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Providing insight into what can be expected from Offshore Wind Farm Layout Optimisation

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Abstract. This is not yet another study into better modelling or optimiser selection for OWFLO. Instead, this study aims to provide insight into what performance can be expected from offshore wind farm layout optimisation(OWFLO) and to know when further optimising is not justifiable anymore. The study consists of three parts. All three parts make use of a referent. (The definition of the term 'referent' as used here is given in the paper.) The first part uses the referent to find and understand the characteristics of the OWFLO problem. Wind farms with 9, 25 and 64 turbines have been optimised 100 times with the referent. The results show a small spread in the performance of the found optimised layouts, indicating that many local optima exist with similar performances in an OWFLO problem. The second part compares performances from optimised layouts with 25 turbines resulting from optimisations with alternative implementation choices, evaluated by the referent model. The difference in performance resulting from the alternative optimisers indicates that improvement of a state-of-the-art optimiser is not expected to lead to much better results. The third part explores the need to improve the analysis by adding a phenomenon currently not considered in OWFLO. The influence of neighbouring wind farms(NBWFs) on layout optimisation without including atmospheric stability is investigated. It is evident that adding NBWFs for accurate energy yield assessments is necessary. However, for layout optimisation, the benefit of including NBWFs is not apparent.

1. Introduction

The past decade has seen a rise in offshore wind farm developments. Traditional offshore wind farm layouts were designed in long straight rows. However, as the wind industry is starting to mature, optimising the placement of the turbines with respect to maximising energy production and cost reduction is increasingly done in practice. In large wind farms, a 0.1% energy gain can result in several million euros in revenue over their lifetime. However, finding the optimal placements for the turbines provides a complex problem. The large number of inter-dependent design variables creates a design problem that is difficult to solve. There is much attention for wind farm layout optimisation in practice and literature. Most of the research is done in selecting and creating the best optimisation algorithms [22] [19] [7] [5] [20] [15], wake models [1] [12] [8] [3] [11], and cost models [16] [6].

The research in different optimisation algorithms is done to find a better optimum without increasing computational costs. Exact optimisation methods have severe difficulties to solve the offshore wind farm layout optimisation(OWFLO) problem. Therefore, optimisers with a heuristic search method are dominant within OWFLO [4]. Although heuristic optimisation algorithms try to alleviate the problem of exact algorithms finding local optima, they are also known to find local optima. This can be identified by the different resulting layouts that almost have the same performance [2].

One of the dominant factors for OWFLO is the effect of wakes, which wake model is selected therefore influences the optimised layout. The research in wake models is done to develop models that come closer to the effect of real wakes. Low computational costs is required in OWFLO, which prohibits the use of high fidelity models. Therefore, simplified engineering wake models are used based on fundamental fluids principles or empirical data. These wake models generally show good results but have limitations.

One of the recurring findings in OWFLO is that every new run of the optimisation leads to a new 'optimum' layout and that the performance of these different optimal layouts is usually almost equal. This indicates the existence of many local optima and the near equality of these optima. The precise shape of the response surface used in the optimisation depends, among other things, on the chosen wake model, superposition model and wind simulations settings and deviates from what it would be for real wake effects. To deal with these issues, developers of OWFLO tools try to find better optimisers, better wake models, and better cost models. Project leaders use these tools to squeeze out the last milli-percentages of increasing AEP to improve funding for their project. However, justification for what is realistically achievable and significant is not given.

The goal of this study is to provide insight into what performance can be expected of OWFLO and to know if further optimising and further improvement of the analysis is justifiable.

The study consists of three parts: finding the characteristics of the OWFLO problem, exploring how OWFLO is influenced by different choices of the wind farm developer, and implementing a possible improvement to OWFLO. All parts make use of a referent, following the idea proposed by Roza [17] and as explained in the next section.

2. Methods

In this section, the meaning of the referent is given together with how the referent is used for finding the characterisation of OWFLO and the way it is used for comparison.

2.1. Use of a referent

The term referent is not used in this paper in its common meaning, but follows the definition by Roza [17]: "A codified, structured, and formal specification of real-world knowledge about what is commonly perceived, understood and accepted by a defined group of people to be the truth or reality, capable of serving as the comparative standard for reality correspondence assessment and associated activities of model or simulation development".

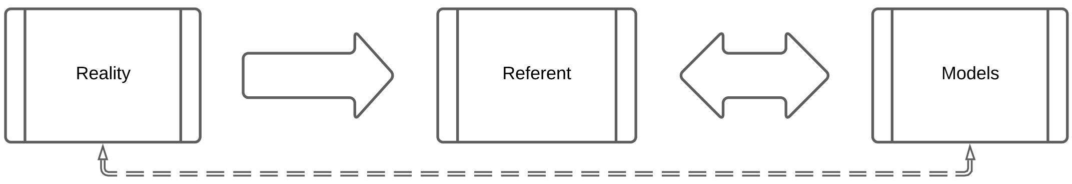

Figure 1: Reality, referent and models diagram

Ideally, to specify and measure the influence from different choices within OWFLO, simulation results would be compared with real-world data, and the found optima would be compared with the known optimum layout. This is indicated by the striped arrow in Figure 1. However, the real-world data of all layouts in the optimisation iterations don't exist, and the true optimum is unknown. Therefore, a computable proxy of reality is obtained from best-practice models and optimisers. This proxy is called the referent.

The referent is expected to exhibit the main features of reality, and an analysis of the referent will thus be used to reveal the characteristics of the real OWFLO problem. The performance of various implementations will be evaluated, with the referent as judge of this performance. This does not provide an absolute qualification of implementation alternatives. Instead, it is expected that in a pool of reasonable implementations, the differences between their performances are representative for the difference of any of them with reality, without revealing rank. The referent provides a somewhat arbitrary anchor point for an analysis of these mutual differences.

Looking back at the definition by Roza, the referent used throughout this paper is not as good as being "understood and accepted by a defined group of people to be the truth or reality". However, the referent is chosen to be "capable of serving as the comparative standard for reality correspondence assessment and associated activities of model or simulation development".

2.2. Referent and alternative implementation choices

2.2.1. Models and optimiser of the referent

The referents problem formulation, analysis, and optimiser choices are illustrated in Figure 2. The problem formulation consists of the objective function, design variables and constraints. For the referent, maximising AEP has been selected as the objective function. This is considered the most straightforward objective function, which can show the OWFLO problem's characteristics. The characteristics found with this objective function are assumed to be also valid for other objective functions as the impact of the AEP is also dominant on economic objective functions. The AEP is calculated by simulating all wind directions([0,1...,359] degrees) and operational wind speeds ([3,4...,25] m/s). The design variables are the continuous x and y coordinates of each wind turbine, while the constraints for the design variables are the outer boundaries of the wind farm.

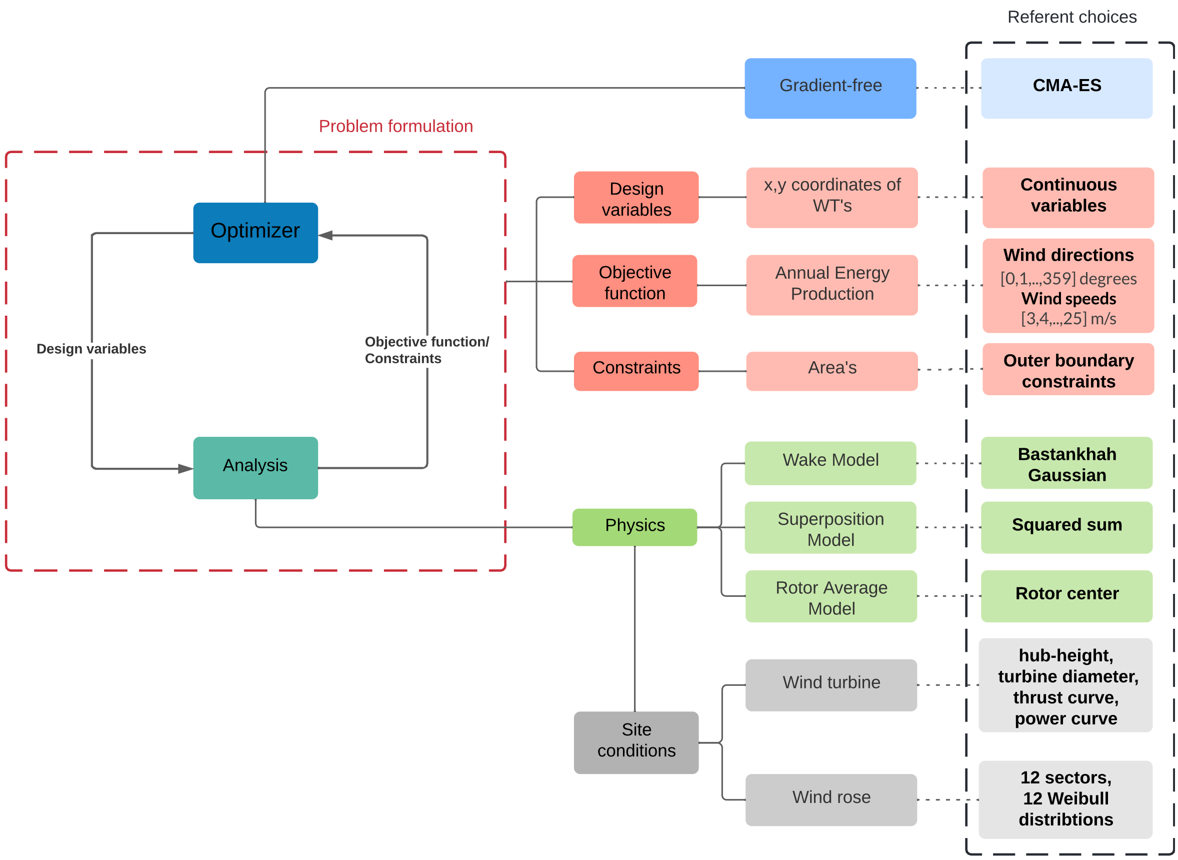

Figure 2: Engineering optimisation model framework, with choices for the implementation of the referent

Within the analysis, the Bastankhah Gaussian(BG) model is selected as the wake model. The implementation is done according to Bastankhah M and Porté-Agel F [3]. The selected superposition model is the squared summation model, which is a simple and widely used summation technique and is obtained by taking the square root of the sum of the upstream single wake deficits squared. The rotor centre model is used, which takes the wind speeds at the centre of the rotor for energy calculations.

The optimiser is a gradient-free optimiser called the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) [10]. CMA-ES is a stochastic numerical optimisation algorithm for non-convex optimisation problems with continuous search spaces.

2.2.2. Alternative models and optimisers

An overview of all the alternative implementation choices and their corresponding acronyms are given in Table 1.

Wake Model	**Superposition Model**	**optimiser**	**Wind Rose**	**AEP calculation**
GC Larsen (GCL)	Linear Sum (LS)	Random Search (RS)	One Weibull distribution (OW)	One Wind Speed 9 [m/s] (OWS9)
NO Jensen (NOJ)	Maximum Sum (MS)	SLSQP	Six Wind Rose sectors (WRS6)	Wind Direction Sample (WDS2)
Zong Gaussian (ZG)		SLSQP + WEC (WEC)	Wind sector Change right (WC R)	
			Wind sector Change left (WC L)	

Table 1: Alternative implementation choices

Details of the alternative wake models of GCL, NOJ and ZG can be found respectively in [12], [11] and [24]. For the superposition model or mixed wake calculations, the linear sum(LS) method and maximum sum(MS) have been used as alternatives. The linear sum method assumes that the velocity deficits within a wind farm are small. Therefore, it takes the net velocity deficit as the sum of deficits from each wake. Instead, the maximum sum method takes into account the maximum deficit found from one wake and neglects all others.

Three alternative optimisers will be used to be compared against the CMA-ES referent optimiser. The random search(RS), the Sequential Least SQuares Programming(SLSQP), and the SLSQP optimiser integrated with a method called Wake Expansion Continuation [22]. Both RS and SLSQP are taken from Topfarm [18]. The WEC method is specifically designed to reduce the multi-modality found in wind farm layout optimisation. The SNOPT + WEC method outperformed many other optimisers for three different farm sizes in the paper 'Best Practices for Wake Model and Optimisation Algorithm Selection in Wind Farm Layout optimisation' [2]. SNOPT was unavailable for this research. However, similar performances were found with SLSQP + WEC when cases from [2] were repeated.

The wind rose setting of the referent model contains a Weibull distribution per wind rose sector. For the first alternative wind rose, these twelve Weibull distributions have been replaced by one Weibull distribution(OW). The one Weibull distribution is made from the averages of the scale and shape parameters of the twelve Weibull distributions and used for all sectors. The second alternative wind condition is reducing the number of wind rose sectors to six(WRS6), giving less accurate wind conditions. The wind sector changes right and left look at the sensitivity of the optimal found layouts to a variability in the wind rose. This variability in the wind rose can come from using incorrect input data. The referent's wind farm sectors are given a full sector rotation counterclockwise(WC L) and clockwise(WC R), which exaggerates the inaccuracy that can normally be expected.

Two alternative ways of calculating the AEP, which increase the computational speed, are used. The first method simulates only one wind speed at 9 m/s(OWS9). This simplification of the representation of wind conditions is known to be used in industry. When simulating with one wind speed, the selected wind speed needs to be around or lower than the rated wind speed of the turbine to have wakes impact the power output of other turbines. The second method is simulating for fewer wind directions(WDS2). The referent simulated the wind conditions for each degree (0,1,..,359), which gives high accuracy. For the comparative analysis, the wind conditions are simulated with a wind direction step size of 2 degrees (0,2,..,358).

2.3. Case studies
2.3.1. Site conditions and turbine
For all cases, the same wind conditions and turbine are used. The wind conditions have been taken from Horns Rev 1 and are illustrated in Figure 3 (left). As wind turbines are still developing at a rapid pace, selecting a state-of-the-art wind turbine was required to make the research relevant now and in the coming years. Therefore, a reference wind turbine called the IEA15MW is used, which was specifically made to give open benchmarks for studies exploring new design methodologies. The IEA15MW is a 15MW offshore wind turbine with a fixed-bottom monopile support structure. It is a Class IB direct-drive machine, with a rotor diameter of 240 m and a hub-height of 150 m [9].

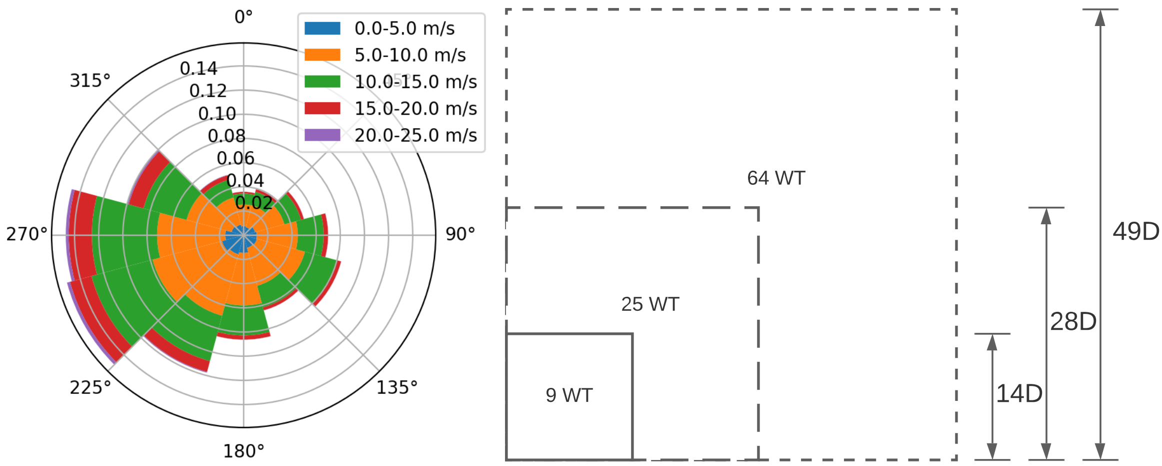

Figure 3: Wind rose of Horns Rev 1 and a visualisation of the area and the number of turbines

2.3.2. Part 1: Cases and approach for characterisation
Three cases have been defined to find and understand the characteristics of the OWFLO problem. All three have a square outer boundary constraint and no area constraints within the boundaries. The number of wind turbines is 9, 25, and 64, with a boundary constraint of 14D x 14D, 28D x 28D, 49D x 49D, respectively. The boundary constraints and their corresponding number of turbines are illustrated in Figure 3 (right), where D is the turbine diameter. The size of the area is made to fit a regular layout with a spacing of 7D. The typical wind turbine spacing that is used in actual wind farms nowadays is 6 to 10D [21], making 7D a reasonable spacing. Each case is optimised a hundred times to explore the local optima.

2.3.3. Part 2: Cases and approach for comparison of implementations
With the prospect of running a substantial number of optimisations, the 25 turbine case described in the previous section is taken for comparing the alternative implementation choices.

The comparative analysis is done by changing one referent implementation choice to an alternative implementation choice. All other settings and models within the referent are kept the same. With the new implementation choice, the OWFLO problem is optimised one hundred times. This results in one hundred layouts and one hundred performances. If a model in the analysis is changed, the performances of the final found layouts are recalculated with the referent's analysis. Only when changing the optimiser this is not necessary. The hundred performances are shown in a boxplot to be compared to other implementation choices and the referent.

2.3.4. Part 3: Cases and approach for neighbouring wind farms
This section will explore the need to improve the analysis by including a phenomenon that was previously not considered. The influence of wind farm wakes on neighbouring wind farms (NBWFs) is chosen to be included in the analysis. Some experts consider understanding and accurately modelling the wakes of wind farms to be important for optimising wind farm layouts [14]. An analysis of the effect of wind farm wakes is done by Nygard and Hansen for the wind farms Rødsand II and Nysted [13]. They concluded that the Jensen model captures the wind farm wakes reasonably well. However, atmospheric stability is known to impact the effect from a wind farm wake on a neighbouring wind farm. A quantitative relationship between wind speed, atmospheric stability, and wake length is needed to account for atmospheric stability. However, this was not available and has been left out of the cases used here.

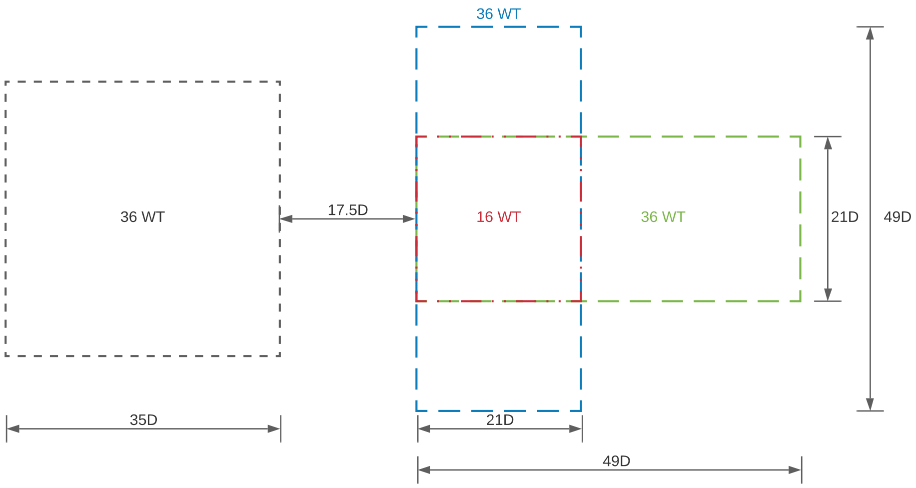

Figure 4: Visualisation NBWF cases

Three cases and a reference case have been defined to show the influence from NBWFs on layout optimisation. The referent settings are used. The wind farm, which is optimised and analysed, has 36 turbines and an area size of 35D x 35D, illustrated on the left in Figure 4. Three different NBWFs with 16, 36 and 36 turbines are used, illustrated on the right in Figure 4.

The wind farm is optimised a hundred times with the blue, red and green NBWFs and without a NBWF(reference), resulting in four times a hundred layouts. The performances of the layouts resulting from optimising without a NBWF are recalculated with a NBWF and compared to the performances of the layouts which were optimised with the corresponding NBWF. Only the performance from the optimised wind farm is considered, not the performance of the NBWF.

3. Results and discussion
In this section the results for the characteristics, the alternative implementation choices and the NBWFs are given.

3.1. Characteristics of the layout optimisation problem
All three cases defined in section 2.3.2 have been optimised one hundred times. This gave a hundred different layouts and a hundred different performances for the cases with 25 and 64 turbines. For the case with 9 turbines, 35 different layouts were found. This means that 65 layouts were nearly identical to a layout found in an earlier optimisation, which corresponded to the same local optimum. The many different found optimal layouts for all three cases confirm that many local optima exist within an OWFLO problem.

A histogram of the performances resulting from the wind farm with 25 turbines is shown in Figure 5. To better illustrate the distribution of performances this case has been optimised a thousand times (only for the results of Figure 4). Although the layouts differ greatly, which will be addressed later, the performances of all layouts are very close to each other. The difference between the highest and lowest found AEP is 0.17% for the 25 turbine case. For the 9 and 64 turbine case these differences are 0.21% and 0.13%, respectively. This indicates a decrease in the spread with an increase in the number of turbines. A normalised boxplot of the cases is shown in Figure 6 to illustrate this decrease.

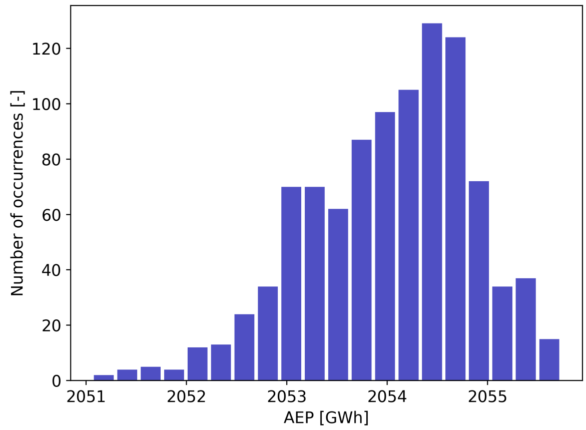

Figure 5: Histogram of the performances of the wind farm with 25 turbines(1000 optimisations).

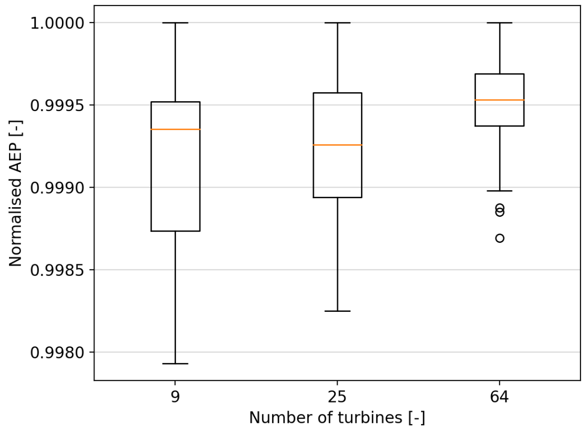

Figure 6: Normalized boxplots of the performances of the three wind farms(100 optimisations).

Figure 7, shows the placement of the turbines for the wind farm with 25 turbines. The scatterplot shows the positions of all the turbines resulting from the 100 optimised layouts. On the top and the right-hand side, a histogram indicates the times a turbine is placed there.

Although not explicitly shown, almost all layouts have turbines in all four corners, leading to the white spaces surrounding these corners. The histograms of the scatterplot show that turbines are more often placed on the left and right boundaries of the site than on the upper and lower boundaries, indicating that more turbines are placed in the direction of the dominant wind. No significant distinction was found between the number of times turbines were placed on the left or right boundary of the site. This is interesting since the wind rose deviates strongly in frequency between easterly and westerly winds. The benefit from placing more turbines on the upstream boundary, to avoid wake effects from the centre turbines, doesn't seem to outweigh the benefit from having the same amount of turbines on the downstream boundary.

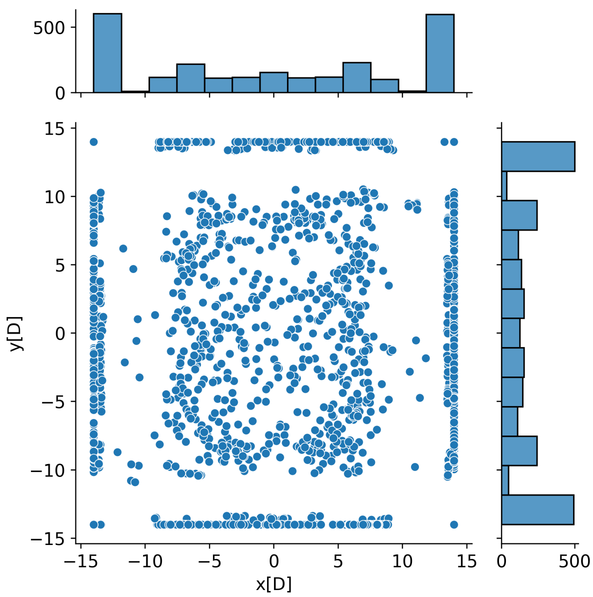

Figure 7: Scatterplot of the placement of the turbines for the wind farm with 25 turbines(100 optimisations).

At all boundaries of the site turbines are often placed a small distance (<1D) from the boundary. This 'second row' is found favourable by the optimiser over putting the turbine exactly on the boundary of the wind farm. Assessment of a small part of the referent's design space revealed that this is a consequence of the trade-off between spacing and wake superposition effects. The results are inconclusive as regards whether this characteristic is an artefact of the chosen models or that it is inherent to wake effects in reality. The second row effect is assessed in more detail in [23].

3.2. Alternative implementation choices

The boxplots of the alternative wake models, superposition models and optimisers are illustrated in Figure 8. At boxplot level, some conclusions can be drawn. The overview shows that for all wake models, the performances medians are relatively close to each other. They indicate that the wake model's influence is relatively small on the optimality of the performances. The main features that the wake models have in common can explain the relatively close performances of the wake models. There are clear differences between the shapes of the wake and the absolute wake deficit. However, when used in optimisation, all models' main feature is creating distance between turbines and pushing the turbines towards the boundaries.

The differences between the superposition models and the referent are minor. Both the medians are well within 1 GWh difference, which relative to the median of the referent is 0.05%. This indicates the little influence the superposition model has on the final found layout's performance.

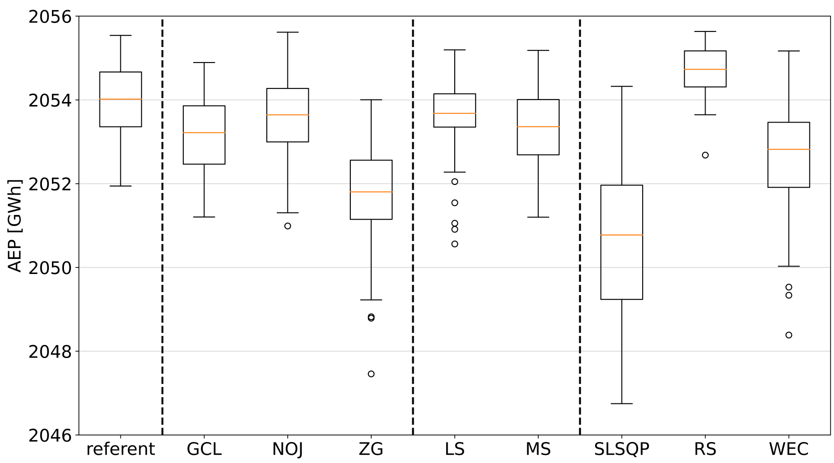

Figure 8: Boxplots of the alternative wake models, superposition models and optimisers.

The boxplot of the SLSQP shows an increased spread with respect to the referent(CMA-ES) optimiser. The SLSQP optimiser has higher susceptibility to lower performance local optima as it is not searching the design space on a global level. The boxplot of the RS optimiser shows a more robust result with a smaller spread and a higher median. The random optimiser, a gradient-free algorithm, is not susceptible to lower performance local optima as it keeps searching globally for better placements of the turbines. Its spread is consistent with the peak in the distribution of performances with CMA-ES, shown in Figure 4. This confirms that the histogram for the referent is representative of the real high-end distribution of performances of local optima, despite its tail for lower performances. Optimising with SLSQP+WEC resulted in an improvement with respect to just SLSQP. However, the optimiser is not able to find the higher end of the performances found by the referent and RS. The bigger success of SNOPT + WEC in [2] may be due to the limited number of wind directions prescribed by their case study. This rough discretization of wind directions results in artificial 'holes' where turbines can 'hide'.

The boxplots of the different wind rose and wind simulations are illustrated in Figure 9. The boxplot from the one Weibull distribution(OW) shows a higher median than that of the referent and less spread. The one Weibull distribution has the same Weibull distribution for all sectors. This seems to aid the optimiser in searching the design space more globally. The smoother response surface resulting from having one Weibull distribution can explain the more robust results than the referent's wind conditions give. The reduction in the number of wind rose sectors to six(WRS6) has some influence on the performance of the found local optima.

However, reducing the number of wind rose sectors to six is considered quite a drastic decrease in the accuracy of the wind rose. Despite this, the median is just 2 GWh, or 0,1 %, lower than the median of the referent. The boxplots of wind sector change left and right show that the influence depends on the direction of the change. The influence from WC L is larger than from WC R.

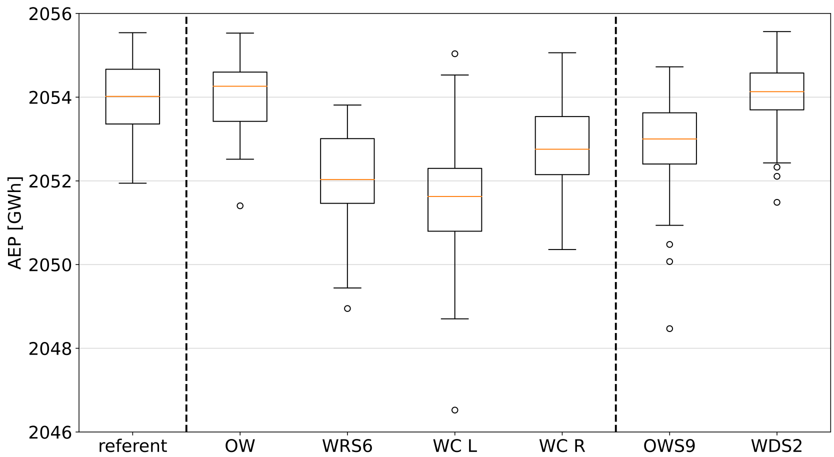

Figure 9: Boxplots of the alternative wind rose and wind simulation.

The boxplot of OWS9 shows that the influence on the performance from simulating with one wind speed is small as most of the OWS9 boxplot overlaps with the referent's boxplot, while the computational speed was twice as high. The small influence shown here provides a justification for simulating with one wind speed and demonstrates how little effect imprecise modelling of the wind speed distribution has on layout optimisation. The boxplot of WDS2 shows a more robust performance than the referent's boxplot. WDS2 helps an optimiser to search more globally without losing the accuracy of the referent's conditions. The computational speed is again twice as high. These results give an incentive for increasing the simulation step size without losing performance. However, it is expected that further increase will eventually result in losing too much accuracy, making the performance drop significantly.

3.2.1. Results from optimising with neighbouring wind farms

The results of the performances by including the NBWFs into the optimisation are illustrated in Figure 10. In Figure 10, 'red', 'green' and 'blue' stand for the performances of the layouts, that were optimised including the colored neighbouring wind farms(shown in Figure 4), and 'no NB' stands for the performance of the layouts resulting from the optimisation done with no neighbouring wind farm. All the performances are calculated with the neighbouring wind farm of the corresponding color present, irrespective of whether this neighbouring farm was considered in the optimisation or not. The resulting boxplots show that for all three cases, the performances of the layouts optimised without a NBWF perform better than the layouts optimised with the corresponding NBWF. This indicates that adding the NBWF to the optimisation actually lowers the performances of the found layouts. The lower performance is the result of the more complicated response surface resulting from the implemented NBWF. The increased complexity of the response surface is more difficult for the optimiser. Another indication of this are the two lower outliers, which shows that the optimiser got stuck in significantly lower local optima.

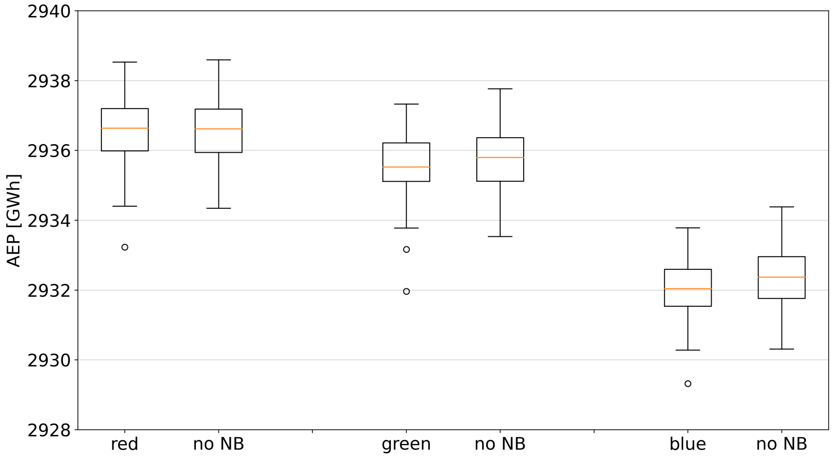

Figure 10: Boxplots of the performances from the optimised layouts with and without NBWF.

4. Conclusions

In this section, the main conclusions of this paper are presented. Optimisation of multiple cases with the referent confirmed that an OWFLO problem contains many local optima. Although the layouts differed significantly, their performances were exceptionally close to each other. The wakes of turbines create the local optima. The decrease in the spread with an increasing number of turbines comes from the almost identical absolute difference between two local optima. As the AEP of the farm increased significantly with an increasing number of turbines, the relative spread decreased. With this small spread of the local optima and with the many local optima with similar performance, it is expected that a global optimum will not be significantly better than the highest found local optimum after a reasonable search. This is further supported by the narrow peak and quick drop-off of the distribution of the local optima.

Although the local optima in terms of layout are slightly different for alternative implementation choices, the influence of these shifts on the performance turned out to be minimal. The main features for layout optimisation, which all alternative implementation models kept, is creating distance between turbines with consideration of the wind rose. Without being able to say which models come closer to reality, their is no justification for choosing any model over another. The spread of the boxplots was found to be related to the roughness of the response surface that alternative implementation choices make. An increase in the roughness of the response surface meant an increase in the spread of the performances.

Improvement of the state of the art of optimisers used for OWFLO is not expected to lead to much better results. This was demonstrated by a comparison of several good optimisers. Nevertheless, one has to be aware that a poor choice of optimiser can significantly reduce optimality of the layout design, as was shown for a gradient-based optimiser with a random start.

Implementing NBWFs for OWFLO seems logical as the influence from the wakes of NBWFs on power production has been proven with multiple studies. Adding NBWFs for accurate energy yield assessments is therefore necessary as the wind farm wake's impact on the energy is clear. However, for layout optimisation, the benefit of including NBWFs is not evident. Other future improvements to the analysis for OWFLO should therefore be done with layout optimisation in mind and not with accurately calculating the energy yield.

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