 15MW semi-submersible foundation medium-speed turbine.

The primary novel contribution of this work is therefore in presenting major replacement rate values for next-generation offshore wind turbines which have been estimated from expert knowledge using a structured and systematic approach. These replacement rate values can be used in activities like operations and maintenance cost modelling, maintenance planning, and spare part inventory planning. A secondary contribution is in also providing a summary of the reasoning provided by experts along with these values.

2. Method

The overall approach applied in this work is based on the Classical Model of structured expert elicitation [14], [15], with steps taken based on guidance produced by the European Food Safety Authority (EFSA) on practically applying expert knowledge elicitation methods [16]. The Classical Model is one of the most widely recognised and applied structured elicitation methods and is characterised by individual interview sessions (with no interaction between experts), the mathematical aggregation of individual expert responses and the weighting of expert responses based on additional seed, or calibration, questions (performance weighting). However, the particular results that are presented within the paper are based on an equally weighted aggregation of responses, rather than performance weighting, as used in the Classical Model. Experts generate a theoretical probability distribution which represents their distribution of uncertainty in what the true value of an unknown parameter could be, typically by providing values for three percentiles (5th, 50th and 95th) [15]. These values are then aggregated across the group. Further detail on the Classical Model and discussion of equal weighting versus performance weighting can be found in [11], [15], [17]–[21].

2.1. Selection of Experts

There are no definitive requirements on the number of experts needed as part of the elicitation process and this is often limited by available resource and availability of experts. Quigley et al. gives a range of 5-20 experts for elicitation using the Classical Model [15] and other sources suggest that between five and ten experts are optimum [22]. An analysis of 33 elicitation studies shows the number of experts varying from four to 21 across these [11]. However, the priority is to ensure that the required range of expertise is covered across the group [16], which was achieved in the present study.

Experts were selected based on the expertise that was considered to be important in estimating the expected component replacement rates in next-generation offshore wind turbines. Firstly, a profile matrix [16] was created outlining the areas of knowledge that was considered by the authors to be required across the group. These areas of knowledge are shown in Table 1. It is accepted that all experts may not have expertise in all areas, but what is considered important is to have coverage across all areas within the group.

The authors then created a long-list of potential experts based on the authors' familiarity with these areas. When potential experts were contacted, some of these also provided names of additional potential experts, which were also added to this long-list, however, no explicit 'snowballing' technique [22] was used. From the long-list, a smaller group of potential experts were chosen. This was done by best matching the known expertise of the potential experts to the requirements outlined in the profile matrix. At this stage, known expertise was judged based on the review of publications, job history available online, for example on LinkedIn, or through the knowledge of the authors.

Potential experts from this smaller group were then contacted and individual interview sessions were completed with six experts. Prior to the interview sessions, experts were sent a questionnaire in which they were asked to summarise their experience and identify the areas outlined within the profile matrix which they had a good understanding of. The number of experts self-identifying as having a good knowledge of each of these areas are also given in Table 1. Across the group of experts there was a combined experience of 85 years within the area wind energy (an average of around 14 years per expert), plus a combined 33 years of experience in other, related areas. The list of expert names can be found in Appendix I.

Table 1. Required areas of knowledge identified by authors in profile matrix, and the number of experts who identified themselves as having a good understanding of each of these areas.

Required areas of knowledge	Number of experts with good knowledge of area
Wind turbine technology	5/6
Offshore Wind	6/6
Wind turbine reliability and maintenance	5/6
Floating wind	5/6
Wind turbine drive-train (gearbox and generator)	5/6
Wind turbine rotor (blades and hub)	4/6
Mathematical probability	5/6

2.2. The interview sessions

Experts were interviewed individually online using either Zoom (five interviews), or Microsoft Teams (one interview). This was a requirement due to the Covid-19 restrictions on in-person meetings across the duration of this work. During the interview sessions, experts were asked 20 questions – 10 seed questions, as required when applying the Classical Model [14], and 10 questions on the variables of interest. The seed questions were based on historical failure rates for onshore wind turbines and were structured in the same way as those for the variables of interest, however**,** as the results presented within this paper are based on an equally weighted mathematical aggregation of expert responses and not performance weighting, only the variables of interest will be discussed.

The 10 variables of interest were the major replacement rates of the following three wind turbine components, within the four next-generation turbine configurations detailed previously,

- electrical generator,
- gearbox, and
- rotor (defined as any of the blades or the hub)

Experts were presented with the publicly available component major replacement rate data for first-generation offshore wind turbines [7], and asked to estimate by what percentage they expected this value to differ when considering the next-generation of offshore wind turbines. Experts were also asked to explain their reasoning for these differences. As is common in structured expert elicitation, experts were asked to provide values for a range of percentiles which represent their uncertainty in what the true values could be. The expert's uncertainty in the exact value of the variable of interest can be thought of as a probability distribution, and in this case the experts were asked to estimate the values for the 5th, 95th, and 50th percentiles of this theoretical distribution of their uncertainty. The 5th and 95th percentile values being the values they thought it was very unlikely that the true value would be below or above, and the 50th percentile being the value they thought it equally likely the true value could be below or above. An example of one of these questions is given in Figure 1 and the full set of questions is given in Appendix II. In the majority of the interview sessions (four out of six), all questions were completed during the session. In the remaining two sessions, four questions were not completed during the session and were then sent to the experts via email and they responded with their values and reasoning. In both cases, these questions were for the variables of interest regarding rotor major replacements.

It is recognised that presenting experts with major replacement rate values for the first-generation of offshore wind turbines creates an opportunity for anchoring bias [23] to occur. The concept of anchoring is explained to the experts as part of the initial training prior to the questions in an attempt to reduce the impacts of this, and the benefits of providing this initial value as a basis for discussion, and to understand why the values provided differ from the currently best available public data, was judged to outweigh the potential risks of anchoring occurring here.

Based on offshore data, the average number of major replacements for a generator in a fixed bottom, 2-4MW turbine with high-speed gearbox and induction generator over the first 8 years is estimated to be around *0.095 replacements/ turbine.yr.* By what percentage do you think the average number of major replacements for a generator will change for a fixed bottom, 15MW, direct-drive turbine with a permanent magnet synchronous generator over the same time period?		
5th percentile	95th percentile	50th percentile
Reasons for answer:		

Figure 1. Example of one of the elicitation questions on the variables of interest.

2.3. Aggregation of values across the expert group

As mentioned previously, each expert provides three values for each question - the 5th, 50th, and 95th percentile of a theoretical probability distribution that represents their uncertainty in the true value. These values must then be aggregated across the group of experts to produce an overall distribution representing the uncertainty of the group. This aggregation was done mathematically using an equal-weighting linear pooling approach. This can be calculated using Equation 1, where $p_i(\theta)$ is the percentile value given by each expert, i, and $p(\theta)$ is the aggregated value for that percentile [21]. Using the equal-weighting approach, the weight given to each expert, w_i is simply 1/n, where n is the number of experts [21].

$$p(\theta) = \sum_{i=1}^{n} w_i p_i(\theta) \tag{1}$$

The aggregated values for each of the components replacement rates within each turbine configuration were then summed together to represent the overall major replacement rate values for each turbine configuration. For example, the aggregated 5th percentile values for the generator and the rotor for the fixed-foundation direct-drive turbine were summed together to give the 5th percentile value for the overall major replacement rate for the fixed-foundation direct-drive configuration. The same was done for the 50th, and 95th percentile values, and for the other turbine configurations.

3. Results and Discussion

3.1. Major replacement rate values

The results calculated using this approach are shown in Table 2 and Figure 2. Table 2 gives the 5th, 50th, and 95th percentile values of the aggregated distribution representing the uncertainty in the major replacement rate of large components in each of the four next-generation offshore wind turbine configurations. Figure 2, then presents these values visually on a modified box plot, where the outer lines represent the aggregated 5th and 95th percentile values, and the inner line represents the aggregated 50th percentile value for each turbine configuration.

Table 2. Aggregated values of the 5th, 50th and 95th percentiles representing the distribution of uncertainty in the major replacement rate value for each turbine configuration.

Turbine configuration	Overall major replacement rate – 5th percentile	Overall major replacement rate – 50th percentile	Overall major replacement rate – 95th percentile
Fixed-foundation, direct-drive	0.023	0.05	0.075
Fixed-foundation, medium-speed	0.045	0.104	0.164
Semi-sub foundation, direct-drive	0.03	0.059	0.084
Semi-sub foundation, medium-speed	0.063	0.119	0.177

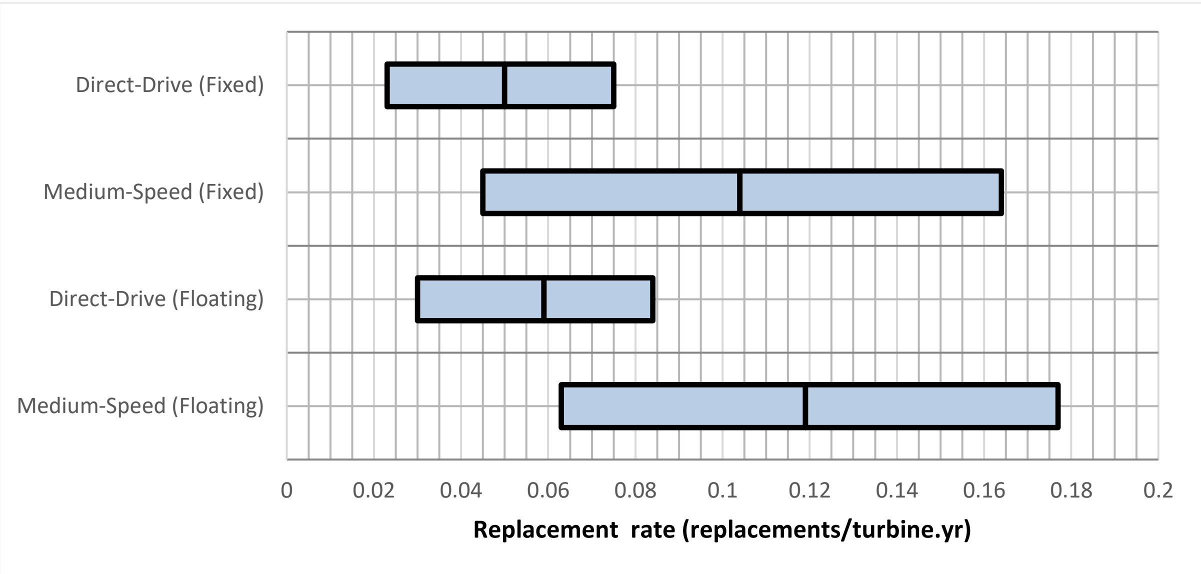

Figure 2. Aggregated values of the 5th, 50th, and 95th percentiles representing the distribution of uncertainty in the major replacement rate value for each turbine configuration shown on a modified box plot.

3.2. Next-generation v first-generation

When comparing the values for each of the next-generation turbine configurations, shown in Table 2, against the published major replacement rate values given in Carroll et al. [7], it can be seen that the overall major replacement rates in these next-generation turbines are expected to be significantly lower than the published values. There are several reasons for this. Firstly, a recurring point across the experts was that the replacement rates of major drive-train components in the first-generation of offshore wind turbines were very high. However, since then, there has been significant learning and experience gained with the operation of offshore turbines, and the replacement rates of these components in the current-generation of offshore turbines are currently much lower than for these first generation. Another reason widely given across experts was the economic and business case drivers for reducing replacement rates of these components. Due to the scale of these 15MW turbines, replacing a gearbox or a generator, particularly in a direct-drive turbine, will be a major and complex operation which will want to be avoided. It was widely thought that the cost of replacing these components in this next-generation of turbines, as well as the economic losses caused by turbine downtime, would have significant negative impacts for project viability if replacement rates similar to the 2-4MW turbines were seen in these next-generation turbines, and there will be expectations as part of the commercial and investment negotiations for these large offshore wind farms to improve reliability. Another reason given by several experts for a reduction in major replacement rates of the generator in these turbines was the potential move to modular generator design. This will allow for parts of the generator to be replaced, rather than a complete major replacement of the component. Potential operational interventions that could also reduce replacement rates were also highlighted, for example increased monitoring of turbines. Several experts highlighted the fact that the current-generation of offshore turbines undergo more pre-emptive maintenance than the first-generation, and these next-generation of offshore turbines will likely have more advanced condition monitoring systems, therefore allowing issues to be addressed before the requirement of a component major replacement. Other reasons for an increase in reliability compared to the first generation of turbines included the move to permanent magnet generators, and the reduction in the number of stages in the medium-speed gearbox compared to the high-speed gearbox.

3.3. Large uncertainty in estimated values

When reviewing the values in Table 2 and Figure 2, it can be seen that these percentile values cover a wide range, therefore highlighting a large uncertainty in what these values may be. This can be expected as these turbines are yet to be constructed and operated. There is no operational data to consider and there are still uncertainties around the specific design of these turbines, and which operation and maintenance strategies will be used. Although major replacement rates are expected to be lower than the first-generation turbines and there are significant economic and business case drivers for these replacement rates to be as low as possible, due to the scale of these next-generation turbines, it was frequently highlighted that there could be technological challenges and limitations that could potentially lead to reasonably high replacement rates in these turbines. The high rated power of these turbines will lead to significantly larger torque values for the gearbox and generator compared to the first-generation of turbines. It was also highlighted that the larger components may lead to an increased risk of failures, if considering failure rate as a function of component size and mass – for example, a blade with a larger surface area will be more likely to have a defect if the likelihood of defects/m^2 is constant. It can also be seen that the percentile range is much wider for the medium-speed configurations than for the direct-drive configurations. This is mainly due to the inclusion of the gearbox in this configuration, therefore introducing a third uncertain parameter in addition to the generator and rotor.

3.4. Direct-drive v medium-speed

When comparing the percentile values for the direct-drive and medium-speed configurations, it can also be seen that, with a higher value for each of the three aggregated percentile values, a higher number of major replacements are expected to occur in the medium-speed turbines. Again, this mainly due to the inclusion of the gearbox in this configuration as an additional large component that is not included as part of the direct-drive configuration. The required number of replacements of part of the rotor is expected to be the same between the different turbine configurations and the number of generator replacements expected to be lower in the medium-speed turbines. However, the medium-speed gearbox was expected to have the highest major replacement rate of all the components. Experts highlighted potentially high major replacement rates for the gearbox based on the historical difficulties with gearboxes in offshore turbines, and the limited experience of designing and operating gearboxes at this scale. However, it should be noted that there is overlap between the range of values shown in Figure 2 for the direct-drive and medium-speed configurations. Therefore, it is considered possible that the medium-speed configuration may have a lower rate of major replacements, it is just considered to be much less likely.

3.5. Fixed v floating

Another interesting comparison is between the estimated major replacement rate values of the fixed-foundation turbine configurations and the floating turbine configurations. It can be seen in Table 2 and Figure 2 that each of the three aggregated percentile values for the floating turbine configurations are slightly higher than that of the equivalent fixed-foundation turbine, therefore highlighting that slightly higher rates of large component major replacements are expected in floating turbines. The main reasons given for this expected increase is that the additional degree of motion and potentially higher nacelle acceleration values could lead to increased loading on the components, and that, due to the expected lower accessibility of floating turbines, maintenance tasks will be more difficult to complete, leading to a larger number of failures. It was also mentioned that the opportunity of applying a tow to shore maintenance strategy in floating turbines to replace major components could make replacing these components less challenging compared to fixed-foundation turbines, therefore reducing the need to reduce replacement rates as low as the next-generation fixed-foundation turbines.

It should however be noted that, although these results show a predicted overall increase in replacement rates in floating turbines compared to fixed-foundation, this agreement was not seen across all experts. Several experts expected a lower replacement rate to be seen in floating turbines. Some of the reasons given for this included knowledge of existing research suggesting that, for some configurations, the loading on the drive-train is not significantly impacted by the turbine wave-induced motion, and highlighting that, as major component replacements in floating turbines may be more challenging than in fixed-foundation turbines, there will be significant drivers to further reduce major replacement operations in floating turbines. It should also again be noted that there is a large overlap between the range of aggregated values shown in Figure 2 for the fixed and floating turbine configurations, therefore suggesting that while a higher rate of major replacements in floating turbines is considered the more likely outcome (when comparing the percentile values), the alternative is possible.

4. Conclusion

As offshore wind turbine technology develops, the complexity of carrying out major replacement operations of large components is expected to increase. It is therefore important that these major replacement operations are planned for at an early stage of the project. However, the number of these major replacement operations that will be required in the next generation of offshore wind turbines is currently unknown. These next-generation turbines are yet to be constructed and failure rate data for the current generation of offshore wind turbines is not publicly available. Therefore, the aim of this work was to estimate the major replacement rate of large components (generator, gearbox, and rotor) in four next-generation offshore wind turbine configurations.

Using a structured expert elicitation approach based on the Classical Model, six wind energy experts with knowledge in a wide range of related areas and a combined 85 years of experience within the area of wind energy, were asked to estimate how they expect the rate of major replacements of large components to change from the publicly available values for first-generation offshore wind turbines, to the next-generation of offshore wind turbines. This paper presents the results based on an equally weighted aggregation of expert responses, and not the performance weighted approach applied in the Classical Model.

Using this approach, the estimated range that these major replacement rate values are expected to be within are presented. It was found that there is still a large uncertainty among experts in what these values will be. However, the results suggest that it is more likely a higher rate of large component major replacement operations will be required in next-generation medium-speed turbines due to the inclusion of the gearbox. The results also suggest a higher rate of major replacements will likely be required in next-generation floating turbines, in comparison to next-generation fixed-foundation turbines.

The results presented within this paper and the conclusions drawn are based on an equally weighted aggregation of expert responses. However, this is not the only approach to aggregating the responses across the group. It has already been highlighted that the overall approach applied in this work is based on the Classical Model in which a performance weighting aggregation is used, and therefore the next steps for this work will be to apply the weighting methods used in this approach and compare the results and conclusions to those produced using the equal-weighting approach. Future work will also look into more detail at the expected major replacement rates of the individual components, and investigate how this varies between the different turbine configurations considered.

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Appendices

If Appendices I and II cannot be found attached to this paper, these can be requested by contacting the corresponding author at brian.jenkins@strath.ac.uk.

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*Any opinions given by experts as part of this work are those of the experts themselves at the time of, and in the context of, the interview sessions and may not be representative of the opinions of their respective companies or institutions. It should also be noted that the results presented are aggregated results of the group, and therefore may not be representative of the opinions of the individual experts making up the group.