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A Generalized Combinatorial Optimization Approach to Wind Power Plant Design

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Abstract: *The paper discusses wind power plant design problems. The main design process steps are described and structured. A generalized combinatorial optimization approach to optimal wind power plants design is proposed. It aims to increase the effectiveness of the design process by mathematical modeling and using optimization problems. The single- or multiobjective optimization problems solutions give optimal values of the design variables. As a result, some preliminary theoretical estimation about the designed wind power plant parameters can be achieved. The application of the proposed approach decreases the design time, costs and related risks to intuitive decision making.*

Keywords: *Renewable energy sources, wind power plants design, mathematical modeling, combinatorial optimization problems.*

1. Introduction

The interest towards energy, produced from renewable sources, has rapidly grown over the years. This means that the energy produced from wind power plants has also gained more interest. The numerous benefits of renewable energy sources usage are widely recognized – they help to overcome climate changing, energy supply and support meeting the long term economic goals. The renewable energy sources include sun, wind, water and geothermal energy, and energy from firewood, animal manure, crop residues and biomass. The wind, used as an energy source, rapidly takes a leading place among the renewable energy sources. The wind is a free, clean and inexhaustible energy source. It is a form of sun energy and is a result of uneven atmosphere heating, the earth spin, earth terrain roughness and will exist until the sun exists. Currently the wind energy is the most widely used non-polluting environment alternative to other traditional energy sources for electricity production. The energy production from renewable sources is encouraged by the European and Bulgarian legislation. Directive 2001/77/EC of the European Parliament and the Council on the promotion of electricity produced from renewable energy sources promotes an increase in the internal electricity market and creates a basis for the future European Community framework. The wind energy use is in the spirit of another European program “Intelligent Energy – Europe” and included in its framework “Sustainable Energy Europe”, initiative of the European Commission. The European Council inspires EU regions to take up the challenges of fulfilling the EU 20-20-20 climate and energy targets of at least 20% reduction in greenhouse gas emissions, 20% increase in energy efficiency and 20% of energy from renewable sources by 2020. Because of the wind energy specifics, the development and design of a wind power plant should conform to different and often contradictory requirements. In this regard, a variety of investigations for effective wind parks design are held. Several scientific research directions can be summarized on the basis of the existing publication analysis:

- statistical investigations of the geographical, climate and ecologic specifics of the wind energy potential or the so called “wind energy audit” (Ucar and Balo, [24]; Chen and Blaabjerg [5]; Ramirez-Rosado et al. [26]; Snyder and Kaiser [31]),
- aero-dynamic investigations of the wind turbines air flows and optimization of the wind turbines as demonstrated in the papers (Nagai et al. [19]; Chattot [2]; Deglaire et al. [5]; Xydis et al. [25]; Frandsen [10]; Guo et al. [14]; Ammara et al. [1])
- wind power plants design, taking into account different economic, technologic and ecologic factors including wind turbines number and type choice, wind turbines optimal placement in the wind park area, etc., as described in (Mustakerov and Borissova [18]; Emami and Noghreh [8]; Sargolzaei and Kianifar [22]; Ettoumi et al. [9]; Grady et al. [12]; Conover [4]).

The investigations of the first scientific direction are specific for each particular country and the results obtained depend on the country geography and climate features. The second scientific direction can be characterized with essential research achievements, technologic solutions and patents used in the development of modern effective commercial wind turbines. The research results from those scientific directions are used in the third development direction – a wind power plant design. This direction is characterized by numerous and contradictory economic, technologic and ecologic requirements leading to difficulties in solving the practical problems. The existing wind power plant design difficulties are solved in many cases on the basis of intuitive and heuristic decisions making (Emami and Noghreh [8]; Grigorios et al. [13]; Mora et al. [17]; Donovan [6]; Elkinton et al. [7]; Grady et al. [12]).

The problems in wind power plant design process and the importance of wind energy use in implementing new energy politics defines the ultimate goal of the investigations and development of mathematical models and methods for optimal wind power plant design. The current paper deals with the development of a generalized optimization approach for wind power plant design process to guarantee the best usage of the available resources while satisfying given restrictions and requirements.

2. Problem formulation

There exists a variety of contradictory economic, technologic and ecologic requirements and criteria for wind power plant design that lead to essential difficulties in proper decision making. In practice, many wind power plant decisions are taken heuristically. To improve the effectiveness of the wind power plant design process, it should be formalized. This means the use of operations research techniques for scientifically reasoned decision making. The usage of mathematical methods gives also some preliminary theoretical estimation for the designed wind power plant characteristics and preliminary evaluation of the satisfaction of given requirements. The availability of such preliminary theoretical evaluation would decrease the risks of taking ineffective or even wrong wind power plant design decisions.

A wind power plant consists of a number of wind turbines, connected by an internal grid which is integrated to the main grid. The numbers of turbines are limited by the wind power plant area. On the other hand, the location of the wind turbines within the wind site (i.e., the wind park layout), is affected by several factors which have to be taken into account – the wind direction, turbines type, wake interactions between wind turbines, wind park site area and shape, etc. It is important during the design phase to assess the best wind power plant layout so that it captures as much as possible power. How to choose the number and the type of the turbines to install depends on a variety of factors – the wind conditions, terrain, investments costs, power output, environmental influence, etc. A 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 site layout is affected by turbines number, wind resource, wake interactions between wind turbines, land availability, etc. Wind resource evaluation is a critical element in wind power plant design process. The energy available in a wind stream is proportional to the cube of its speed. Furthermore, the wind resource itself is seldom a steady, consistent flow. It varies with the day time, season, height above ground, and type of terrain. Proper placing in windy locations, away from large obstructions, enhances a wind turbine's performance. As a result of the technological advances there exists a number of different types and models of wind turbines that can be used. The different wind turbines have different technical characteristics influencing their effectiveness, power production and price, and all of these define the necessity for proper wind turbines choice.

The application of mathematical modelling and optimization to engineering systems design and in particular to wind power plant design in order to assist the designers in improving the system performance, is known as design optimization. It is widely recognized as a rational and powerful tool to the optimal design solution. Such applications consist of mathematical modeling of the original design problem and optimization problems solving in seeking its optimum (Mustakerov and Borissova [18]; Fujita [11]). When a variety of discrete design solutions exists, a combinatorial optimization approach can be used to reduce the possible solutions by modeling of the problem based on the characteristics of a specific situation before optimization computation and to look for an optimal solution (Fig. 1).

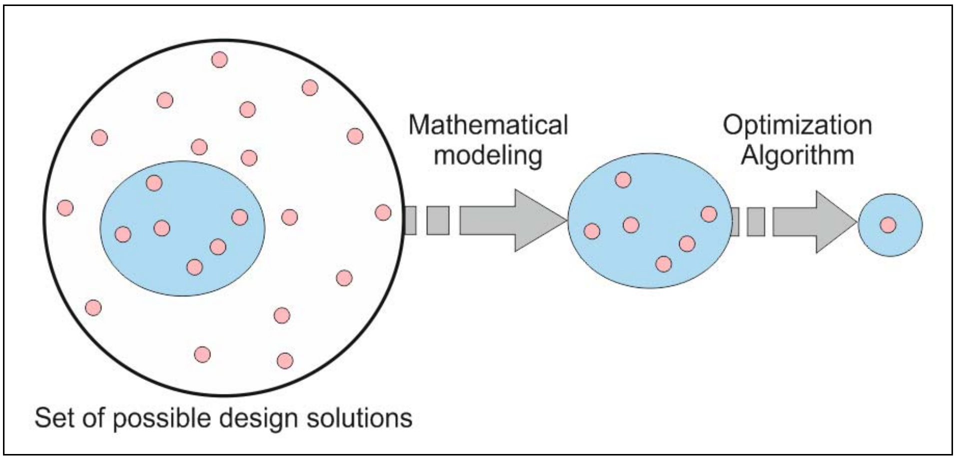

Fig. 1. Combinatorial optimization design approach

The design problems discussed can be classified as application of an interdisciplinary branch of applied mathematics for improvement of the effectiveness of the wind power plants design process. To minimize the investment costs and to maximize the utilization of wind-generated electricity, connected to the electric grid, a proper approach based on combinatorial optimization for the wind power plant design is proposed.

3. Wind power plant design process

The financing of a wind power plant project requires careful consideration of all different aspects, as well as the associated legal and commercial arrangements. Before investment, any project finance lender will want to know if there is any risk that repayment will not be made over the loan term. The investors have to make careful consideration of the technical, financial and other risks, as well as considering how the investment in a project fits in with the bank’s own investment strategy. All of these considerations are generalized by the activities needed to be included in the proper methodology. They involve four different directions: wind resources evaluation, mathematical modelling and optimization (operations research methods), risk analysis and software programming, as shown on Fig. 2.

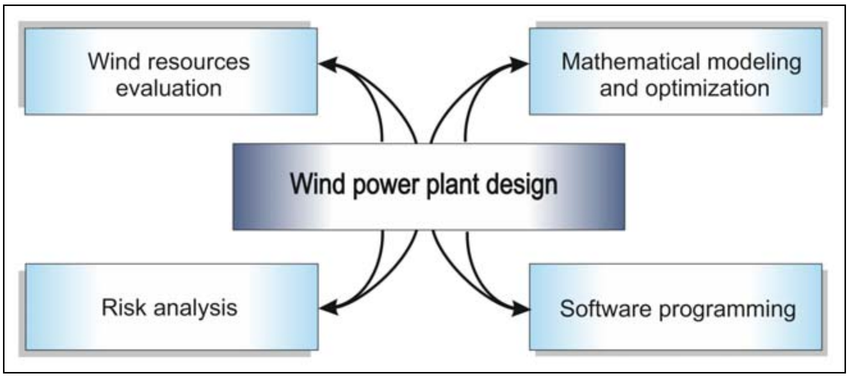

Fig. 2. Basic directions of the wind power plant project

To realize the wind power plant project, the main stages of the optimal design can be ordered in a structured diagram shown in Fig. 3.

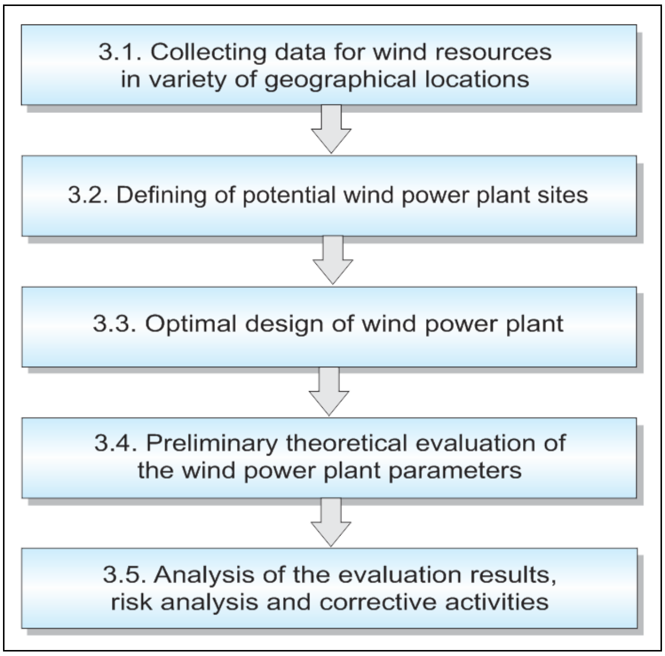

Fig. 3. Stages of optimal wind power plants design

3.1. Collecting data for wind resources in variety of geographical locations

The most important factor in selecting the geographical location of a wind power site is the wind resource itself. The knowledge of the wind resource is needed to estimate the energy production of the designed wind power plant. To estimate it, a "wind atlas" of the potential wind power plant geographical locations should be created. The first step is to eliminate all sites that are not expected to have sufficient wind resource. The second step is to mount the proper equipment for wind parameters data collecting. The data quality depends on the quality of the measurement equipment, the number of heights to collect wind speeds, the recording methods used, and a data capture rate. It is important that the airflow measured to be clear of obstructions, such as trees and buildings, and that the height is adequate to assess wind speeds at typical wind turbine heights. The variability of the wind makes accurate measurements difficult, so rather expensive equipment is often required. The wind direction is also an important item of information, as well as the correlation between speed and direction. The measurements have to be taken consistently from the same location for a sufficient time period. As a result the wind speed, direction frequency distribution and wind profile for each site will be available, i.e., the wind atlas is created. The wind atlas data can be used to classify the potential wind site location according to the wind resources parameters.

3.2. Defining of the potential wind power plant sites

When selecting a potential wind power plant site, it should be taken into account that all the land with a good wind energy resource may not be suitable for wind park development. Initially, the sites where wind turbines either cannot or should not be installed should be eliminated. For example, the following factors would be used to eliminate a potential wind power plant site (C o n o v e r [4]):

- national parks or other areas officially protected from development,
- migration routes of birds,
- areas with high concentrations of rare or endangered birds,
- urban areas,
- some military areas,
- highly culturally sensitive areas (e.g., religious, historic, or archeological sites).

There are many other factors that also affect site suitability. The costs and performance of a project must be considered in the site selection process too. Other factors to consider in the evaluation include whether or not transmission lines with insufficient capacity to support a project should or could be upgraded. Remote and/or complex terrains increase the development costs. Such terrains may also limit the size of the turbines that can be installed. It can also lead to less-than-optimal turbine siting because the terrain features affect the project layout. The proximity of the site to access roads is also a consideration. The orientation of the terrain relative to the prevailing wind directions will heavily affect the site’s capacity potential, as well as its energy production.

3.3. Optimal design of a wind power plant

The ideal wind power plant design is dictated by a goal to maximize energy production, minimize capital and operating costs, and comply with different constraints. There are many and often conflicting, requirements included into the design process. The wind power plant is typically laid out considering various site sizes, site layouts, turbine types, hub heights, rotor diameters, etc. Placing of the wind turbines on the site must be considered carefully to avoid unacceptably high wake losses.

The considerations from Stages 3.1 and 3.2 are taken into account in the development of a proper mathematical model used to realize a mathematically reasoned wind power plant design. The mathematical model should consider the ability of the site to accommodate the planned project size and the potential future expansion. This is particularly true if significant investment in the transmission system upgrades is required to deliver energy from the project to the site. The site's capacity must be determined using turbines that can be transported to and erected on the site. Typically, a more complex terrain will be more optimally developed with relatively smaller turbines because larger cranes and trucks are needed for larger turbines. The capacity is usually affected by the amount of the terrain that is relatively high compared to the surrounding area, such as long ridgelines or plateaus. Areas with more isolated hilltops offer less ideal locations for turbines, hence may hold less capacity.

The wind turbine type is one of the key factors to consider during the complex process of designing a wind power plant. The wind turbines are developed to reflect specific wind conditions. The wind turbine generators classes are defined by the International Electrotechnical Commission standard, based on three parameters: the average wind speed (at the turbine's hub height), extreme 50-years gust, and how much turbulence is available on the wind site as shown in Table 1 (**http://windwire.blogspot.com/2009/05/iec-classification-of-turbines.html**).

Table 1. Wind Turbine Generators Classes

Wind Turbine Generators Class	I	II	III	IV
Annual average wind speed	10 m/s	8.5 m/s	7.5 m/s	6.0 m/s
Extreme wind speed 50-year gust	70 m/s	59.5 m/s	52.5 m/s	42.0 m/s
Turbulence Class A	18%			
Turbulence Class B	16%			

Note. Turbulence is the standard deviation of wind speed measured at 15 m/s wind speed.

Different industrial wind power plant costs investigations show that 60-80% of the overall investment costs constitute of the installed wind turbines price. On the other hand, the cost of the commercial wind turbines vary from $1 to $2 million per 1 MW of nameplate installed capacity. The smaller turbines, fewer than 100 kW in size, cost less but are more expensive regarding the installed electrical power. The wrong choice of the wind turbine type, height, number, placement, etc., could lead to wind power plant ineffectiveness and to significant economic losses. Taller towers increase the wind turbine energy production but cost more to build, so this tradeoff must be optimized during the design process. The choice of a wind turbine type would determine the most suitable one for particular wind conditions on the site. Wind turbines are typically arranged in rows perpendicular to prevailing winds. 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 of 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 the wind energy behind the neighbouring turbines (Sørensen [23]; Grady et al. [12]). 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. The minimum distance between the turbines is 8-12 rotor diameters in the prevailing wind direction and 1.5-3.0 rotor diameters in the crosswind direction (Emami and Noghreh [8]). If the wind is consistently from one direction, then the within row spacing is less and the row to row spacing is greater. For sites that have energetic winds from multiple directions, the row to row spacing and the within row spacing are similar. Relevant investigations are to be done concerning mathematical models formulation, taking into account the various aspects of the wind power plant design problems.

The development of proper mathematical models and methods for optimal choice of the wind turbines type, the number and placement based on trustworthy data about the wind resources, considering technologic and ecologic restrictions would optimize the wind power plant effectiveness toward costs.

3.4. Preliminary theoretical evaluation of the wind power plant parameters

One of the major advantages of mathematical modeling use is the possibility to get theoretical estimation about the designed wind power plant parameters. Some of the essential wind power plant parameters include the separation distance between turbines, as well as the hub height and rotor diameter of the wind turbines in the wind power plant. Using the separation distances, the turbines placement, i.e., the wind power plant layout could be determined. As a result of the design process, the theoretical evaluation of a particular wind power plant overall installed power capacity and the expected output power could be determined. Both the installed power capacity and the expected output power depend on the turbines type and number. The expected wind power plant output capacity could be estimated, taking into account the local wind conditions and wind turbines' type and number. The information about the wind power plant design parameters could be used from the investors to make careful consideration of the technical, financial and other risks.

3.5. Analysis of the evaluation results, risk analysis and corrective activities

An analysis of the evaluation results has to be done about the adequacy towards the design goals. If the results do not correspond to the goals, some modification and adjusting of the models and methods are to be done. Taking into account that analysis, the developed mathematical model adequacy and optimization problems effectiveness are to be estimated. The most appropriate methods for solving the formulated optimization problems have to be specified as well.

Like any other major energy project, the wind power plant projects are related to different technologic and economic problems, and proper risks analysis should be considered. In principle, any similar project based on new technology and on renewable energy sources use involves significant investments and is characterized by the existence of economic risks due the non-deterministic wind energy nature. That is why risk analysis is an essential step to be considered. The overall stage result should define the proper corrective activities if they are needed for the previous stages to get the expected design goal satisfaction. The described wind power plant design process can be implemented as a standalone software application or to be integrated into a Computer Aided Design (CAD) system package for combined techno-economic design, analysis, planning and optimization of the wind power plant projects.

4. A generalized combinatorial optimization approach for wind power plant design

In the current paper a generalized combinatorial optimization approach is proposed for Stage 3.3, concerning the optimal wind power plant design process.

The wind power plant design process is characterized by some design variables that should have their values from preliminary defined finite discrete sets. For example, $a \in \{a_1, a_2, a_3, \ldots, a_n\}$ is a design variable for choosing of the wind turbines type from available n types. Each of the design variables has its own parameters that can be expressed by a matrix structured in columns representing the particular parameter and rows, representing the set of values for a particular design variable value. If a_i^1 is the rated power of i-th turbine, a_i^2 is the rotor diameter, a_i^3 is the hub height, a_i^4 is the turbine noise, etc., up to a_i^m , then the corresponding matrix defining the variable a decision space for i = 1,.., n, is

$$\begin{pmatrix} a_1^1 & a_1^2 & \ldots & a_1^m \\ a_2^1 & a_2^2 & \ldots & a_2^m \\ . & . & \ldots & . \\ . & . & \ldots & . \\ a_n^1 & a_n^2 & \ldots & a_n^m \end{pmatrix}. \qquad (1)$$

Another wind power plant design variable example could be a particular wind park site that has to be chosen from available k sites, represented by $b \in \{b_1, b_2, b_3, \ldots, b_k\}$. The decision space of this variable can be defined analogically by a matrix consisting of wind site parameters. If b_j^1 is the wind site size of j-th site, b_j^2 – the wind site shape, b_j^3 – the wind site roughness, etc., up to b_j^k then the variable decision space for j = 1,.., s is described as

$$\begin{pmatrix} b_1^1 & b_1^2 & \ldots & b_1^k \\ b_2^1 & b_2^2 & \ldots & b_2^k \\ . & . & \ldots & . \\ . & . & \ldots & . \\ b_s^1 & b_s^2 & \ldots & b_s^k \end{pmatrix}. \qquad (2)$$

Thus, the other wind power plant design variables could be introduced to reflect the specifics of the design process.

The main idea of the combinatorial optimization approach proposed is to use binary integer variables to select the best design variables parameters values. For this purpose, the corresponding vectors of the binary integer variables are introduced. For example, the parameter values of the design variable *a* are chosen by the vector *X*

(3)
$$X = \begin{pmatrix} x_1 \\ x_2 \\ . \\ . \\ x_m \end{pmatrix}, \; x_i \in \{0, 1\}, \; \sum_{i=1}^{m} x_i = 1,$$

and for the design variable *b* by the vector

(4)
$$Y = \begin{pmatrix} y_1 \\ y_2 \\ . \\ . \\ y_k \end{pmatrix}, \; y_j \in \{0, 1\}, \; \sum_{j=1}^{k} y_j = 1.$$

The choices of the design variables are realized by multiplication of the matrix of the design variables parameters to the binary integer variable vectors, as it is shown for *a* and *b* example:

(5)
$$a = \begin{pmatrix} a_1^1 & a_1^2 & \ldots & a_1^m \\ a_2^1 & a_2^2 & \ldots & a_2^m \\ . & . & \ldots & . \\ . & . & \ldots & . \\ a_n^1 & a_n^2 & \ldots & a_n^m \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ . \\ . \\ x_m \end{pmatrix}^{\mathrm{T}},$$

(6)
$$b = \begin{pmatrix} b_1^1 & b_1^2 & \ldots & b_1^k \\ b_2^1 & b_2^2 & \ldots & b_2^k \\ . & . & \ldots & . \\ . & . & \ldots & . \\ b_s^1 & b_s^2 & \ldots & b_s^k \end{pmatrix} \begin{pmatrix} y_1 \\ y_2 \\ . \\ . \\ y_k \end{pmatrix}^{\mathrm{T}}.$$

The realistic design process is characterized by the existence of some relations between the design variables parameters that can be expressed by functional restrictions of the type

(7)
$$g = f(a, b).$$

On the other hand, the design variables parameters in practice can also be considered to have some preferable values. These types of requirements can be taken into account by the lower and/or upper boundaries for the parameters values:

(8)
$$L_p \le a_i^p \le U_p,\ p \in \{1, 2, ..., m\},$$
$$L_r \le b_j^r \le U_r,\ r \in \{1, 2, ..., k\}.$$

The wind power plant design must satisfy some criteria for optimal design defined as functions of the design variables parameters:

(9)
$$f_t(a_i, b_j).$$

Some examples of known criteria to be used in optimization problem formulation are:

- minimizing the cost per unit energy (M o s e t t i et al. [16])

(10)
$$\text{costs} = N\left(\frac{2}{3} + \frac{1}{3}\exp(-0.00174\ N^2)\right)$$

where N is the number of installed turbines;

- minimizing the levelized cost of energy (M a n w e l l et al. [15])

(11)
$$\text{LCOE} = \frac{C_{\text{c}}\text{FCR} + C_{\text{O\&M}}}{\text{AEP}}$$

where C_{c} is the total installed capital cost of the wind power plant (turbine, infrastructure and transmission costs), FCR is the fixed energy charge rate, $C_{\text{O\&M}}$ is the annual operation and maintenance costs, AEP is the annual energy production;

- maximizing the installed wind plant power P

(12)
$$P = NP_{\text{wt}}$$

where N is the number of installed turbines and P_{wt} is the single wind turbine rated power.

Similar criteria or a combination of them can be used to formulate single- or multiple objective optimization problems of the type max (or min) (9) subject to (3)-(8), whose solutions will define an optimal or Pareto-optimal wind power plant design. An example of the application of the proposed approach for optimal wind power plant design is described in (M u s t a k e r o v and B o r i s s o v a [18]). The solutions of the formulated single-criterion mixed-integer nonlinear programming optimization problems give the optimal wind turbines type and number and the corresponding site layout under given wind park area conditions, shape and size. The wind turbines number is defined on the basis of a given wind park area size and turbines' spacing recommendations. The values of the separation distance coefficients and turbines number define the wind park turbines placement accordingly to the given uniform or predominant wind direction cases. The developed wind park design approach was tested numerically by solving different optimization problems formulations using real turbines data for two basic wind directions cases – uniform and predominant wind for a square and rectangular wind park shape. The numerical experiments show that the approach proposed can be adjusted to different practical needs by introducing proper requirements and restrictions in the optimization problems formulations.

5. Conclusions

The existing problems in wind power plant design process define the ultimate goal of the investigations and development of mathematically reasoned methods for optimal wind power plant design. The current work investigates the wind power plant design process and the main stages for optimal design achievement. A structured approach for wind power plant design, based on original generalized combinatorial optimization modeling technique is proposed. The investigations purpose is to increase the effectiveness of the design process and to decrease the investments risk of intuitive decisions taking. The core idea of the proposed approach is the use of discrete combinatorial models for formulating a single- or multiobjective optimization problem. Their solutions give optimal or Pareto-optimal values of the wind power plant parameters, while satisfying the given technical, economic and other requirements. The approach proposed allows flexible adjustment to wind power plant design particularities by modification and extending of the proposed combinatorial optimization model or by using other modeling techniques and optimization methods. The described wind power plant design process can be implemented as a standalone software application or to be integrated into a CAD system package for combined techno-economic design, analysis, planning and optimization of wind power plant projects.

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