*AMO - Advanced Modeling and Optimization, Volume 19, Number 1, 2017*

# WIND POWER PLANT LAYOUT DESIGN AND ASSESSMENT CONSIDERING FORBIDDEN ZONES FOR LOCATION OF TURBINES

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## Abstract

The design, planning and building of wind farms is influenced by the wind energy potential. This is complex process that can be affected by many factors including terrain specifics. The objective of this paper is to provide an approach for assessment of wind farm parameters taking into account the presence of forbidden zones where for different reasons it is not possible to place a turbine. For the goal, a mathematical model is used to determine different wind power plant layouts corresponding to a predefined subset of suitable wind turbines. The proposed algorithm for design and assessment of parameters of wind farm with forbidden zones is numerically tested. The obtained results show the applicability of the described algorithm considering land availability, wind turbines parameters and wind resources.

**Key words:** *Wind farm layout design, wind parameters, forbidden zones, mixed integer optimization model.*

## 1. Introduction

The design, planning and operational aspects of wind energy systems require detailed engineering knowledge and scientific skills to estimate wind farm characteristics. One of the most significant obstacles to developing wind energy systems is land use restrictions. Development of wind power plants requires land with sufficient wind resources, proximity to the power grid, and compatibility with environmental and regulatory requirements [Rodman & Meentemeyer, 2006]. The development of new

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AMO - Advanced Modeling and Optimization. ISSN: 1841-4311

wind energy project requires a significant consideration of land use issues [Kusiak & Song, 2010]. The most important factor in selecting a wind site is the wind resource. It defines ability of a wind turbine to extract power from varying wind [Ustuntasa & Sahin, 2008]. Wind turbines are available in various sizes and output power to operate over a range of wind speeds. They are usually integrated into array to create a wind power plant. It is important to predict the amount of output energy considering the terrain specific before realizing the wind power plant. For industrial wind power plant it is often difficult to design the most productive layout of turbines within wind site. A computational optimization for a wind power plant can specify a layout for which predicted energy production gains is best. The overall goal is to maximize energy production while minimizing capital and operating costs under given constraints. The wind power plant design considers various parameters such as site sizes, site layouts, turbine types, and hub heights. Spacing of wind turbines on the site must be considered carefully to avoid unacceptably wake losses [Shakoor et al., 2016]. The optimum layout for the specific site is affected by used turbines type [Ghosh, 2010; Mustakerov & Borissova, 2011]. There is pressure to build more compact wind farms to optimize land use but it is important to consider wind power losses for very close turbine spacing (wake effect). To overcome the wake effect some recommendations for inter-turbine distances vary from 1.1 to 3 rotor diameters (for prevailing wind direction) and 6 to 12 rotor diameters (for opposite wind direction) [Smith et al., 2006; Grady, et al., 2005].

The changes in energy production lead to costs that are more essential than infrastructure costs. That is why, the energy production is used as dominant design parameter [Kusiak & Song, 2010, Gonzalez et al, 2014]. The wind plant infrastructure also constitutes a significant part of the overall project costs. The terrain specific is important to be considered. High ground terrains are preferred for wind turbine placement, and flat valleys may also be suitable if they act as a wind channel [Rodman & Meentemeyer, 2006].

The wind turbine placement is one of the most important factors to make wind energy project economically viable. The good selection of turbines location determines investments success. The location of the wind turbines within the wind site is affected also by several factors which have to be taken into account – the wind direction, turbines type, wake interactions between wind turbines, wind power plant area and shape, etc. [Borissova & Mustakerov, 2010]. These locations need to have constantly high wind speeds to ensure the maximum efficiency but factors like the availability of transmission lines, value of energy to be produced, cost of land, etc., are to be considered too [Kesraoui et al., 2011]. Speaking about the land issue, some approaches involve forbidden areas where for different reasons it is not possible to place a turbine

[Grady et al., 2005; Serrano-Gonzalez et al., 2010; Serrano-Gonzalez et al., 2011]. The existence of forbidden areas can be due to physical obstacles, archaeological ruins, natural areas, visual impact or any kind of specific constraints [Serrano-Gonzalez et al., 2011]. To assess wind power plant parameters considering the land specifics, it is necessary to simultaneously consider the energy production, investment costs and the existing of forbidden areas (if any) where is not possible to place a turbine. In the paper an algorithm for design and assessment of wind power plant potential on terrain with forbidden zones is presented.

## 2. Problem formulation

The investigated problem aims to assess the most appropriate design of wind plant layout taking into account the wind power plant parameters and considering forbidden zones to place turbines. The illustration of terrain with forbidden zones that is used as example in the paper is shown in Fig. 1.

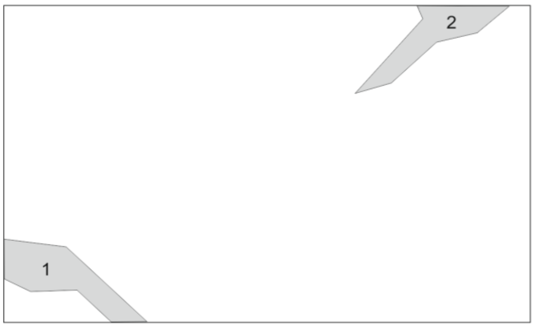


*Fig. 1. Wind site area with two forbidden zones (1) and (2)*

If a number of turbines' types are given, the problem is to choose the most appropriate type and number, and their location taking into account the forbidden zones and to assess the costs and energy output of a wind power plant.

## 3. Algorithm for assessment of wind power plant layout design considering the forbidden zones for location of turbines

The proposed algorithm is based on combinatorial optimization model for theoretical estimation of the annual wind power plant energy per unit of costs. It is adapted from [Mustakerov & Borissova, 2011] and considers wind farm layout design for given turbines types and known site conditions. This model is used to define a single-criterion mixed-integer nonlinear problem as follows:

(1) $$\max\left(\frac{\eta 8760\, NP}{N\left(\frac{2}{3}+\frac{1}{3}\exp(-0.00174N^2)\right)}\right)$$

subject to

(2) $$N=\left(\frac{L_x}{k_x D}+1\right)\left(\frac{L_y}{k_y D}+1\right)$$

(3) $$k_x^{\min}\le k_x\le k_x^{\max}$$

(4) $$k_y^{\min}\le k_y\le k_y^{\max}$$

(5) $$SD_x = k_x D$$

(6) $$SD_y = k_y D$$

where the costs of wind power plant are expressed as $costs = N(\frac{2}{3}+\frac{1}{3}e^{-0.00174N^2})$ [Shakoor et al., 2016; Mustakerov & Borissova, 2011, Grady et al., 2005] and has dimensionless unit costs per year. The extracted energy from $N$ number of turbines is represented as $E=\eta 8760NP$, where $\eta$ is nominal utilization coefficient; 8760 is the number of the hours over the year, $P$ is the rated power of given wind turbine type and $D$ is its diameter. The wind power plant is of rectangular shape with dimensions $L_x$ and $L_y$. The uncertainties in wind conditions lead to probabilistic evaluation of this effect. That is why as a good practical assessment for inter-turbines distances that take into account the wake effect, the turbines distances can be expressed analytically through number of rotor diameters [Patel, 1999; Donovan, 2005; Marmidis et al, 2008]. The separation distances between turbines in columns and rows $SD_x$ and $SD_y$ are determined by coefficients $k_x$ and $k_y$.

The solution of optimization problem (1) – (6) will define the number of turbines and their layout for given dimensions of wind site and wind conditions. The obtained layouts for turbines placement are optimal in sense of maximizing of energy per unit of costs.

The diagram of the proposed algorithm is shown in Fig. 2.

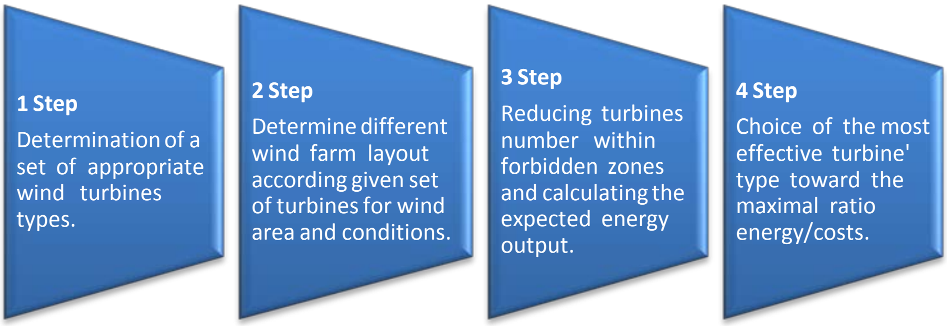


*Fig. 2. Algorithm for design and assessment of wind power plant with forbidden zones*

It is assumed that wind speed and direction, and probability of their occurrence are known. This information is used on the 1st step of the algorithm to select a number of appropriate wind turbines types. The 2nd step uses combinatorial optimization model (1) – (6) for determination of different wind power plant layouts for each of the given turbines types. The designated locations of the turbines of each type are investigated on 3rd step whether some of them fall into the forbidden zones. If this is true, the corresponding turbines are excluded from the layout. This results in reducing of the overall number of turbines. Then the ratio energy output/costs for each of turbines types and corresponding layouts is calculated by the expression used in objective function (1) as:

$$\frac{\eta 8760\, NP}{N\left(\frac{2}{3}+\frac{1}{3}\exp(-0.00174N^{2})\right)} \tag{7}$$

The results for the energy output/costs ratio calculated by (7) are used on the 4th step of the algorithm to select the most effective turbine's type considering the restriction about forbidden zones.

## 4. Numerical testing

The applicability of the proposed algorithm for design and assessment of wind power plant considering terrain with forbidden zones is numerically tested. It is assumed that by some practical investor' recommendations three types of wind turbines are used with parameters shown in Table 1.

*Table 1. Wind turbines parameters*

| WT# | Turbine type | Rated power, MW | Rotor diameter, m |
|---|---|---|---|
| 1 | Enercon E-92 | 2350 | 92 |
| 2 | Vestas V100 | 2600 | 100 |
| 3 | SWT-3.6-107 | 3600 | 107 |

Wind site area with dimensions 3 km x 1 km and 2 prohibited zones (Fig. 1) for uniform and predominant wind directions is used for testing. In the case of uniform wind direction, the separation coefficients between columns and rows in wind site are within the limits of 4.5 to 5.5 rotor diameters as recommended by Patel [Patel, 1999]. For non uniform wind, the separation coefficients for predominant wind direction are limited between 9 and 11 rotor diameters and are limited between 1.5 to 3 rotor diameters for perpendicular wind direction [Marmidis et al, 2008; Donovan, 2005]. The obtained results for each turbine type from Table 1 by using the optimization problem (1) – (6) are summarized in Table 2.

*Table 2. Numerical results*

| WT # | Wind direction | Turbines number without forbidden zones | Turbines number with forbidden zones | $k_x$ | $k_y$ | Energy/Costs without forbidden zones | Energy/Costs with forbidden zones |
|---|---|---|---|---|---|---|---|
| 1 | Uniform | 35 | 32 | 5.35 | 5.35 | 8744.870 | 8544.502 |
|  | Predominant 1 north to south | 69 | 62 | 1.53 | 10.60 | 9262.531 | 9257.937 |
|  | Predominant 2 west to east | 64 | 60 | 10.84 | 1.50 | 9259.982 | 9254.891 |
| 2 | Uniform | 35 | 32 | 5.02 | 5.02 | 9675.176 | 9453.492 |
|  | Predominant 1 north to south | 63 | 57 | 1.55 | 9.75 | 10244.07 | 10231.26 |
|  | Predominant 2 west to east | 60 | 57 | 10.33 | 1.50 | 10239.45 | 10231.26 |
| 3 | Uniform | 35 | 32 | 4.83 | 4.83 | 13396.40 | 13089.45 |
|  | Predominant 1 north to south | 60 | 54 | 1.52 | 9.11 | 14177.71 | 14146.93 |
|  | Predominant 2 west to east | 56 | 54 | 9.66 | 1.51 | 14160.98 | 14146.93 |

For uniform wind direction, the numerical testing determines equal layouts for all three turbines types from Table 1 (Fig. 3). The places where turbines cannot be installed turbines due the existence of forbidden areas are marked as x.

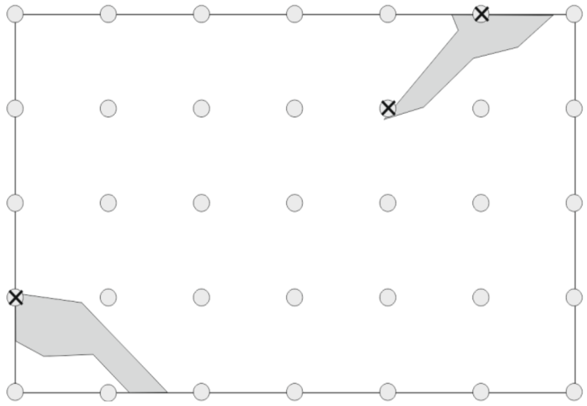
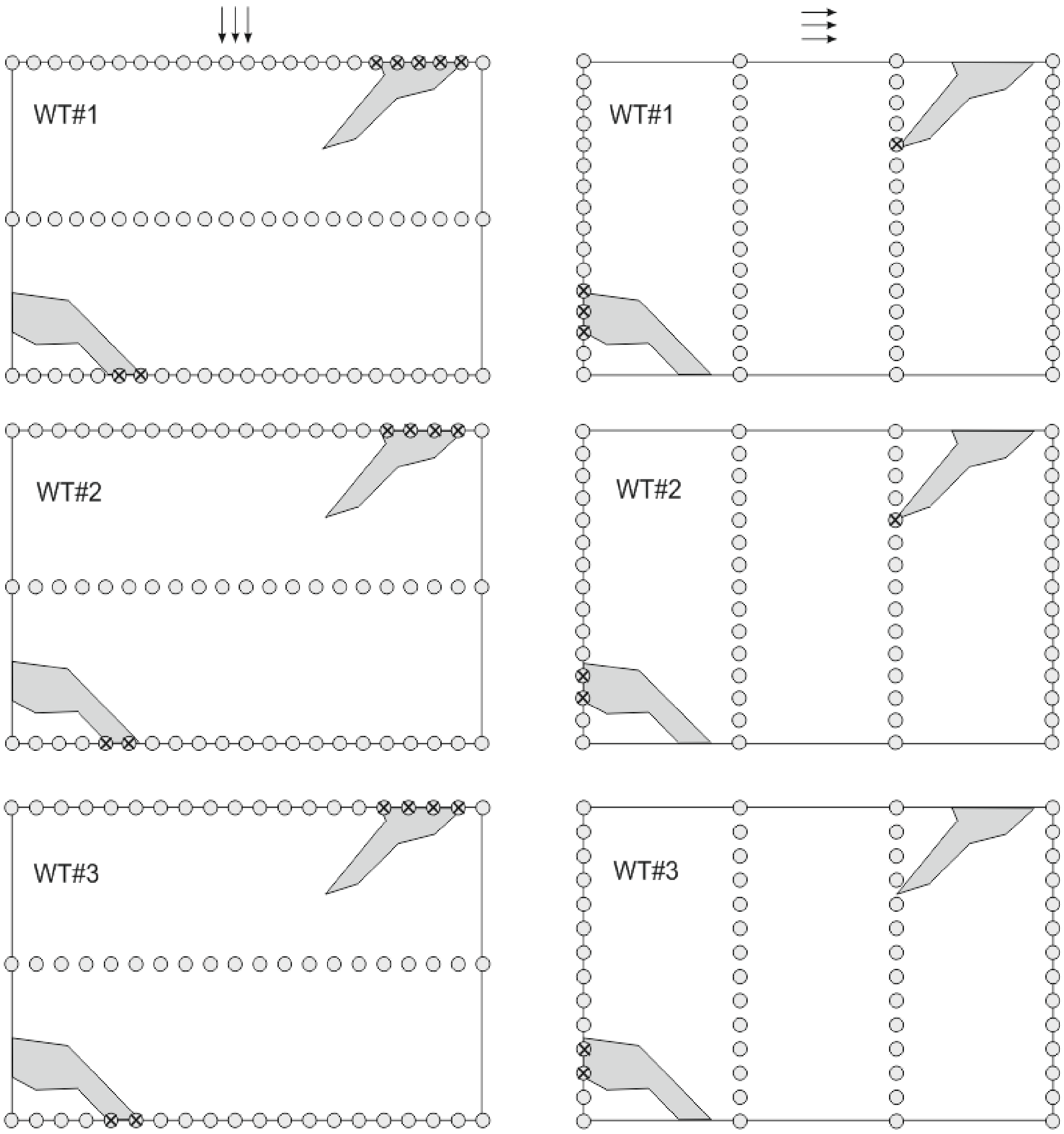


*Fig. 3. Wind turbines layout for uniform wind direction and forbidden zones*

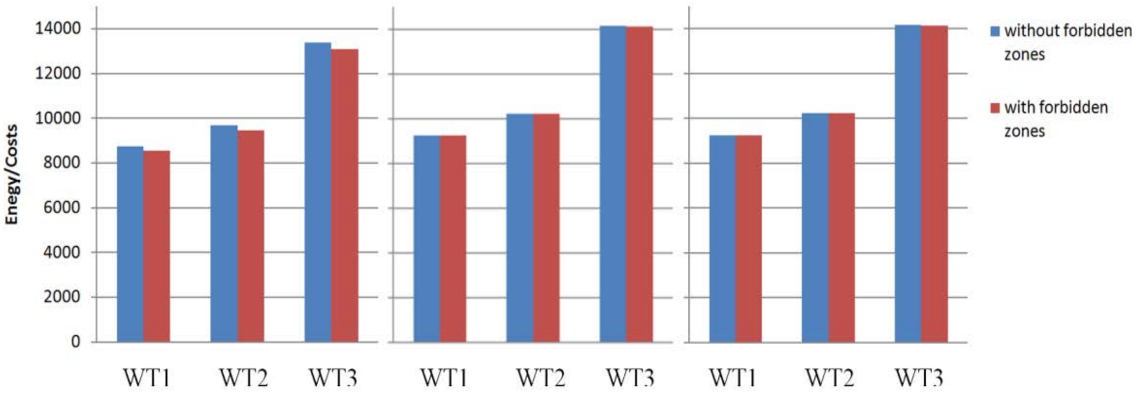
Fig. 4 illustrates non-uniform wind direction case for two opposite predominant wind directions for the same wind site.



*(a)* *(b)*

*Fig. 4. Wind turbines layout for 2 opposite predominant wind directions and forbidden zones (a) north to south wind direction, (b) west to east wind direction*

The performance of the investigated wind site in regard to maximization of energy output and investment costs ratio are illustrated in Fig. 5 for all turbines types from Table 1.



*(a)* *(b)* *(c)*

*Fig. 5. The wind site performance toward turbines type and energy/costs ratio for: (a) uniform direction; (b) predominant direction north-south; (c) predominant direction west-east*

## 5. Results analysis and discussion

The solution of formulated optimization tasks on step 2 of the algorithm (Fig. 2) are obtained by means of LINGO v. 12 solver system. The solution times took a few seconds on PC with Intel Core i3 CPU at 2.93 GHz, 3.37 GB RAM under MS Windows OS.

The analysis of testing results for given wind site and turbines shows that maximum of energy production per unit of costs can be achieved if turbine WT3 is used (Fig. 5a, b, c).

Due to small differences in used turbines rotor diameters (less than 10 %) the number and layouts of turbines are equal in case of uniform wind direction (see Fig. 3). Nevertheless of the equal number of turbines, the differences in the turbines' rated power have significant impact on the energy production as it is seen in Fig. 5a.

For non-uniform wind direction, the number of turbines is different as result from the existence of forbidden zones. The analysis of testing results in Table 2 and Fig. 3 and Fig. 4, shows that the turbines with smaller rotor diameter are less effective. This is because they require placement of greater number of turbines which in turn decreases the energy/costs ratio. Along with this, the experiments show that the turbines with larger rotor diameter have less probability to fall in forbidden zones.

## 6. Conclusion

The proposed algorithm aims to assists the process of the development of wind power plant project. The innovative idea in the described algorithm is using of combinatorial optimization for determination of best wind power plant layout taking into account the existence of forbidden zones in wind site. The numerical testing shows the practical applicability of the algorithm. Using of the proposed algorithm allows preliminary assessment of wind power plant project for different number and types of turbines toward energy/costs ratio while forbidden zones are available.

The proposed algorithm for design and assessment of the parameters of wind power plant with forbidden zones could be used with other single or multi-objective mathematical models for determination of wind turbines placement.

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