

A GRASP-VNS algorithm for optimal wind-turbine placement in wind farms

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ABSTRACT

The wake effect is the key factor affecting the low efficiency of wind power production. It is very important to predict the relationship between the cost and the produced power for various wind-turbine placements under various wind speeds and directions. This paper proposes a GRASP-VNS algorithm for the optimal placement of wind turbines. Four different wind-farm conditions were considered: (a) uniform wind with single direction, (b) uniform wind with variable directions, (c) non-uniform wind with variable directions, and (d) non-uniform and variable-direction wind with land constraint. The proposed GRASP-VNS algorithm combines two well-known metaheuristics, GRASP and VNS, to create additional advantages in yielding the search trajectory. Intensive experiments assuming the four wind-farm conditions were performed. Statistical analyses show that the proposed GRASP-VNS algorithm significantly outperforms three existing GA-based methods.

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1. Introduction

The key solution to slow down global warming without negatively affecting economic development is to replace the use of fossil fuel with that of renewable energy from natural sources such as wind, sunlight, rain, tides, and geothermal energy. Wind power is growing at an annual rate of 30% due to its low cost and emission-free production and has been widely used in Europe, America, and Asia. The leading countries, such as the United States, China, Spain and Germany, produce 10,000–40,000 MW annually. To improve the efficiency of wind power production, several issues have been contemplated and can be categorised as follows. (1) Because currently wind power cannot fully satisfy energy demands, an efficient integrated conversion scheme using multiple power sources is necessary [1–3]. (2) The conversion of wind power is performed using wind turbines. Hence, the structural system design of a wind turbine, including the blades, engines, and the tower structure [4–8], is a critical factor for maximal energy extraction. (3) To maximise the power production per unit of cost, the number of installed turbines and the spacing between them should be optimised [9–16].

Table 1 lists related studies performed to tackle the noted three types of wind power problems in ascending order of publication year. It can be observed that the optimal wind-turbine placement (OWTP) problem has caught the most attention from researchers, and the publications dedicated to this problem cover a longer span of years than those addressing the other two problems. In addition, the growing number of OWTP publications in more recent years

demonstrates the increasing importance of determining the optimal placement of wind turbines to maximise the power-production efficiency and minimise the incurred cost. Among the methods that have been applied to solve the OWTP problem, the genetic algorithm (GA) is the most prevalent one [9–14]. Not until recently were other metaheuristics such as simulated annealing [15] and particle swarm optimisation [16] adopted.

This paper deals addresses the wind-turbine placement problem and provides the following contributions. (1) The research is extended in the direction of using metaheuristics to solve the OWTP problem. In particular, the GRASP approach [17], with the VNS [18] serving as the local search component, is adopted. The GRASP scheme is suited to tackle the OWTP problem due to GRASP's use of incremental construction to find a solution, which aligns well with the fact that the optimal placement of a wind turbine is dependent on the positions of wind turbines that have already been installed. (2) The experimental results show that the proposed method outperforms several existing GA-based approaches in solving benchmark OWTP problem instances under varying wind conditions. (3) A new problem instance involving wind blowing along multiple directions and at variable speeds with land constraints is introduced in this paper. This problem is more like what is observed in the real environment and provides a basis for practical feasibility analyses of the employed method.

2. Problem definition

In this section, the optimal wind-turbine placement (OWTP) problem is described, and a mathematical formulation of the problem is proposed.

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Table 1

The related works for the noted three types of wind power problems.

	Integrate power conversion	Structural system design	Wind-turbine placement
Mosetti et al., 1994 [9]			•
Takewaki, 1996 [4]		•	
Negm & Maalawi, 2000 [5]		•	
Sinha et al., 2003 [1]	•		
Zoumas et al., 2004 [2]	•		
Yang et al., 2004 [6]		•	
Grady et al., 2005 [10]			•
Sourkounis & Ni, 2006 [7]		•	
Huang, 2007 [11]			•
Lee, 2008 [3]	•		
Sareni et al., 2009 [8]		•	
Wan et al., 2009 [12]			•
Wang et al., 2009 [13]			•
Bilbao & Alba, 2009 [15]			•
Emami & Noghereh, 2010 [14]			•
Wan et al., 2010 [16]			•

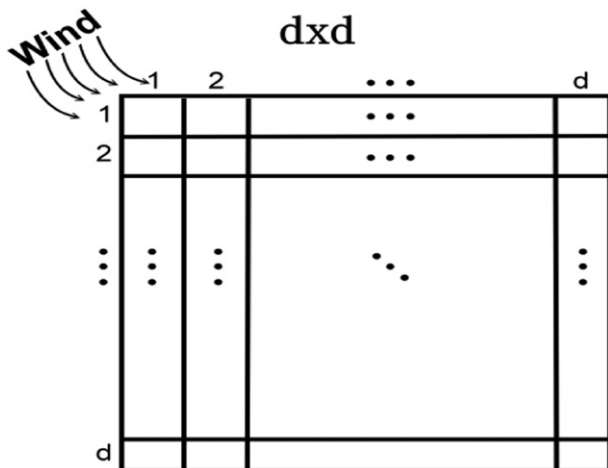
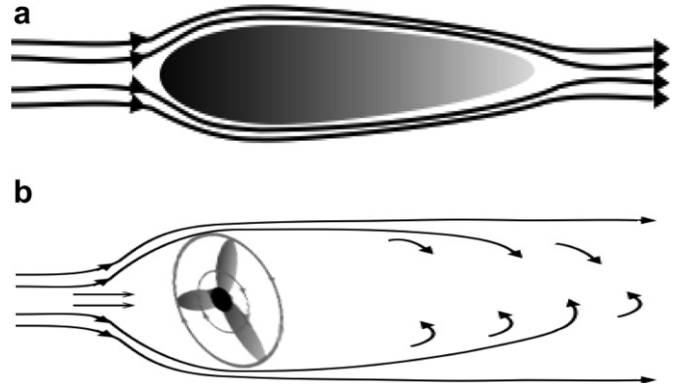
2.1. Problem description

Given land with potential wind energy, a square wind farm bounding the indicated land can be planned. The square wind farm is divided into $d \times d$ grids (see Fig. 1); the grids inside the land area are marked as candidates for placing a wind turbine, and the others are marked as being unsuitable for turbine placement. A rule of thumb for determining the inter-turbine spacing is 8–12 rotor diameters apart along the windward direction and 1.5–3 rotor diameters apart along the crosswind direction. Hence, the width of each grid, at the centre of which a wind turbine would be placed, is set to 5 rotor diameters.

The wake zone in a wind farm depends on the terrain, wind direction, and surface roughness. An object with a streamlined shape (see Fig. 2(a)) would cause a smaller wake zone than that of another object with a rough shape (see Fig. 2(b)). Most researchers, such as Mosetti et al. [9], have adopted the wake model to estimate the downstream wind speed of a turbine. As illustrated in Fig. 3, the radius of the wake (r_1) increases linearly with the downstream distance (y), and the radius of the downstream wake (r_2) is derived as

$$r_2 = r_1 \left(\frac{1-a}{1-2a} \right)^{\frac{1}{2}} \quad (1)$$

$$a = \frac{1 - (1 - TC)^{\frac{1}{2}}}{2} \quad (2)$$

**Fig. 1.** Square wind farm consisting of $d \times d$ grids.**Fig. 2.** Wake zone of downstream wind.

where a is the axial induction factor and TC is the turbine thrust coefficient. The wind speed (W_i) of the turbine along the downstream direction is given by the following expression.

$$W_i = W_0 \left(1 - \left(\frac{2a}{1 + \alpha(y/r_2)} \right) \right) \quad (3)$$

where W_0 is the mean wind speed and α is the entrainment constant, which is determined by the hub height (H) of the wind turbine and the surface roughness (H_0) as follows.

$$\alpha = \frac{0.5}{\ln(H/H_0)} \quad (4)$$

Finally, the velocity downstream of n turbines is derived as

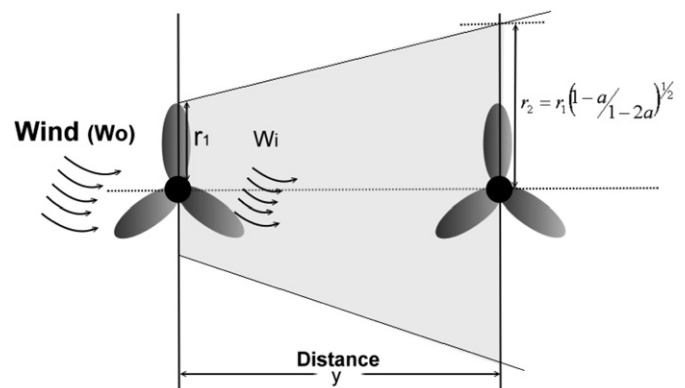
$$\overline{W}_i = W_0 \left(1 - \left(\sum_{j=1}^n \left(1 - \frac{W_j}{W_0} \right)^2 \right)^{\frac{1}{2}} \right) \quad (5)$$

2.2. Mathematical formulation

The OWTP problem aims to minimise the annual cost per unit power production subject to the wind farm constraints (grid placement, land usage, etc.) With the notations described in Table 2, our addressed OWTP can be mathematically formulated as follows.

2.2.1. Model OWTP

$$\text{Minimise } f(X) = C(X)/E(X) \quad (6)$$

**Fig. 3.** Wind wake model.

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