Authors’ response to comments of reviewers

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Authors’ Response to the Comments of Reviewer #1

The authors would like to thank the reviewer for the comments and advice on the submission. The manuscript has been revised accordingly, and the detailed responses are provided below.

Overview: *The paper approaches the topic of wind turbine extreme load statistical extrapolation by proposing the use of a multi-modal distribution. The characteristics of the distribution are compared against other common choices with various fitting methods. The topic is discussed clearly and the paper is well organized. I have some minor comments.*

Response: Your review of the manuscript and providing valuable comments are appreciated. The issues highlighted are addressed, and changes have been made to the revised manuscript. (The line numbers in the changes sections are the number in the revised manuscript.)

Comment 1: *Introduction: Authors did a good job (in my opinion) to provide reference to previous work. I think the importance of the topic could be stressed better in more general standpoint for a less experienced reader. Providing a bit more context regarding how IEC61400-1 prescribes to employ statistical extrapolation techniques in the context of DLC calculations is advised.*

Response 1: Thanks for your comments.

Changes 1: In line 22, "The ultimate design load assessment procedure prescribed by the IEC aims at ensuring the structural integrity of the turbine when subjected to rare extreme loading conditions. The standards assume three types of scenarios for simulating such rare events: 1) extreme environmental conditions that result in extreme loads, 2) occurrence of faults potentially combined with extreme environmental conditions, and 3) rare occurrences under normal operation. The last option is represented by Design Load Case (DLC) 1.1. It encompasses loads resulting from site-specific atmospheric turbulence occurring during the turbine’s normal lifetime, i.e., the normal turbulence model. It establishes the characteristic load value corresponding to a 50-year return period, which could be obtained by statistical analysis of extreme loading using load extrapolation methods. The design load is then obtained by multiplying the characteristic loads by an appropriate partial safety factor. (IEC, 2019)"

Comment 2: *I find the acronyms a bit confusing. I would advise to use only capital letters for them. Also strongly advise to include a nomenclature section.*

Response 2: Thanks for your comments.

Changes 2: A "Nomenclature" section is added at line 306, and the capital letters are used for acronyms in the text and figure labels.

Comment 3: *Section 3: I cannot understand in which fitting methods and for which distributions only the tail data (above 80 % quantile) is used to fit the distributions. I have understood that in the case of gmm the entire population is used. Please rephrase this section (or parts of it) to improve clarity in this regard.*

Response 3: Thanks for the comments, in the LS estimated AFFA approaches, GEV (LS), Weibull (LS), and Lognormal (LS), only the tail data (above 80% quantile) is used to fit the theoretical distributions.

Changes 3: In line 117, "This comparison involves a total of 11 methods:

1. FFAA with GEV, Weibull, and lognormal as short-term distributions(referred to as FFAA (GEV), FFAA (Weibull), FFAA (Lognormal)) conditional on wind speeds, where the MLE is used for model parameter estimation.

2. AFFA with the three distributions using MLE and LS for model parameter estimation (referred to as GEV (MLE), Weibull (MLE), Lognormal (MLE), GEV (LS), Weibull (LS), and Lognormal (LS))

3. AFFA with GMM using AIC and LS for finding the number of components (referred to as GMM (AIC) and GMM (LS))

In the LS estimated AFFA approaches, GEV (LS), Weibull (LS), and Lognormal (LS), only the tail data (above 80% quantile) is used to fit the theoretical distributions, where the probability of exceedance of the tail data is calculated as Pt."

Comment 4: *L257: "Choosing an appropriate distribution model remains a challenge, and this issue also exists in the ffaa approach." As in compared to affa? Please explain more clearly.*

Response 4: The authors would like to state that the theoretical distributions are not flexible, and choosing a specific distribution for a response variable whose underlying distribution is unknown is challenging. For FFAA, as from section "4.1 Wind turbine response distribution modeling", choosing either of the three distributions will give a large prediction error. For AFFA, certain distributions may perform well for certain response variables but exhibit significant prediction errors for others. For instance, as shown in section "4.2 Wind turbine response distribution extrapolation", the lognormal distribution performs well for the first three cases but demonstrates the largest prediction error for the last case.

Changes 4: As the paragraph is intended to explain the flexibility of GMM, the sentence has been deleted to avoid confusion.

Comment 5: *Figure 5: there seems to be quite some difference between the curves here. The main body of text does not reflect this in my opinion. Could you elaborate?*

Response 5: Thanks for your comments.

Changes 5: In line 271, “The extreme load estimation for the maximum out-of-plane blade tip deflection is compared using Weibull(LS) with data above the 50th to 90th quantiles. Fig. 5 illustrates significant differences when different amounts of tail data are used."

The authors thank the reviewer for the comments and advice on the submission. The manuscript will be revised accordingly and the detailed responses are provided below.

General comment:

Overview: *The main objective of the paper is to present a comparison of the wind turbine response in a Gaussian mixture distribution function and common unimodal distribution functions. The paper is well organized, and the distribution procedure is described clearly.*

Response: Your review of the manuscript and providing valuable comments are appreciated. The issues highlighted are addressed and changes have been made in the revised manuscript. (The line numbers in the changes sections are the number in the revised manuscript.)

Comment G.1: *The nominated distributions for the comparison include just three general distributions. The process or reason behind these distributions is not clear. As GMM has several parameters, it is expected that it has better GoF (Goodness of Fit) compared to simple two- or three-parameter distributions. In order to have a fair judgment, it is expected that mixture probability density functions such as GEVWeibull or Weibull-Weibull are used in the comparison process. A list of such distributions is presented in the paper by Jung (http://dx.doi.org/10.1016/j.enconman.2016.12.006).*

Response G.1: Thanks to the reviewer for pointing out the additional methodologies with mixture probability distributions, they add to the discussion and we have included a short comment to inform the readers about this alternative. Given that the paper already has a large number of methodologies tested, we think that including additional options may make the paper less readable and hence have decided not to make calculations with mixture distributions. In our view, applying mixture distributions could have benefits for modeling the entire population, but when only interested in the tail, the performance will likely be similar to the tail-only fits using the least-squares approach with a single distribution, because the tail is often dominated by the behavior of one of the underlying distributions.

Fig. 1 illustrates the PDF of response (c) in place of response (d) to showcase the possibility of the wind turbine response being multimodal.

Changes G.1: In line 65, "Mixture probability distributions (e.g. Weibull-Weibull), as discussed in Jung and Schindler (2017), can be beneficial for accurately modeling an entire multimodal statistical population. In the tail of the response, the model will likely be dominated by only one of these distributions; hence the tail behavior predicted by a mixture distribution model is expected to be similar to that of a unimodal distribution fit focused on tail data only."

In line 158: The PDF of wind turbine response (c) from MCS is shown in Fig. 1, which is multimodal.

In line 166: the Fig. has changed to wind turbine response (c);

Comment G.2: *The authors used two random seeds in simulations. Different random seed numbers have an effect on the response of the turbine and, consequently, on the distribution of the extreme loads. That is why the IEC has a recommendation for the minimum number of seeds at different wind speeds. The number of seeds should be justified at least by a reference or with sensitivity analysis, as it is in contrast with IEC regulation for ultimate analysis (Annex G of IEC).*

Response G.2: We would like to clarify that we did not perform the simulations, and the authors from Barone et al. (2011) generated the simulation data, which was 96 years of simulations and computationally demanding in 2012. We agree that more seeds should be used, but it is computationally challenging for 96 years of simulations even today.

Comment G.3: *There are several places where authors claim a statement without a related reference. Some of the examples are stated in specific comments. As the authors used load data from a previous publication, it is worth mentioning the DLCs that are included in the referenced publication in order to clarify the load's condition for the reader.*

Response G.3: DLC 1.1 is used in the referenced publication.

Changes G.3: In line 150, "The FAST aeroelastic code is used for the five million aero-elastic simulations (Barone et al., 2011), which is based on design load case (DLC) 1.1 in IEC 61400-1 (IEC, 2019)."

Comment G.4: *As a reader, in the result section, the superiority of using GMM is not established clearly. For example, it seems the results in Table 1 are, to some extent, close.*

Response G.4: Yes, In terms of prediction error for a specific application, the superiority of GMM over other distributions is marginal. Nevertheless, the key advantage of employing GMM lies in its consistent performance owing to its high flexibility. GMM tends to exhibit favorable performance for diverse applications. While the lognormal distribution excels in three out of four compared scenarios, a notable prediction error is anticipated if the lognormal distribution is chosen for case (d).

Changes G.4: In line 223, "The distinguishing factor between GMM and other distributions lies in its performance consistency. Given the uncertainty about the underlying data distribution, opting for a flexible distribution with reliable performance, like GMM, becomes advantageous as it mitigates the risk of significant prediction errors caused by an inappropriate model selection."

Specific comment:

Comment S.1: *In Section 1, line 20, the sentence "Using crude MCS for analysis with such low probabilities requires at least . . . " needs to be referenced.*

Response S.1: Thanks for the comments.

Changes S.1: In line 18: "The extreme response with a 50-year return period is usually extrapolated from 10-min simulations, and estimating the 50-year extreme response corresponds to an exceedance probability $p = 3.81 \times 10^{-7}$ from 10-min simulations. The coefficient of variation (c.o.v.) of the MCS estimator is $\sqrt{(1-p)/(pN)}$, where N is the sample size(Ditlevsen and Bjerager, 1986). Using crude MCS for analysis with such low probabilities requires at least $\frac{10}{3.81\times10^{-7}} = 26,280,000$ simulations for sufficient accuracy, i.e., a c.o.v. $\approx \sqrt{1/10} \approx 0.316$."

Comment S.2: *In Section 1, line 43, the sentence "An improper distribution could result in a far-off extreme load prediction" needs to be referenced. Is there any study that shows how much the results change with improper distribution?*

Response S.2: In Freudenreich and Argyriadis (2008), "Because of the load-influencing effect of the wind turbine control system, the fit of the distribution functions to the data points was difficult. The obtained loads differed up to 25%, depending on the fitting quality." Both Freudenreich and Argyriadis (2008) and Dimitrov (2016) showed the difference in extreme load prediction due to the different distributions used.

Changes S.2: In line 51, the reference is added: An improper distribution could result in a far-off extreme load prediction (Freudenreich and Argyriadis, 2008; Dimitrov, 2016).

Comment S.3: *In Section 1, line 54, the sentence: "Fitting wind turbine extreme response with unimodal distributions directly will have a large estimation error at both the center and the tail distribution" needs to be referenced.*

Response S.3: The sentence is not referenced from previous work but is based on this study, so it is moved to the Results section.

Changes S.3: The sentence is moved to line 163.

Comment S.4: *In Section 3, line 96, it doesn't mention what MSE stands for. It is mentioned later in Section 4.2, but for readers, it should be cleared the first time it is used.*

Response S.4: Thanks for your comments. 'MSE' stands for mean squared error.

Changes S.4: "mean squared error" has been added before the first 'MSE' in line 107.

References

Barone, M. F., Paquette, J. A., Resor, B. R., and Manuel, L.: Decades of wind turbine load simulation, No. SAND2011-3780C, 2011.

Dimitrov, N.: Comparative analysis of methods for modelling the short-term probability distribution of extreme wind turbine loads: Methods for modelling the probability distribution of extreme loads, Wind Energy, 19, 717–737, https://doi.org/10.1002/we.1861, 2016.

Ditlevsen, O. and Bjerager, P.: Methods of structural systems reliability, Structural Safety, 3, 195–229, https://doi.org/10.1016/0167-4730(86)90004-4, 1986.

Freudenreich, K. and Argyriadis, K.: Wind turbine load level based on extrapolation and simplified methods, Wind Energy, 11, 589–600, https://doi.org/10.1002/we.279, 2008.

IEC: International standard IEC61400-1: Wind turbines - part 1: design guidelines, Fourth edition, 2019.

Jung, C. and Schindler, D.: Global comparison of the goodness-of-fit of wind speed distributions, Energy Conversion and Management, 133, 216–234, https://doi.org/10.1016/j.enconman.2016.12.006, 2017.