Method Comparisons for Wake Model and Optimization Algorithm Selection in Wind Farm Layout Optimization

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I. Introduction

The problem of wind farm layout optimization is multivariate and multimodal. Inclusion of both many possible inputs (turbine cost, turbine location, wind data granularity, geographic peculiarities, etc.) and many possible target functions (minimize construction costs, maximize energy production, minimize environmental impact, etc.) make the problem as simplistic or as complicated as the user desires. Computer automated modelling is used to analyze variable permutations and optimize target function calculations on a scale far greater than could be accomplished solely through real-world experimentation. For these computer optimizations to be successful, two separate factors must be addressed:

1) Choice of model inputs and target
2) Optimization algorithm selection

Many papers have been written on various turbine and wake models, and even more have been written on optimizations algorithms. However little has been published on comparative pairings of the two, and how they play out with wind farm characteristics (i.i geography, wind resource, etc.)

We therefore undertook designing a series of simplified wind farm scenarios formed into case studies, where participants would use their model and method pairings to discover as optimal a solution as they were able. Our intent is to assist researchers in the field by presenting a standardized method of comparing widn farm layout optimization methods. Case studies 1 and 2 (cs1 & cs2) were wind farm scenarios with circular boundaries of three differnt sizes to observe patterns over increasing complexity. Case studies 3 and 4 (cs2 & cs4) introduced both non-uniform boundaries and a more complicated wind resource than cs1 & cs2, to further test participant methods.

Mention results here

II. Methodology

Feedback we received from particiants of cs1 & cs2 were that the wind farm scenarios were too simplistic. This was by design, to both incentivize participation and to allow the case study results to be valid for general application. But with this feedback in mind, we chose to increase the complexity of both the wind resource and the wind farm boundary.

Regarding the wind farm boundary, a cs1 participant requested a farm boundary that existed in the real world, as opposed to the contrived ones used in the first two studies. We therefore selected for our model parcels III and IV of the Borssele Wind Farm, which is located in the North Sea between the Netherlands and England. This farm offered two characteristics that gradient-based optimizers would have difficulty with: (1) concavities in the boundaries (2) disjoint boundary sections. The boundary sizing was scaled so the model turbines we used would be adequately spaced, but the boundary shapes are those of the real-world farm, depicted in fig FIGURE.

The first two case studies gave a simplified wind resource of directions and a constant wind speed across all directions. To increase realism in cs3 & cs4 we gave participants NumDir and frequencies for NumSpeeds for each direction, giving NumDataPoints pieces of wind information in cs3 & cs4 as opposed to the NumDataPoints given in cs1 & cs2.

For cs3 the goal was to isolate variability in participants' optimization methods. In order to do this we pre-coded a representative wake model as a control variable and permitted participants to use any optimization strategy to alter

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turbine locations that would deliver the best annual energy production (AEP) for the farm. We used only parcel IIIa of the Borssele farm in this case study, since it includes concavities but avoids the disjoint boundary problem.

The cs4 boundary invloved five parcels from the Borssele farm. Besides adding the complexity of disjoint boundary sections, we also permitted participnats to use whatever wake model they chose for optimization purposes, though final comparisons would be conducted with our supplied EWM.

A. Common to Both Case Studies

Though testing for different variables, certain wind farm attributes were common to all case studies. A brief list of these common variables is described below.

1. Wind Turbine Specifications

We used IEA 5 MW offshore reference turbine in cs3 & cs4, since our wind farms are modelled after an offshore location. The this turbine is open source, and the turbine is designed as baseline for offshore wind turbine specifications [**?**]. The power curve for the IEA 5 MW turbine is defined as shown in Eq. (1) and Fig. 1. The specifications of the turbine necessary for our simplified version of Bastankhah's Gaussian wake model (used in cs3) are shown in Table 1.

$$P(V) = \begin{cases} 0 & V < V_{cut\text{-}in} \\ P_{rated}\left(\frac{V - V_{cut\text{-}in}}{V_{rated} - V_{cut\text{-}in}}\right)^3 & V_{cut\text{-}in} \leq V < V_{rated} \\ P_{rated} & V_{rated} \leq V < V_{cut\text{-}out} \\ 0 & V \geq V_{cut\text{-}out} \end{cases} \tag{1}$$

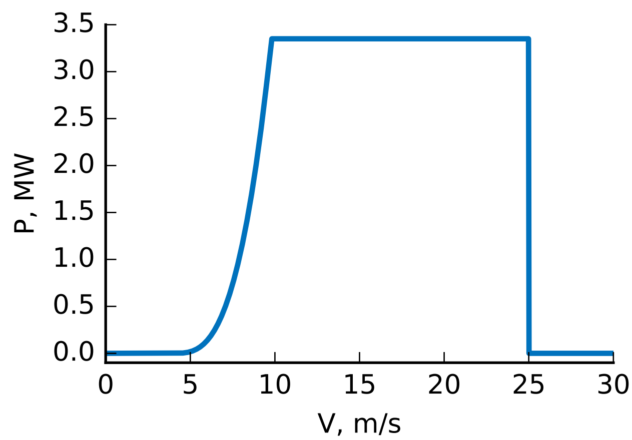

Figure 1 Graphical depiction of IEA's 5-MW onshore reference turbine's power curve.

Table 1 Attributes for IEA's 5-MW onshore reference turbine

Rotor Diameter	130	m
Turbine Rating	5	MW
Cut-In Wind Speed	4	m/s
Rated Wind Speed	9.8	m/s
Cut-Out Wind Speed	25	m/s

2. Farm Geography

To focus on optimization method and EWM variability, as well as to avoid introducing too many unnecessary variables, the wind farms for all scenarios were on flat and level terrain. To reduce boundary impacts on farm design, we chose a radially symmetric farm boundary. Turbine (x, y) hub locations were restricted to be on or within the boundary radius. Turbines were further constrained to be no less than two rotor diameters apart from any other turbine.

Farm diameter sizing for each scenario needed to be restrictive enough to avoid simply placing all turbines on the boundary but also permit meaningful turbine movement by the optimizers. Although the participants were not required to use the example starting layouts that we provided, we tried to provide reasonable example layouts by dispersing the turbines as much as possible in an orderly way. This was done by placing turbines in evenly spaced concentric rings. The boundary radii of the various wind farms we defined were selected to permit turbine placement in concentric rings with a minimum turbine spacing of five rotor diameters.

3. Wind Attributes

The wind distribution frequency and wind speed were the same for all wind farm scenarios in both case studies. Freestream wind velocity was constant in all wind directions, at 9.8 m/s, regardless of turbine location or time of day. This wind speed was used because it is the rated wind speed of the IEA 3.35-MW wind turbine. Using this incoming wind velocity maximized power production variability between wind turbines in the farm. In setting the scenario's freestream velocity for the turbine's rated wind speed, any wake effects moved air speeds down below rated power. With greater variability in the power production, more local optima would be experienced by participant optimizers. A lack of such local optima in a design space permits even ineffective optimizers to find a superior result. Since the presence of many local optima is a feature observed on many wind farm optimization problems, we strove to create such design spaces with our case study scenarios, as it allows us to test the exploration capabilities of the various optimization algorithms.

The selection of the wind rose was a major factor in the frequency and magnitude of local optima resulting from turbine placement. We selected a wind rose with an off-axis wind frequency distribution, binned for 16 directions. When we tested this wind rose against 1,000 randomized starting turbine locations, it gave few optimized results with relatively high AEP values. We interpreted this to be indicative of the presence of many local optima. The wind rose we used is depicted in Fig. 2, in polar coordinates. In this figure, a greater magnitude in the radial direction from the origin indicates a higher wind frequency from that specific direction.

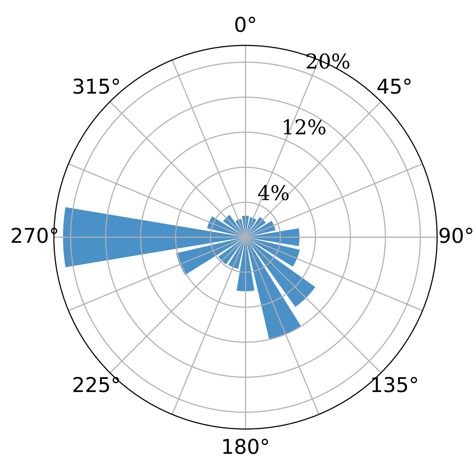

Figure 2 The wind frequency distribution for our case studies.

B. Case Study 1: Optimization Only

The purpose of this case study was to determine the best optimization practices for WFLO, using a single representative EWM. We selected a generalized wake model that both gradient-based and gradient-free optimization algorithms could use and that was computationally inexpensive in comparison to LES and DNS methods.

1. Wake Model

The wake model selected for case study 1 was a simplified version of Bastankhah's Gaussian wake model [**? ?**]. This wake model is described Eq. (2).

$$\frac{\Delta U}{U_\infty} = \left(1 - \sqrt{1 - \frac{C_T}{8\sigma_y^2/D^2}}\right)\exp\left(-0.5\left(\frac{y-\delta}{\sigma_y}\right)^2\right) \tag{2}$$

In Eq. (2), $\Delta U/U_\infty$ is the wake velocity deficit, $C_T = 8/9$ is the thrust coefficient, $y - \delta$ is the distance of the point of interest from the wake center in the cross-stream horizontal direction, D is the turbine diameter, and σ_y is the standard deviation of the wake spread in the cross-stream horizontal direction as defined in Eq. (3):

$$\sigma_y = (k_y x) + \frac{D}{\sqrt{8}} \tag{3}$$

In Eq. (3), x is the downstream distance from the turbine generating the wake to the turbine of interest, and D is the turbine diameter. The variable k_y is determined as a function of turbulence intensity (I). In this case study turbulence intensity was treated as a constant of 0.075, and we therefore used a corresponding k_y of 0.0324555 [**? ?**].

Increasing turbulence intensity has numerous effects and draws attention away from the main purpose of this case study, which was to observe the differences of optimization strategies. For the wake model we used (shown in Eq. (2)), increasing the turbulence intensity widened the wake cone, but second and third order effects are unknown. As such, this first IEA37 set of case studies used a very low intensity in an attempt to minimize the considered variables.

2. Farm Sizes

Variability in wind farm size (and thus number of design variables) affects optimization algorithm performance. To study how increased farm size (i.e. design space complexity) impacts the performance of optimization algorithms, three wind farm sizes were specified in case study 1. The three wind farms had 16, 36, and 64 turbines, respectively. The three farm boundary radii were 1300 m, 2000 m, and 3000 m, respectively. The boundary radii were determined in the manner described previously in Section II.A.2. The turbine numbers were selected as perfect squares that roughly double in size. Perfect squares were used to permit participants to use even grid turbine arrangements, if desired.

3. Supplied Code

We provided participants with a link to a GitHub repository* which included files with the following contents:

- Turbine characteristics, wind frequency, and wind speed in IEA 37's `.yaml` schema
- Example turbine layouts for each farm size (in `.yaml` format)
- Python parsers of the `.yaml` schema
- Python target function to calculate AEP (given `.yaml` turbine locations and farm attributes)

We selected the programming language Python, since it is widely used by researchers in the industry, and is open source. Participants were allowed to alter our specific code implementation or replicate the provided model in another language to speed up the code or for compatibility with their optimization methods. This was with the understanding, however, that final wind farm layouts would be evaluated with the original Python code that we provided.

C. Case Study 2: Combined Physics Model/Optimization Algorithm

The intent of this case study was to assess both the effects that different optimization methods and physics model approximations have on turbine location recommendations. Case study 2 differs from case study 1 in that 1) no wake model was provided and 2) only a single wind farm size was to be optimized. Participants were free to choose their preferred EWM and optimization method combination.

1. Wake Model

Unlike case study 1, participant-reported AEP values were not comparable, since each participant used a different EWMs to calculate AEP. To help us make fair comparisons and conclusions, we conducted a cross-comparison of results between participants. For the cross-comparison, each participant provided their optimal turbine layout in the

*https://github.com/byuflowlab/iea37-wflo-casestudies standardized `.yaml` format. Each participant was then provided with every other participants' optimized layout file. Participants then used their own wake model to calculate the AEP of the other participant's proposed farm layouts with their EWMs. From this portion of the case study, we hoped to learn if any participants' results were consistently seen as superior by other EWMs.

2. Farm Attributes

The wind farm size for the combined case study was limited to nine turbines. We did this to limit the computation time requirements when assessing results in a standardized LES, discussed later in Section IV. We used the previously described method under Section II.A.2 to determine the boundary radius, which for the 9 turbine case is 900 m. The wind rose and wind speed were the same as in case study 1.

III. Results

A. Case Study 3: Concave Boundary

B. Case Study 4: Disjoint Boundary

IV. Conclusion

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Appendix