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# Wind Park Layout Design Using Combinatorial Optimization

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## 1. Introduction

The energy sector has essential influence on climate change and atmospheric pollution. Wind energy, being a clean and renewable energy, can greatly contribute to decreasing of the air pollution negative impacts. Generally speaking, the production of renewable energy from wind can have a positive socioeconomic benefit – it not only help to reduce the climate changing but also support meeting of the long-term world economical goals. Taking that into account, many countries are encouraging the building of industrial wind parks. The building of a wind park is an expensive and complex task involving a wide range of engineering and scientific knowledge. The design of a wind park can have profound implications for its future profitability. Sustainable wind park development has to be done in an ecological way which means evaluating of the all possible positive and negative influences on the environment. The development of new wind energy projects requires also a significant consideration of land use issues. One of the most important factors in selecting a wind energy site is the availability of proper wind resources. The wind itself is a variable source of energy. The ability of a wind turbine to extract power from varying wind is a function of three main factors – the wind power availability, the power curve of the generator, and the ability of the turbine to respond to wind fluctuations (Üstüntaşa & Şahin, 2008). Wind turbines are available in various sizes and power output. They are designed to operate over a range of wind speeds (3-25 m/s) and can be erected singly by an individual property owner or grouped together to form a wind farm (wind park) connected to a public grid (Rodman & Meentemeyer, 2006). The common challenge for the wind park designer is to maximize the energy capture within the given restrictions (White et al., 1997; Kusiak & Song, 2010). As there is pressure to build more compact wind farms to optimize land utilization, an determination of array losses for very close turbine spacing is required (Smith et al., 2006). The investigations on wind energy using essentially cover four principal topics (Ettoumi et al., 2008). The first one deals with the sensors and instrumentation used for wind measurements. The second one examines the evaluation of wind energy potential for a given region using various statistical approaches. The third is focused on the design and characterization of wind energy turbines. The fourth is the design and development of wind parks. The results of investigations in those areas are used by wind park planners to develop cost-effective wind parks.

The investigations discussed here concern the problems associated with the forth topic – design of the wind park layout, including choice of the turbines type, number and their placement in the wind park area. How to choose the number and the type of the turbines to install depends on a variety of factors – wind conditions, terrain, investments costs, power output, environmental influence, etc. More powerful turbine is usually preferred to the less powerful one since both the cost of a turbine and the energy it generates is usually proportional to its nominal power. The placement of wind turbines on the wind park site (i.e. wind park layout) is affected by several factors which have to be taken into account – the number of turbines, wind direction, wake interactions between wind turbines, land availability (area and shape), etc. For the goal a combinatorial design model for defining wind turbines type, number and placement is proposed. It is used for formulation of mixed-integer nonlinear discrete combinatorial optimization tasks satisfying different design requirements and restrictions. The tasks solutions results define different optimal wind park layout designs. The solutions results can be used also to evaluate the impact of alternative wind park layout schemes on the investment costs and wind park power output.

## 2. Mathematical methods in wind park design

An interdisciplinary branch of applied mathematics and formal science that uses mathematical modelling methods and algorithms to arrive at optimal or near optimal solutions to complex practical problems is known as *operations research*. Operations research helps the management to achieve its goals using scientific methods and can be used in particular for wind park design decisions. It is often concerned with optimizing of some objectives (maximum of profit, performance, etc. or minimum of loss, risk, cost, etc.) at limited resources. The majority of real-world optimization problems are multiobjective by nature – they have more than one and usually conflicting objectives that must be satisfied simultaneously. Instead of aiming at a single solution finding, the multiobjective optimization methods try to produce a set of good trade-off solutions (Pareto-optimal solutions) from which the decision maker could select. Nevertheless, there exist some practical problems where the single criterion optimization would be able to get an optimal solution with less calculation difficulties. One of the questions that should be answered when using optimization methods for the wind park design is the effectiveness and advisability of single or multicriteria optimization application.

The general wind park design goal is maximizing electrical energy production while minimizing the costs. Up to day different approaches to the wind park design are developed. At the early stage a suitable wind park site is identified by its geographical location and based on long-term wind records for annual wind speed variation (White et al., 1997). The determining of the wind turbines number in the designed wind park is a decision making parameter that should take into consideration the limited wind park geographical area. The separation distance between the turbines is another parameter to be considered when defining the wind park layout and depends on the needed recovery of wind energy behind the neighbouring turbines (Grady et al., 2005; Sørensen, 2006). The number and separation distances between turbines are used to define the wind park layout. The wind park layout design is usually performed in a heuristic trial and-error iterative approach taking into account all social, environmental and technical constraints (Mora et al., 2007). The intuitive spacing scheme results in sparse wind parks layouts and in inefficiently using of the wind energy potential of the site (Ammara et al., 2002). The production of industrial quantities of electricity requires getting as much as possible electrical power output, i.e. the

wind park with as many powerful wind turbines as it is possible. The best solution should define the wind turbines number, type and their placement in the given geographical area. Profit-to-cost or profit-to-area ratios could be used as performance metrics of investment (Kongnam et al., 2009). Several methods have been applied in order to try to optimize wind park layout. Genetic algorithms are used for defining of optimal wind turbines placement. A square shape of the wind park is subdivided into a 10 x 10 grid and cells to install turbines are determined so as to minimize the cost per unit energy (Mosetti et al., 1994; Grady et al., 2005; Emami & Nogreh, 2010). The effectiveness of genetic algorithms is demonstrated for solving the wind park micro-siting optimization problem. However, due to the binary coding method of the genetic algorithms, turbines could only be installed in the center of selected cells. Another application of genetic algorithm is also used to maximize an economic function, which is related to turbine parameters and locations also in a square grid (Mora et al., 2007). A generic model for optimizing in-land wind farm layout considers circular wind park radius and turbine distance constraints. The model maximizes the energy production by placing wind turbines in such a way that the wake loss is minimized (Kusiak & Song, 2010). The uncertainties of wind speed distribution and power-speed characteristics are considered in mixed-integer nonlinear programming approach used to determine the optimum wind park electricity generation. It takes into account the profit-to-cost and profit-to-area ratios to evaluate the investment alternatives (Kongnam et al., 2009). Optimal placement and arrangement of wind turbines in a wind park while maximizing energy production and minimizing installation cost, is done by mean of Monte Carlo simulation (Marmidis et al., 2008). Variations of the vertex packing problem are used to determine the optimal positions of wind turbines within a wind farm. The maximum power generation is sought considering constraints for the number of turbines, turbine proximity, and turbine interference (Donovan, 2005). The characteristic of wind turbine generation is represented by an analytical expression, which is used to solve distributed generation sizing and placement problem while minimizing the real power loss in the system. It is used in a methodology for finding the optimal size and location for connecting wind type distributed generation in primary distribution systems (Mahat et al., 2006).

As could be seen from the survey, the wind park layout design is an important and complex problem. Different mathematical methods and approaches are developed to get mathematically reasoned (optimal) solutions in contrast to the experience based heuristic approaches. Using of mathematical methods has also the advantage of getting of preliminary theoretical estimation about the designed wind park characteristics and satisfaction of the given requirements. The preliminary evaluation is important because it decreases the risks of taking ineffective or even wrong wind park design decisions.

## 2.1 Generalized discrete combinatorial optimization description

The wind park design has common specifics of the engineering systems design. One of the possible approaches to these problems is using of discrete combinatorial optimization modelling (Mustakerov & Borissova, 2007). That approach could be shortly described by assuming of the existence of finite discrete sets of values for some design variables  $a$ ,  $b$ , ...,  $c$ :

$$a = \begin{pmatrix} a_1 \\ a_2 \\ \dots \\ a_i \end{pmatrix}, b = \begin{pmatrix} b_1 \\ b_2 \\ \dots \\ b_j \end{pmatrix}, \dots, c = \begin{pmatrix} c_1 \\ c_2 \\ \dots \\ c_k \end{pmatrix} \quad (1)$$

The values of the design variables define some discrete sets of system parameters:

$$\begin{aligned}\forall i: P_{a_i} &= \{P_{a_i}^1, P_{a_i}^2, \dots, P_{a_i}^r\} \\ \forall j: P_{b_j} &= \{P_{b_j}^1, P_{b_j}^2, \dots, P_{b_j}^s\} \\ &\dots \\ \forall k: P_{c_k} &= \{P_{c_k}^1, P_{c_k}^2, \dots, P_{c_k}^t\}\end{aligned}\quad (2)$$

The choice of particular elements of  $a, b, \dots, c$  is formalized as choice of the system parameters by means of binary integer decision variables  $x, y, \dots, z$ :

$$\begin{aligned}\forall r: P_a^r &= \sum_i P_{a_i}^r x_i \\ \forall s: P_b^s &= \sum_j P_{b_j}^s y_j \\ &\dots \\ \forall t: P_c^t &= \sum_k P_{c_k}^t z_k\end{aligned}\quad (3)$$

where:

$$x = \begin{pmatrix} x_1 \\ x_2 \\ \dots \\ x_i \end{pmatrix}, y = \begin{pmatrix} y_1 \\ y_2 \\ \dots \\ y_j \end{pmatrix}, \dots, z = \begin{pmatrix} z_1 \\ z_2 \\ \dots \\ z_k \end{pmatrix}\quad (4)$$

are subject to restrictions for single element choice:

$$\begin{aligned}\sum_i x_i &= 1, x_i \in \{0, 1\} \\ \sum_j y_j &= 1, y_j \in \{0, 1\} \\ &\dots \\ \sum_k z_k &= 1, z_k \in \{0, 1\}\end{aligned}\quad (5)$$

The real engineering design problems are characterized by the existing of some technological and user requirements between the design variables described as functions:

$$\begin{aligned}g_1 &= f_1(a, b, c, \dots) \\ g_2 &= f_2(a, b, c, \dots) \\ &\dots \\ g_m &= f_m(a, b, c, \dots)\end{aligned}\quad (6)$$

and restrictions for system parameters:

$$L_a^r \leq P_a^r \leq U_a^r\quad (7)$$

The combinatorial optimization design approach needs defining of some objective functions:

$$\begin{aligned} f_{\phi} &= \phi(P_a^r, P_b^s, \dots, P_c^t) \\ f_{\varphi} &= \varphi(P_a^r, P_b^s, \dots, P_c^t) \\ &\dots \\ f_{\gamma} &= \gamma(P_a^r, P_b^s, \dots, P_c^t) \end{aligned} \quad (8)$$

They are used to formulate single criterion

$$\max(f_{\phi} + f_{\varphi} + \dots + f_{\gamma}) \quad (9)$$

or multicriteria:

$$\max(f_{\phi}, f_{\varphi}, \dots, f_{\gamma}) \quad (10)$$

formulations of discrete combinatorial optimization tasks whose solutions define optimal or Pareto-optimal design elements combinations.

## 2.2 Discrete combinatorial optimization for wind park layout design

The described generalized discrete combinatorial optimization approach is applied to wind park layout design. In most cases, the wind park layout design should conform to a preliminary chosen geographical area with known parameters – wind conditions and area shape and size. The design goal is to determine the optimal wind turbines type, number and placement to get maximal power output while minimizing the investment costs and considering different technological and functional requirements and restrictions. One of the requirements concerns the spacing between turbines in a wind park. If the wind strikes a next turbine before the wind speed has been restored from striking the previous turbine, the energy production from the second turbine will be decreased, the so called *wake effect*. Spacing the turbines further apart will produce more power, but at the expense of more land, more roads, and more electrical wire. The separation distance between the turbines depends on the needed recovery of wind energy behind the neighbouring turbines (Grady et al., 2005; Sørensen, 2006). The spacing of a cluster of wind turbines in a wind park depends on the terrain, the wind direction and speed, and on the turbines' size. There exist some recommendations for the turbines separation distances depending on the wind directions and rotor diameters sizes. Two typical cases of wind directions are assumed – uniform and predominant wind direction – Fig. 1.

The uniform wind direction indicates equal distances between turbines in rows and columns of approximately 5 rotor diameters (Grady et al., 2005). In the case of predominant wind direction, the recommended turbines spacing is 8 to 12 rotor diameters in rows apart in the windward direction and 1.5 to 3 (Grady et al., 2005; Marmidis et al., 2008; Donovan, 2005) or 2 to 4 rotor diameters (Johnson, 2006) in the crosswind direction. Spacing the turbines further apart will decrease the wake influence and presumably will capture more wind power but at the expense of land wasting. The concept of operating wind turbines as closely as it is possible has the potential advantages in reducing capital costs associated with design and construction, while improving wind turbine system reliability and operating efficiency (Ransom et al., 2010).



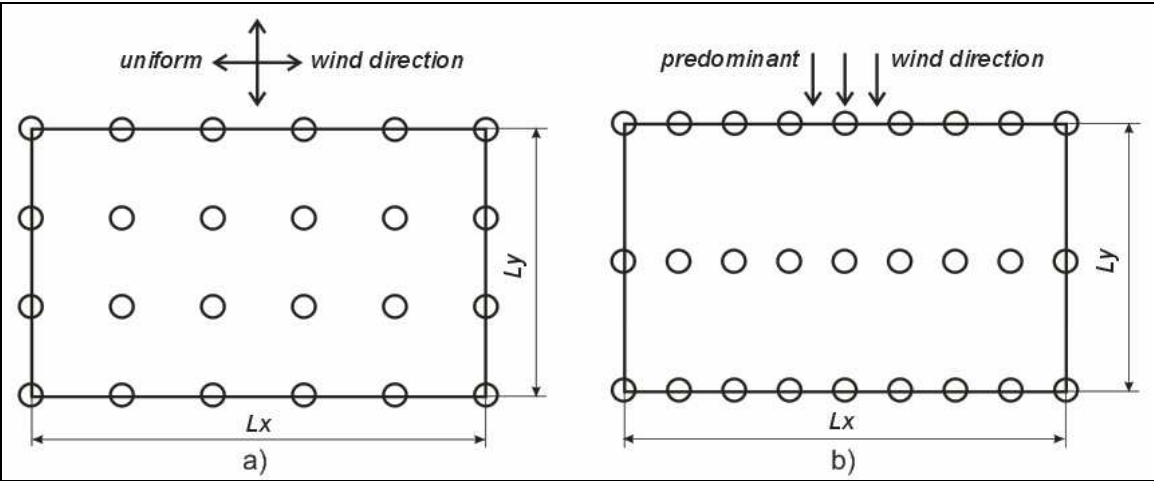


Fig. 1. Wind turbines placements patterns: (a) uniform and (b) predominant wind direction

One of the essential parameters to be considered in the wind park layout design modeling is the overall turbines number. Using the patterns shown in Fig. 1, the total number of turbines  $N$  within park area can be defined as multiplication of rows and columns turbines numbers  $N_{row}$  and  $N_{col}$ :

$$N = N_{row}N_{col} \tag{11}$$

The number of wind turbines in row and column  $N_{row}$  and  $N_{col}$  for rectangular area with dimensions  $L_x$  and  $L_y$  and separation distances between turbines  $SD_x$  and  $SD_y$  can be defined as (Johnson, 2006):

$$N_{row} = \frac{L_x}{SD_x} + 1 \tag{12}$$

$$N_{col} = \frac{L_y}{SD_y} + 1 \tag{13}$$

The existing recommendations about the turbines separation distances are taken into account by introducing of coefficients  $k_{row}$  and  $k_{col}$  (Mustakerov & Borissova, 2010). By using  $k_{row}$  and  $k_{col}$ , the separation distances can be expressed by the turbine rotor diameter  $D$  as:

$$SD_x = k_{row} D \tag{14}$$

$$SD_y = k_{col} D \tag{15}$$

Substituting (14) and (15) into (12) and (13) the row and column turbines numbers can be defined as functions of turbines rotor diameter:

$$N_{row} = \frac{L_x}{k_{row}D} + 1, integer \tag{16}$$

$$N_{col} = \frac{L_y}{k_{col}D} + 1, integer \tag{17}$$

To increase the flexibility of the modeling, the coefficients  $k_{row}$  and  $k_{col}$  are considered to be continuous variables limited by upper and lower values (Mustakerov & Borissova, 2010):

$$k_{row}^{\min} \leq k_{row} \leq k_{row}^{\max} \quad (18)$$

$$k_{col}^{\min} \leq k_{col} \leq k_{col}^{\max} \quad (19)$$

As a result of technological advances, there exist a number of different types and models of wind turbines that can be used in the wind parks design. The different wind turbines have different technical characteristics reflecting on power production and price. Because of the fact that purchasing of the wind turbines is one of the most essential investment for the wind park developing, the choice of optimal wind turbines' type and number is a critical step for wind park design. The choice of identical turbines for particular wind park developing is assumed to be an advantage from the technological and maintenance point of view. The wind turbines type choice is modeled by using of binary integer variables  $x_i \in \{0, 1\}$ , complying with restriction:

$$\sum_i x_i = 1 \quad (20)$$

The binary integer variables and the integrality requirement on the turbines number transform the model into discrete mixed integer programming problem. It should be pointed out that most of engineering design optimization problems are mixed integer-discrete-continuous, non-linear programming problems. It is quite often in practice of wind park design to solve them as continuous problems and to use the nearest available discrete value (Johnson, 2006). The result in this case is not optimal or even unfeasible if equality types of restrictions are existing (Lampinen & Zelinka, 1999; Taha, 2006; Shapiro, 1979). The existence of integrality requirement increases the difficulty of finding a solution but could be not avoided if a true optimal solution is needed.

The developed combinatorial wind park layout design approach is based on simultaneous choice of multiple wind turbine parameters considered as design variables (Mustakerov & Borissova, 2010). For example:

- an important parameter influencing the overall wind park electrical energy output is the wind turbine rated power. The turbine choice among the set of  $m$  available different turbines with rated power  $P_{wt}^i$  is formalized as:

$$P_{wt} = \sum_i^m x_i P_{wt}^i \quad (21)$$

- the rotor diameter  $D$  is another of the important wind turbine parameters defining the turbine's effectiveness. It defines also the separation distance between turbines and indirectly the number of turbines in a given limited wind park area. The choice of particular wind turbine rotor diameter among the given set of  $m$  different types of turbines with known rotor diameters can be done analogically to (21) as:

$$D = \sum_i^m x_i D_{wt}^i \quad (22)$$



- the wind speed in the wind park geographical location influences the turbine's choice by considering of their nominal wind speed parameter  $S_{wt}^i$  :

$$S = \sum_i^m x_i S_{wt}^i \quad (23)$$

- the height of the wind turbine tower  $H$  is another parameter that can be considered in the turbines choice (the wind speed increases with the height and the turbine effectiveness increases respectively):

$$H = \sum_i^m x_i H_{wt}^i \quad (24)$$

Using the same technique other essential wind turbine parameters (electrical output voltage, frequency, noise, etc.) could be considered in the wind turbine type choice.

Because the wind turbines parameters are taken as design variables some requirements about their values can be taken into account by introducing of lower and upper limits:

$$P_{wt}^{\min} \leq P_{wt} \leq P_{wt}^{\max} \quad (25)$$

$$D_{\min} \leq D \leq D_{\max} \quad (26)$$

$$S_{\min} \leq S \leq S_{\max} \quad (27)$$

$$H_{\min} \leq H \leq H_{\max} \quad (28)$$

The turbine's optimal choice should be done accordingly to some optimization criteria. A widely accepted criterion for wind park design is the minimum cost per unit energy produced ratio.

$$\left( \frac{\text{costs}}{P} \right) \quad (29)$$

where the wind park costs per year is defined as function of the turbines number  $N$  (Grady et al., 2005; Mosetti et al., 1994; Marmidis et al., 2008):

$$\text{costs} = N \left( \frac{2}{3} + \frac{1}{3} \exp(-0.00174N^2) \right) \quad (30)$$

and total power extracted by all of the turbines in the wind park is (Grady et al., 2005; Johnson, 2006)

$$P = NP_{wt} \quad (31)$$

where  $P$  is the wind park total power output,  $N$  is number of wind turbines and  $P_{wt}$  is the single wind turbine power production. The single wind turbine power  $P_{wt}$  depends on the wind conditions (wind speed, direction, intensity and probability) and on turbine's type -

rotor and tower size, rated power, thrust coefficient, etc. (Kongnam et al., 2009; Mosetti et al., 1994; Marmidis et al., 2008). The wind park electrical energy production for a year can be estimated by using some practically determined nominal power utilization coefficient  $\mu$  (Lepa et al., 2008) of the total wind park installed power. In the proposed modelling approach the wind park power output per year is estimated by the number of the hours over the year  $h_y$ , nominal power utilization coefficient  $\mu$ , number of wind park turbines  $N$  and single turbine power rating  $P_{wt}$  as (Mustakeroov & Borissova, 2010):

$$P = h_y \eta N P_{wt} \quad (32)$$

The advantage of the described modeling approach is the possibility to introduce different criteria, relations and restrictions to satisfy more precisely different requirements about the designed wind park layout.

### 2.3 Optimization task formulation

The proposed modeling approach is used to formulate a single criterion mixed-integer nonlinear optimization task:

$$\min \left( \frac{\text{costs}}{P} \right) \quad (33)$$

subject to:

$$\text{costs} = N \left( \frac{2}{3} + \frac{1}{3} \exp(-0.00174 N^2) \right) \quad (34)$$

$$P = h_y \eta N P_{wt} \quad (35)$$

$$N = N_{row} N_{col}, \text{ integer} \quad (36)$$

$$N_{row} = \frac{L_x}{k_{row} D} + 1, \text{ integer} \quad (37)$$

$$N_{col} = \frac{L_y}{k_{col} D} + 1, \text{ integer} \quad (38)$$

$$k_{row}^{\min} \leq k_{row} \leq k_{row}^{\max}, k_{row} > 0 \quad (39)$$

$$k_{col}^{\min} \leq k_{col} \leq k_{col}^{\max}, k_{col} > 0 \quad (40)$$

$$P_{wt} = \sum_i^m x_i P_{wt}^i \quad (41)$$

$$D = \sum_i^m x_i D_{wt}^i \quad (42)$$

$$H = \sum_i^m x_i H_{wt}^i \quad (43)$$

$$\sum_i^m x_i = 1, x \in \{0,1\} \quad (44)$$

The objective function defines the profitability of the wind park design by minimization of the investments while maximize the wind park electrical power generation. Thus, the solution of the formulated optimization task (33) – (44) will be a compromise between the overall wind park investments costs and wind turbines energy output. Both depend on the type of wind turbines, on their number and placement within park area. On the other hand, the number of the wind turbines depends of the size of the wind park and wind direction. The wind park energy output is function of the number of installed turbines, their rated power and wind conditions. The wind conditions for the particular wind park are taken into account by using the statistically defined nominal power utilization coefficient  $\mu$  of the total wind park installed power.

The solution of the formulated optimization task (33) – (44) define the optimal type and number of wind turbines for a given wind park area. It also defines the values of the coefficients  $k_{row}$ ,  $k_{col}$  and the corresponding separation distances between turbines. The turbines number and their separation distances define the optimal wind park layout design. The calculated values of the costs and wind park electrical power output give some preliminary theoretical estimation of the wind park design and its effectiveness.

### 3. Numerical testing

The proposed combinatorial optimization approach to wind park layout design is tested numerically by using formulation (33) – (44) and real data of commercial wind turbines shown in Table 1 (Wind-energy-market, 2010; Enercon, 2010; Vestas, 2010). Each row of Table 1 represents a particular turbine type and each column represents the corresponding parameter value to be used in the numerical testing. The number of turbines types and the number of their parameters define the number of the optimization model variables and restrictions. It should be noted, that the turbines and parameters shown in Table 1 are just a sample used to illustrate the practical applicability of the proposed wind park design approach. Real design problem would include much more design items leading to large scale optimization tasks formulations.

Two basic wind conditions are considered – uniform wind direction and known predominant wind direction. Changing the layout of a wind park will presumably result in different investment costs and park power output. That is why the different layouts have to be compared in order to find the design that minimizes the investments and supplies the expected level of power output. For the goal, a number of different optimization tasks formulations defining different layouts are tested numerically by means of LINGO v. 11 optimization solver.

The values of the coefficients  $h_y$  and  $\mu$  used to calculate expected wind park power output per year are taken to be  $h_y = 8760$  hours over the year (365 days  $\times$  24 hours) and  $\mu = 0.3$  (30% nominal turbines power utilization).

i	Wind turbine		Rated power output, $P_{wt}^i$ , MW	Rotor diameter, $D_{wt}^i$ , m	Tower height, $H_{wt}^i$ , m
	Type	Model			
1	1.1	enercon's E-33	0.330	33.4	37
2	1.2				44
3	1.3				50
4	2.1	enercon's E-48	0.800	48.0	50
5	2.2				60
6	2.3				76
7	3.1	enercon's E-53	0.800	52.9	60
8	3.2				73
9	4.1	Vestas V52	0.850	52.0	49
10	4.2				65
11	4.3				74
12	5.1	enercon's E-44	0.900	44.0	45
13	5.2				55
14	6.1	Vestas V82	1.650	82.0	78
15	7.1	Vestas V80	2.000	80.0	60
16	7.2				78
17	7.3				100
18	8.1	enercon's E-82	2.000	82.0	78
19	8.2				138
20	9.1	enercon's E-70	2.300	71.0	58
21	9.2				113
22	10.1	Vestas V90	3.000	90.0	95
23	10.2				105
24	10.3				125

Table 1. Commercial wind turbines parameters

3.1 Uniform wind direction case

Eight mixed-integer discrete nonlinear optimization tasks defining wind park layout design for uniform wind direction case are solved. Four of them consider square wind park shape with dimensions  $L_x = 2$  km,  $L_y = 2$  km and the other four – rectangular wind park shape with the same area ( $L_x = 4$  km,  $L_y = 1$  km).

The task (33) – (44) for square wind park has four different formulations as follows:

- **Task 1a** – (39) and (40) use boundary values  $k_{row}^{min} = k_{col}^{min} = 4.8$  and  $k_{row}^{max} = k_{col}^{max} = 5.2$  for the turbines separation coefficients following the recommendations for the uniform wind direction case.
- **Task 1b** differs from **Task 1a** by adding of the restriction for the wind turbine rotor diameter  $D < 70$  m. That additional restriction shifts the choice of wind turbines toward to smaller wind turbines types.
- **Task 1c** and **Task 1d** are equivalent to the tasks 1a and 1b but have relaxed boundaries for the coefficients  $k_{row}^{min} = k_{col}^{min} = 4.5$  and  $k_{row}^{max} = k_{col}^{max} = 5.5$  in (39) and (40) to illustrate the influence of the separation distances on the tasks solution.

The tasks solutions (Table 2) define optimum wind turbines placement illustrated on Fig. 2.

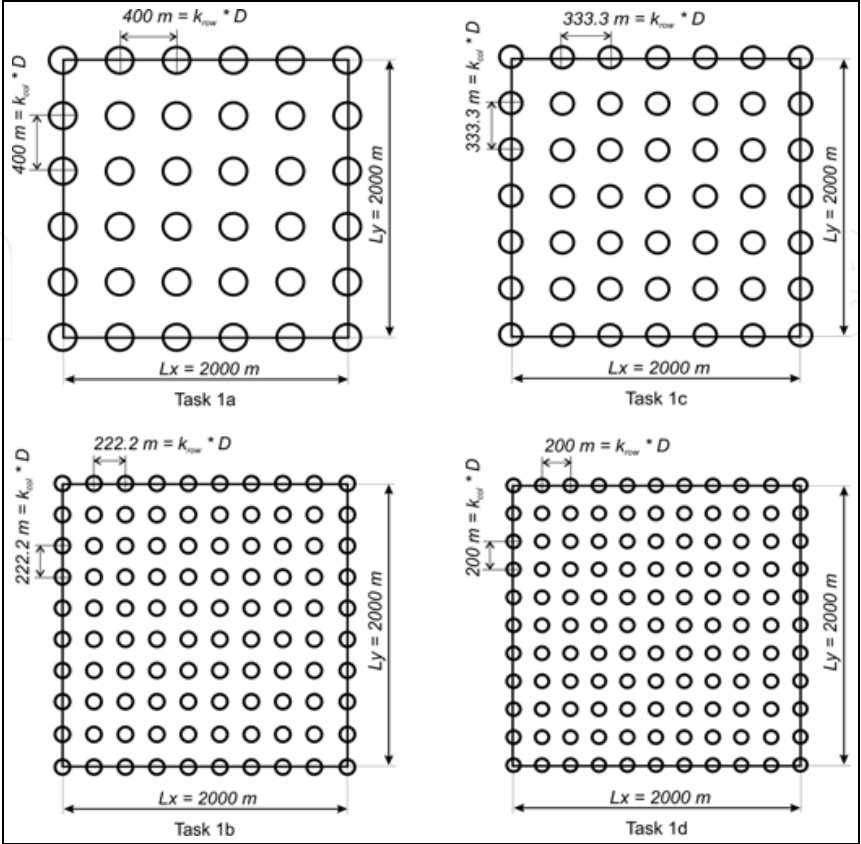


Fig. 2. Wind turbines placement for uniform wind direction and square wind park area

Task	Chosen type of wind turbine	Turbines number	Total installed power, MW	Separation coefficients	Separation distances, m	Cost per unit energy
<b>Task 1a</b> $4.8 < k_{row} < 5.2$ $4.8 < k_{col} < 5.2$	8.1 enercon's E-82 $P_{wt} = 2 \text{ MW}$ , $D = 82 \text{ m}$ , $H = 78 \text{ m}$	$N = 36$ $N_x = 6$ $N_y = 6$	72	$k_{row} = 4.88$ $k_{col} = 4.88$	$SD_x = 400$ $SD_y = 400$	0.000133
<b>Task 1b</b> $4.8 < k_{row} < 5.2$ $4.8 < k_{col} < 5.2$ $D < 70$	5.1 enercon's E-44 $P_{wt} = 0.9 \text{ MW}$ , $D = 44 \text{ m}$ , $H = 45 \text{ m}$	$N = 100$ $N_x = 10$ $N_y = 10$	90	$k_{row} = 5.05$ $k_{col} = 5.05$	$SD_x = 222.2$ $SD_y = 222.2$	0.000282
<b>Task 1c</b> $4.5 < k_{row} < 5.5$ $4.5 < k_{col} < 5.5$	9.1 enercon's E-70 $P_{wt} = 2.3 \text{ MW}$ , $D = 71 \text{ m}$ , $H = 58 \text{ m}$	$N = 49$ $N_x = 7$ $N_y = 7$	112.7	$k_{row} = 4.7$ $k_{col} = 4.7$	$SD_x = 333.3$ $SD_y = 333.3$	0.000111
<b>Task 1d</b> $4.5 < k_{row} < 5.5$ $4.5 < k_{col} < 5.5$ $D < 70$	5.1 enercon's E-44 $P_{wt} = 0.9 \text{ MW}$ , $D = 44 \text{ m}$ , $H = 45 \text{ m}$	$N = 121$ $N_x = 11$ $N_y = 11$	108.9	$k_{row} = 4.54$ $k_{col} = 4.54$	$SD_x = 200$ $SD_y = 200$	0.000282

Table 2. Optimal tasks solutions for uniform wind direction ( $L_x = 2000 \text{ m}$ ,  $L_y = 2000 \text{ m}$ )

It is interesting to evaluate the influence of the wind park geometrical shape on the wind turbines choice and placement for uniform wind direction case. The described above optimization tasks are solved for the equivalent wind park area but with rectangular shape ( $L_x = 4\text{ km}$  and  $L_y = 1\text{ km}$ ) as Task 1a-1, Task 1b-1, Task 1c-1 and Task 1d-1. The solution results define optimum wind turbines placement illustrated on Fig. 3 and the corresponding solution data are shown in Table 3.

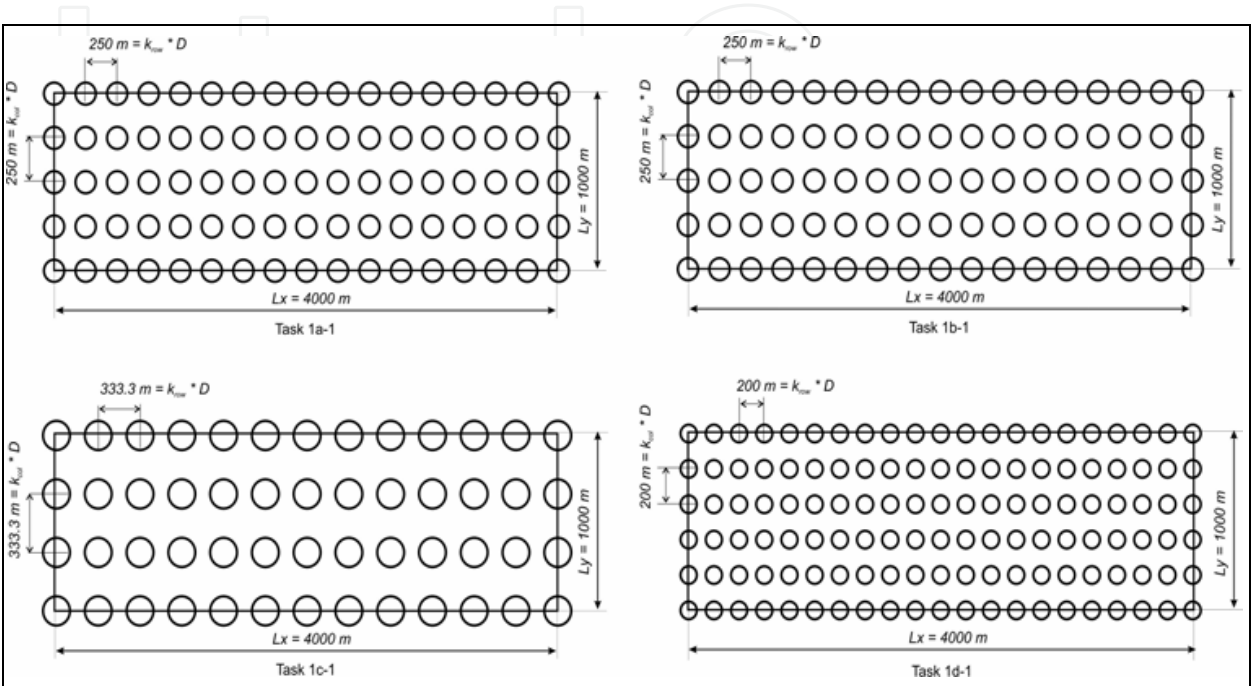


Fig. 3. Wind turbines placement for uniform wind direction and rectangular wind park area

Task	Chosen type of wind turbine	Turbines number	Total installed power, MW	Separation coefficients	Separation distances, m	Cost per unit energy
<b>Task 1a-1</b> $4.8 < k_{row} < 5.2$ $4.8 < k_{col} < 5.2$	4.3 Vestas V52 $P_{wt} = 0.85\text{ MW}$ , $D = 52\text{ m}$ , $H = 74\text{ m}$	$N = 85$ $N_x = 17$ $N_y = 5$	72.25	$k_{row} = 4.8$ $k_{col} = 4.8$	$SD_x = 250$ $SD_y = 250$	0.000298
<b>Task 1b-1</b> $4.8 < k_{row} < 5.2$ $4.8 < k_{col} < 5.2$ $D < 70$	4.1 Vestas V52 $P_{wt} = 0.85\text{ MW}$ , $D = 52\text{ m}$ , $H = 49\text{ m}$	$N = 85$ $N_x = 17$ $N_y = 5$	72.25	$k_{row} = 4.8$ $k_{col} = 4.8$	$SD_x = 250$ $SD_y = 250$	0.000298
<b>Task 1c-1</b> $4.5 < k_{row} < 5.5$ $4.5 < k_{col} < 5.5$	9.1 enercon's E-70 $P_{wt} = 2.3\text{ MW}$ , $D = 71\text{ m}$ , $H = 58\text{ m}$	$N = 52$ $N_x = 13$ $N_y = 4$	119.6	$k_{row} = 4.69$ $k_{col} = 4.69$	$SD_x = 333.3$ $SD_y = 333.3$	0.000111
<b>Task 1d-1</b> $4.5 < k_{row} < 5.5$ $4.5 < k_{col} < 5.5$ $D < 70$	5.1 enercon's E-44 $P_{wt} = 0.9\text{ MW}$ , $D = 44\text{ m}$ , $H = 45\text{ m}$	$N = 126$ $N_x = 21$ $N_y = 6$	113.4	$k_{row} = 4.54$ $k_{col} = 4.54$	$SD_x = 200$ $SD_y = 200$	0.000282

Table 3. Optimal tasks solutions for uniform wind direction ( $L_x = 4000\text{ m}$ ,  $L_y = 1000\text{ m}$ )



The tasks 1a-1, 1b-1, 1c-1 and 1d-1 are also solved for changed wind park orientation i.e. for  $L_x = 1$  km and  $L_y = 4$  km. The solutions results show that changing of the wind park rectangular shape orientation for the uniform wind direction case does not affect the turbines choices but only interchanges the values of  $N_{row}$  and  $N_{col}$ .

3.2 Predominant wind direction case

The predominant wind direction case is characterized by a statistically defined prevailing wind direction that blows most frequently across a particular geographical region. The **Task 1a** and **Task 1b** are reformulated as **Task 2a** and **Task 2b**, considering the predominant wind direction by using different separation distances coefficients limits in (39) and (40) accordingly to the recommended values as:  $k_{row}^{min} = 1.5$ ,  $k_{row}^{max} = 3$ ,  $k_{col}^{min} = 9$ ,  $k_{col}^{max} = 11$ . The tasks 2a and 2b are reformulated as **Task 2c** and **Task 2d** by using relaxed separation distances coefficients limits  $k_{row}^{min} = 2$ ,  $k_{row}^{max} = 4$ ,  $k_{col}^{min} = 8$ ,  $k_{col}^{max} = 12$ . The corresponding optimum wind turbines placement is shown on Fig. 4 accordingly to the solutions results in Table 4.

Task	Chosen type of wind turbine	Turbines number, $N$	Total installed power, MW	Separation coefficients,	Separation distances, m	Cost per unit energy
<b>Task 2a</b> $1.5 < k_{row} < 3$ $9 < k_{col} < 11$	9.1 enercon's E-70 $P_{wt} = 2.3$ MW, $D = 71$ m, $H = 58$ m	$N = 76$ $N_x = 19$ $N_y = 4$	174.8	$k_{row} = 1.56$ $k_{col} = 9.39$	$SD_x = 111.1$ $SD_y = 666.6$	0.000110
<b>Task 2b</b> $1.5 < k_{row} < 3$ $9 < k_{col} < 11$ $D < 70$	5.1 enercon's E-44 $P_{wt} = 0.9$ MW, $D = 44$ m, $H = 45$ m	$N = 138$ $N_x = 23$ $N_y = 6$	124.2	$k_{row} = 2.07$ $k_{col} = 9.09$	$SD_x = 91$ $SD_y = 400$	0.000282
<b>Task 2c</b> $2 < k_{row} < 4$ $8 < k_{col} < 12$	10.2 Vestas V90 $P_{wt} = 3$ MW, $D = 90$ m, $H = 105$ m	$N = 36$ $N_x = 12$ $N_y = 3$	108	$k_{row} = 2.01$ $k_{col} = 11.11$	$SD_x = 181.8$ $SD_y = 1000$	0.000089
<b>Task 2d</b> $2 < k_{row} < 4$ $8 < k_{col} < 12$ $D < 70$	5.1 enercon's E-44 $P_{wt} = 0.9$ MW, $D = 44$ m, $H = 45$ m	$N = 132$ $N_x = 22$ $N_y = 6$	118.8	$k_{row} = 2.16$ $k_{col} = 9.09$	$SD_x = 95.2$ $SD_y = 400$	0.000282

Table 4. Optimal tasks solutions for predominant wind direction ( $L_x = 2000$  m,  $L_y = 2000$  m)

It could be expected that in the case of predominant wind direction the geometrical shape of the wind park influence the choice of wind turbines type and number. To investigate that the optimization tasks 2a, 2b, 2c, 2d are solved as **Task 2a-1**, **Task 2b-1**, **Task 2c-1**, **Task 2d-1** for rectangular wind park shape with dimensions  $L_x = 4$  km and  $L_y = 1$  km. Their solution results are shown in Table 5 and optimum wind turbines placement - on Fig. 5.

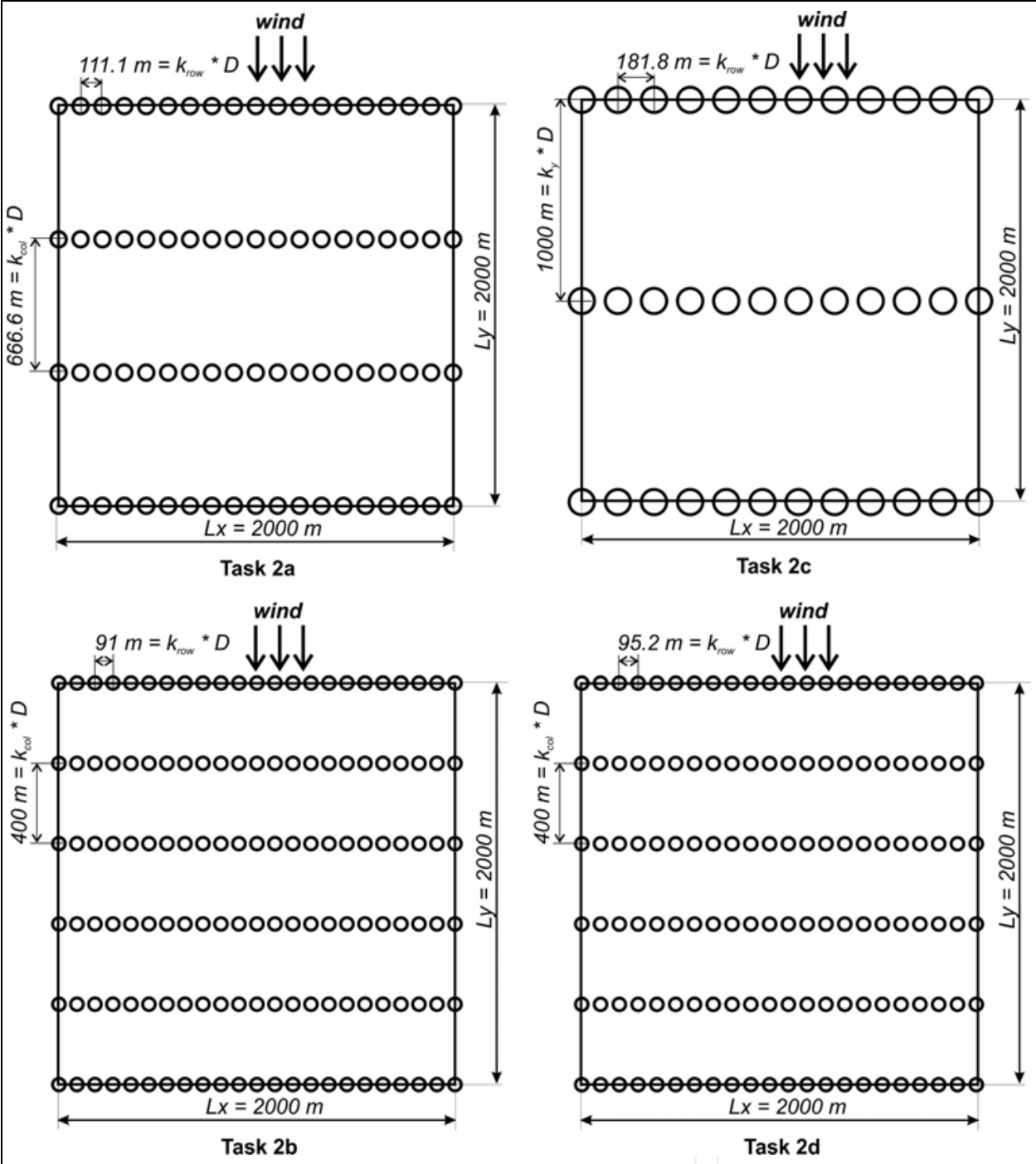


Fig. 4. Wind turbines placement for predominant wind direction and square wind park area

To investigate the influence of the rectangular wind park orientation toward predominant wind direction the tasks 2a-1, 2b-1, 2c-1 and 2d-1 are reformulated as **Task 2a-2**, **Task 2b-2**, **Task 2c-2** and **Task 2d-2** with interchanged wind park dimensions as  $L_x = 1\text{ km}$  and  $L_y = 4\text{ km}$ , i.e. for changed wind park orientation toward wind direction. The corresponding solutions results and wind turbines placements are shown in Table 6 and on Fig. 6 respectively.

Task	Chosen type of wind turbine	Turbine s number, N	Total installed power, MW	Separation coefficients,	Separation distances, m	Cost per unit energy
<b>Task 2a-1</b> $1.5 < k_{row} < 3$ $9 < k_{col} < 11$	4.3 Vestas V52 $P_{wt} = 0.85$ MW, $D = 52$ m, $H = 74$ m	$N = 156$ $N_x = 52$ $N_y = 3$	132.6	$k_{row} = 1.51$ $k_{col} = 9.61$	$SD_x = 78.43$ $SD_y = 500$	0.000298
<b>Task 2b-1</b> $1.5 < k_{row} < 3$ $9 < k_{col} < 11$ $D < 70$	4.1 Vestas V52 $P_{wt} = 0.85$ MW, $D = 52$ m, $H = 49$ m	$N = 156$ $N_x = 53$ $N_y = 3$	132.6	$k_{row} = 1.51$ $k_{col} = 9.61$	$SD_x = 78.4$ $SD_y = 500$	0.000298
<b>Task 2c-1</b> $2 < k_{row} < 4$ $8 < k_{col} < 12$	10.2 Vestas V90 $P_{wt} = 3$ MW, $D = 90$ m, $H = 105$ m	$N = 46$ $N_x = 23$ $N_y = 2$	138	$k_{row} = 2.02$ $k_{col} = 11.11$	$SD_x = 181.8$ $SD_y = 1000$	0.000086
<b>Task 2d-1</b> $2 < k_{row} < 4$ $8 < k_{col} < 12$ $D < 70$	5.1 enercon's E-44 $P_{wt} = 0.9$ MW, $D = 44$ m, $H = 45$ m	$N = 132$ $N_x = 44$ $N_y = 3$	118.8	$k_{row} = 2.11$ $k_{col} = 11.36$	$SD_x = 93$ $SD_y = 500$	0.000282

Table 5. Optimal solutions for predominant wind direction and rectangular wind park area ( $L_x = 4$  km,  $L_y = 1$  km)

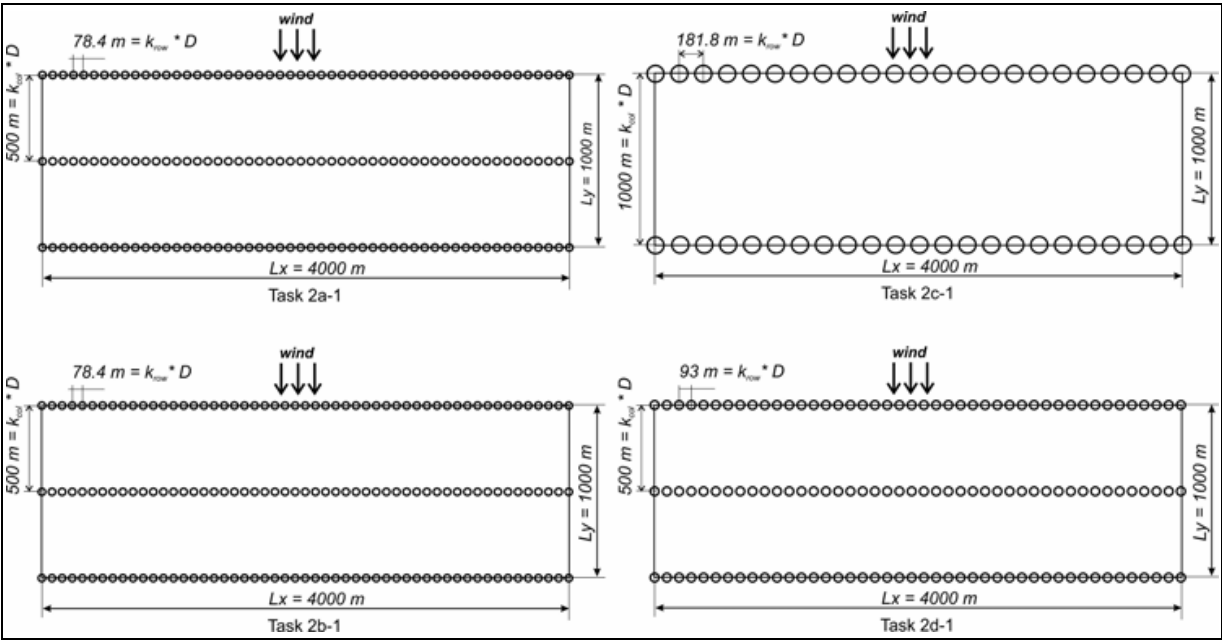


Fig. 5. Wind turbines placement for predominant wind direction toward the long side of rectangular wind park shape

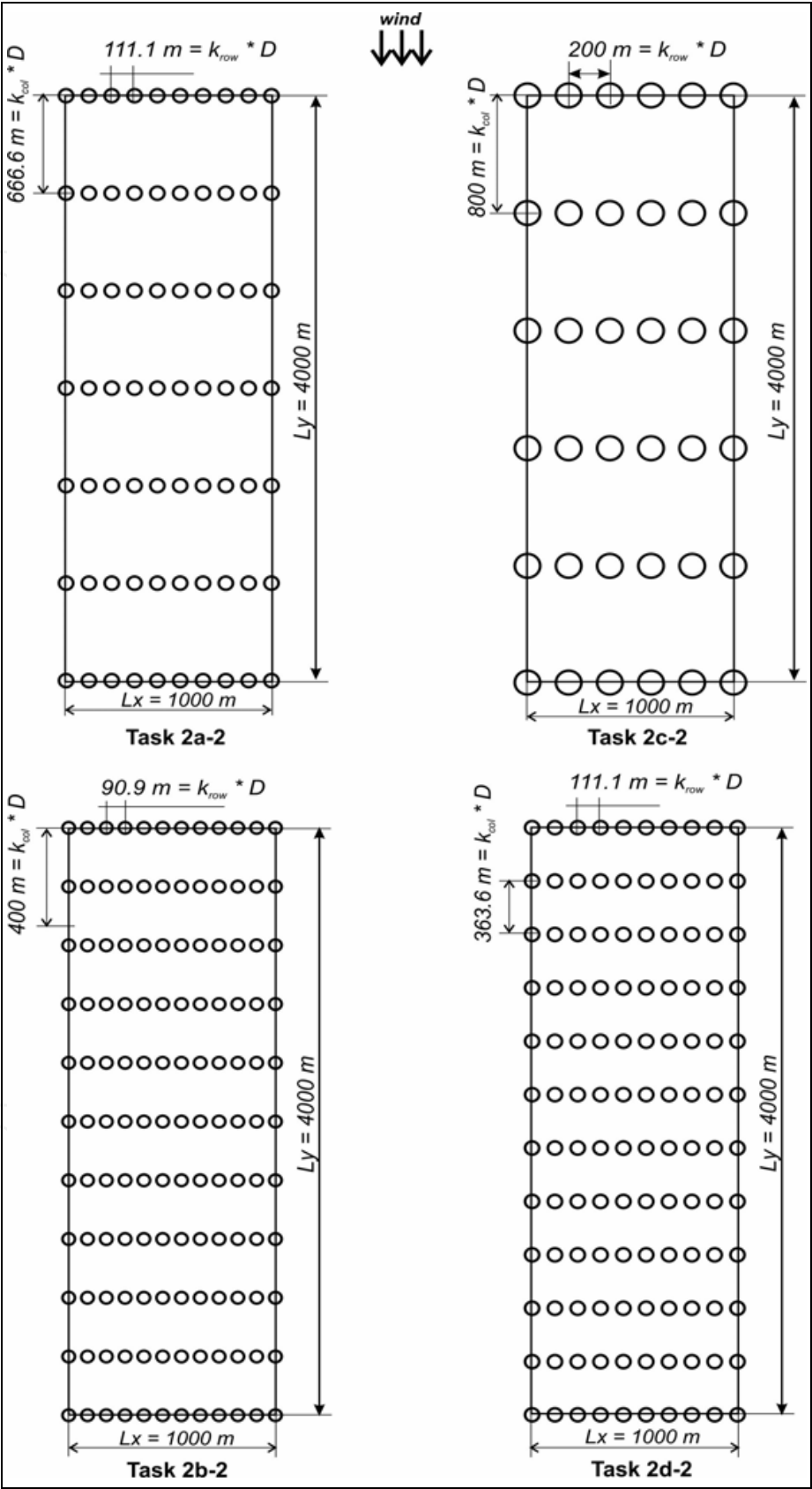


Fig. 6. Wind turbines placement for predominant wind direction toward the short side of rectangular wind park shape

Task	Chosen type of wind turbine	Turbines number, $N$	Total installed power, MW	Separation coefficients,	Separation distances, m	Cost per unit energy
<b>Task 2a-2</b> $1.5 < k_{row} < 3$ $9 < k_{col} < 11$	9.1 enercon's E-70 $P_{wt} = 2.3$ MW, $D = 71$ m, $H = 58$ m	$N = 70$ $N_x = 10$ $N_y = 7$	161	$k_{row} = 1.56$ $k_{col} = 9.39$	$SD_x = 111.1$ $SD_y = 666.6$	0.000110
<b>Task 2b-2</b> $1.5 < k_{row} < 3$ $9 < k_{col} < 11$ $D < 70$	5.1 enercon's E-44 $P_{wt} = 0.9$ MW, $D = 44$ m, $H = 45$ m	$N = 132$ $N_x = 12$ $N_y = 11$	118.8	$k_{row} = 2.07$ $k_{col} = 9.09$	$SD_x = 90.9$ $SD_y = 400$	0.000282
<b>Task 2c-2</b> $2 < k_{row} < 4$ $8 < k_{col} < 12$	10.2 Vestas V90 $P_{wt} = 3$ MW, $D = 90$ m, $H = 105$ m	$N = 36$ $N_x = 6$ $N_y = 6$	108	$k_{row} = 2.22$ $k_{col} = 8.88$	$SD_x = 200$ $SD_y = 800$	0.000089
<b>Task 2d-2</b> $2 < k_{row} < 4$ $8 < k_{col} < 12$ $D < 70$	5.1 enercon's E-44 $P_{wt} = 0.9$ MW, $D = 44$ m, $H = 45$ m	$N = 120$ $N_x = 10$ $N_y = 12$	108	$k_{row} = 2.52$ $k_{col} = 8.26$	$SD_x = 111.1$ $SD_y = 363.6$	0.000282

Table 6. Optimal solutions for predominant wind direction and rectangular wind park area ( $L_x = 1$  km,  $L_y = 4$  km)

4. The numerical testing analysis and discussions

The first obvious result of the tasks solutions is that the different tasks formulations with different restrictions define different turbines' type and number choices. The increasing of the feasible space for the separation coefficients  $k_{row}$  and  $k_{col}$  by defining wider limits of their values also define different choices as it is illustrated by the solutions of **Task 1a** compared to **Task 1c**, **Task 1a-1** to **Task 1c-1**, **Task 2a** to **Task 2c**, **Task 2a-1** to **Task 2c-1** and **Task 2a-2** to **Task 2c-2**. Generally speaking, in the uniform wind direction case the larger feasible interval of the separation coefficients  $k_{row}$  and  $k_{col}$  define better choices in respect to the installed power and cost per unit of energy (**Task 1a** and **Task 1c**, **Task 1a-1** and **Task 1c-1**). For the predominant wind direction case such tendency is not observed (**Task 2a** and **Task 2c**, **Task 2a-1** and **Task 2c-1**, **Task 2a-2** and **Task 2c-2**). Changing of the wind park square shape to rectangular shape influences the turbines type and number choices in most uniform and predominant wind direction cases – **Task 1a** and **Task 1a-1**, **Task 1c** and **Task 1c-1**, **Task 2a** and **Task 2a-1** and **Task 2a-2**, **Task 2c** and **Task 2c-1** and **Task 2c-2**. Some tasks solutions define the same turbine's type choice but different turbines number. As it is expected, the changing of the wind park rectangular shape orientation for the uniform wind direction case does not affect the solutions choices but only interchanges values of  $N_{row}$  with  $N_{col}$  respectively. For the predominant wind direction case the turbines choice depends on



the rectangular shape orientation toward the wind direction (**Task 2a-1** and **Task 2a-2**, **Task 2b-1** and **Task 2b-2**, **Task 2c-1** and **Task 2c-2**, **Task 2d-1** and **Task 2d-2**). In that case again some tasks solutions define the same turbines type choice but different turbines number (**Task 2c-1** and **Task 2c-2**, **Task 2d-1** and **Task 2d-2**). The solution results show that the wind park shape and orientation should be taken into account when formulating the optimization tasks to get optimal wind park layout design. The turbines rotor diameter restriction narrows the turbines type choice and in some cases results in equivalent turbines type (**Task 1b** and **Task 1d**, **Task 2b** and **Task 2d**, **Task 2b-2** and **Task 2d-2**) but with different turbines number. The wind turbines choice optimality is judged by the used optimization criterion – the value of costs per unit energy. The comparison of the those values in last columns of tables 2, 3, 4, 5 and 6 shows that using of small number of big wind turbines (with bigger rated power and rotor diameter) is more economically justified to that optimization criterion then using of large number of smaller wind turbines. The best costs per unit of energy values are obtained for **Task 1c** ( $P_{wt} = 2.3$  MW,  $D = 82$  m), **Task 1c-1** ( $P_{wt} = 2.3$  MW,  $D = 71$  m), **Task 2a** ( $P_{wt} = 2.3$  MW,  $D = 71$  m), **Task 2c** ( $P_{wt} = 3$  MW,  $D = 90$  m), **Task 2c-1** ( $P_{wt} = 3$  MW,  $D = 90$  m), **Task 2a-2** ( $P_{wt} = 2.3$  MW,  $D = 71$  m) and **Task 2c-2** ( $P_{wt} = 3$  MW,  $D = 90$  m). Nevertheless it is important to note that the size of wind turbines is closely related to the wind conditions of the given wind park area. That means the optimal wind turbines choice should take into account the wind conditions of the particular area by introducing of the proper relations and restrictions. The tasks **1b**, **1d**, **1b-1**, **1d-1**, **2b**, **2d**, **2b-1**, **2d-1**, **2b-2** and **2d-2** illustrate that by adding the restriction for the size of the turbine rotor diameter which defines the choice of smaller turbines.

The formulated optimization tasks are based on the sample data from Table 1. They are used to illustrate numerically the applicability of the proposed wind park layout design approach. The tasks solution times are about a few seconds on PC with Intel Core i3 CPU/2.93 GHz and 3 GB RAM. Larger sets of turbines and parameters together with additional restrictions can be taken into consideration to get a better conformance to the particular wind park design requirements. That will reflect in increasing of the optimization tasks solutions space but also will increase the size of the tasks and eventually their computational difficulties.

The widely used in wind park design cost per unit energy ratio optimization criterion is one of the possible optimization criteria. It could be refined by using of statistical data for the wind conditions of particular geographical area and calculating of more precise value for the nominal power utilization coefficient  $\mu$ . Other analytical formulas for wind park power output and other optimization criteria including different economical, technological and ecological requirements could be used.

## 5. Conclusions

The wind park layout design is important for ensuring of the expected wind power capture without increasing of the project costs. A combinatorial optimization modeling approach for wind park layout design considering the wind park area shape, size, orientation and different requirements and restrictions is proposed. It is used for formulation of single criterion mixed-integer nonlinear optimization tasks. The relation of investment costs and power output as function of wind turbines number and type is used as optimization criterion. The solutions of formulated optimization tasks give the optimal wind turbines



type and number for given wind park area. It is assumed that from technological point of view it is better to have all wind park turbines of the same type. The wind turbines number is defined on the basis of given wind park area size and turbines' spacing recommendations. Two basic wind directions cases are presumed – uniform and predominant wind directions for square and rectangular wind park, both with equivalent area. The turbines' spacing is modeled by introducing of variable separation distances coefficients within given lower and upper limits. The values of the separation distance coefficients and turbines number define the wind park turbines placement taking into account the wind direction.

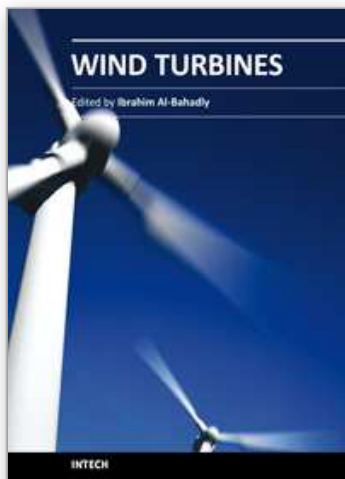
The developed wind park design approach was tested numerically by solving of different real data optimization tasks formulations involving different separation coefficients limits and wind park shapes and orientations. The wind park orientation for the uniform wind direction does not change significantly the layout design – it only exchanges the numbers of turbines in rows and columns for the case of rectangular wind park. For the predominant wind direction case and rectangular shape of the wind park the turbines choice and placement depends on the park orientation toward the wind direction. The optimization tasks solutions show that the different practical requirements and restrictions define in general, different turbines choices. The solution results confirm the practical conclusion that using of big size turbines is more profitable than large numbers of small size turbines. The numerical testing shows the applicability of the developed optimization approach to wind park layout design. It could be used in the design of both onshore and offshore wind farms design by introducing of specific requirements as variables relations and restrictions. The proposed approach can be programmed as module in computer aided design system. It could be used also as a computer simulation tool for different wind park design conditions thus assisting mathematically reasoned decision making as contradiction to the heuristic approaches.

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## **Wind Turbines**

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The area of wind energy is a rapidly evolving field and an intensive research and development has taken place in the last few years. Therefore, this book aims to provide an up-to-date comprehensive overview of the current status in the field to the research community. The research works presented in this book are divided into three main groups. The first group deals with the different types and design of the wind mills aiming for efficient, reliable and cost effective solutions. The second group deals with works tackling the use of different types of generators for wind energy. The third group is focusing on improvement in the area of control. Each chapter of the book offers detailed information on the related area of its research with the main objectives of the works carried out as well as providing a comprehensive list of references which should provide a rich platform of research to the field.

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