

Response to Reviewer 1

Integrated Wind Farm Layout Optimization Accounting for Wake-Induced Blade Fatigue and Wake-Steering Effects on LCOE

We thank the reviewer for their valuable and constructive feedback, which has significantly helped us to improve the quality of our manuscript. The comments have led us to validate the model more extensively against higher-fidelity simulations and consequently close the fidelity loop. For this revision, we have carried out more than 100 additional OpenFAST simulations and more than 300 FAST.Farm simulations of two-turbine arrays, complete wind farms and randomly generated parks. We repeated all layout optimizations with the validated model. Individual replies to all comments are given below, and the comments of the reviewer are set in grey. Page and line numbers refer to the marked-up manuscript.

Summary of the main changes.

- We show three uses of the lifetime-aware LCOE. It reveals a fatigue cost of 33% of the LCOE at the study site, which a fixed-lifetime LCOE misses. It ranks layouts differently from the fixed-lifetime LCOE where wake fatigue matters. It also evaluates fatigue-aware operation. Derating selected turbines lowers the LCOE by up to 4.9 EUR/MWh, and FAST.Farm confirms the underlying load reduction.
- The OpenFAST validation now uses six seeds per condition. We corrected a normalisation error in the post-processing of the pooled seeds, and the model now agrees with OpenFAST within 5.3%.
- We validated the model against FAST.Farm at two-turbine and park scale. Based on these simulations, the wake-turbulence closure now depends on each downstream rotor's lateral position in the wake. This captures the higher turbulence at the wake edge.
- We repeated all optimizations with the validated model. For the study site, we also optimized on a 5° wind rose. Two further layouts test the method on a dense layout and on a standard benchmark layout.
- New sections show how the fatigue cost depends on the wind conditions of the site (Sect. 3.8) and how the lifetime-aware LCOE prices fatigue-aware operation (Sect. 3.13). A Pareto analysis of energy against blade life is added (Sect. 3.5).

Summary comment

Reviewer 1

The proposed model consistently underpredicts the total fatigue loads. While the authors motivate the use of the model primarily on the basis of its low computational cost, computational efficiency alone does not sufficiently justify its use within an optimization framework when the model exhibits a systematic bias relative to the higher-fidelity reference. [...] Furthermore, the manuscript does not appear to close the fidelity loop by evaluating the identified optimal layouts using a higher-fidelity simulation framework, such as FAST.Farm. [...] In particular, it would allow the authors to quantify the extent to which the systematic fatigue underprediction affects the resulting layouts and economic conclusions.

Reply. We agree that a systematic bias would affect the optimized layouts. We addressed this concern in two steps.

During the evaluation of the extended six-seed OpenFAST campaign (Comment 3), we noticed an error in the post-processing of the Miner accumulator. The rainflow cycles of all seeds of a condition were pooled into one accumulator but normalised with the reference cycle count of a

single seed. Consequently, the pooled DEL was inflated by a factor of $n_{\text{seeds}}^{1/m}$. The error affected only the validation, which used three pooled seeds, and not the calibration, which used a single seed. We corrected the normalisation of the rainflow cycles, and the model now agrees with OpenFAST within 5.3% combined across the five turbulence levels. Furthermore, the errors of the individual conditions are no longer of a single sign (Table R1). Four larger deviations occur at 8 m s^{-1} , which carries less than 0.1% of the annual damage at the study site.

Table R1	submitted (3 seeds)	revised (6 seeds)
combined error across 5 TI levels	15.7%	5.3%
mean error per condition	14.4%	5.1%
conditions with error above 10%	20 of 20	4 of 20
sign of the error	all negative	mixed

Following the reviewer’s suggestion to close the fidelity loop with farm-scale simulations (Comment 5), we compared the model with FAST.Farm. With the local wind speed and turbulence intensity of FAST.Farm at each rotor, the load model reproduces the blade-root DEL of 666 turbine-cases in complete wind farms within 8 to 9%, without bias for waked rotors. The comparison showed that the submitted manuscript’s closure averaged wake turbulence over the rotor area. It therefore missed the higher turbulence at the edge of a wake, where a rotor carries up to 20% more DEL than an aligned rotor. We therefore applied a spatially resolved closure that samples the turbulence profile of Ishihara and Qian (2018) at the centre of the downstream rotor. We calibrated its single parameter on 63 two-turbine FAST.Farm cases. The closure then reproduces the effect of the lateral offset within 9 percentage points (root mean square). All optimizations of the revised manuscript use this closure, and Comment 5 elaborates on its farm-scale validation.

We compute all results in the revised manuscript with the validated model. With it, the lifetime-aware LCOE reveals a fatigue cost of 33% at the study site that the fixed-lifetime LCOE does not price.

Changes in the manuscript. Sect. 3.2 reports the six-seed validation (p. 17, l. 417). Sect. 2.1 describes the closure (p. 5, l. 105) and Fig. 2 its mechanism (p. 6). Sect. 3.3 presents the FAST.Farm validation (p. 20, l. 464).

Comment 1

Reviewer 1

The motivation for developing a new fatigue model is not sufficiently clear. Several existing studies have constructed surrogate models based on aeroelastic simulations, which could potentially provide a similar reduction in computational cost while retaining a closer connection to the underlying high-fidelity simulations. If computational cost is the primary motivation for developing the proposed model, the authors should explain why an aeroelastic-simulation-based surrogate model is not considered a suitable alternative. In particular, a surrogate model could be constructed over the coarse grid of wind speeds and directions considered in this study.

Reply. We thank the reviewer for this question, which the submitted manuscript did not answer sufficiently. Computational cost was not our only motivation, and the introduction now states the other reasons for a physically structured model in more detail.

The fatigue model’s inputs are the effective wind speed, the effective turbulence intensity and the yaw angle at each turbine. All three change when the optimizer moves a turbine. A surrogate trained on the resource grid would therefore be evaluated mostly outside its training data, because the optimizer constantly creates new layouts.

In addition, each term of a structured model belongs to a mechanism and can be tested in isolation. Two findings of the revision particularly show this benefit. The first is the error we

found in the rainflow cycle accumulation. The bias of the submitted validation had the same sign in all conditions, but no term of the model could explain it. This pointed us to the post-processing rather than to the model. The second is the wake-turbulence closure. When FAST.Farm revealed a discrepancy, we fed the load model with the turbulence from FAST.Farm and found no bias. This located the error in the wake-turbulence closure, and we replaced only this term. A fitted surrogate would have absorbed the same error into its weights. Overall, it makes the model more explainable.

Changes in the manuscript. An additional paragraph in the introduction gives the reasons for the physically structured model (p. 3, l. 61).

Comment 2

Reviewer 1

The discretization used for wind speed and wind direction appears to be too coarse. Given that the proposed models are intended to significantly reduce computational cost, a finer discretization of the wind speed and wind direction bins should be feasible and would likely provide a more accurate representation of the operating conditions. The authors should provide justification for the selected discretization and investigate the sensitivity of the results to a finer discretization.

Reply. We agree and have extended the analysis in three ways. We re-optimized all scenarios of the study site on a 5° rose instead of only re-evaluating the 10° layouts. We also added the dense Lillgrund wind farm (Dahlberg, 2009), whose rows at 3.3 rotor diameters are aligned with the dominant wind direction. We optimized both the Lillgrund layout and the IEA Wind Task 37 benchmark layout (Baker et al., 2019) on 10° and 5° roses.

At the study site, the 10° and 5° results agree. The conclusions there therefore do not depend on the discretization. For the dense layout, however, the discretization matters. A coarse rose underestimates the wake exposure of turbines placed between its bin centres. We therefore recommend optimizing layouts with aligned rows on a rose that resolves their wake corridors. On both roses, the lifetime-aware objective finds the layout with the lowest lifetime-aware LCOE. It lowers the LCOE by 0.9% on the 10° rose and by 0.3% on the 5° rose. The fixed-lifetime LCOE ranks the same layout as more expensive.

Changes in the manuscript. Sect. 3.5 reports the 5° campaign of the study site (p. 26, l. 563). Sect. 3.9 presents the Lillgrund and IEA Wind Task 37 layouts on both roses (p. 29, l. 622).

Comment 3

Reviewer 1

Only three random seeds are used to validate the proposed model against OpenFAST. The authors should justify this choice, particularly given that six seeds are commonly used in wind turbine aeroelastic simulations to obtain more robust estimates of fatigue-related quantities. Additional seeds should be considered to determine whether the observed model discrepancy is consistent across different realizations of the turbulent wind field.

Reply. We agree and extended the OpenFAST campaign to six seeds per condition. This extension revealed the normalisation error described under the summary comment, and with six seeds and the correct normalisation the model agrees with OpenFAST within 5.3%.

We also increased the number of seeds in all other simulations. Every FAST.Farm comparison uses three seeds per case, with both layouts of a pair sharing the ambient wind field of each seed, so that the scatter between turbulence realizations does not mask the difference between layouts. The layout optimizations now use eight random and eight warm-started seeds per scenario. We report the spread of the seeds with every result.

Changes in the manuscript. Sect. 3.2 and its figures are based on the six-seed campaign (p. 17, l. 417). Sect. 2.5 describes the convergence procedure of the optimizations (p. 15, l. 377).

Comment 4

Reviewer 1

The manuscript considers several single-objective optimization studies. A multi-objective optimization formulation considering LCOE and lifetime, for example, could provide a more comprehensive assessment of the trade-off between economic performance and structural fatigue. Such an analysis could potentially provide additional insight into the Pareto-optimal trade-offs between these competing objectives and would represent a stronger contribution to the state of the art than the current set of single-objective studies.

Reply. We thank the reviewer for this suggestion. We have added a Pareto analysis of energy against blade life, and we explain why we retain the lifetime-aware LCOE as the quantity to be optimized.

The lifetime-aware LCOE already combines the two objectives the reviewer names, energy yield and structural life. In a weighted-sum or Pareto formulation, the rate at which energy is exchanged for blade life is chosen by the analyst, either as a weight or as a point on the front, and the recommended layout depends on that choice. In the lifetime-aware LCOE, this exchange rate follows naturally from the discount rate, CAPEX and OPEX. A shorter blade life shortens the period over which a turbine earns back its investment. We regard this as one of the central methodological contributions of the paper and have made it more explicit in Sect. 2.3.

At Lillgrund, more energy comes at the cost of blade life. The lifetime-aware LCOE balances both without a weighting factor. On the 10° rose, the fixed-lifetime LCOE ranks the lifetime-aware layout 0.3 EUR/MWh worse than the AEP-optimal layout. The lifetime-aware LCOE ranks it 0.6 EUR/MWh better, at an energy cost of 0.6%. For the study site, we evaluated 400 random feasible layouts together with the optimized layouts. There, less wake exposure improves energy and blade life together. AEP and minimum blade life are positively correlated ($r = 0.40$), and the optimized layouts lie at the upper end of both.

The one parameter we do choose is the reference load DEL_{ref} . It is in practice available from certification, and it sets the absolute scale of the fatigue cost rather than the exchange rate between energy and life. Sect. 3.10 shows that the relation between the scenarios is the same over a range of -12 to $+15\%$ around the demonstration value. Over this range, the fatigue cost of Scenarios A and B falls from 62.3 EUR/MWh to zero, and Scenario C follows them within 0.5 EUR/MWh.

Changes in the manuscript. Sect. 2.3 states why the lifetime-aware LCOE is optimized as a single objective (p. 14, l. 347). Sect. 3.5 presents the Pareto analysis in a new figure (p. 25, l. 558).

Comment 5

Reviewer 1

The optimal layouts identified using the proposed reduced-order models should be evaluated using a higher-fidelity simulation tool such as FAST.Farm. This validation is particularly important given the systematic underprediction of fatigue observed during the OpenFAST validation. Evaluating the final layouts using FAST.Farm would allow the authors to determine whether the trends and improvements predicted by the optimization framework persist when the layouts are evaluated using a higher-fidelity model.

Reply. We thank the reviewer for this suggestion, which led to the largest part of the revision. We evaluated the model against FAST.Farm at three levels.

- **Two-turbine arrays.** 63 seeded cases at spacings of 3.3 to 7 rotor diameters and lateral offsets of 0 to 1.5 diameters show how the position of a downstream rotor in the wake affects its load. Its DEL exceeds that of the upstream rotor by 4% in full alignment, by 16 to 20% at half a diameter of offset, and by 1% at one diameter. The closure reproduces this dependence with one fitted efficiency, within 9 percentage points (root mean square).
- **Complete layouts.** Thirteen nine-turbine layouts, among them the optimized layouts A and C, were simulated against an AEP-optimal reference layout at rated wind speed, for 29 combinations of layout and wind direction with three seeds each. The model ranks the layouts consistently with FAST.Farm wherever their differences exceed the seed scatter. Over 1343 turbine-cases at four wind speeds, the closure is unbiased at and above rated. Below rated it underestimated the wake-added turbulence at the higher thrust coefficient. We correct this with a thrust-dependent scaling, which we tested on layouts not used for fitting.
- **Independent parks.** Twelve randomly generated six-turbine parks, not used for any calibration, confirm the model on 36 waked turbines, with ratios of 1.04 at 9 ms^{-1} and 0.96 at rated wind speed.

FAST.Farm also confirms that derating changes the blade-root loads as the model predicts. Derating layout A to 0.8 of rated power raises its L10 blade-root DEL by 9.4% at rated wind speed, against 9.5% predicted, and lowers it by 5.4% at 18 ms^{-1} , against 5% predicted.

The trends predicted by the optimization framework therefore persist in FAST.Farm. The model ranks layouts correctly. It overestimates the magnitude of their differences by about a factor of two, which we state as a limitation. This discrepancy is discussed in the revised manuscript. Nevertheless, the consistent ranking across the tested cases supports the model's use for layout and operational optimization. Quantitative differences should be interpreted with appropriate caution.

FAST.Farm also confirms why the gain of a lifetime-aware layout depends on the site. At 18 ms^{-1} , which carries 86% of the annual damage at the study site, the low thrust coefficient leaves little wake-added turbulence. FAST.Farm finds the same worst-turbine DEL for layouts A and C there, with a ratio of 1.002 over 17 paired runs. The benefit of a lifetime-aware layout therefore depends on the site. We show this in three new subsections on the site wind conditions (Sect. 3.8), a dense layout (Sect. 3.9) and fatigue-aware operation (Sect. 3.13).

Changes in the manuscript. Sect. 3.3 presents the FAST.Farm validation at all three levels (p. 20, l. 464). Sects. 3.8, 3.9 and 3.13 are new (p. 27, l. 600, p. 29, l. 622, p. 34, l. 712). The abstract (p. 1, l. 1), the discussion (p. 36, l. 749) and the conclusions (p. 38, l. 813) are revised accordingly.

References

- Baker, N. F., Stanley, A. P. J., Thomas, J. J., Ning, A., and Dykes, K.: Best practices for wake model and optimization algorithm selection in wind farm layout optimization, in: AIAA Scitech 2019 Forum, American Institute of Aeronautics and Astronautics, <https://doi.org/10.2514/6.2019-0540>, 2019.
- Dahlberg, J.-Å.: Assessment of the Lillgrund Windfarm: Power Performance, Wake Effects, Tech. Rep. 6_1 LG Pilot Report, Vattenfall Vindkraft AB, Stockholm, 2009.
- Ishihara, T. and Qian, G.-W.: A new Gaussian-based analytical wake model for wind turbines considering ambient turbulence intensities and thrust coefficient effects, *Journal of Wind Engineering and Industrial Aerodynamics*, 177, 275–292, <https://doi.org/10.1016/j.jweia.2018.04.010>, 2018.