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A review of recent evolutionary computation-based techniques in wind turbines layout optimization problems

Review Article

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Abstract: This paper presents a mini-review of the main works recently published about optimal wind turbines layout in wind farms. Specifically, we focus on discussing articles where evolutionary computation techniques have been applied, since this computational framework has obtained very good results in different formulations of the problem. A summary of the main concepts needed to face the problem are also included in the article, such as a basic wake model and several cost models and objective functions previously used in the literature. This review includes works published in the most significant journals and international conferences, and it gives a brief remark of the optimization models proposed and the implemented algorithms, so it can be useful for readers who want to be quickly introduced in this research area.

Keywords: wind turbines layout • evolutionary computation techniques • wind farms

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1. Introduction

Wind power is one of the most promising sources of renewable energy in the world. Currently, wind power represents over 12% of the total power consumed in countries such as USA, Germany or Spain, and it is expected that this percentage grows up to an amazing 20% by 2025. This figure situates wind energy as one of the main actors in the energetic mix of different countries, which are definitely promoting its development [1].

The majority of the wind power consumed in the world is generated in large facilities, known as *wind farms*. The number and size of these facilities have dramatically increased in the last few years almost in all developed countries, and also in several developing countries [1, 2]. In parallel with this increase in wind farms installations, new exciting research

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possibilities have arisen. Problems such as optimal design of wind farms have been frequently tackled in the literature, and they are also of great importance for practitioners and energy companies. In these problems, intelligent approaches such as evolutionary algorithms have shown a much better performance than traditional algorithms, and thus there has been a dramatic increasing in the application of these novel techniques.

In this paper we review the main works dealing with evolutionary techniques in a problem that arises in wind farm design, specifically the wind turbines layout optimization problem. After a first review of the main concepts necessary to define the problem, we discuss on different evolutionary computation-based approaches that can be found in the literature for tackling this problem. The review is comprehensive and up-to-date, and includes papers published in the main international journals and conferences on evolutionary computation or energy.

We have organized the rest of the paper in the following way: next section reviews the main wake and cost models implemented in different works in the literature. Section 3 is the body of the paper, where the main works on evolutionary algorithms for wind farm design are described and commented on. This section concludes with a note on a open-source software which is currently used for practitioners interested in wind farm design. Finally, Section 4 ends the paper giving some final remarks.

2. Main wake and cost models in the literature

In this section we describe the main wake and cost models described in the literature that are necessary to define the wind turbines layout optimization problem. A widely used wake model in the literature was first proposed by Mosetti et al. [3], and applied later in many following works such as [4–7]. Though it is simple (and therefore is not an accurate representation of a realistic wake) it has been profusely used, since it can be extended with extra constraints to make it closer to reality, and it can be used to compare different algorithms in the same conditions.

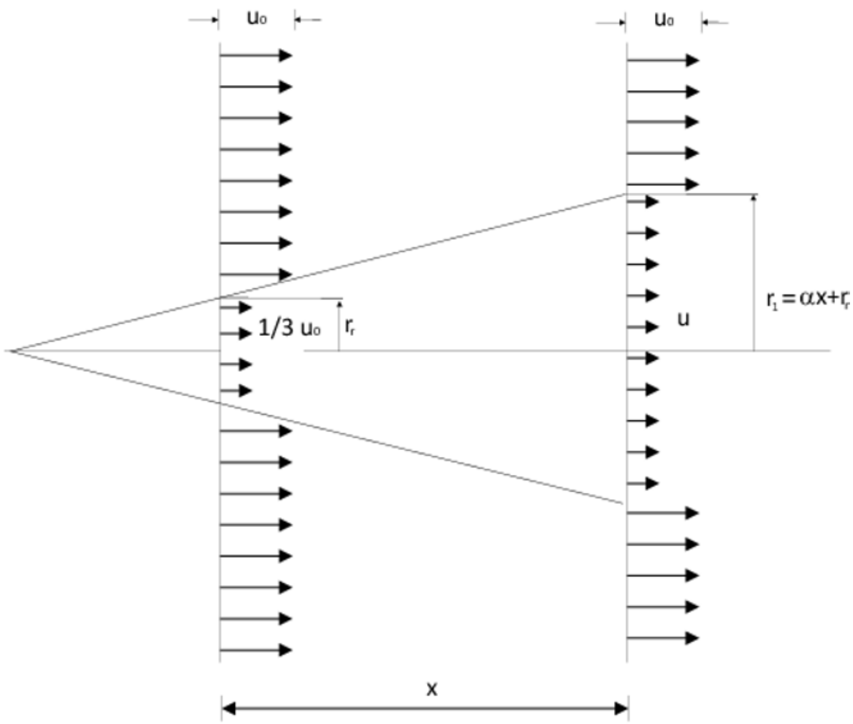

Figure 1. Schematic of a wake model.

Figure 1 shows and schematic of the wake model considered. This model has been simplified by applying the continuity equation in the control volume in Figure 1:

$$\rho u_0 A_0 = \rho u_1 A_1 = \rho u_i A_i. \tag{1}$$

So if we assume that wind speed will decrease by a units its speed after passing through a turbine:

$$\rho(a u_0) A_r + \rho u (A_1 - A_r) = \rho u A_r, \tag{2}$$

where $A_1 = \pi r_1^2$, $A_r = \pi r_r^2$ and $r_1 = \alpha x + r_r$. Substituting in Equation (2) we obtain:

$$u = u_0 \left[1 - \frac{2a}{\left[1 + \alpha \frac{x}{r_1}\right]^2} \right], \tag{3}$$

where u_0 is the mean wind speed, a is the axial induction factor, x is the distance downstream from the turbine, r_r is the downstream rotor radius and α is the entrainment constant. In addition, r_1 and the turbine coefficient C_T can be calculated from r_r and a, through the so-called *Betz* equations:

$$r_1 = r_r \sqrt{\frac{1-a}{1-2a}}, \tag{4}$$

$$C_T = 4a(1-a). \tag{5}$$

Finally, the entrainment constant α can be empirically calculated as:

$$\alpha = \frac{0.5}{\ln \frac{z}{z_0}}, \tag{6}$$

where z is the hub height of the wind turbine, and z_0 is the surface roughness.
Using these equations, and assuming that the kinetic energy deficit of a mixed wake is equal to the sum of the energy deficits, the resulting wind speed downstream of N turbines can be calculated as follows:

$$\left(1 - \frac{\overline{u}}{u_0}\right)^2 = \sum_{i=1}^{N} \left(1 - \frac{u_i}{u_0}\right)^2. \tag{7}$$

The power equation given in [3, 4, 6] is the following:

$$P_{total} = \sum_{i=1}^{N} 0.3 u_i. \tag{8}$$

In other works such as [8], the total power is calculated by means of simulation, using a Weibull distribution and the power curve of the turbine. Figure 2 shows and example of power curve for a real wind turbine.

2.1. Cost models and objective functions

Any problem of wind turbines layout must be defined under an assumption of cost model, in order to define the objective function to be optimized. The first cost models used for this problem in the literature ([3, 4]) assumed that the non-dimensionalized cost/year of a single turbine is 1, and a reduction in the cost of each turbine when a large number are installed, the total cost/year for the entire wind farm is:

$$cost = N\left(\frac{2}{3} + \frac{1}{3} e^{-0.00174 N^2}\right). \tag{9}$$

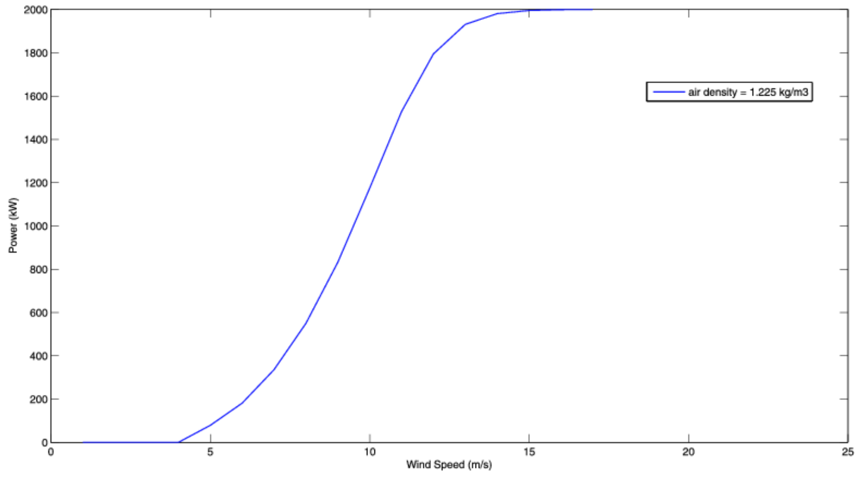

Figure 2. Example of power curve.

Using this cost models, the following objective function can be defined:

$$g = \frac{cost}{P_{total}}. \tag{10}$$

This objective function leads to solutions which maximizes the total power obtained in the wind farm, whereas the cost is minimized.
Note that different objective functions can be considered, even using the same wake and cost modeling, such as in [6], where the following was considered:

$$g = w_1 cost_m + w_2 \frac{1}{P_{total}}, \tag{11}$$

$$w_1 + w_2 = 1, \tag{12}$$

where $cost_m$ is the per unit value of cost/year of the whole wind farm. Note that the objective function given by Equation (11) not only optimizes the placement of wind turbines, but also has control on cost.
In [9, 10] and [11] a novel cost model based on profitability of investments in the wind farm was presented. Note that this cost function includes more aspects that only the wind turbines layout, i.e. budgetary issues, connection to the main electrical line etc. Basically, this model is based on the following objective function to be maximized:

$$NPV(x, i, t) = \frac{N_1(x)}{i+1} + \ldots + \frac{N_t(x)}{(i+1)^t} + IC(x), \tag{13}$$

where IC is the initial capital investment, N_k stands for the net cash flow of the kth year, i is the discount rate (capital cost), t is the number of years spanned by the investment and finally x is the solution vector containing the location and height of the wind turbines.

3. Recent evolutionary computation-based approaches for wind turbines layout optimization

Evolutionary algorithms and related techniques have arisen as very attractive techniques in wind farm design and specifically in wind turbines layout problems [1]. In this section we review the main works published on this topic, with a brief comment on the technique and characteristics of the implemented algorithm. The section concludes with comments on useful, open source wind farm design software.

3.1. Evolutionary computation techniques for wind turbines layout

The seminal paper in the use of evolutionary computation techniques for wind turbines layout in wind farms is the work by Mosetti et al., [3]. This paper proposed a genetic algorithm to tackle the problem of the optimal positioning of turbines in a wind farm. The model proposed in [3] consists of modeling the wind farm as a square divided into cells in which turbines can be situated. A useful wake model was proposed and several experiments considering different average wind speed and direction were presented. This initial work has been the base of different recent approaches which has improved the initial model. For example, in [4] Grady et al. showed that better results can be obtained in the problem by improving the genetic algorithm used, using the same model as in [3]. Another improvement with the same model has been recently proposed by Emami et al. in [6]. This paper proposes a modification of the objective function of the problem, to take into account deployment cost and efficiency of the turbines. The authors show that this modification leads to better design results than previous approaches using a standard genetic algorithm.

Another interesting and recent work, including a different optimization model is the paper by Riquelme et al. [9]. In this work a variable-length genetic algorithm with novel procedures of crossover is applied to solve a problem of optimal positioning of wind turbines, considering monetary cost as the objective optimization function. The authors show that their variable-length evolutionary approach is able to obtain good results in terms of the objective function, considering different types of wind turbines to be used. A similar approach using a hybrid evolutionary algorithm was previously presented in Martínez et al. [12]. This approach has been further studied in [10, 11].

Also significant is the work by Wang et al. [8], where a new improved wind and turbine model has been considered within a genetic algorithm. Specifically, a more elaborate wind speed simulation than other approaches is considered, based on a Weibull distribution. The authors have shown that this new model is able to produce better results than previous approaches in the literature. Also following this trend, the work by Kusiak et al. [7] proposes to incorporate different sophisticated models in different part of the problem. Specifically, a complete study of the problem including different cost of turbines and their maintenance, a wind turbine wake model similar to the one described in [3], a Weibull distribution for modeling the wind speed and direction in each point of study, are considered. The authors propose then an evolutionary programming approach to solve the continuous optimization problem of optimal positioning of wind turbines using these novel models.

In last two years other approaches to wind farm design based on evolutionary algorithms and related techniques have been published, such as the works by Wan et al. [13, 14], based on real-coded genetic algorithms and particle swarm optimization, respectively. The use of real encoding is interesting in wind turbines positioning, since it allows to improve the accuracy of the optimal turbine sitting, i.e. the location of each wind turbine in a given cell can be modified to maximize the energy produced by that turbine. The paper by Sisbot et al. [15] is based on a multi-objective evolutionary algorithm which maximizes the power production capacity while constrains the budget of installed turbines. The algorithm evolves individuals of the Pareto optimal solution, which are evaluated in terms of the different criteria considered in the optimization. This is one of the first works dealing with multi-objective evolutionary techniques applied to a wind farm design problem. Another interesting paper is the work by Huang [16] based on hybrid genetic algorithms, in which the genetic algorithm is combined with a steepest ascent hill-climbing local search technique and with an heuristic method to reduce the computation time in finding the local optimum.

3.2. Off-shore wind farms design problems

Different computational optimization methods has been also applied to the design of off-shore wind farms, in different works [17–21]. In the works by Elkinton et al. [17–19], a novel model for the design of off-shore wind farms is presented, and several approaches were compared in this problem. A greedy algorithm, a genetic algorithm, a pattern search approach and a simulated annealing technique were tested in this problem. In [20], Zhao et al. presented a different approach to the design of off-shore wind farm design, focussed on minimizing the connections between wind turbines, considering a fixed turbines layout. The authors tested their approach in a real design of an off-shore facility in Liverpool Bay. Three different genetic algorithms were tested, with diverse selection and initialization mechanisms, such as rank-based selection or the niching method. Finally, Rivas et al. in [21] used a simulated annealing algorithm to solve a problem of optimal turbine sitting in wind farms.

3.3. An open-source software for wind turbines layout

Finally, we would like to finish this section with a brief note on useful software for wind farm design. Currently, the most used free software for wind farm turbines layout is *OpenWind*[1]. This is a wind farm design software for engineers and scientists. The software is open source and free to download and use. This software is based on the following heuristic algorithm:

1. The heuristic starts in a given valid (which fulfils all the problem's constraints) layout. Once a starting valid layout is available, the heuristic does a full test of the layout to get the starting energy. It then tests the layout again to get its first optimizing benchmark. It then begins to optimize the layout to evolve to better situations after a number of iterations.

   Each iteration of the optimizer consists of the following steps:

2. The heuristic attempts to find a new valid position for each turbine. If the turbine made a good move last iteration, it will attempt the same direction than last time. Otherwise, it finds a new random perturbation adding a Gaussian-distributed random noise to the turbines x and y coordinates. If the new position is not a legal position or it obstructs another turbine, then a new random perturbation is made and so on until all the turbines have new legal positions.

3. The heuristic then runs an energy capture and if the total energy is greater than the benchmark energy, it accepts the entire new layout and returns to step 2.

4. If the new layout was not accepted as a whole, the heuristic analyzes each turbine in a separate way: if that turbine has less energy than in its benchmark position, the perturbation for this turbine is discarded, and it is returned to its last position and benchmark energy. After analyzing all the turbines, the heuristic sums the total energy from all the turbines and if it is equal or greater than the benchmark energy, it runs another energy capture to see if it really constitutes an improvement. If not then all the perturbations are discarded and return to step 2. If so, then all these new positions and energies are accepted as the new benchmark energies and the heuristics returns to step 2.

The OpenWind heuristic is fast and can be used in combination with evolutionary algorithms to improve the quality of the latter. A hybrid evolutionary algorithm with the OpenWind heuristic as initial point could be a very attractive algorithm to face difficult wind farm design problems, including new sets of constraints or different cost models.

4. Conclusions

In this paper we have reviewed the most significant works on wind turbines layout optimization using evolutionary computation techniques, published up to date in the main international journals and conferences. The most used wake and cost models have also been revisited in the initial section of the paper. In the main body of the article, we have described the different approaches proposed and also the most interesting aspects of the evolutionary algorithms proposed. A note on free software available on the Internet which could complement or be hybridized with evolutionary algorithms has been given as a final contribution of this paper.

Acknowledgement

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[1] *http://www.awsopenwind.org/*

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