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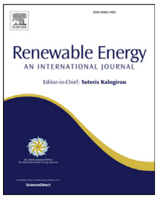

Informed mutation of wind farm layouts to maximise energy harvest

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ABSTRACT

Correct placement of turbines in a wind farm is a critical issue in wind farm design optimisation. While traditional “trial and error”-based approaches suffice for small layouts, automated approaches are required for larger wind farms with turbines numbering in the hundreds. In this paper we propose an evolutionary strategy with a novel mutation operator for identifying wind farm layouts that minimise expected velocity deficit due to wake effects. The mutation operator is based on constructing a predictive model of velocity deficits across a layout so that mutations are inherently biased towards better layouts. This makes the operator informed rather than randomised. We perform a comprehensive evaluation of our approach on five challenging simulated scenarios using a simulation approach acceptable to industry [1]. We then compare our algorithm against two baseline approaches including the Turbine Displacement Algorithm [2]. Our results indicate that our informed mutation approach works effectively, with our approach identifying layouts with the lowest aggregate velocity deficits on all five test scenarios.

1. Introduction

Effective optimisation of large wind farms layouts is a significant open research problem for two primary reasons.

The first reason is that solving this problem well is relevant to the global economy. Worldwide, the wind power industry is rapidly expanding, and the Global Wind Energy Council predicts that wind energy production could reach as much as 2000 GW (GW) globally by 2030 [3]. This would account for approximately 18% of the world's energy production [3], and cost reductions in the production of this renewable energy are therefore critical.

As the demand for wind energy increases, so too must the size of the wind farms. For example, the London Array [4], commissioned in 2013, generates 630 MW (MW) of power and comprises 175 offshore turbines. This generates enough power to service 490,000 households. In the US, the Alta Wind Energy Plant [5] consists of 600 turbines generating power equivalent to the usage of 257,000 households. Both of these are dwarfed by the Gansu project in China [6], which is planned to generate 20 GW by 2020, and is being constructed from smaller 100–200 MW farms with an estimated 36 turbines being added to the farm per day. Clearly, even small efficiencies at any of the stages in wind farm design have the potential to translate into significant gains.

The particular cost saving avenue we focus on in this paper is that of arranging the turbines in a farm to minimise *wake effects* [7,8]. Wake effects occur when one wind turbine is placed downstream of either another turbine or an obstacle such as a building. Wakes are characterised by decreased air stream velocity along with higher turbulence and vorticity compared to the surrounding unaffected air stream. Wake effects typically are a cause of power losses due to the reduced velocity of the wind [8]. They also lead to increased maintenance costs due to the increased turbulence, especially so when a turbine is partially inside a wake and partially outside [8]. Increased noise is also a consequence of the wake effect [8].

Proper turbine placement inside a wind farm to minimise wake effects, therefore, is a pressing problem.

The second primary reason why the wind farm layout optimisation problem is interesting for research is from the perspective of computational intelligence. The problem itself is challenging because there is usually no means of solving layout problems analytically, and the various objective functions that are used are highly non-linear, discontinuous due to layout constraints, and multimodal. Therefore, the most frequent way of solving this problem is to approximate a solution using a metaheuristic search algorithm such as a genetic algorithm (e.g. Ref. [9]) or local search (e.g. Ref. [2]).

Characteristics of the problem further add to the computational challenge, and those are the high dimensionality of layouts (for example, a 500-turbine layout in which the turbines are homogenous and specified completely by a two-dimensional position amounts to a thousand dimensional optimisation problem), and the time

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complexity of the evaluation function, which is at least quadratic in the number of turbines depending on the particular method used. For large layouts, this means that effectively, only a small fraction of the search space can be explored in a reasonable amount of time.

In this paper, we propose and evaluate a new algorithm for solving the wind farm layout optimisation problem. The algorithm is inspired by the idea of searching using an evolutionary algorithm (EA) that has an *informed mutation operator* [10], in comparison to a typical evolutionary approach that uses an uninformed or randomised operator. In theory, informed operators have a higher probability of making improvements whereas uninformed operators have no such bias. The former should therefore help an EA reach a better quality solution more readily than the latter.

The cost of using an informed operator, however, is that it is more complex than an uninformed operator, and this typically makes the operator problem-specific. In other words, the informed operator can only be used for solving the wind farm layout optimisation problem. In this research, we use machine learning as a basis for making our mutation operator informed.

Previously, we have already conducted a preliminary investigation of this approach vs. an identical approach that uses an uninformed mutation operator [11]. The results were positive when evaluated on a set of benchmark problems, and therefore in the current paper we continue our investigation by providing (i) a modified version of our algorithm that has been further enhanced and improved, and (ii) a more extensive evaluation of our approach, this time comparing to the current state-of-the-art algorithm, namely the turbine displacement algorithm (TDA) [2].

2. Background

In this section we describe the wind farm layout optimisation problem itself. We then discuss the wind farm layout evaluation method used in this research, and then the current state-of-the-art layout optimisation algorithm from the literature, TDA [2], is described.

2.1. The wind farm layout optimisation problem

A *wind farm* is defined as a collection of possibly heterogenous wind turbines that are located in the same approximate area and are used to harvest kinetic energy from the wind. Wind farms may be on-shore or off-shore. If on-shore, then they may be located on terrain that is either flat or rugged. In the latter case, modelling the wind farm is more difficult, and therefore many current approaches make the assumption of near-smooth terrain so that turbine positions can be specified solely by two dimensional coordinates.

A wind farm typically constrains the positions of its turbines within its layout regions. There are various reasons for this. The two main ones are firstly the presence of obstacles (e.g. roads and buildings) on the layout where turbines cannot be placed, and secondly the fact that two turbines cannot be positioned too closely together due to safety concerns. This minimum distance constraint arises because the immediate wake of a wind turbine is extremely turbulent, and therefore turbines placed too closely together may damage each other. A separation between turbines of eight times the turbine's rotor radius is therefore recommended [1].

Despite minimum distance constraints, turbines still interact with each other (albeit less strongly), and it is this interaction that leads to the optimisation problem. The primary means by which two or more turbines interact is called the wake effect, which was discussed in the Introduction.

To explain the wake effect, it is easiest to envisage a single turbine placed such that its rotor blades are perpendicular to the current wind direction. Such a turbine is unhindered in its ability to harvest the kinetic energy of the wind. It should be able to harvest 100% of the potential energy that it could harvest: we therefore say that its *expected velocity deficit* is 0.0, or conversely, its *expected wake free ratio* – which amounts to 1.0 minus the expected velocity deficit – is 1.0.

Now imagine a second turbine directly behind the first turbine: the second turbine experiences the velocity deficit caused by the first turbine. This results in the second turbine being unable to harvest the same amount of kinetic energy as the first turbine – in fact, the second turbine will only be able to extract some fraction, for example 80%, of the energy that the first turbine harvests. This situation corresponds to the second turbine having a velocity deficit of 0.2.

The wake that a turbine generates is a spreading cone of gradually decreasing velocity deficit. The cone's apex corresponds to the turbine's position, and the rate of velocity deficit decreases with distance depending on several factors including the angle made between the turbine's rotor blades and the wind direction, the diameter of the rotor blades, the wind speed, and the terrain roughness [1].

If a turbine lies in the wake of more than one other turbines, then the velocity deficits aggregate [1]. This may result in some turbines having a very high velocity deficit compared to others.

The calculation is also complicated by the fact that turbines will experience different expected velocity deficits for each different predominant wind direction. Fig. 1 illustrates this. In the figure, the same small layout is depicted twice, the versions differing only in wind direction. Clearly, when wind is blowing north (Fig. 1 (a)), there are no velocity deficits between turbines; but when the wind direction changes (Fig. 1(b)), two of the turbines experience velocity deficits, and one of the turbines lies in the wake of not one but two other turbines.

It is evident, then, that the total power output of a wind farm depends heavily on the expected velocity deficits of the individual turbines that make up the farm. These in turn are functions of the turbines' relative and absolute positions on the farm along with the predominant wind speeds and directions. Therefore different

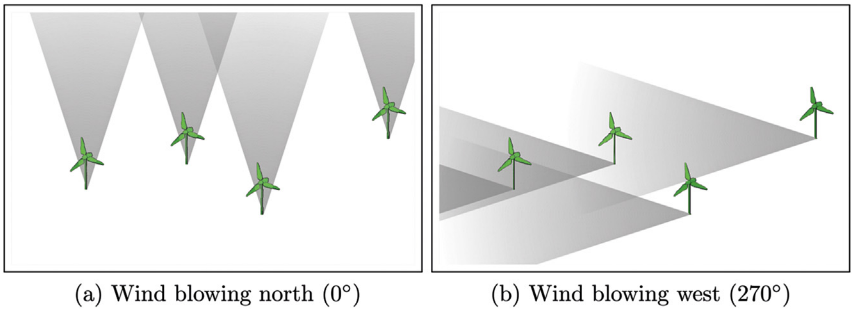
(a) Wind blowing north (0°) (b) Wind blowing west (270°)

Fig. 1. The same four-turbine layout showing turbine positions and turbine wake interferences for two different wind directions. Wakes are depicted as cones. Darker areas of the layout indicate regions of increasing velocity deficit; white areas indicate areas of no velocity deficit.