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Wind farm design in complex terrain: the FarmOpt methodology

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Abstract

Designing wind farms in complex terrain is becoming more and more important, especially for countries like China, where a large portion of the territory is featured as complex terrain. Although potential richer wind resources could be expected at complex terrain sites (thanks to the terrain effects), they also expose many challenges for wind farm designers/developers. In this study, we present the FarmOpt methodology for designing wind farms in complex terrain, which combines the state-of-the-art wind resource assessment methods with engineering wake models adapted for complex terrain and advanced layout optimization algorithms. Various constraints are also modelled and considered in the design optimization problem for maximizing the annual energy production (AEP). A case study is presented to illustrate the effectiveness of the methodology. Further developments of the FarmOpt tool are also briefly introduced.

Key words: wind farm design, complex terrain, layout optimization, FarmOpt

1. Introduction

The development of wind energy in the last several decades has led to the proliferation of wind farms (WFs) world widely, both at onshore and offshore sites. For onshore wind farm constructions, since a lot of good sites in flat terrain have already been occupied, more attentions are paid to complex terrain sites, especially for countries featured by a large percentage of mountainous terrain, such as China.

Comparing with those built in flat terrain, WFs built in complex terrain benefit from possible richer wind resources at certain locations (brought by the speed-up effect due to terrain topography changes), but they are also more likely in the exposure of more complex flow conditions, higher fatigue loads, more expensive installation, operation and maintenance costs, and other disadvantages [1]. Usually WFs in complex terrain are designed mainly based on wind resource assessment, using both linear models such as BZ flow model (used in WAsP), and nonlinear models, such as various CFD models [2]. Although the wind resource consideration is the most important one for WF design in complex terrain, one can expect to achieve even better designs by: considering the interactions of the wind turbine (WT) wake effects and the boundary layer flow over complex terrain, and using WF layout optimization methods.

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In the Sino-Danish research cooperation project FarmOpt [3], we developed such a WF design tool (the FarmOpt tool). The flowchart of the FarmOpt methodology is shown in Figure 1.

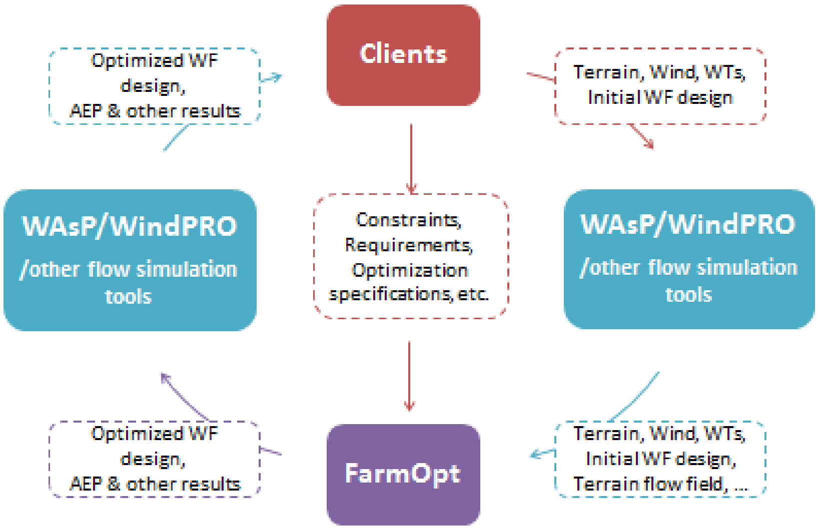

Figure 1. Flowchart of the FarmOpt methodology.

FarmOpt models the flow field by adding wake effects on top of the terrain flow field obtained by using existing industry standard wind resource assessment tools such as WAsP or WindPRO. Then the design optimization problem is solved by using advanced WF optimization algorithms, such as Random Search [4]. Realistic constraints or requirements specified by the clients (typically WF developers) are also considered, such as constraints on WF boundary, exclusive zones, terrain ruggedness degree, minimal distance between WTs, minimal mean wind speed, and so on.

The FarmOpt project is scheduled to end this year, and the tool is planned to be integrated with WindPRO and WAsP in the upcoming future releases. We present the details of this methodology and the usage of this tool in a real complex terrain WF design optimization problem in this paper.

2. Wind farm modelling

2.1 Wind resource

Using site measurements and standard wind resource assessment tools, such as WAsP and WindPRO, one could get the essential information regarding the wind resource and terrain effects for a given site.

FarmOpt currently has interface with WAsP and WindPRO, mainly utilizing the resource grid calculated in WAsP or WindPRO, which contains the sector-wise information for each grid on Weibull parameters, mean wind speed, speed-up factor, turning angle, etc. Either the traditional linear model (BZ in the conventional WAsP) or a more advanced model such as WAsP CFD [5] (an integrated part of WAsP designed for wind resource assessment in complex terrain) can be applied to calculate the resource grid. FarmOpt extracts the relevant information on wind resource and terrain effects from the resource grid and then finds the required information for any location under any given inflow wind direction by interpolation. Some of the interpolated values are shown in Figure 2.

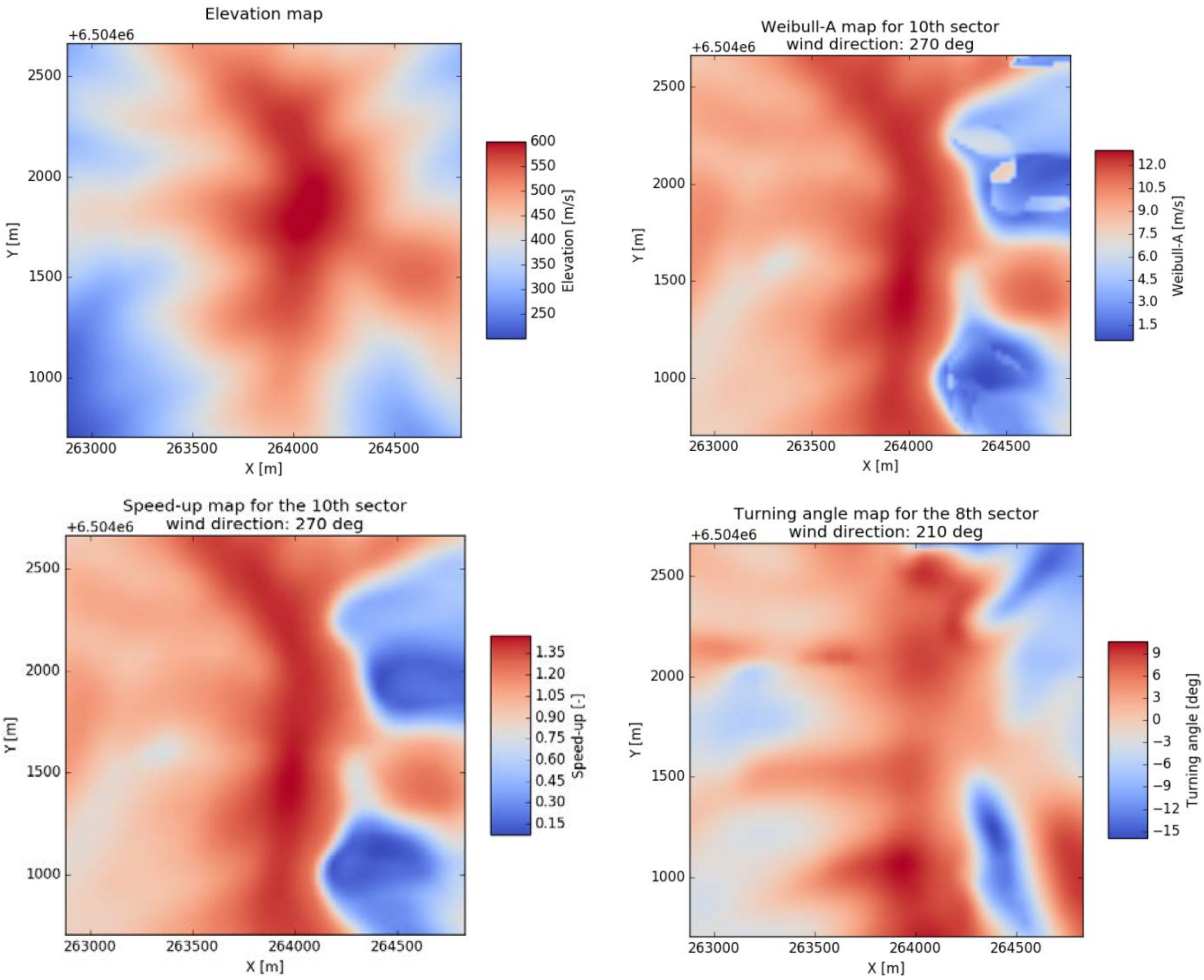

Figure 2. Terrain and wind resource information for a complex terrain site: (up-left) elevation; (up-right) Weibull-A parameter; (down-left) speed-up factor; (down-right) turning angle.

2.2 Wake modelling

An adapted Jensen wake model developed for WFs in complex terrain [6] is used in FarmOpt, which assumes: (1) centerline of the wake zone behind a rotor follows the ground of terrain along the wind direction; (2) velocity deficit and radius of the wake zone develop linearly according to the traveling distance of the wake; (3) multiple wakes and/or partial wakes merged at each rotor satisfy the kinetic energy deficit balance assumption. This wake model is fast to run and yields adequate results.

2.3 Constraint modelling

Wind farm design in complex terrain inevitably encounters various constraints and requirements, which might come from the considerations on wind resource, flow characteristics, terrain features and so on. FarmOpt includes a constraint module to account various constraints. Currently, it has modelled the constraints on mean wind speed, terrain ruggedness degree, inclusive zones, exclusive zones and minimal distance requirements between any two WTs. Other constraints can be easily added. An example of such constraint modelling is shown in Figure 3.

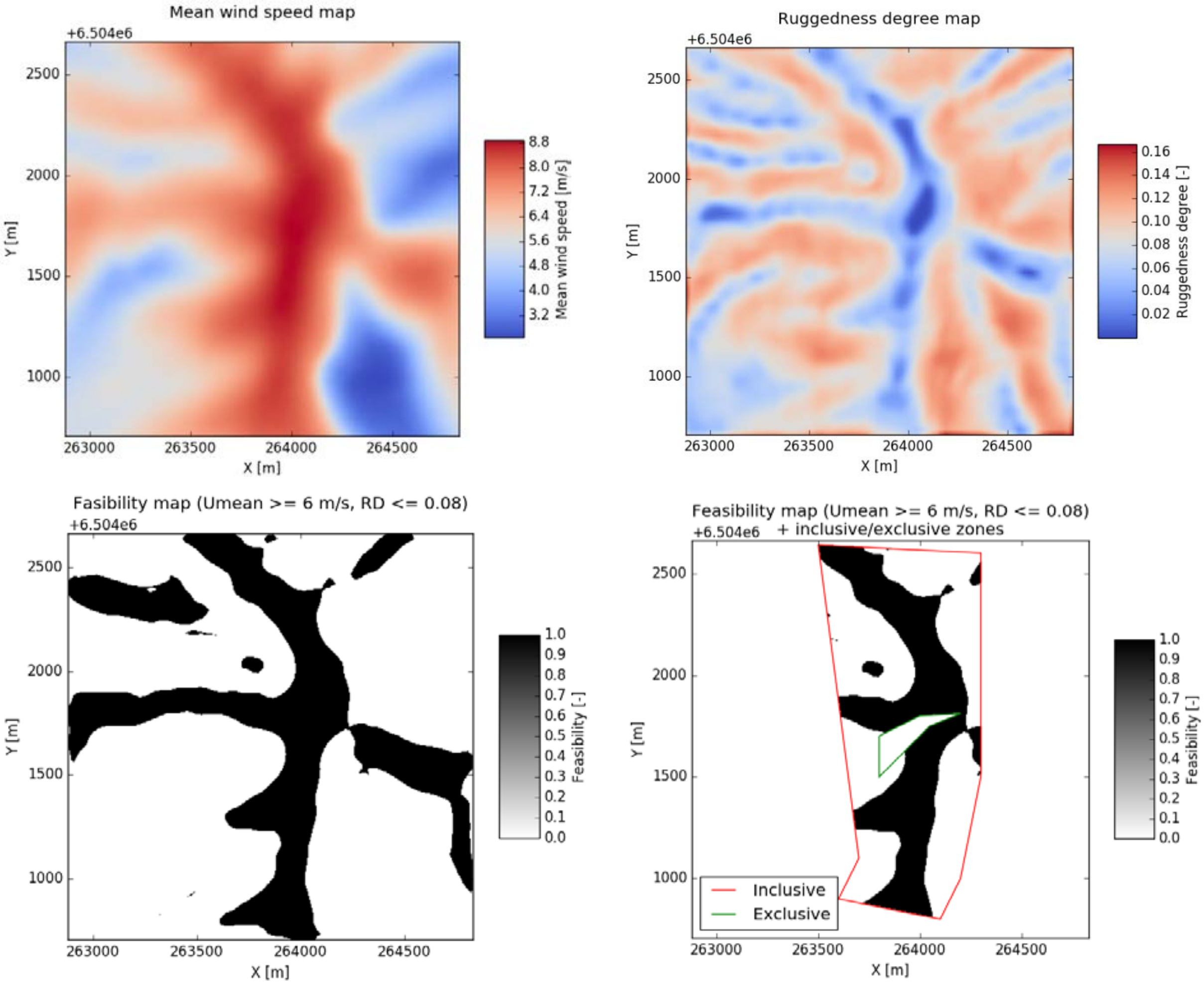

Figure 3. Constraint modelling of FarmOpt: (up-left) map of mean wind speed; (up-right) map of ruggedness degree; (down-left) constraints on minimal mean wind speed and maximal ruggeness degree; (down-right) adding constraints on inclusive zone and exclusive zone.

3. Layout optimization

FarmOpt has a modular architecture, including modules of objective function, constraints and optimization. It can be extended for different objective functions and different optimization algorithms. Currently, it is setup for carrying out layout optimization of wind farms to maximize AEP by using the Random Search algorithm [4]. The flowchart of this algorithm is shown in Figure 4. Details of this algorithm can be found in [4].

4. Case study

To demonstrate the effectiveness of FarmOpt, we present here a case study for an anonymous WF in complex terrain with 8 WTs, which has a total capacity of 22 MW with 8 WTs. This WF is located in southern Europe. Its original layout and the WT characteristics are shown in Figure 5.

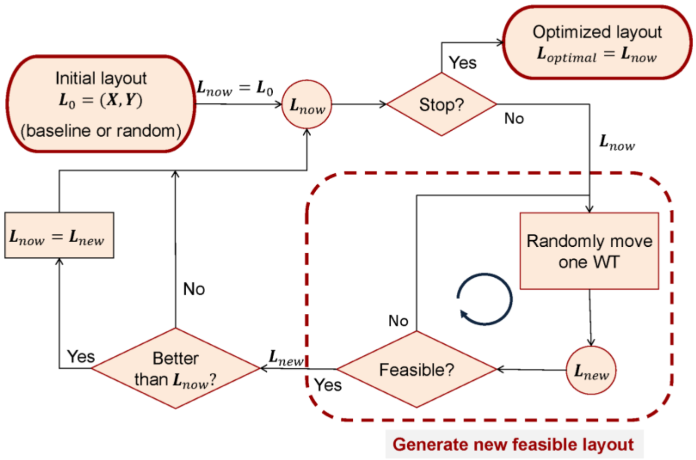

Figure 4. Flowchart of the Random Search algorithm for layout optimization

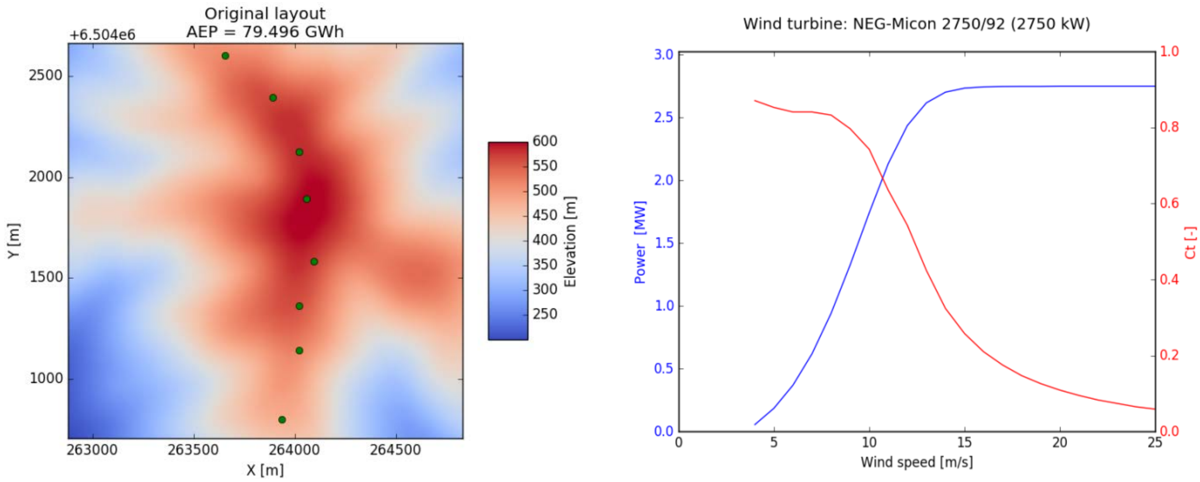

Figure 5. A small wind farm in complex terrain: (left) the original layout; (right) WT characterisitcs

Constraints on ruggedness degree, mean wind speed are shown in the sub-plot (down-left) of Figure 3. Using 1000 evaluations yields substantial improvements of AEP (3.72% and 1.14%). Also the minimal distance requirement (Dmin) has a large influence on the results, as shown in Figure 6.

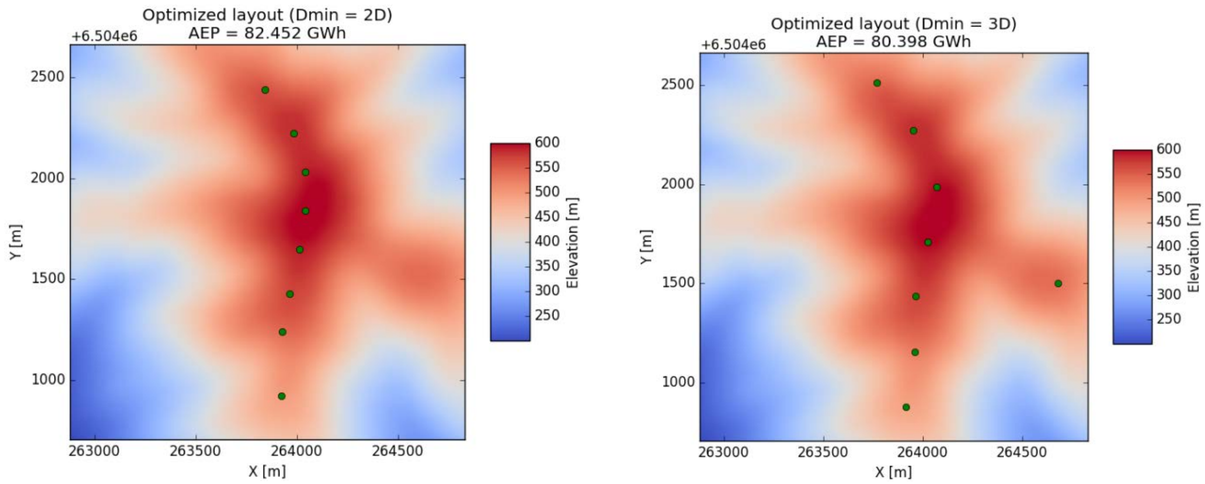

Figure 6. Optimized layouts with different minimal distance requirements using 1000 evaluations

5. Conclusions and further developments

The FarmOpt methodology for designing wind farms in complex terrain has been developed, which combines the state-of-the-art wind resource assessment methods with engineering wake models adapted for complex terrain and advanced layout optimization algorithms. As an illustration, FarmOpt has been performed for a small wind farm in complex terrain with improvements as compared to the original layout. To better address the overall design optimization of wind farms in complex terrain, some on-going and planned developments are needed:

- More accurate engineering wake models by considering the streamlines of the terrain flowfield;
- Parallization to speed-up the optimization process for WFs with a large number of WTs.

Acknowledgements

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