

# PLACEMENT OF WIND TURBINE IN WIND FARM LAYOUT OPTIMIZATION TECHNIQUES AND WAKE-A REVIEW

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## ABSTRACT

*Wind farm utilization rate and energy production can be increased by using an efficient layout optimization method. Wind speed, turbine placement, and hub height have been adjudged by previous researchers as factors that may increase the wind farm's energy production. Nonetheless, future improvements have revealed that a multi-objective optimization problem can be used to create extremely efficient and maximum energy production whilst reducing cost to the barest minimum. This is due to the fact that the primary goal of wind farm optimization is to maximize energy production. But in a small area of wind farms, wind turbines can be severely influenced by the wake effect compared to other wind turbines, resulting in greater turbulence, wear of the wind turbine blades, and lower energy produced by the wind farm. As a result, the authors evaluated the various optimization algorithms used to build the wind farm architecture more efficiently while taking into account critical characteristics such as wind speed, annual energy production cost, and wake losses in this study. This is because the potential size of the wind turbine in the solution space is yet to be solved. As continuation of this study, the authors will explore the possibility of using some new metaheuristic algorithms such as Atomic Orbital Search (AOS) algorithm of Wind farm layout design will also be explored.*

**Keywords:** Wind Farm Layout; Wake Effect; Energy Production, Optimization Techniques, Wind Turbines

## 1 INTRODUCTION

**I**n some major parts of the world, wind energy has attracted great attention due to its usage as an alternate means of generating electricity. Wind energy is generated with the use of wind turbines that are manufactured in different sizes. The turbines convert kinetic energy into electric energy [1, 2, 3]. The wind turbine comprises parts such as the blades, tower, high-speed shaft amongst others as depicted in Figure 1.

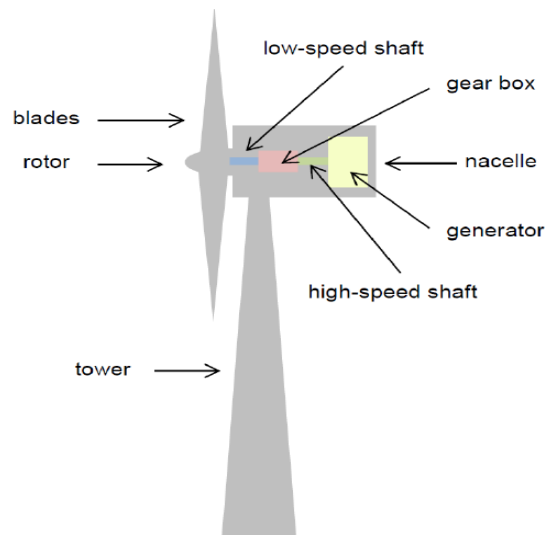


Figure 1. Wind Turbine

Nonetheless, the placement of more than one wind turbine on a wind farm has posed challenges to academia and industry experts [4, 5]. This is due to the fact that the deployment of wind turbines in a wind farm is usually affected by the wake effect amongst other problems. Thus, increasing the total cost of energy production [6]. This made the industry experts and academia employ various wind turbine placement techniques using different optimization algorithms such as the Genetic Algorithm (GA), Particle Swarm Optimization algorithm (PSO), Artificial Bee Colony algorithm (ABC) amongst others, to maximize energy and reduce the cost of energy production [7, 8]. But it is worthy of note that wind energy is dependent on wind conditions in which the wind condition varies with the height, wind speed, and altitude of the wind turbines. Wake models started from basic models developed in the early 1980s and have evolved to a more complex based model in recent times as a tool to study wake effects, wind turbine design, and wind farm development [9]. From past research works, [10, 11, 12] it is evident that wind speed fluctuation is the primary cause of lower wind farm efficiency. Also, aerodynamic losses within vast arrays of turbines are a significant issue in wind farm operations considered. Wind turbines produce a lower momentum wake region downstream due to the process of extracting energy from the atmospheric boundary layer. Energy losses due to wake within a wind farm are functions of occurring wind speed and direction. These energy losses are caused by the placement of wind turbines usually when partially aligned to the angle of the incoming wind and also when the wind speed is below the required value [13]. Therefore, the design of wind farm layouts is important to extract the most gain based on existing historical observed wind speed distribution and direction. This paper presents a review of optimizing wind farm layout by optimally placing wind turbines with respect to wake issues. This is because not all the wind turbines on wind farms can obtain the normal velocity of wind that can capture wind energy because of wake effects. The wake effect can cause up to a 15% difference in energy production from the ideal value. Therefore, there is a need to employ the use of an optimization algorithm in the placement of wind turbines in wind farm layout design. The structure of the review paper is as follows: section 1 presents the introduction, section 2 presents the optimization models (wake models), review of previous optimization algorithms that have been employed to optimize the placement of wind turbines in wind farm layout. Section 3 presents some of the adopted methodologies while section 4 presents the conclusion and summary of the review.

## 2 OPTIMIZATION MODELS

This section reviews the pertinent optimization models that are used in wind farm layout design given multiple turbines on wind farms as shown in Figure 2.

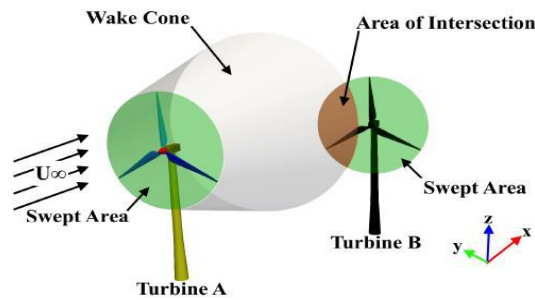


Figure 2. Optimization Model [14]

## 2.1 Wake Models

For a decade now, the increased cluster density in wind farms has fueled research into wind turbine rotor aerodynamics popularly known as wake modeling. Wake modeling is a field of study in which the flow behind a rotor of a wind turbine is defined and predicted using mathematical or physical models. Wake models are analytically defined and quantitatively represented to incorporate them into the mathematical formulae of wind farm optimization. In the past, researchers have developed different wake models to optimize wind farm layouts. Some of the most used wake models are the Jensen Wake models, the Larsen model, the infinite wind farm boundary layer model, and the dynamic wake meandering model. These wake models are said to have been conceived and developed by the Technical University of Denmark [15]. The Jensen wake model developed by [16] is currently the most widely used in the field of wind farm optimization. This is due to the fact that the Jensen wake model by most researchers is considered practicable and simple. The schematic of the Jensen wake model is depicted in Figure 3.

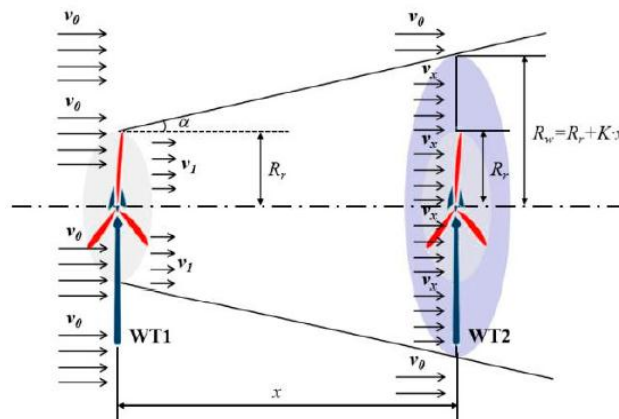


Figure 3. The Jensen Wake Model [15, 16]

According to the developers of this model, the wakes behind the wind turbines are expected to expand linearly and the wind speed within the wakes at various heights is considered to be the same [17]. The Larsen Wake Model was earlier developed by the authors in [18] as far back as 1988 as commercial software named WindPRO. The software was used to make basic wake calculations considering only a single wake case [19]. This was later modified by the authors in [20] to consider multiple wake cases. The main difference between the earlier and the latter are the wind farm approach and the set boundary condition(s). The infinite wind farm boundary layer model often referred to as the Frandsen model [21] was originally developed for natural conditions only. Nevertheless, with a view to making the model robust, it has been extended by research works like [22] to support other atmospheric conditions. The infinite wind farm boundary layer is depicted in Figure 3. Based on the diagram in Figure 4, the model assumes that inside an infinite wind farm with the same turbine type and size, two layers in the atmospheric boundary layer (ABL) exist, one above and one below the turbines' hub height  $h$ .

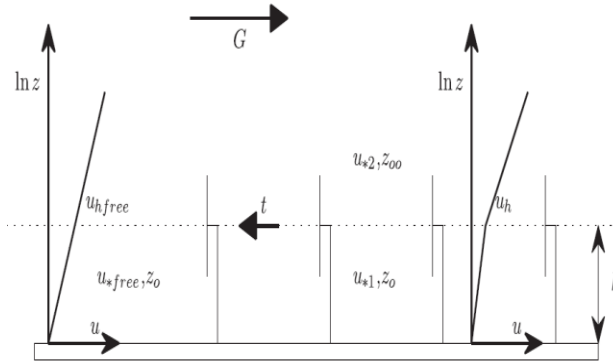


Figure 4. The Infinite Wind-Farm Boundary-Layer Model Concept of Frandsen [19, 20]

The dynamic wake meandering model (DMW) was coined after research performed by works of [23-25]. The wake is described as a passive tracer driven by large-scale turbulence patterns in the atmospheric boundary layer in the dynamic wake meandering model [26]. The authors will explore the possibility of using some new metaheuristics algorithms such as Atomic Orbital Search (AOS) algorithm [41], Smell Agent Optimization [42], Aquila Optimizer [43], etc. Different model of Wind farm layout design will also be explored.

## 2.2 Wind Farm Turbine and Cost Model

The wind farm turbine and cost model are obtained from the Jensen wake model because the model is most commonly used in literature due to its simplicity and practicability. Based on the Jensen wake model presented in Figure 1, researchers have been able to calculate the deficit in wind speed using the formula presented in equation (1). The wake diameter changes with rotor diameter and the wake minimization coefficient, which is kept constant throughout the investigation; the method for calculating this coefficient is outlined in [11].

$$Wind_{vd} = inc_w \left[ (1 - \sqrt{1 - T_c}) \left( \frac{D}{wake_D} \right)^2 \right] \quad (1)$$

The parameters in the equation are defined as follows [14]:

$Wind_{vd}$  is the wind velocity deficit in m/s;  $inc_w$  is the incoming wind speed in m/s;  $T_c$  is the trust coefficient;  $D$  is the rotor diameter in meters;  $wake_D$  is the wake diameter in meters.

To estimate the total energy production, the power of each wind turbine must be calculated under the wake effect. As a result, the energy production of the wind turbine is roughly computed as follows:

$$EP_p = \frac{1}{2} \pi \rho \frac{D^2}{4} \int (wind_{vd} - inc_w)^3 \quad (2)$$

Where  $\int$  is the efficiency factor?; The total power produced under wake effect in a wind farm is expressed as:

$$Wind_{power} = \sum_{i=1}^{N_t} EP_p \quad (3)$$

Where  $N_t$  is the number of wind turbines. Similarly, the efficiency of the entire wind farm under adequate energy production is determined using the expression in equation (4)

$$\int_{wind} = \frac{wind_{power}}{\frac{1}{2} \pi \rho \frac{D^2}{4} \int inc_w^3} \quad (4)$$

Suppose the lap overlap area of the wind turbines is  $A_{ov}$  and the number of upstream wind turbines is  $N_{up}$ , the total deficit velocity can be expressed as:

$$deficit_v = \sqrt{\sum_{i=1}^{N_{up}} \left(\frac{A_{ov}}{A}\right) (wind_{vd})^2} \tag{5}$$

It is worthy of note that because of the wake effect, not all wind turbines in wind farms can achieve the optimal wind velocity to collect the wind energy; precisely, only a downstream wind turbine can capture the wind, which first lowers and then gradually climbs to a specific value passed by the upstream wind turbines [27]. Since the goal of this paper is to enhance the wind farm's energy production by optimizing the placements of wind turbines, there is a need to formulate a multi-objective optimization function that comprises the wind speed, wake effect, and turbine placement. The multi-objective formulation for this paper is presented in equation (6).

$$\begin{aligned} \min f(x) &= (f_1(x), f_2(x), \dots, f_k(x)) \\ \text{subject to } x &\in s \end{aligned} \tag{6}$$

The basic information features required in optimizing the placement of wind turbines in wind farm layout are presented in Table 1. The table shows the parameters of three basic turbines as the U50, HJWT77, and HS50 wind turbines. The features of wind turbines are necessary to be initialized using any chosen [28] optimization algorithm with a corresponding wake model. In this paper, a review of placement of wind turbine in a wind farm layout is presented and various method of improving the placement layout is discussed.

Table 1: Optimization Values

Wind turbines features	HS50	U50	HJWT77
Rated power (kW)	750	750	1500
Hub height (m)	50	50	70
Rotor diameter (m)	50	50	77
Cut-in wind speed (m/s)	3.5	3	3.5
Rated wind speed (m/s)	12	12.5	13
Cut-out wind speed (m/s)	25	25	25

### 3 OPTIMIZATION ALGORITHMS

Even though various studies have been done to solve the wind farm layout problem utilizing heuristic optimization technology, mathematical programming, or a hybrid method, that focuses on increasing the wind farm's energy production, the solution space is still yet to be fully addressed. Therefore, this subsection presents a review of the different optimization algorithms used in wind farm layout optimization with the common types of wake models. The flow chart for applying optimization techniques to optimally deploy wind turbines on wind farms is presented in Figure 5.

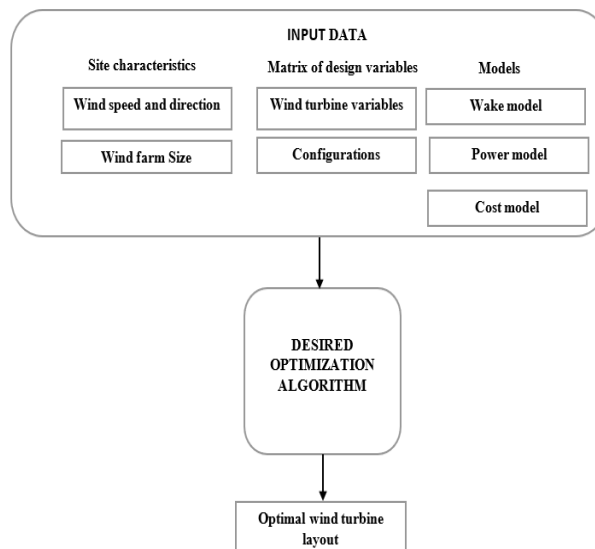


Figure 5. Generalized Optimization Flowchart for Wind Turbine Placement

Wind flow layout optimization has been the subject of numerous research investigations. The grid-based technique and the unrestricted layout approach are the two main approaches to layout optimization. The grid-based technique divides a wind farm into equal-sized cells and places turbines in the middle of these cells, whereas the unrestricted layout approach allows turbines to be put anywhere inside the wind farm. Based on these two general approaches, optimization techniques are applied to determine the optimal position of wind turbines inside the wind farm [29]. The gradient-based optimization method and non-gradient-based method are primarily the two branches of optimization algorithms used. From past research works, it has been justified that it is hard to discover the optimal solution for a non-convex optimization problem with a wide searching region, and the gradient of the objective function cannot be calculated for particular problems. Therefore, modern research works adopted the use of a meta-heuristic algorithm to help find an optimized solution without using gradient information. Particle Swarm Optimization (PSO) [7, 32], multi-objective lightning search algorithm (MLSA) [32], Biogeography Based Optimization (BBO) [4], Genetic Algorithm (GA) [5, 34], are some of the metaheuristic approaches that have been employed in wind farm layout optimization. Nonetheless, the PSO and GA are commonly utilized in these strategies. Therefore, there is a need to further explore the efficiency of other optimization algorithms such as the Atomic Orbital Search Optimization Algorithm, Smell Agent Optimization, Aquila Optimizer, amongst others to optimally deploy wind turbines in wind farms. Authors like [7] used particle swarm optimization to build an optimization technique for positioning wind turbines in a large-scale offshore wind farm. This is because the wake effect on wind farm yields gets more noticeable as the size of the wind farm grows. As a result, the scientists needed to create a mathematical model that took into account the wind direction and wake deficit. More than one wind scenario has also been considered using optimization algorithms like GA as presented in the work of [35-36]. The goal was to maximize annual energy production using economies of scale and discrete wind farm area representation while keeping installation costs to a minimum. The wind turbine farm layout was optimized by [4] using a biogeography-based optimization approach. Because it was an unconventional optimization algorithm, the Biogeography Based Optimization (BBO) optimization algorithm was applied in their study. The authors advised the number of wind farms that should be employed in a given wind farm layout using this optimization approach. However, in the solution space, the possible size of the wind turbine has not been fully addressed. Other evolution algorithms can be utilized as well. [37] offered a concept that used a constructive method to optimize wind farm layout in order to gather maximum wind energy. The scientists used a mathematical optimization approach to determine the best location for wind turbines on the wind farm. The common Jensen's wake model was used to create this mathematical optimization approach, and the findings were validated against existing literature. However, the research only considers the radius of the wind turbine and the distance between turbines as restrictions leaving out other wind turbine features as presented in table 1. The authors in the work of [6] devised a novel approach for selecting wind turbines in wind farm layouts, significantly streamlining the process. The parameters of commercially available wind turbines were used to construct the presented selection method. In constructing an optimized model, the authors evaluated assumptions and constraints obtained from existing works of literature such as site factors, wind conditions, layout plan, and wind turbine characteristics. Jensen's model was used to replicate the model's wake effect, and a turbine thrust was added like a function to the model. [33] used a multi-objective lightning search method to optimize the architecture of wind farms. The multi-objective lightning search method was used to optimize wind farm layouts, resulting in a more effective layout that increased annual energy production whilst reducing the wake impact. To determine the performance of the suggested method, it was compared to three other candidate's evolution algorithms namely; PSO, GA, and strength Pareto evolutionary algorithm (SPEA). However, in the solution space, the possible size of the wind turbine has not been fully addressed. To optimize wind farm layout, a metamodel and an Evolution Algorithm/Particle Swarm Optimization Algorithm (PSO) were utilized [28]. The authors looked into possible solutions to the offshore wind farm's turbine layout difficulty. Using the Korean offshore as a case study, the work presented a combined model for minimizing wake losses and maximizing the yearly energy production of wind farms. The wind turbine site was optimized using the optimization technique. Based on the review of using different optimization algorithms to optimize the placement of wind turbines on wind farms with corresponding wake models, it is evident that obtained results are dependent on the type of algorithm used with the

wake models as well as how the mathematical model is being formulated. Therefore, a good optimization algorithm and mathematical modelling of the wind turbine placement is recommended in order to avoid wake effects, high cost of production and energy losses.

#### 4 CONCLUSIONS

In this article, the authors reviewed and evaluated the various optimization algorithms used to build the wind farm architecture more efficiently while taking into account critical characteristics such as wind speed, annual energy production cost, and wake losses. Based on the review, it was resolved that the optimal placement of wind turbine in wind farms with a view to increasing the energy production is dependent on type of optimization algorithm used and the accuracy of the formulated wind farm model to be optimized. Also, the Jensen model is the most widely used wake model in wind farm layout optimization. Consequently, there is a need to use more optimization algorithm with a view to comparing their performance on wind farm layout optimization problems.

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