Discussion of:

Adaptive stratified importance sampling: hybridization of extrapolation and importance sampling Monte Carlo methods for estimation of wind turbine extreme loads

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The authors present a novel, hybrid approach to statistical load extrapolation. The method employs the importance sampling theory for estimating the contribution of samples in different wind speed bins to the variance of the extrapolated values. The result is an adaptive, stratified importance sampling procedure which converges faster than the traditional method of stratified sampling.

The article is well written and easy to read. The formulas seem free of technical errors. Some parts of the method may need a more rigorous description though – see the specific comments.

I think the article will also benefit from expanding some of the discussions and referring to additional literature. The authors may want to consider the publications listed as references in this document. Some further details about the references follow in the comments below.

General comments

1) As the authors say on Page 2, line 9: "Monte Carlo methods: exceedance probabilities are written as expectations of indicator functions". This is in fact a passing definition for structural reliability problems, regardless of the method used for the integration (the computation of the expected value). We can therefore make a parallel between the statistical extrapolation and the structural reliability analysis problems. This means we can take inspiration from literature where e.g. adaptive importance sampling is used as a tool for reliability analysis. Some examples include [1], [2] where search-based (adaptive) importance sampling is formulated and also [3] where it is applied to a dynamical system.
2) The current results section mainly shows the behaviour of the ASIS algorithm, but it is impossible to judge how it will compare to standard extrapolation procedures using the same number of FAST simulations. The algorithm suggested by the authors is essentially an approach for "guided" sampling from the joint distribution of environmental conditions. It would be really interesting to see a comparison with e.g. direct sampling from the long-term distribution using a pseudo Monte-Carlo simulation with low-discrepancy series, followed by extrapolation directly from the empirical CDF of the long-term load distribution.
3) Statistical extrapolation is a very academic exercise. In the last years the wind energy scientific society has published multiple papers which present attempts at improving the efficiency and reducing the uncertainty in load extrapolation. But the majority of these solutions represent highly complex algorithms with many parameters to tune and with tricky implementation which can easily

be done in a wrong way. My general concern with statistical extrapolation is that this complexity hinders the adoption of new research in industry as it requires a significant level of very specific expertise in order to achieve a correct and robust implementation. As a confirmation to this observation, the coming IEC 61400-1 ed.4 standard actually suggests methods for doing extrapolation with even lower complexity (and most probably higher uncertainty) than what was suggested in ed.3 of the same standard. This should not be viewed as a criticism to the present paper or its authors – but in my opinion the focus of future research in statistical extrapolation should not only be towards improving accuracy or efficiency, but also towards achieving robust and easy to implement solutions. This is something the authors may want to give a thought to and eventually discuss in their paper.

Specific comments:

4) Page 5, line 24: The authors use 10 peaks per 10-minute simulation. However, they do not seem to take any measures for ensuring statistical independence between the peaks (or there is no description of any measures they have taken). Thus, there is a very high chance that some of the events they have identified as peaks are correlated (e.g. they have small time separation). The result is most likely a (slight) over-prediction of the exceedance probabilities. A simple and straightforward measure for reducing dependency could be enforcing some minimum time separation between successive 1-minute peaks. Typically time separation equivalent to the time for 1-2 rotor revolutions should be sufficient to eliminate dependence almost entirely.
5) Figure 1: The amount of variability in the peaks is also a consequence of the authors' choice to use one-minute peaks. Drawing the same plot for the 120 ten-minute peaks per bin would show lower variation.
6) Section 2.2: Some good additional references to consider in this section are [4] which presents an excellent method for accounting for independence between peaks, [5] which is an extensive parametric study on extrapolation considering, among other things, the effect of number of peaks on extrapolation accuracy, and [6] where the seed-to-seed variability is addressed explicitly, though with focus on fatigue loads.
7) Section 2.4: I think this section can be removed or shortened significantly without reducing the quality of the paper. To me, what the authors try to define in the section is that the extrapolation per wind speed represents a set of conditional approximations which can best be described by a Rosenblatt transformation [7]. The IFORM method is related to the Rosenblatt transformation as the Rosenblatt transformation is a convenient way to draw the IFORM contours. Further, the IFORM method is meant to be applied to static quantities as e.g. 10-minute statistics of environmental conditions. The inventor of the method (S. Winterstein) has also worked on re-formulating the IFORM for dynamic problems as the one considered by the authors of the present paper [8]. Another relevant method is the tail-equivalent linearization method (TELM) [9], which employs FORM for approximation of the extreme response of dynamical systems. In general my feeling is that discussing FORM or IFORM in the current version of this paper is a distraction from the main scope – but if it is necessary to retain it, the TELM method could be a possible bridge.
8) Page 11, lines 15-25: As the authors state, this algorithm will converge to a local optimum, and measures should be taken to ensure that the global optimum is found. We could again make the parallel to structural reliability, where multiple failure modes lead to a system reliability problem

with multiple design points ("local minima") and the failure domain may be non-convex. When employing (adaptive) importance sampling, the system reliability problem is normally approached by using multiple "seeds" of importance sampling densities which are initially placed in the different parts of the variable domain. Melchers [2] for example suggests using stratified sampling or purely random sampling to generate the set of initial locations of the importance sampling densities. The authors may want to consider such an approach for their problem – it can potentially also help with the issue of the largest variance being at different wind speeds for different load channels.

9) Figure 2: A good reference for the effect of number of peaks (time series) on the extrapolation is [5], where this is investigated for several types of extrapolation methods, distribution fits, and with up to 1000 minutes of time series per extrapolation. Another relevant study is the one by Zwick & Muskulus [6] where they thoroughly investigate the seed-to-seed variability problem, though without considering extrapolation.

Technical comments:

10) Page 7, line 28: Y*f] is probably a typo. Did the authors mean [Y*f]?

References:

[1] Au, S. K. & Beck, J. A new adaptive importance sampling scheme for reliability calculations. *J. Struct. Saf.* **21,** 135–158 (1999).

[2] Melchers, R. E. Search-based importance sampling. *J. Struct. Saf.* **9,** 117–128 (1990).

[3] Mori, Y. & Ellingwood, B. Time-dependent system reliability analysis by adaptive importance sampling. *Struct. Saf.* **85,** 1–9 (1993).

[4] Naess, A. & Gaidai, O. Estimation of extreme values from sampled time series. *Struct. Saf.* **31,** 325–334 (2009).

[5] Dimitrov, N. Comparative analysis of methods for modelling the short-term probability distribution of extreme wind turbine loads. *Wind Energy* **19,** 717–737 (2016).

[6] Zwick, D. & Muskulus, M. The simulation error caused by input loading variability in offshore wind turbine structural analysis. *Wind Energy* **18,** 1421–1432 (2015).

[7] Rosenblatt, M. Remarks on a Multivariate Transformation. *Ann. Math. Statist*. **23** (3), 470-472 (1952).

[8] Lutes, L. D. & Winterstein, S. R. Design Contours for Load Combinations: Generalizing Inverse FORM Methods to Dynamic Problems. *Proceedings, 7th Comput. Stoch. Mech. Conf.* (2014).

[9] Fujimura, K. & Der Kiureghian, A. Tail-equivalent linearization method for nonlinear random vibration. *Probabilistic Eng. Mech.* **22,** 63–76 (2007).