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Judgment-based dynamic fragility assessment of gearboxes to extreme weather events: preliminary findings

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Abstract. This study presents the preliminary dynamic fragility outputs for a case study [1.5–2) MW capacity class onshore wind turbine gearbox, impacted by 3 s average wind gusts. Windstorms and gearboxes are amongst the leading sources of onshore wind turbine insurance claim payouts, yet the relationship between the two is not well understood. A gearbox dynamic fragility framework is developed to quantify the uncertainty in wind gust fragility at different stages of the gearbox's operational life. An anonymized, Cooke's method approach is used to elicit and to objectively aggregate exceedance probabilities from 11 respondents in the wind energy supply chain. Preliminary findings suggest that the probability of full gearbox replacement increases with both time-phased degradation and wind gust speed and aligns well with empirical reliability data. Compared to a 10 m s^{-1} wind gust, a 70 m s^{-1} wind gust increases the gearbox replacement probability by 13–14% between 0 and 15 years of operational life. The outputs highlight areas of uncertainty requiring further validation and set the foundation for the development of wind gust vulnerability functions, which quantify the insurance losses expected from wind gust events.

1. Introduction

1.1 Background

In 2024, annual capacity additions of onshore wind were only second to solar photovoltaics in the renewable energy sector, globally [1]. However, renewable energy projects remain more vulnerable to weather-related events compared to fossil fuel alternatives, due to larger land area requirements and greater site constraints [2]. Being relatively new assets, they also have a low exposure history to natural hazard events [3]. Therefore, practically applicable vulnerability

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models are needed by the insurance sector to reduce uncertainty in evaluating insurance premiums for protecting these assets against future weather-related risks [3].

At present, windstorms are amongst the leading natural causes of property damage insurance claims for onshore wind turbines, with gearbox and blade damage accounting for the highest proportion of associated losses [4]. Previous studies, such as [5] and [6], have explored the potential relationship between wind gusts and gearbox damage, but significant epistemic uncertainties remain regarding the exact nature of such failures. Whilst wind fragility functions for structural components of wind turbines, such as the tower, do exist in publicly available literature, a lack of representative functions are reported in [3] for non-structural components such as the gearbox. This gap in knowledge limits the practical applicability of using existing vulnerability functions to develop insurance risk models for onshore wind assets subjected to extreme wind events.

1.2 Research aim and objectives

This study aims to quantify uncertainties in the damage probability of onshore wind turbine gearboxes when subjected to wind gust events at different points in their service life.

To achieve this, gearbox damage states (DSs) are defined, and a novel dynamic fragility assessment framework is developed, incorporating both wind gust loading and time-dependent degradation. The Cooke's method [7], an established structured elicitation approach used in the past to construct fragility curves for assets exposed to natural hazards [8, 9], is used to assess wind gust fragility over time. Perspectives from the wind energy supply chain, insurance sector and utility sector are captured. The elicitation exercise is developed in conjunction with the International Energy Agency (IEA) Wind Task 43 - Wind Energy Digitalization, a research activity which aims to unlock the full value of wind energy through initiatives such as data-driven decision-making [10]. This study addresses one of the key aspects of this by harnessing expert knowledge to produce quantitative results which directly link to stakeholder value.

The current paper focuses on the preliminary outputs from the exercise conducted with the wind energy supply chain and highlights epistemic uncertainties where further empirical validation or numerical methods are required.

2. Fragility Assessment Framework

2.1 Gearbox damage state development

Figure 1 defines three gearbox DSs: *None* (ds_0), *Uptower repair/replacement* (ds_1) at the nacelle, and *Full gearbox replacement* (ds_2) with a refurbished or new gearbox. Whilst higher DSs indicate greater financial consequences for the original equipment manufacturer (OEM) and wind farm operator, they are not necessarily sequential.

DSs and failure locations were identified from a 2021 Electric Power Research Institute (EPRI) report on wind turbine gearbox reliability [11]. Example failure modes were then identified through a 2012 EPRI report [12] and the ONYX Insight's Failure Atlas Archive [13]. They were then refined through discussions with members of an IEA Wind Task 43 use case sub-working group as well as one-to-one feedback from the wind energy supply chain.

Further feedback was sought from over 100 stakeholders at the 2025 Drivetrain Reliability Collaborative (DRC) workshop. This is an annual event covering topics including reliability, digitalization, as well as wind plant operations and maintenance. Attendees represent the drivetrain supply chain, with the majority being owners and operators from industry. Subsequently, vibration range and oil contamination levels were identified as key indicators to be

detailed across all DSs for the elicitation exercise. Indicator thresholds were defined for vibration using broad-band root-mean-square acceleration and velocity values for onshore wind turbine gearboxes with rolling bearings, provided in the draft ISO 20816-21:2025 [14] standards. For oil contamination, the ISO 4406 cleanliness code thresholds were defined through documentation on industry recommendations for lubrication [15–17] and the draft IEC 61400-4:2025 [18] standards for gearbox design. Iron concentration limits were also determined based on [16], as it is noted in [15] as the main element to observe for wear in wind turbine gearbox oils.

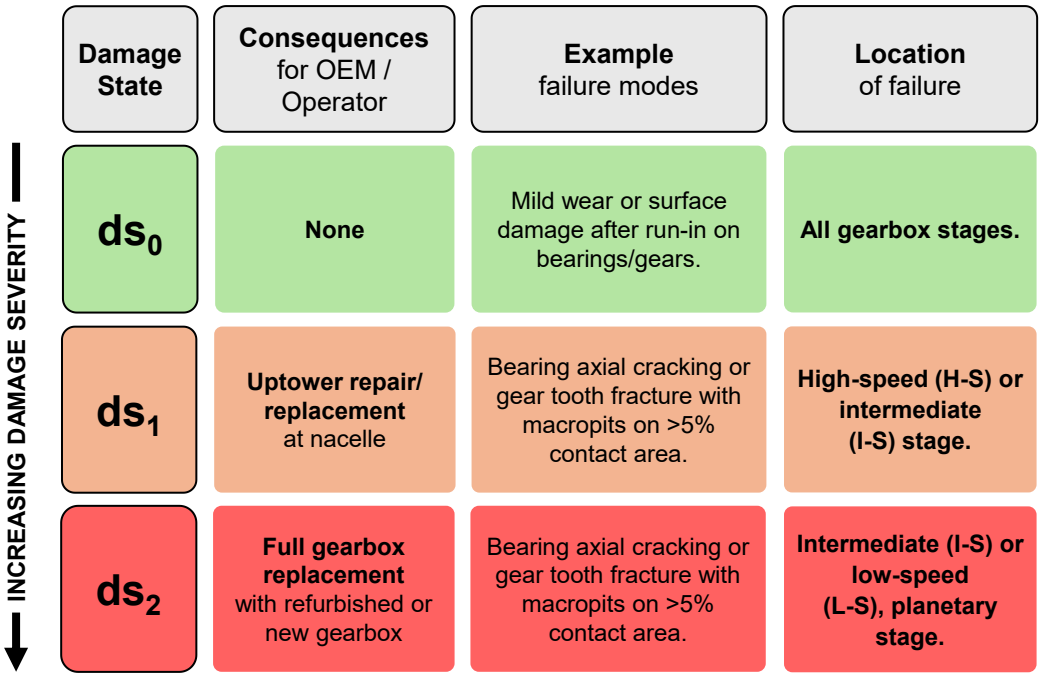


Figure 1. Gearbox damage state taxonomy. Based on [11–13].

2.2 Dynamic fragility assessment framework

The dynamic fragility framework (a Bayesian network model illustrated in Figure 2) represents how an individual wind gust event interacts with a pre-existing gearbox DS during normal time-phased degradation. This leads to an acceleration in time-phased degradation and is reflected by an increase in exceedance probabilities at higher gearbox DSs.

Using this framework, fragility surfaces for ds_1 and ds_2 can be developed based on hazard intensity measures: t_{year} [years], the time-phased degradation (e.g. due to fatigue or wear) under rated wind speeds, and v_{gust} [m s^{-1}], the 3 s average wind speed of the gust event. The conditional, cumulative damage probabilities required for the framework are derived through the elicitation approach detailed in Section 3. They are:

- **$P(DS \geq ds_i \mid t_{year}, v_{gust} = 0\ m\ s^{-1})$, where i = 1 or 2:** The exceedance probabilities at ds_1 and ds_2, respectively, at any stage during operational life. It is assumed that the gearbox operates continuously at rated wind speeds (on average) and is at ds_0 at 0 years of life.
- **$P(DS \geq ds_i \mid v_{gust}, DS = ds_0 @ t_{year})$, where i = 1 or 2:** The exceedance probabilities at ds_1 and ds_2, respectively, at any intensity of v_{gust}, given the gearbox is currently at ds_0 in its operational life.

- **$P(DS \geq ds_2 \mid v_{gust}, DS = ds_1 @ t_{year})$:** The exceedance probabilities at ds_2 at any intensity of v_{gust}, given the gearbox is currently at ds_1 in its operational life.

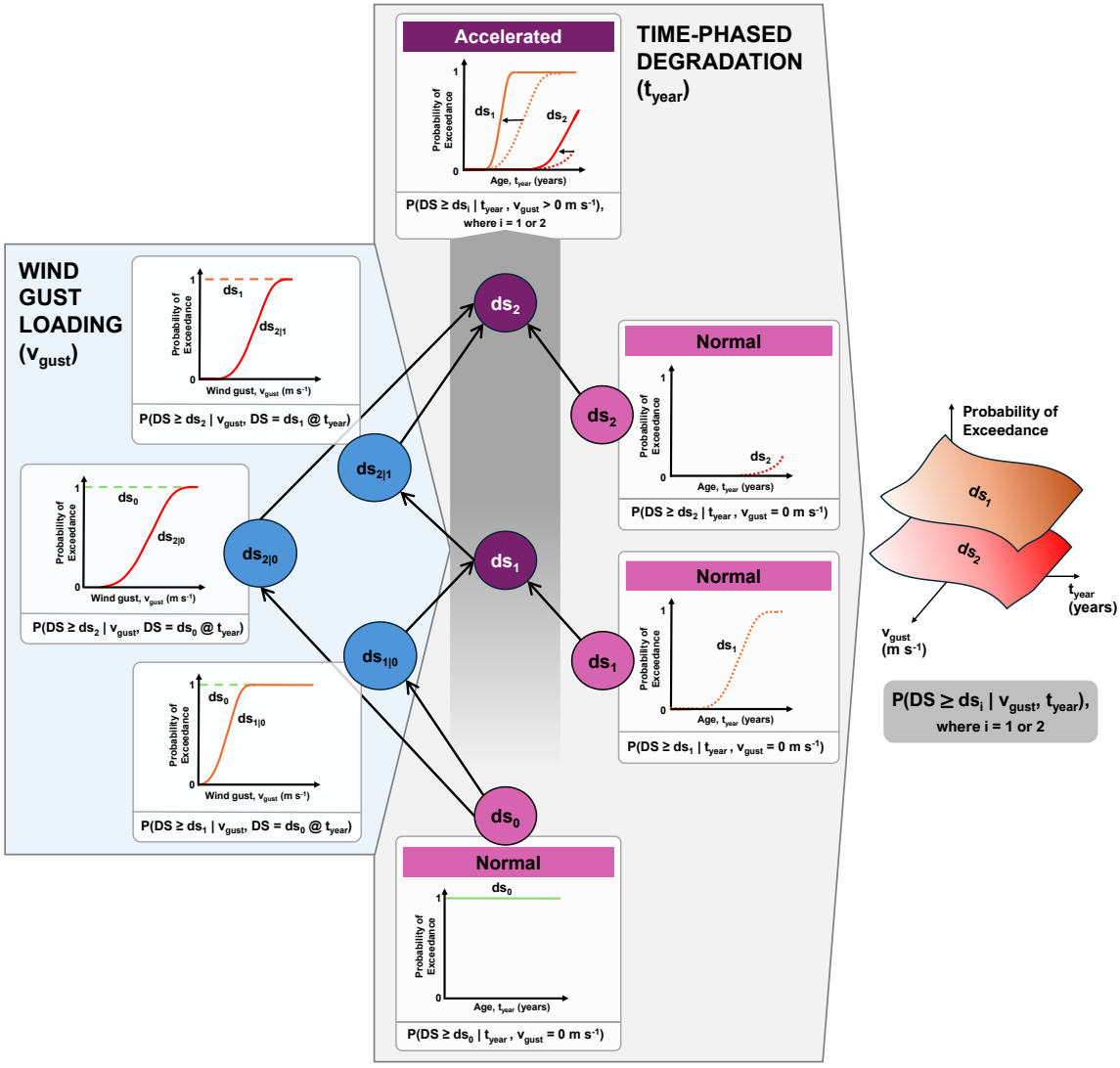


Figure 2. The dynamic fragility framework: a Bayesian network model for assessing fragility at ds_1 and ds_2 respectively, as a function of the time-dependent degradation over years (t_{year}), and gust event wind speed (v_{gust}).

3. Elicitation Method

This section details the anonymized, online elicitation exercise for fragility assessment that was developed for wind energy supply chain respondents. The Cooke's method approach reaches a consensus by mathematically assessing the performance of the respondents [19]. The successful application of the method required the determination of an unambiguous problem with clearly stated target questions. This was formulated through the aforementioned IEA Wind Task 43 sub-working group discussions, as well as one-to-one feedback from the wind energy supply chain

and insurance sector. The ability of the experts to assess the uncertainty was assessed through their responses to a number of seed questions, whose true values were known to the host.

3.1 The problem statement

As a baseline for the elicitation approach, a [1.5–2) MW capacity class onshore wind turbine was defined, recognizing greater experience in the field for this capacity class compared to larger [2–3) MW or ≥3 MW alternatives [20]. It complies with IEC Class II [21] design standards, which is representative of a typically insured European wind farm located in plain terrain. At the site, wind loading is assumed to be perpendicular to the rotor.

The gearbox was detailed as three-point mounted, with one set of main bearings, and had a 1P2H arrangement [22], i.e. one epicyclic planetary stage followed by two helical parallel stages. It was assumed to be properly maintained, with bearing and gear material quality as well as gearbox lubrication, meeting industry standards [18] and recommendations [15, 16]. A further assumption is made that the gearbox is uptower serviceable with a 100% success rate, to avoid the influence of serviceability constraints on the elicited exceedance probabilities. As per the IEC 61400-1 [21], both the turbine and gearbox have an expected lifetime of 20 years.

Hazard intensity values chosen for the exercise are, t_{year} = [5, 10, 15, 20] years and v_{gust} = [10, 25, 40, 55, 70] m s^{-1}. Following feedback from stakeholders at the 2025 DRC workshop, a control system response was defined for different v_{gust} intensities. All v_{gust} values between 10–40 m s^{-1} occur within power production thresholds. Whilst those between 55–70 m s^{-1} exceed the control system's cut-out wind speed, automatically triggering a normal shutdown response during wind loading. Only v_{gust} = 10 m s^{-1} occurs below the turbine's 10-minute average rated wind speed.

3.2 Online elicitation exercise survey

The elicitation exercise was conducted via an online Qualtrics survey, where respondents were allocated a randomly generated ID, to allow for anonymous withdrawal. The survey included four parts, as shown in Table 1, and was estimated to take up to 2 hours to complete.

Table 1. Elicitation exercise structure with mandatory (M) and optional (O) parts.

Part	Description
(1) Preliminary Questions (M)	Respondents are asked basic, non-personal information to provide context, e.g. years of experience.
(2) Seed Questions (M)	• Respondents are asked questions, for which answers can be derived from insurance claims data and publicly available literature. • These responses help weight the answers given for the target questions (part 3), before they are aggregated.
(3) Target Questions (M)	• Respondents answer questions with **unknown** answers. • These responses mainly focus on the dynamic fragility framework exceedance probabilities (see Section 2.2).
(4) Debrief Questions (O)	Respondents reflect on their target question (part 3) responses.

For each seed and target question (parts 2 and 3), respondents provide a best estimate (median) and a 90% uncertainty interval (lower and upper bounds). In line with

recommendations [19], eight seed questions with known answers are used to assign performance-based weights to respondent judgments in the target questions. Overall, the experts were invited to answer 25 target questions, 23 of which elicited probabilities of exceedance (detailed in Section 2.2) at four t_{year} and five v_{gust} intensities (detailed in Section 3.1). To support conversion of fragility into business interruption (BI) losses, two additional target questions elicit the expected downtime days at DSs: ds_1 and ds_2. This study does not consider BI losses at ds_0.

3.3 Reaching consensus

The Cooke's Classical Model [7] is utilized to pool the expert opinions by assigning a performance-based weight for each respondent based on their responses to the seed questions. The weight accounts for two objective metrics: the calibration score and information score [23]. A respondent with a high calibration score will have most true values fall within their 90% confidence interval [19]. This is conditional on the true values being close to equally distributed above and below the respondent's best estimates [19]. Meanwhile, a respondent who is able to capture the true value within a relatively narrow 90% uncertainty interval will have a higher information score [19].

The closed-source EXCALIBUR v1.0 [24] software is used to implement the Cooke's method on the elicited values. Conducting the exercise both anonymously and remotely encourages respondents to confidently provide their true judgments whilst completing the exercise more flexibly. However, it inhibits the host of the exercise from directly clarifying inputs from respondents. Therefore, elicited values in the Qualtrics survey are checked and cleaned before processing. First, finalized submissions with empty mandatory question inputs are identified and excluded (following review, none were removed). If non-numerical characters are present, they are removed or translated into numerical values. Probabilities accompanied with a '%' symbol and/or are >1, are assumed to be a percentage. If the lower bound, best estimate and upper bound values are not in ascending order, they are assumed to be misplaced and are re-ordered. The values are then manually entered into the software for each respondent, without adjusting the tool's default floating point data format. Here, probabilities are entered as percentages. Finally, if three unique values are not provided for the best estimate and 90% uncertainty interval, values are adjusted by the smallest increment in the dataset (this was identified as 0.01).

A global weighting scheme is used in this study, where a joint respondent weight calculated across the seed questions is applied uniformly to each of the target questions [23]. Decision maker (DM) optimization is selected in the software before it is run. Best estimate fragility values and confidence intervals, aggregated with performance-weighting (PW), are subsequently obtained. Aggregated results with equal weighting (EW) are also determined for comparison. Both outputs are integrated into the dynamic fragility model described in Section 2.2 and are described further in Section 4.2.

4. Results and Discussion

4.1 Respondent background

Eleven complete submissions were made by wind energy supply chain respondents, which is sufficient for a meaningful elicitation [25]. A diverse range of stakeholders completed the exercise, with 42% identifying as wind plant owners and/or operators. The remainder identified as one or more of the following: consultants, condition monitoring and data analytic solution providers, turbine component OEMs, researchers, lubricant manufacturers, wind plant developers and other (insurance). All respondents had some experience with onshore wind turbine gearbox operation,

with 73% of respondents having six or more years of experience. Ten out of eleven respondents drew their experience exclusively from assets in Europe and/or North America.

4.2 Accelerated time-phased fragility: preliminary findings

Figure 3 displays the best estimate exceedance probabilities with 90% confidence intervals for full gearbox replacement (ds_2), when impacted by v_{gust} extremes: [10, 70] m s^{-1} at [0, 5, 10, 15, 20] years of time-phased degradation at rated wind speeds (t_{year}). Figure 3A and 3B present the aggregated values for ds_2 following EW and PW, respectively. In both cases, best estimate fragility values for ds_2 and their uncertainty bounds increase with time-phased degradation under rated wind speeds, and 3 s average wind gust speed.

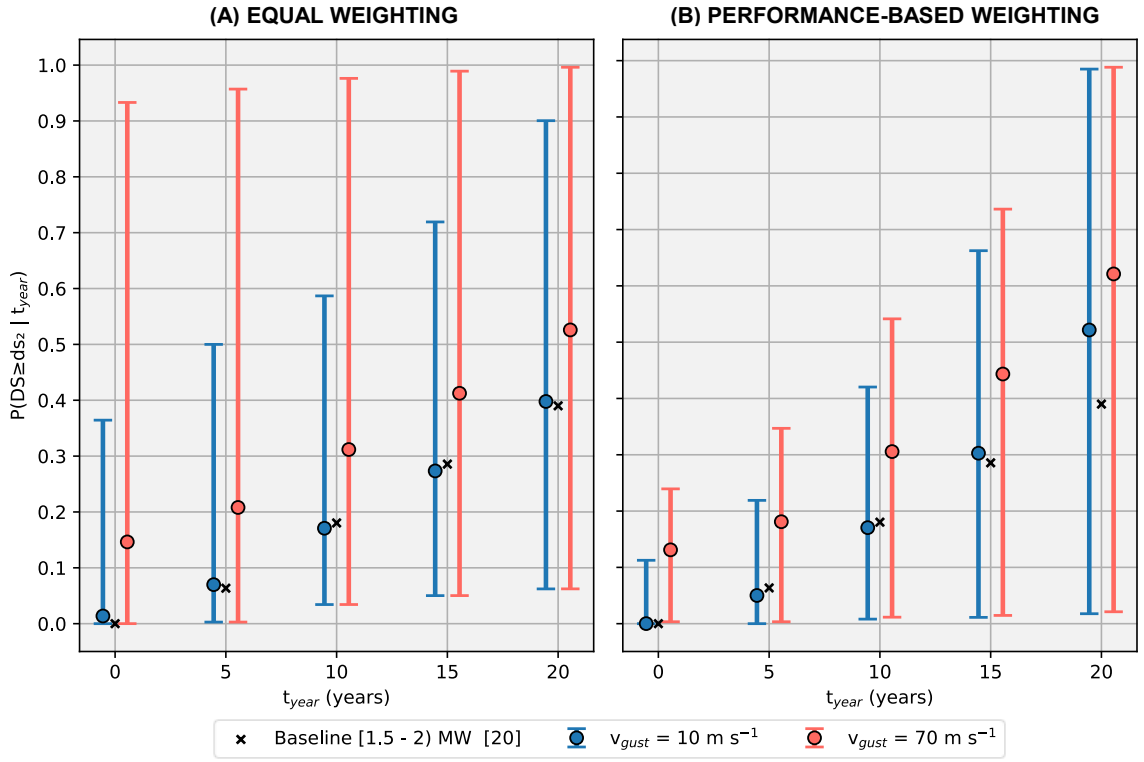


Figure 3. Accelerated time-phased fragility for ds_2 due to impact from v_{gust} = [10, 70] m s^{-1}. Based on (A) equally weighted responses or (B) performance-weighted responses. Empirical cumulative gearbox replacement rates for [1.5–2) MW capacity class wind turbines [20] are also plotted as a baseline.

Aggregation with PW as opposed to EW leads to a narrower confidence interval for $t_{year} \leq 15$ years, highlighting how the Cooke's method weighting scheme can better constrain the uncertainty. In this time range, best estimate aggregated exceedance probabilities are lower with PW than EW. Conversely, for t_{year} = 20 years there is a larger uncertainty with PW compared to EW aggregation, suggesting that the highest-weighted respondents believe that it is not possible to constrain the uncertainty based on existing knowledge in the field. This therefore requires further empirical or analytical investigation.

Performance-weighted responses in Figure 3B show that the difference in uncertainty intervals between v_{gust} = 10 m s^{-1} and 70 m s^{-1} decreases slightly with operational years. This suggests that the uncertainty with ds_2 fragility is influenced more by time-based degradation than

by the impact of wind gusts, with increasing operational life. This indicates that maintenance schedules could be more important than gust-resilient design for mitigation strategies. At t_{year} = 20 years, there are large uncertainty intervals for the fragility values (with >96% variability). This implies that the best estimates have high epistemic uncertainty, as discussed earlier, and cannot be reliably applied within the vulnerability assessment of end-of-life turbines. However, this is not the case between t_{year} = 0 and 15 years. Here, the difference in best estimate exceedance probabilities for v_{gust} = 10 m s^{-1} and 70 m s^{-1} remain at 13–14% (nearest integer) regardless of increasing fragility due to time-phased degradation. From initial observations within the same timeframe, it is also to be noted that the exceedance probabilities increase gradually between the v_{gust} extremes.

The empirical cumulative gearbox replacement rates over operational years, for [1.5–2) MW capacity class (onshore and offshore) wind turbines, are also plotted in Figure 3. They represent ds_2 fragility values due to time-phased degradation under typical operational conditions for the same capacity class used in the elicitation exercise. The empirical rates are extracted at the same t_{year} timepoints as the exercise, from a best estimate Weibull mixture fitted to a subset of failure data covering >600 wind farms [20]. At the lower v_{gust} value (10 m s^{-1}) the aggregated best estimate ds_2 exceedance probabilities show good agreement with the empirical values under typical conditions, regardless of weighting method. The only outlier is the exceedance probability at t_{year} = 20 years, following PW aggregation, which was significantly higher than the empirical failure rate. This could be due to the low reliability of the best estimate fragility values (with PW aggregation) at this timepoint, discussed earlier. At v_{gust} = 70 m s^{-1}, which exceeds the IEC Class II design limit (i.e. a 59.5 m s^{-1}, 3 s average wind speed with a 50 year return period [21, 26]), elicitation exercise best estimates fragility values were at least 12% (nearest integer) higher than the empirical datapoints.

The fragility values with PW aggregation for ds_1 have large uncertainty intervals (with >89% variability) at $t_{year} \geq 10$ years. This implies that more than half the best estimate fragility values for ds_1 show high epistemic uncertainty and cannot be reliably used in the vulnerability assessment of older turbines. This therefore requires further investigation.

5. Conclusion

This paper presents an elicitation-based framework to assess the dynamic onshore wind turbine gearbox fragility to wind gust events. The anonymised Cooke's method approach is adopted, with equal and performance-weighted exceedance presented for ds_2. The fragility of a [1.5–2) MW class gearbox at this damage state, is shown to increase with time-phased degradation and wind gust speed. Between 0 and 15 years of service life, a 70 m s^{-1}, 3 s wind gust (as opposed to a 10 m s^{-1} equivalent) is shown to increase the probability of reaching or exceeding full gearbox replacement by 13–14%, for the same capacity class. However, at the end of operational life (20 years), the highest-weighted respondents are shown to be cautious with their exceedance probabilities due to a lack of existing knowledge in the field.

Nevertheless, empirical data aligns well with the exercise outputs, demonstrating the value of knowledge engineering in delivering insights for natural hazard risk assessments. In this regard, the gearbox dynamic fragility framework developed can enable data interoperability between the insurance sector and the wind energy supply chain.

5.1 Future work

In combination with future analyses for ds_1, the outcomes of this work will support the development of probabilistic vulnerability functions linking wind gust events to financial losses (both property damage and business interruption) associated with [1.5–2) MW class gearbox failure, at different points in the gearbox operational life. Future work will also compare these results with the elicitation outputs from the insurance and utility sectors. The problem statement can also be adapted and applied for higher capacity class gearboxes (≥2 MW), to assess the applicability of the elicitation approach for newer classes of gearboxes with lower field experience.

To support wind digitalization efforts, future work must also address the limitations in the described elicitation approach. Open-source variants of EXCALIBUR (such as ANDURIL [27]) must be explored, with closer attention given to the validation of anonymized survey data inputs. This will enable the integrability of the Cooke's method within knowledge-based systems, such as digital twins utilizing operational data from wind assets [28].

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