Reply to the comments of the final reviewer

We are thankful to the final reviewer for the close reading of the manuscript and the valuable comments. Inspired by reviewer's constructive suggestions, we have made a *major revision of the manuscript* with way too many minor changes in the text to be all shown in this report. This is also the reason we didn't submit a marked-up manuscript version showing the changes made.

Below comes the full list of reviewer's comments with our responses.

Overall

Comment 1. The article is very abstract and very much written as if intended for an OR audience. WES is an application-oriented journal where the domain focus of wind energy is the common denominator – thus, papers should be rooted in the realism of the domain. This should be improved substantially in the paper and several suggestions to do so are made by section.

Response 1. To address this general comment concerning somewhat abstract nature of our paper, we removed some of the technical parts and added three flowcharts. We did our best (under the high time pressure for the corresponding author working on his PhD dissertation and with another coauthor being on a long-term sick leave) to constructively respond to the majority of the more detailed comments and suggestions of the reviewer. We hope that the revised article could be published in your journal.

Comment 2. The introduction does not clearly state what NextPM is and how it extends the state of the art. This should be crystal clear. Flow diagrams may help. Or using a motivating real example and then comparing for that example how NextPM will work as contrasted to PMSPIC.

Response 2. Many changes in the text address this comment. In particular, we added three flow diagrams.

Comment 3. The lack of wind-specific context in the entire methods portion of the paper (sections 2 and 3) is a problem – see detailed notes below

Response 3. See the responses to the detailed comments of the reviewer.

Comment 4. Section 4 also is quite abstracted from reality and some of the data uses is old or model parameterization not thoroughly justified. Different turbine components are listed but there is no discussion of them (figure 1)

Response 4. See Response 1.

Comment 5. Have a native English speaker edit the paper for syntax – a lot is well written but there are also many places where sentences are hard to read and I had to read them multiple times to get their intent.

Response 5. We did our best to clarify the unclear parts of the paper.

Abstract

Comment 6. Discussion on global warming in abstract is unnecessary – okay for introduction but abstract should be succinct and to the point, suggest eliminating entire first paragraph.

Response 6. The paragraph is removed.

Comment 7. The abstract reads too much like a marketing pitch for NextPM – I suggest rewording it to put more emphasis on the scientific contribution to the state of the art.

Response 7. The abstract is rewritten.

Introduction

Comment 8. Lazard 2017 is a bit outdated – suggest updating reference to most recent Lazard.

Response 8. The reference is replaced by Lazard 2020.

Comment 9. Citation on O&M costs for offshore as percent of total? There are many – see cost of wind energy review from NREL or various other sources

Response 9. We have edited:

"A large part of the total cost associated with wind turbines is due to operation and maintenance: 34% for the fixed-bottom offshore wind turbines, according to \cite{stehly20202019}."

Comment 10. The literature review is okay but there is a decent amount of literature in this space that is not addressed. Suggest the author look at the work from U. Strathclyde, ECN/TNO O&M calculator, Fraunhofer IWES, work by Dimitrov et al, and commercial capability of Peak Wind/Lautec/SeaImpact to supplement existing literature base.

Particularly the O&M calculator from TNO provides a breakdown of planned and unplanned maintenance as well as a breakdown of failure types with a range of severity from minor repair to component replacement. It seems in the paper you are focusing on component replacement – yes? Be a bit more clear about this.

Most maintenance models like the ones from the organizations above are time-series based which makes optimization of scheduling quite difficult – though there are efforts out there even in commercial tools

Response 10. We have added one reference from U. Strathclyde, Browell (2016).

Comment 11. Define what you mean by multi-component systems – it is somewhat obvious but important

Response 11. We have added

"In the context of wind farm maintenance, each wind turbine is viewed here as a system comprising multiple components such as the gearbox, power generator, rotor and main bearing. Whenever one of the components is broken, the whole system stops functioning. …"

Comment 12. How are the models in Moghaddam and Usher nonlinear?

Response 12. Both the objective function and the constrains of the optimization models by Moghaddam and Usher are non-linear. A reference to \cite{andreasson2020introduction} is added.

Comment 13. It is not clear what the PMSPIC model does at all – flow diagrams would be VERY helpful to illustrate what that model does and what your model does (in order to contrast the two effectively) – already in the introduction you should be stating at a high level how the NextPM algorithm is different from and improves upon PMSPIC

Response 13. We made a significant effort to clarify this at different parts of the article. In particular, see the second flowchart.

Comment 14. It seems like the lines 53 to 57 are a bit thrown in there.

Response 14. The paragraph is removed, and four references are taken away from the list of references.

Comment 15. It would be helpful to have a bit more of the big picture to better contextualize the work. Here is a suggested path for reworking the introduction:

Start with the real-world issue: offshore wind O&M is costly – how costly? See NREL work for example – therefore want to reduce

How does O&M for offshore wind work? again, see ECN O&M calculator as a good high level overview of how offshore wind O&M works in practice

But, many of these models rely on time-series simulation of the failures and logistics where there are many underlying probabilistic / uncertain events both with component failures (of various types) and access issues (related to weather conditions)

Thus, this becomes a very challenging optimization under uncertainty problem

How have people tackled this before?

In general, operations research communities have looked at O&M optimization via several techniques

For wind specifically, optimization of O&M has been tackled in x,y, z ways

In this paper, we build on the state of the art with a new algorithm, NextPM, that does x,y,z and thus has potential for capturing a,b,c, additional realism of the offshore wind O&M optimization problem and/or improves the computational efficiency by leveraging d,e,f…

The paper is organized as follows…

Response 15. The Introduction is thoroughly revised.

Comment 16. Appendix A and B have only the formal optimization problem formulations – is it necessary to have them as two separate appendices? Or appendices at all? Personally I prefer to see the problem formulation in situ and up front as it is the central organizing basis for an optimization study

Response 16. Appendix B is removed, and Appendix A is presented as a new Section 3.4.

Optimal rescheduling algorithm

Comment 17. Before jumping to the description of the algorithm, consider describing it at a highlevel in plan language

Response 17. A flow diagram is added.

Comment 18. FYI: A key cost of offshore wind failures is not the component costs but the downtime and associated loss of energy production. Most of the O&M models mentioned above also calculate availability which can then translate directly to revenue losses

Response 18. Thank you for sharing this valuable information!

Comment 19. FYI: most models above also treat dt is a uncertain variable since it is highly weather dependent, bj and cj are also uncertain but models often treat them as deterministic – i.e. failures are probabilistic but the costs to repair them are deterministic

Response 19. Thank you for sharing this valuable information!

Comment 20. Line 85 – need to explain here in plain terms what lamda is

Response 20. See Response 28 below.

Comment 21. Again, I think a flow diagram would help here. Can you represent visually or in plan language what the optimization problem you are trying to solve is? Contextualize it with an example using a wind turbine? And contrast it with a baseline approach? It is still unclear what is novel here.

Response 21. We added a flow diagram and explained how the methods work.

Comment 22. I am not sure why section 2 is a stand-alone section. It seems to me it is part of the methods and I recommend section 2 and 3 be merged and made subsections of an overarching methods section

Response 22. We hope the Section 2 is more justified in the revised version of the paper.

Comment 23. It is still not clear what NextPM is doing by the end of section 2 nor NextOM

Response 23. See response 21.

Optimal plan for next preventive maintenance

Comment 24. Overall section 3 would benefit from more contextualization from the real world offshore wind O&M problem. Nothing about section 3 seems tied specifically to the offshore wind O&M optimization problem. – can you bring in real world examples to help contextualize the approach and demonstrate its uniqueness and value from an offshore wind problem-specific perspective?

Response 24. We believe we have addressed this issue in our case studies.

Comment 25. Line 101-103 – this is important and should be discussed in the introduction. Also, it should be explained WHY this approach is being taken. It is not self-evident.

Response 25. We explained more carefully the role and practical choice of the parameter r in Section 4.1.

Comment 26. Line 104: Explain what z and x are from a real-world perspective

Response 26. We have made it clearer.

Comment 27. Line 110: why? Explain why this approach is being taken

Response 27. This is explained in Section 2.

Comment 28. Line 142 and 152 – why is lambda introduced? Please explain more clearly

Response 28. More explanation of lambda is added around the line 152.

Comment 29. Lines 212-215 should be brought into the introduction. It should already be clear up front how this work will extend the state of the art (though details can remain in a later section)

Response 29. We have changed the introduction to address this comment.

Comment 30. Also, line 212 is the FIRST mention in all of section 2 and 3 of a wind turbine. Nothing about the work to this point is tied to the offshore wind problem specific context… this is a problem for publishing in WES and needs to be remedied before acceptance to publication (see earlier notes on same topic)

Response 30. We acknowledge that our paper is not tied to the offshore wind problem specific context. However, see Response 11.

Numerical studies

Comment 31. There are much more recent papers related to wind turbine failures rates and repair costs – see work from organizations mentioned above and also reporting from NREL, ORE Catapult, BVG Associates, and others

Response 31. Unfortunately, we could not find a later than \cite{tian2011condition} reference suitable for the current context.

Comment 32. Typical farm lifes are more like 25 to 30 or longer – lifetime from a financing perspective is often 20 but has been getting longer

Response 32. This parameter has been changed from 20 to 30 in our calculations.

Comment 33. Line 224 – explain this lambda value better– at least in a footnote if not in a paragraph. What computer simulations elsewhere and why not reported???

Response 33. Yes, we have replaced

"… based on the analysis of computer simulations which is not reported here."

by

"… based on \cite{gustavsson2014preventive}."

Comment 34. Line 223 and line 235 – the decision of the specification of r is not well explained

Response 34. Explained on line 245.

Comment 35. Line 239 – d= 5, 5 what?

Response 35. See Response 38.

Comment 36. Lines 240-245, for wind systems, components are designed for the full plant lifetime (in this case 20 years). Any component replacement prior to that is considered a premature failure and thus is typically in the bucket of unplanned maintenance. Condition monitoring can help detect components that will fail prematurely, which is where the approach in this paper would become relevant. But it is odd to say that PM replacement (for any major component is 43 months) this would be SUPER short from an industry perspective. Again, this entire work seems pretty unlinked to the wind specific O&M problem

Response 36. Yes, 43 months is what our algorithm has produced for the next PM time under the assumptions made for the study. With different input parameters the output would be different.

Comment 37. Figure 1 shows the components but neither of the two figures are really well explained. It would be good to separate these into 2 figures and clearly explain what each of them means

Response 37. Yes, we divided Figure 1 into two figures and added explanations.

Comment 38. Line 250- Mobilization cost of d = 10, 10 what?

Response 38. Yes, now we repeatedly mention in the text that the cost unit is 1000 USD.

Comment 39. Part A and B and C headers (line 252, line 264 and line 272 respectively), make these separate lines and not in paragraph text

Response 39. Done.

Comment 40. Explain better what you mean by winter versus summer start – does this make sense from a real world problem perspective?

Response 40. We have clarified the three different settings. As to the reviewer's question: "does this make sense from a real world problem perspective? "- we think we addressed this question by our finding that:

"in all of the seasonal settings, the proposed PM activities are scheduled for summer months (having lower mobilization costs)."

Comment 41. I recommend doing Part C first – this would be the baseline (all corrective no predictive maintenance) – part A introduces some level of PM and then part B considers the seasonal effects. Then, include the percent savings in each of table 2 and 3 and reference back to the CM analysis

Response 41. Good idea, done.

Comment 42. Need to explain lines 286 to 289 better. How can you do a fair comparison?

Response 42. We have added an extra sentence:

"To make a fair comparison, we characterize both approaches in terms of the time average maintenance costs."

Comment 43. Line 304 – 5 hours to solve what? The full optimization problem?

Response 43. Yes, we added "the full optimization problem".

Comment 44. The overall comparison of NextPM and PMSPIC seems incomplete – are there caveats to this? What are the key assumptions you are making that might be limiting the external validity of the work?

Response 44. We have clarified the principal differences using new Figures 1 and 2.

Conclusions

Comment 45. Consider revisiting the conclusions after the rest of the paper is reworked and better tied to the wind energy problem

Response 45. Done.

Comment 46. Do not mention preliminary results (not shown) on computational time… either show them or don't mention them – i.e. leave it as future work

Response 46. Done.

Comment 47. Also, what is the future work? where will this effort go? What will it take to make this actually useful for wind farm O&M planning?

Response 47. We briefly mention the future work.

Comment 48. Line 316-317 again is more like a marketing pitch

Response 48. Line 316-317 are changed.