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MULTI-PERSON SELECTION OF THE BEST WIND TURBINE BASED ON THE MULTI-CRITERIA INTEGRATED ADDITIVE-MULTIPLICATIVE UTILITY FUNCTION

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Abstract. Energy generation and savings is a vital problem for the social and economic development of a modern world. The construction of wind farms is a challenge of crucial importance to Lithuania. Offshore wind farms are one of the possibilities of the multiple use of marine space. Wind energy industry has become the fastest growing renewable energy in the world. An offshore wind farm is considered one of the most promising sources of green energy towards meeting the EU targets for 2020 and 2050. They provide long-term green energy production. The major purpose of this study is the selection and ranking of the feasible location areas of wind farms and assessing the types of wind turbines in the Baltic Sea offshore area. Multi-criteria decision making methods represent a robust and flexible tool investigating and assessing possible discrete alternatives evaluated applying the aggregated WSM and WPM method namely WASPAS. The following criteria such as the nominal power of the wind turbine, max power generated in the area, the amount of energy per year generated in the area, investments and CO_2 emissions have been taken into consideration.

Keywords: offshore, wind turbine, foundations, MCDM, WASPAS.

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Introduction

Climate change and global warming are the most critical issues facing the world today (Hessami *et al.* 2011). World politicians of the highest rank speak that the energy production system is to be changed; otherwise, our planet will face catastrophic consequences. Green energy (wind, sun, water and other resources), which, for some time, has been considered to be only an enthusiastic invention, is getting more and more attractive for big business investments.

The current concerns about climate change relate strongly to past technological developments that have fundamentally changed the structure of the energy sector by making possible the diffusion of new and less costly technologies (Soderholm, Pettersson 2011). The rapid development of wind energy technology has made it to be the most promising alternative to conventional energy systems in recent years (Lee *et al.* 2009).

Wind energy is presented as one of the strategies for tackling global warming and accomplishing the Kyoto Protocol (Gamboa, Munda 2007). Recently, wind energy has started to be valued as the national wealth of each country just like the resources of organic fuel (oil, gas). These sources of energy, unlike organic fuel, are inexhaustible. Employing them ensures great ecological, social and political advantages, and in the nearest future, will undoubtedly bring economic benefits.

Over the past decade, many countries have invested heavily in wind power, and the current energy policies imply that there is a lot more investment to come in (Green, Vasilakos 2011). Most of the existing wind power plants are constructed on land while some countries (first of all in Europe) have started to invest into developing sea wind power parks. Offshore wind energy generation is the fastest growing source of renewable energy in the world (Singh *et al.* 2010).

1. Description of offshore wind power turbines

The problems of sustainable energy generation are complicated. Modern technologies should be defined applying a multiple criteria set. The criteria describing alternatives have different measurement units and optimization directions.

Martin *et al.* (2013) applied the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method for assessing the conceptual design process of floating offshore wind turbine support structures. Collu *et al.* (2012) investigated the design space of a floating

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support structure for an offshore vertical axis wind turbine. The alternatives are ranked based on the TOPSIS method. Lozano-Minguez *et al.* (2011) provided a systemic assessment of the selection of the most preferable, among different configurations, offshore support structures taking into consideration several criteria through TOPSIS for benchmarking candidate options. Lee *et al.* (2012) presented an integrated MCDM model incorporating Interpretive Structural Modelling (ISM), the Fuzzy Analytic Network Process (FANP) and the VIKOR method. Kaya and Kahraman (2010) applied an integrated fuzzy VIKOR and AHP method to determine the best renewable energy alternative for Istanbul. Van Haaren and Fthenakis (2011) proposed a spatial multi-criteria methodology implemented in New York State, and the results were compared with the locations of the existing wind turbine farms and based on multi-criteria analysis. Khan and Rehman (2012) presented study on the efficient design of wind farms in Saudi Arabia. The conducted analysis has been based on a fuzzy logic decision making approach.

While onshore wind is developing by leaps and bounds, in the meantime, offshore wind has also attracted people's attention in recent years. As generally known, wind energy is clean and inexpensive, but space for turbines is becoming scarce, which makes offshore wind an attractive choice (Leung, Yang 2012).

New investment in the capacity of offshore wind generation has shown a remarkable increase. The total offshore installed capacity in Europe has increased from under 50 MW in 2000 to about 1471MW by the end of 2010 thus translating to an average annual rate of growth in about 50% per year (Green, Vasilakos 2011).

Conducting the research and development of offshore wind power began in the '70s of the last century. After more than 30 years of progress, offshore wind power technology is becoming more and more mature and has entered the stage of large-scale development (Zhixin *et al.* 2009).

Europe has always been the leader in offshore wind technology. Looking back on the history of offshore wind, it is necessary to mention Denmark that is not only the second highest contributor to offshore wind in Europe but also a pioneer in this field. One should never forget that the United Kingdom is the leader in producing European wind energy.

Despite its growth, the current share of offshore capacity remains relatively low when compared to that operating onshore (only over 2% of total wind capacity for EU-27) (Green, Vasilakos 2011). It is expected that in 2020, European offshore wind power capacity could reach the one-third of electricity demand for Europe) (Zhixin *et al.* 2009).

Despite many advantages, sea energy production presents plenty of challenges that should be overcome in order to ensure more successful development of sea wind power plants. First of all, the cost of constructing an offshore wind farm is 1.5–2 times greater than that of the onshore one, as towers, foundations, underwater cabling and installation offshore are more difficult and expensive (Offshore Wind Collaborative Organizing 2005). Since the offshore wind farm is far away from the shore, maintenance and repair are also more challenging due to difficulty in accessing the site. What is more, the need for crane vessels in repair makes it 5–10 times more expensive than onshore repair (Van Bussel, Zaaijer 2001).

The operation of wind power plants depends on two most important components: wind turbines and wind. A rotor of a wind turbine consists of blades and a rotor hub. The requirements set for the blades include the maximal diameter of the rotor and the height of its axe as well as aerodynamic efficiency to get as much energy from the wind as possible, low weight, simple production technology, sufficient resistance to mechanical loads and weather impact, durability (Gipe 2004).

Previous investigations have shown that for an efficient wind farm, operation distance between adjacent wind turbines should make 5–10 diameters of the rotor (Maeda *et al.* 2004). However, in the case of a possibility of positioning wind farms considering wind direction, a distance between wind power plants may be reduced (Markevičius *et al.* 2007).

Wind velocity is the most important parameter for evaluating wind energy resources. Any choice for designing wind turbines must be based on the average wind velocity at the selected site for constructing wind turbines (Katinas *et al.* 2009).

The wind and its speed in the industry of wind power plants is the most important feature, because it determines where the wind power park is going to be located, what size it will have to fit and whether it is going to be constructed in this place at all. The amount of energy produced by a wind turbine during a long period of time may be calculated rather precisely because the average wind speed and direction at a certain place change insignificantly.

Regular measurements of wind velocities and directions have been performed in Lithuania since 1945. The measurements are performed typically at a height of 10 m above the ground level every 3 h. All readings are averages over the specified periods of time. Monthly and annual averages are also determined (Katinas *et al.* 2009).

An onshore wind farm can be typically utilized about 2000–3000 h per year while an offshore farm normally achieves a utilization rate of approximately 3000–4000 h annually. In addition, the environmental costs of offshore installations are overall lower than those typically experienced at onshore farms (Soderholm, Pettersson 2011).

Offshore winds are less turbulent (because the ocean is flat relative to onshore topography), and they tend to flow at higher speeds than onshore winds thus allowing turbines to produce more electricity. Because the energy produced from the wind is directly proportional to the cube of wind speed, increased wind speeds of only a few miles per hour can produce a significantly larger amount of electricity. For instance, a turbine at a site with an average wind speed of 26 km/h would produce 50% more electricity than that at a site with the same turbine and an average wind speed of 22 km/h (Kurian *et al.* 2009).

As regards big wind turbines, steel pipes narrowing towards the top are used for the tower, although other structures are also suitable for low power wind turbines.

In general, the support of the wind power plant at sea is influenced by (Structural Engineers Club 2014):

- wind;
- wave and current loads;
- hydrodynamic and hydrostatic water pressure;
- own weight;
- operational load;
- ice;
- fluctuations in temperature;
- forces on the top of the body that appear from the movement of the blades;
- other impacts of ships, rust, deposits, etc.

For designing wind power plants, one may not take into consideration some of the loads.

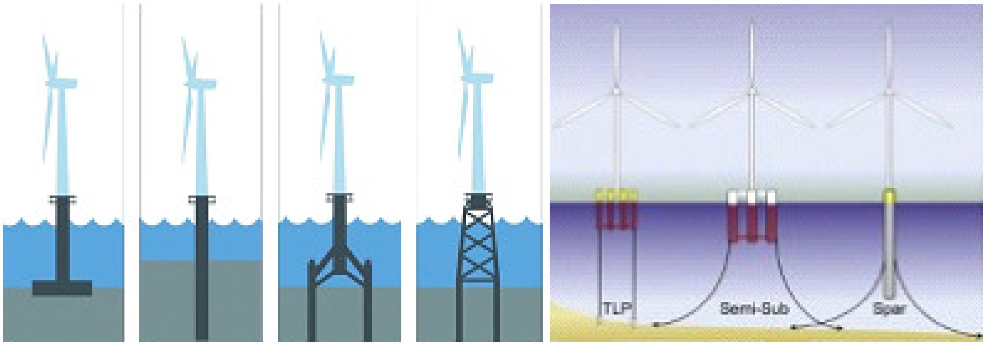
One of the most important features of offshore wind generators are the selection of foundations. The foundations of a tower are different when constructed in the sea and on land. Wind pressure forces act on the wind turbine. For example, if the diameter of the rotor of the wind turbine reaches 100 m, under the wind speed of 25 m/s, the air mass equal to 470 t/s goes through the rotor. The turbine tower itself has to stand wind pressure at wind speed equal to 50 m/s. Therefore, the resistance of the basement must meet high demands.

The price of constructing the basement of the wind power plant and the foundations themselves differ a lot depending on whether they are built in the sea or on land. For a typical onshore wind power station, the cost of foundations normally represents 4–6 percent of the total investment costs (Lemming *et al.* 2008). Offshore foundations constitute a significant fraction of the overall installed cost that varies between 15% and 40% (Houlsby, Byrne 2000). Higher costs can also be explained by the fact that, so far, no well-developed supply industry for installation work offshore has been offered, and that during recent years, offshore wind power industry has been forced to compete with more established fossil fuel industry for these installation services (Sovacool *et al.* 2008).

In the case of offshore wind power development, water depth considerably affects the economics of the wind power project when establishing the offshore foundations the type of which is dependent on water depth and soil conditions, etc. (Kim *et al.* 2013).

The main types of the foundations of wind power plants in the sea are discussed below:

- *Gravity base structure* (Fig. 1a) foundations are typically used at sites where the installation of piles in the underlying seabed is difficult, such as on a hard rock ledge in relatively shallow waters (Malhotra 2010). The maximum depth achieved applying this system can reach 10 m. Concrete is the only material used for producing it (Singh *et al.* 2010).
- *Monopole* (Fig. 1b) covers a simple design and consists of a steel pipe pile (Carey 2002). The diameter varies from 6 to 8 m. (Singh *et al.* 2010) and wall thickness as much as 150 mm (Carey 2002). Depth achieved by the monopole is in the range of 25 to 30 m. It is a steel tabular structure the manufacturing of which is simple and quick (Singh *et al.* 2010). Monopoles are flexible (Carey 2002).
- *Tripod* (Fig. 1c) has a structure that is considered to be relatively lightweight. Under the central steel column, which is below the turbine, there is a steel frame that transfers forces from the tower into three steel piles installed at each leg position to anchor the tripod to the seabed. The three piles are driven 10–20 m into the seabed. The tripod can also be installed using suction buckets. The foundations of the tripod have good stability and overall stiffness. The tripod support structure is pre-assembled in an onshore construction yard. The entire structure is placed on a suitable vessel such as a barge and transported to the offshore location where it is slowly lowered onto the seabed ensuring it is entirely level. When the piles are at the required depth, a connection between the top of the pile and the pile sleeve is made by filling the annulus with grout or by means of a swaged connection (Four C Offshore 2013b).



(a) (b) (c) (d) (e)

Fig. 1. The types of the foundations of the offshore wind turbine: a – gravity base structure, b – monopole, c – tripod, d – jacket structures, e – floating platform (First for Technology and Innovation 2013)

- *Jacket structures* (Fig. 1d) contain many variants of the three or four-legged jacket/lattice structure typically consisting of corner piles interconnected with bracings with up to 2 m in diameter. These types of structures are considered well suited for sites with water depth ranging from 20 to 50 m. Proponents cite the advantages of the jacket structures and refer to low wave loads in comparison to monopoles (jacket structure is very stiff and the area facing wave movement is smaller than that of monopoles), which makes fabrication expertise is widely available in part due to Offshore Oil and Gas industry supply chain. Others cite disadvantages that embrace high initial construction costs, potentially higher maintenance costs and moderately difficult and expensive transportation (Four C Offshore 2013a).
- *Floating platform* (Fig. 1e) is the structure that must provide enough buoyancy to support the weight of the turbine and to restrain pitch, wave as well as roll motion within acceptable limits. Therefore, a classification system has been developed and divides all platforms into three general categories based on ballast, mooring lines and buoyancy (Singh *et al.* 2010).

2. Case study

The existing offshore wind farms offer important advantages for aquaculture plans, especially in terms of a lack of major physical constrains, e.g. navigation routes, submarine cables, marine protected areas. Moreover, enhanced current velocity, due to the presence of the piles and air fluxes of the turbines, may increase the environmental suitability of aquaculture plans in these areas. In addition, the transmission of localized depleted water masses or waste material towards near-shore zones can be avoided, excluding a potential impact close to the coast. On the other hand, other environmental constrains (e.g. temperature and variability of salinity, dissolved oxygen concentrations, phytoplankton dynamics) also need to be considered when planning aquaculture activities (Benassai *et al.* 2011).

Four alternatives to the development of the wind power park in the Baltic Sea near the Lithuanian coast could be considered. The main technical parameters and requirements as well as the preliminary price are provided in Table 1.

Alternative A_A – Nordex N80 2.5 MW Wind Turbine (Clean Technology 2010). Nordex offers the N80 2.5 MW wind turbine. A three-bladed rotor incorporated in the wind turbine measures 80 m in diameter and offers a swept area of 5026 m². The rotor operates at speeds ranging from 10.8 to 18.9 rpm and its maximum tolerable tip speed may reach 80 m/s.

Alternative A_B – Vestas V90 3.0 MW Wind Turbine (Vestas 2013). The V90-3.0 MW® is designed to be low weight ensuring easy transportation and installation while reducing foundation costs thanks to its lower load. The nacelle is lighter because its gearbox has an integrated main bearing that eliminates the need for a traditional main shaft.

This turbine delivers exceptional performance, high yield and can be supplied in a variety of hub heights (65–105 m) to accommodate site-specific needs. The tower for offshore is designed site-specific and is furthermore protected with a special offshore coating to withstand a harsh environment.

Alternative A_C – GE Energy 3.6 MW Wind Turbine (GE Energy 2008). Engineered for high-speed wind sites and harsh marine environment, the 3.6 MW machine features exceptionally robust marine design. The generator and gearbox are supported by elastomeric elements to minimize noise emissions.

Alternative A_D – REpower M5 5.0 MW Wind Turbine (Wind Energy Solutions 2013). The REpower 5M has a rated power of 5 megawatt and a rotor of 126 metres in diameter. The 5M is one of the largest and most powerful wind turbines in the world. The 5M sets new standards of the economic viability of wind farms, especially in offshore installations.

In order to proceed with the successful application of multi-criteria analysis, it is essential, on the one hand, to determine and examine an adequate number of criteria that will give a representative and complete picture of investigated alternative scenarios, whereas on the other, to calibrate the criteria that will be examined according to their characteristics (Rousis *et al.* 2008).

In total, five individual criteria have been selected (Project POWER 2008):

- *Nominal power of the wind turbine* – depends on the type of the wind power plant to be constructed;
- *Max power in the area* – the park of power plants may be constructed very widely or vice versa. Each separate wind power plant has the required operation area. This way, we may assess power plants in a certain area;

Table 1. The main parameters of wind power plants

Manufacturer		Nordex	Vestas	GE	REpower
Turbine Model		Nordex N80	Vestas V90	GE 3.6 sl	REpower M5
Rated Power	kW	2500	3000	3600	5000
Rotor Diameter	m	80	90	104	126
Hub Height	m	100	105	100	100
Swept Area	m^2	5026	6362	8495	12469
Price	€	3000000	3600000	4320000	6000000
Turbine Area	km^2	0.448	0.567	0.757	1.111

- *Amount of energy per year* – how much energy do wind power plants park produce in reality?
- *Investments* – the price for developing wind power plants, construction from the idea of design to construction and commissioning. This criterion is crucial for constructing a park, since one wind power plant costs several millions, and the park is developed through many years and the total sum usually is very big;
- *CO_2* – This is one of the most important criterions indicating why the park of wind power plants is constructed. The situation may vary in each country.

Five possible alternative places for constructing wind power plants in the Baltic Sea, near the Lithuanian coast (Fig. 2) can be marked. We will choose the most suitable wind power plant for each of such places in accordance with the criteria introduced above.

3. Systemized results

On the basis of the analyzed reports on constructing wind power plants in the sea, the basic calculation data matrices were done, which would help with doing calculations for choosing the type of wind power plants using multi-criteria calculation methods.

The basic details necessary for choosing a type of wind power plants in five construction sites are provided in Tables 2–6 (Project POWER 2008).

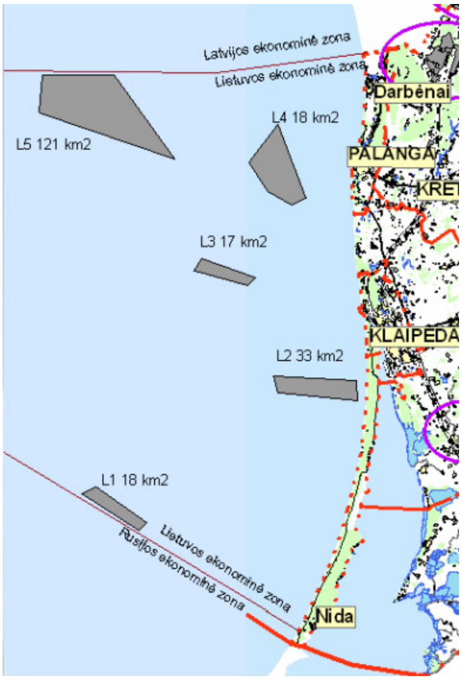


Fig. 2. Possible places for constructing wind power plants in the sea (Klaipėda Science and Technology Park 2010)

Table 2. L_1 alternative

				L_1	
Manufacturer		**Nordex**	**Vestas**	**GE**	**REpower**
Turbine model		Nordex N80	Vestas V90	GE 3.6 sl	REpower M5
Rated power	MW	2.5	3.0	3.6	5.0
Max capacity	MW	100	96	86.4	80
Net energy for sale	10^3MWh	356.4	360.2	334.0	327.7
Capital costs	10^6€	358.969	341.100	314.184	290.447
CO_2	10^3 t	223.10	225.50	209.05	205.13

Table 3. L_2 alternative

				L_2	
Manufacturer		**Nordex**	**Vestas**	**GE**	**REpower**
Turbine model		Nordex N80	Vestas V90	GE 3.6 sl	REpower M5
Rated power	MW	2.5	3.0	3.6	5.0
Max capacity	MW	185	174	158.4	150
Net energy for sale	10^3MWh	553.2	551.0	515.4	519.3
Capital costs	10^6€	466.923	427.553	384.003	348.567
CO_2	10^3 t	346.32	344.95	322.61	325.06

Table 4. L_3 alternative

				L_3	
Manufacturer		**Nordex**	**Vestas**	**GE**	**REpower**
Turbine model		Nordex N80	Vestas V90	GE 3.6 sl	REpower M5
Rated power	MW	2.5	3.0	3.6	5.0
Max capacity	MW	95	90	79.2	75
Net energy for sale	10^3MWh	310.2	310.1	280.7	282.4
Capital costs	10^6€	259.662	240.048	210.979	192.561
CO_2	10^3 t	194.2	194.1	175.7	176.8

Table 5. L_4 alternative

		L_4			
Manufacturer		**Nordex**	**Vestas**	**GE**	**REpower**
Turbine model		Nordex N80	Vestas V90	GE 3.6 sl	REpower M5
Rated power	MW	2.5	3.0	3.6	5.0
Max capacity	MW	267.5	255	226.8	215
Net energy for sale	10^3MWh	753.1	762.7	696.8	703.9
Capital costs	10^6€	632.161	582.605	507.556	457.270
CO_2	10^3 t	471.4	477.5	436.2	440.6

Table 6. L_5 alternative

		L_5			
Manufacturer		**Nordex**	**Vestas**	**GE**	**REpower**
Turbine model		Nordex N80	Vestas V90	GE 3.6 sl	REpower M5
Rated power	MW	2.5	3.0	3.6	5.0
Max capacity	MW	675	639	576	545
Net energy for sale	10^3MWh	2438.1	2428.2	2255.7	2262.1
Capital costs	10^6€	1596.710	1462.0126	1290.070	1160.311
CO_2	10^3 t	1526.3	1520.0	1412.1	1416.1

Table 7. Nine-point scale of a pairwise comparison (Saaty 1980)

Intensity of importance	Definition
1	Criteria *i* and *j* are of equal importance
3	Criterion *i* is moderately more important than criterion *j*
5	Criterion *i* is strongly more important than criterion *j*
7	Criterion *i* is very strongly or demonstrably more important than criterion *j*
9	Criterion *i* is extremely more important than criterion *j*
2, 4, 6, 8	Compromise values between two adjacent judgments
Reciprocals nonzero	If activity *i* has one of the nonzero numbers assigned to it when compared with activity *j,* then, *j* has the reciprocal value when compared with *i*

Table 8. Pair-wise comparisons considering criteria

	Expert 1						
	X_1	X_2	X_3	X_4	X_5	**Products**	w_1
X_1	1	4	0.167	1	6	1.320	0.195
X_2	0.25	1	0.2	0.333	4	0.582	0.086
X_3	6	5	1	1	5	2.724	0.403
X_4	1	3	1	1	6	1.783	0.264
X_5	0.167	0.25	0.2	0.667	1	0.354	0.052

Table 9. Criterion weights

	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7	Exp. 8	Exp. 9	Exp. 10	Average
X_1	0.195	0.261	0.240	0.086	0.171	0.087	0.162	0.088	0.181	0.112	0.158
X_2	0.086	0.207	0.292	0.330	0.271	0.191	0.202	0.170	0.154	0.162	0.206
X_3	0.403	0.089	0.158	0.196	0.194	0.300	0.343	0.385	0.308	0.394	0.277
X_4	0.264	0.390	0.162	0.345	0.207	0.366	0.254	0.304	0.315	0.290	0.290
X_5	0.052	0.054	0.148	0.043	0.158	0.056	0.039	0.054	0.043	0.043	0.069

4. Determination of criteria weights

The decision has been made using the derived weight *w* of evaluative criteria (Saaty 1980). The experiments conducted by Saaty shows that most individuals cannot compare more than seven, plus/minus two criteria (Table 7).

The AHP initial pair-wise comparison matrix is as follows:

$$A = \left(x_{ij}\right) = \begin{bmatrix} 1 & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_m} \\ \frac{w_2}{w_1} & 1 & \cdots & \frac{w_2}{w_m} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_m}{w_1} & \frac{w_m}{w_2} & \cdots & 1 \end{bmatrix}, \qquad (1)$$

$$x_{ij} = 1, x_{ij} = \frac{1}{x_{ij}}, x_{ij} \neq 0.$$

$$w_j = \left(\prod_{k=1}^{p} y_{jk} \right)^{\frac{1}{p}}, j = \overline{1,n},\ k = \overline{1,p}. \qquad (2)$$

Also, the consistency index and consistency ratio should be calculated (Saaty 1980).

Ten experts prepared different pair-wise comparison matrixes the examples of which are shown in Table 8.

The weights of the criteria of the fuzzy group have been established and presented in Table 9.

5. Calculation method

A multi-person decision-making problem is defined as a decision situation in which an alternative to the given problem should be chosen. WASPAS method for finding a solution to the problem has been selected. The initial information on the problem has been provided by different people or experts.

Zavadskas *et al.* (2012) proposed aggregating WSM (Weighted Sum Model) and WPM (Weighted Product Model) methods. WASPAS (Weighted Aggregates Sum Product Assessment) method was developed. The optimization of the weighted aggregated function has been suggested, which allows reaching the highest accuracy of measurement. Zavadskas *et al.* (2013) used WASPAS and MOORA (Multiple Objective Optimization on the basis of Ratio Analysis) as well as MULTIMOORA (MOORA plus Full Multiplicative Form) methods for the multiple criteria assessment of building designs.

Hashemkhani Zolfani *et al.* (2013) applied Stepwise Weight Assessment Ratio Analysis (SWARA) and WASPAS methods for evaluating shopping mall sites in Tehran.

Dėjus and Antuchevičienė (2013) suggested employing Multiple Criteria Decision Making (MCDM) technique for assessing and selecting appropriate solutions to occupational safety and proposed formulating considered alternatives from typical solutions to ensuring their quality and then applying the entropy method for determining relative significance to evaluation criteria. Finally, WASPAS method for ranking alternatives has been used.

Staniūnas *et al.* (2013) referred to multi-criteria decision making method WASPAS and to the scenarios evaluating the modernization of multi-dwelling houses.

Šiožinytė and Antuchevičienė (2013) presented a model for improving daylight in the reconstructed building and simultaneously analysing the process of saving the features of vernacular architecture, which is based on WASPAS method.

Chakraborty and Zavadskas (2014) explored WASPAS method as an effective MCDM tool while solving eight manufacturing decision making problems. The method has been observed to find out the capability of accurately ranking alternatives in all considered selection problems.

Normally, information can be represented by any of the following three preference structures (Herrera *et al.* 2001):

- As a preference ordering alternatives. In this case, alternatives are ordered from the best to worst without any other additional information;
- As a utility function. In this case, an expert gives a real valuation (a physical or monetary value) on each alternative, i.e. the function that associates each alternative with a real number. This indicates the performance of that alternative according to that point of view;
- As a preference relation. This is the most usual case because most procedures for decision-making problems are based on a pair comparison in the sense that processes are linked to some degree of the credibility of the preference of any alternative over another.

The description of WASPAS method is presented below.

First, the initial decision-making matrix is formed. Next, a step – initial decision-making matrix is normalized as:

$$\bar{x}_{ij} = \frac{x_{ij}}{\max_i x_{ij}} \qquad (3)$$

for criteria that must be maximized, and:

$$\bar{x}_{ij} = \frac{\min_i x_{ij}}{x_{ij}} \qquad (4)$$

for criteria that must be minimized.

Some multi-criteria utility functions are additive and some are multiplicative. Therefore, a proposal to integrate both additive and multiplicative utility functions to one has been made. For this reason, the applied function is as follows:

$$K_i = \lambda \sum_{j=1}^{n} \bar{x}_{ij} w_j + (1-\lambda) \prod_{j=1}^{n} \bar{x}_{ij}^{w_j}, \qquad (5)$$

λ is used 0.5.

6. Summary of calculations

Following the calculations done employing WASPAS method (Table 10), it has been determined that the best option of assessing the types of wind power plants situated in different possible places of construction is the 4th one, which is Repower M5 5.0 MW Wind Turbine (Fig. 3).

Considering the suggested options, this is the most powerful (5 MW) wind power plant having the biggest rotor of 126 m in diameter and the average height of 100 m.

Due to its modular structure and logistical flexibility, the 5 M is suitable for onshore and offshore installation. The offshore version is specifically designed for withstanding extreme environmental conditions. This includes, for example, the redundancy of key components to guarantee

Table 10. Solution results

	L_1 Alternative		L_2 Alternative		L_3 Alternative		L_4 Alternative		L_5 Alternative	
	K_i	Rank	K_i	Rank	K_i	Rank	K_i	Rank	K_i	Rank
A_A	0.8463	4	0.8311	4	0.8278	4	0.8204	4	0.8246	4
A_B	0.8733	3	0.8595	3	0.8558	3	0.8525	3	0.8538	3
A_C	0.8816	2	0.8786	2	0.8680	2	0.9002	2	0.8739	2
A_D	0.9320	1	0.9420	1	0.9295	1	0.9359	1	0.9386	1

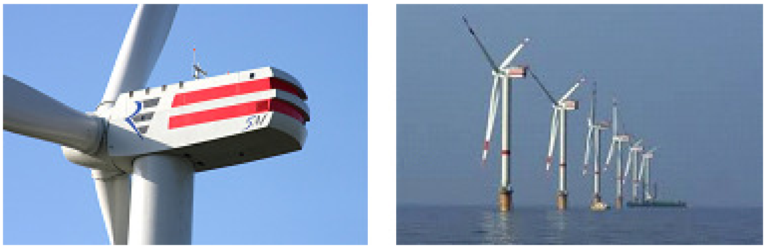


Fig. 3. REpower M5 5.0 MW Wind Turbine (Wikimedia commons 2012)

maximum availability, effective protection against corrosion and a permanent monitoring system (Wind energy solutions 2013).

Conclusions

Recently, wind energy has become more and more valued. Although most of the constructed wind power plants have been constructed on land, those erected in the sea are taking the lead nowadays.

The construction sequence of the wind turbine should be as follows: $A_D \succ A_C \succ A_B \succ A_A$.

Although investments in the production of wind energy in the sea are much bigger and construction is incomparably more complicated than investments and construction on land, the possibilities of payoff are significantly higher because the wind in the sea is much stronger.

Calculations have been done applying WASPAS method and show that the best type of the wind power plant suitable for all options is REpower M5 5.0 MW Wind Turbine.

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