Reply to the comments of the reviewers

We are thankful to the reviewers for the close reading of the manuscript and the valuable comments. Below comes the full list of reviewers' comments and the changes we made in response.

Comment 1. Line 13 – Define CM as corrective maintenance

Change 1: at line 13, we changed

"Among other things, this analysis reveals a dramatic cost reduction achieved by the NextPM model as compared to the the pure CM strategy."

to

"Among other things, this analysis reveals a dramatic cost reduction achieved by the NextPM model as compared to the the pure corrective maintenance (CM) strategy."

Comment 2. Line 41 – Would 'mobilization costs' work better than 'set-up costs'?

Change 2: we changed "set-up costs" to "mobilization costs" everywhere.

Comment 3. Define OM as opportunistic maintenance in line 38 instead of line 85

Change 3: at line 38, we changed

"The article Sarker and Faiz (2016) looks at opportunistic maintenance which is a special kind of preventive maintenance."

to

"The article Sarker and Faiz (2016) looks at opportunistic maintenance (OM) which is a special kind of preventive maintenance."

Comment 4. Line 203 – May be worth stating this relates to onshore wind farms – 20 years seems low for an offshore project.

Change 4: at line 203, we changed

"The lifetime of the wind turbine is assumed to be 20 years, which is the typical case in the industry now, according to Ziegler et al. (2018)."

to

"The lifetime of the wind turbine is assumed to be 20 years, which is a typical life length for onshore wind farms, according to Ziegler et al. (2018)."

Comment 5. I would prefer an equally sized left panel in comparison to the right panel

Change 5: we changed the size of the figure such that they are equally sized now.

Comment 6. Could you refer to a source for the mobilization costs in line 226?

Change 6: at line 239, we added

"These numbers are obtained based on a discussion with the experts within the Swedish Wind Power Technology Centre (SWPTC)."

Comment 7. Overall, I am unclear on what contribution this paper makes to the literature on maintenance in general, or turbine maintenance in particular. The problem context that is presented – maintenance of a single turbine comprising four components – seems like a substantial simplification of the actual problem facing wind farm operators, and so some reflection on how this work would actually be applied in a practical setting would be useful.

Change 7: after the line 48, we add

"However, the PMSPIC model is very complex and solving it takes a long time. This motivated us to build a new optimisation model which would be both accurate and could be solved really fast. For simplicity, our modelling idea is presented in the framework of a single turbine as multiple component system, however this framework with a little effort can be extended to the setting of several wind turbine farms."

Change 8: after line 278, we add a new paragraph

"In this paper our NextPM model is applied to a system of four components belonging to a single wind turbine. However, we claim that our approach can handle the case of, say, ten turbines with 80 components in total. Preliminary results (not shown) demonstrate that the computational time required by our algorithm grows linearly with the increased number of components, while the PMSPIC's computational time grows exponentially fast."

Comment 8. Section 1: in the discussion on maintenance literature, it will be useful to be clearer which papers are specific to wind turbine maintenance, as it currently reads as if these are all generic maintenance studies. More broadly, it would be useful to have more of a review of the literature on turbine maintenance – there is a substantial body of research in this area, and it is unclear exactly what the contribution of this paper is.

Change 9. We add four papers to the list of references:

[1] Zheng R, Zhou Y, Zhang Y. Optimal preventive maintenance for wind turbines considering the effects of wind speed[J]. Wind Energy, 2020, 23(11): 1987-2003.
[2] Davoodi A, Peyghami S, Yang Y, et al. A Preventive Maintenance Planning Approach for Wind Converters[C]//2020 5th IEEE Workshop on the Electronic Grid (eGRID). IEEE, 2020: 1-8.
[3] Wang J, Zhang X, Zeng J, et al. Optimal dynamic imperfect preventive maintenance of wind turbines based on general renewal processes[J]. International Journal of Production Research, 2020, 58(22): 6791-6810.
[4] Zhang C, Gao W, Guo S, et al. Opportunistic maintenance for wind turbines considering imperfect, reliability-based maintenance[J]. Renewable energy, 2017, 103: 606-612.

Change 10. Before line 49 we add

"The recent literature on wind turbine preventive maintenance planning extends the modelling scope by paying special attention to particular performance factors for the wind power systems. Zheng et al. (2020) look into the effects of the varying wind speed on the wind turbine maintenance planning. Davoodi et al. (2020) single out the converter as a crucial component of the wind turbine and builds an optimization model to find the optimal replacement times for the converters. Wang et al. (2020) and Zhang et al. (2017) deal with imperfect preventive maintenance. Meanwhile, the main concern of our paper is the computational time of the optimization model. An optimization algorithm with drastically reduced computational time can be used as a key module in a maintenance scheduling app."

Comment 9. Section 3.5: the differences between the authors work and the PMSPIC model could be clearer – this section presents the mathematical formulation PMSPIC, but more reflection on how these differences can be interpreted would be useful, including the differences which give rise to the substantial differences in computing times that are mentioned in Section 4

Change 11. I added a new paragraph after line 200

"The main difference between PMSPIC and the NextPM model is that the PMSPIC generates a maintenance plan for the whole lifetime of the wind turbine, while the NextPM model produces an optimal schedule only for the next PM activity. By focusing on one PM activity at a time and implementing a different model structure we succeeded in substantial reduction of the computational time."

Comment 10. The statement "Among other things, the graph explains why the choice of r = 80 is justified" should be clarified.

Change 12. The line 207

"r = 80, see Section 4.1 for motivation,"

is replaced by

"r = 60, see Section 4.1 for motivation,"

Change 13. After the line 216 we add

"Here, a_t describes the monthly maintenance cost in the single component setting, if the next PM is planned at time t (assuming that at time 0 the component was as good as new). In this section we analyze the behavior of the function a_t under some realistic model parameters. As a result, we propose r=60 as a practical length of the planning period for our algorithm."

Change 14. Line 221

"Among other things, the graph explains why the choice of r = 80 is justified"

is replaced by

"A smaller value of the parameter r would reduce the computational time of the NextPM model. On the other hand, from the perspective of the Algorithm 1, it is desirable to choose r such that at least one PM activity is scheduled during the planning horizon. Since the observed optimal time to perform the next PM is at month 43, we propose setting r=60."

Comment 11. I'm not clear as to the purpose of the three studies, or the sub-parts within the studies. It would be useful to have the analysis approach set out more clearly to emphasise what the authors are aiming to demonstrate.

See Change 13 for Study 1.

Change 15. Concerning Study 2 we added a paragraph after the line 224

"In this section, we study how different mobilization costs d_t result in different optimal PM schedules. Part A deals with the seasonally changing d_t with the average bar d =10. Part B takes up a similar case with a lower bar d = 5. In Part C we compare the next PM plan with a pure CM strategy."

Change 16. Concerning the third case study, after the line 267 we add

"In this case study, we compare the outputs of the NextPM model and the optimization model PMSPIC."

Comment 12. Tables 4-6 aren't numbered and don't have any captions.

Change 17. We added numbers and captions.

"Table 4: Outputs of the NextPM and PMSPIC models for d=1."

"Table 5: Outputs of the NextPM and PMSPIC models for d=5."

"Table 6: Outputs of the NextPM and PMSPIC models for d=10."

Comment 13. It's not clear to me how the discussion and interpretation in Section 4.3 relate to the data that us shown in the tables. There is no real explanation on what the "matlab" and "AMPL" times actually represent. Also, the PMSPIC algorithm seems to identify solutions which are more optimal, but there is no reflection on this.

Change 18. The paragraph starting at the line 265

"The main difference between NextPM and PMSPIC lies in the effectiveness of the algorithms reported in the rightmost columns. For example, if d= 10, then the NextPM optimisation runs 10000 times faster than the PMSPIC optimisation."

is replaced by

"Tables 4-6 reveal that the next PM schedules produced by NextPM and PMSPIC are quite similar. The observed small differences in the maintenance costs do not imply that PMSPIC gives better solutions, since NextPM calculates the maintenance costs within a different modelling framework.

The main advantage of NextPM compared to PMSPIC is in the computational speed. The effectiveness of the algorithms is reported in the two rightmost columns. The "Matlab" column gives the time it takes to generate the main parameters of the model. For the NextPM the number of parameters is much smaller, and they are c_{s,t}^j D_{s,t}^j. The "AMPL" column gives the time it takes to solve the optimisation model. For example, if d= 10, the NextPM optimisation runs 10000 times faster than the PMSPIC optimisation."

Comment 14. If I am correctly understanding the optimal PM times that are shown throughout Section 4, these seem extremely long (e.g. 4 years plus). Typical planned maintenance schedules for turbines are much more frequent, so it would be useful to have some reflection on why these results are so different.

Change 19. After line 220, we add

"Notice that by preventive maintenance, we don't mean the practice of regular inspection of the components' condition. Our concern is the optimal planning of preventive replacements of the components based on their age. In this case study the starting age of the component is zero, which partially explains the seemingly long next PM replacement time of 43 months."