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Multi-Criteria Evaluation of Spatial Aspects in the Selection of Wind Farm Locations: Integrating the GIS and PROMETHEE Methods

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Abstract: Apart from wind potential, there are many other spatial factors which impact the possible implementation of wind farm projects. The spatial advantages and limitations of these factors can be used as criteria for selecting the most suitable location for a potential wind farm. The specific method for evaluating wind farm locations in this paper is novel because of its choice of spatial criteria and its two-stage evaluation procedure. The first stage involves the elimination of unfavorable areas for locating a wind farm, based on elimination criteria, using GIS. The second stage is the selection of the most suitable wind farm location using the PROMETHEE method. This is based on the multi-criteria evaluation of locations according to different weight categories and scenarios. The results are then multiplied based on which decision-making subjects can make appropriate decisions. The results indicate that the method presented has a universal character in terms of its application. However, its specifics in terms of quantitative statements for the individual spatial criteria used in the evaluation depend on the specifics of national and international regulations, the area in question and the particular project. By integrating the spatial criteria with the relevant legislation, this method has potential for global application. It aims towards systematicity, efficiency, simplicity and reliability in decision-making. In this way, potential conflicts and risks for investors and other users of the space are prevented in the earliest development phase of a wind farm project.

Keywords: wind farm; location selection; multi-criteria evaluation; spatial aspects; GIS; PROMETHEE method

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1. Introduction

The increasing share of green energy in the total energy balance is evidence of dynamic growth in the use of renewable energy sources at a global level. Wind energy plays a significant role in this growth [1], indicating the necessity for more space to be given over to wind farm projects. Therefore, choosing locations for wind farms and determining the spatial micro-locations for wind turbines [2] is particularly significant.

There are many different methods and techniques that can be used for the purpose of choosing locations for specific activities [3–7].

Manipulating spatial data is one of the key factors in choosing the optimal location for any human activity, with the use of GIS tools and techniques considered to be an essential component of this process [4,5,8,9]. In addition to providing data on the location of certain spatial phenomena and activities, GIS tools offer the possibility of crossing, overlapping and organizing data, as well as carrying out various spatial analyses. Hence, their role in selecting locations for wind farms has become irreplaceable.

The application of GIS tools, such as multi-criteria analysis (MCDMA), makes various techniques and methods available, which provide a scientific and professional basis for evaluating candidate locations for a particular human activity. The most commonly applied methods of multi-criteria analysis include: Multi-Attribute Utility Theory (MAUT), the Analytic Hierarchy Process (AHP), Decision Making Trial and Evaluation Laboratory (DEMATEL), Elimination and Choice Translating Reality (ELECTRE), the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), and the Borda count ranking method [10]. In addition to methods based on multi-criteria analysis, more recent research has increasingly used statistical methods, as well as fuzzy theory and its modifications, when choosing locations [6,11–13].

When it comes to the selection of wind farm locations, previous research can be classified into three categories: GIS, multi-criteria analysis and statistical methods [14]. All of the techniques and methods have been used individually or in combination for selecting wind farm locations, and a significant number of authors have dedicated their scientific work to this field [3–7]. The aim of the present research was to create a universally applicable and specific approach for determining optimal locations of wind farms based on the principles of integrating the GIS (elimination phase) and PROMETHEE (multi-criteria evaluation phase based on weighting factors and different scenarios) methods [4,5,15]. It was important for the approach to be relatively fast, understandable and reliable, based on the principles of preventive protection, which would enable investors and other users of the space to carry out activities with minimal risk (especially important for investors), with no spatial conflicts.

In addition to integrating the GIS and PROMETHEE methods, this study is novel in its choice of criteria used to evaluate locations for the development of wind energy, which include relevant legislation, empirical data based on specialized software models and specific studies carried out on representative samples, the specificities of the space, and the specifics of each particular wind farm project.

The methodological procedure was applied to an area of the Republic of Serbia (Southeastern Europe) due to the availability of relevant data required for implementing the procedure, but it is universally applicable.

2. Methodological Framework

Most scientific research carried out on the theme of selecting locations for wind farms is based on the combined application of GIS and other methods of multi-criteria analysis. Van Haaren et al. [4] affirmed the use of GIS when selecting locations for wind farms by developing a tool to determine the most favorable location for wind farms in New York State, based on SMCA (Spatial MultiCriteria Analysis). Sotiropoulou et al. [15] highlighted the complexity of decision-making with regard to the location of wind farms and proposed the use of the PROMETHEE II MADM METHOD to conduct a GIS analysis on the suitability of various locations. Villacreses et al. [5] used GIS and MCDMA methods (AHP, OWA, OCRA, VIKOR and TOPSIS) to determine the most favorable location for wind farms in mainland Ecuador.

Some scientists also rely on the independent application of multi-criteria methods. Wu et al. [16] proposed the use of the innovative PROMETHEE method integrated with conflict analysis to solve MCDMA problems consisting of quantitative and qualitative criteria. Rehman et al. [17] used the PROMETHEE method of multi-criteria analysis to determine the most suitable wind farm locations in Saudi Arabia.

In contrast to the research mentioned above, this paper does not take the criterion of wind speed into account since it is considered to be the starting point, i.e., the main prerequisite for locating wind farms. Determining the wind potential and estimating the production precede the selection of the micro-location of a wind farm, based on empirical data from previously conducted macro-level measurement campaigns carried out by state institutions or investors. It is logical that areas with average wind speed values below the cost-effectiveness limit are omitted from any further evaluation.

One characteristic of this paper is its simplification of the methodological procedures used in the evaluation (MCDMA, GIS, PROMETHEE), which increases the likelihood of its use by interested experts.

A particularly significant part of the research is the fieldwork carried out by the authors since they visited each of the candidate locations in order to determine the factual situation for assessing the individual evaluation criteria.

As seen in Figure 1, the first stage in selecting a wind farm location is the elimination stage, in which unfavorable locations are identified based on elimination criteria. The first step is to identify those criteria.

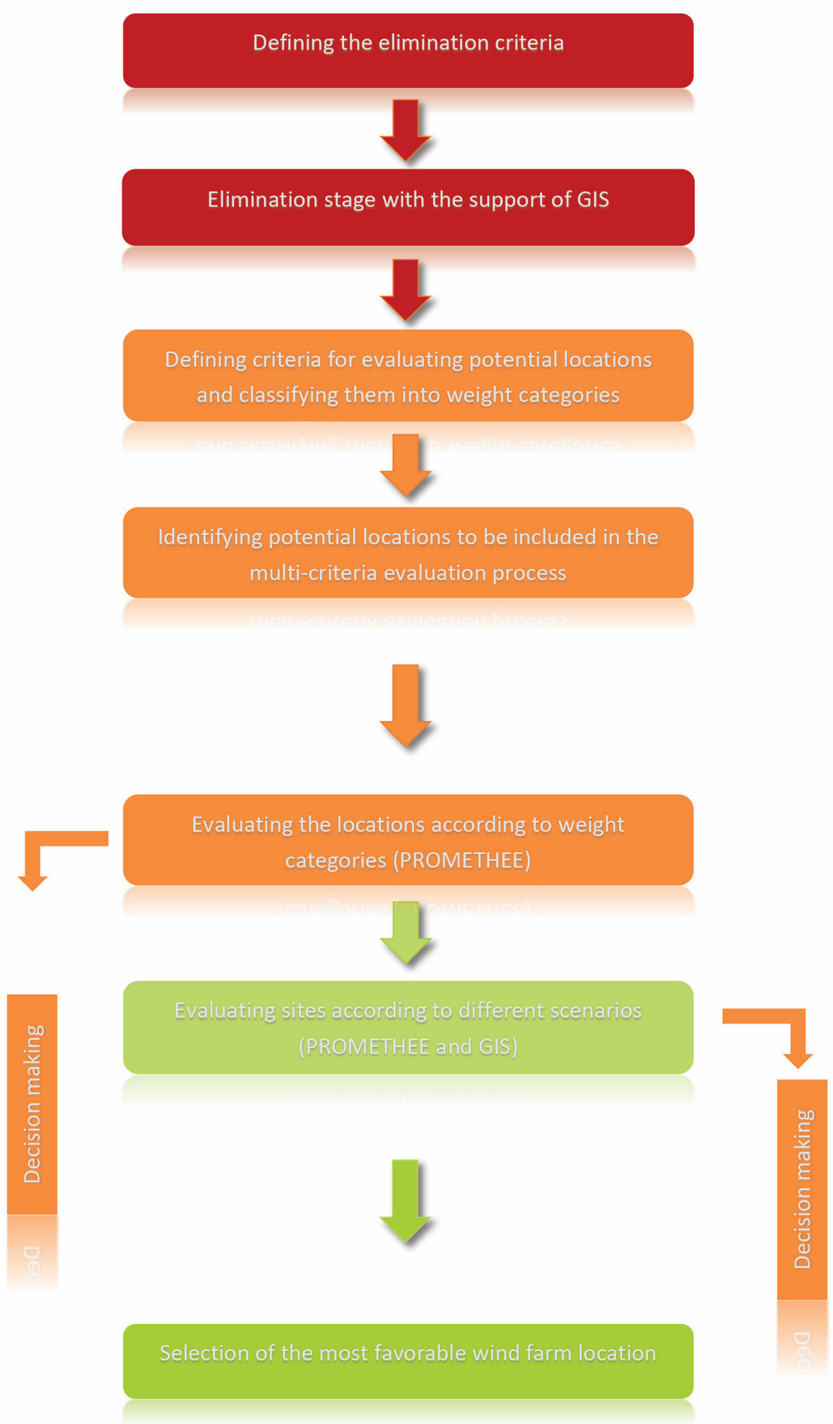

Figure 1. Procedure for selecting the location of wind farms based on the principles of the GIS and PROMETHEE methods.

Elimination criteria are based exclusively on spatial data and rooted in the relevant legislation and empirical standards in the field of wind energy (required distances from protected areas, inhabited places, buildings, infrastructure corridors, etc.). They are the product of local legal regulations and the results of software modeling, based on a large number of empirical samples. This paper uses the authors' empirical data on the significance of individual criteria for selecting locations, obtained during the development of the following wind power projects in the Republic of Serbia: Maestrale Ring (800 MW); Vetrozelena (300 MW); Lovcenac (300 MW); Cibuk 1 (158 MW); Crni Vrh (150 MW); Bela Anta (120 MW); Košava (105 MW); Feketic (90 MW); and Nikine Vode (45 MW). These make up a representative sample.

Bearing in mind the importance, but also the specificity of legislation in the field of wind power, both locally and globally, the elimination criteria may only slightly differ from country to country and from continent to continent. Apart from these small differences in quantitative statements (necessary distances), they can be considered universal. Table 1 presents the elimination criteria for an area of the Republic of Serbia, which is situated in Europe. The authors had access to all the relevant regulations and spatial data for these criteria necessary for implementing the elimination phase.

Table 1. Selection of elimination criteria for determining unfavorable and potentially favorable areas for wind farm locations.

Elimination Criteria	Reasoning	References from Other Studies	Source of Data Used in the Paper
1. NATURA 2000 [1] areas	This elimination criterion refers to the area of Europe, but it can be applied to all other continents, taking into account protected natural areas and national parks, especially IBA (Important Bird Area) areas, considering that wind farms can have a dominant impact on flying fauna.	[15,18–25]	Spatial plan of the Republic of Serbia 2021–2035 (SPRS)
2. Water surfaces	All water surfaces (watercourses, lakes, Ramsar wetland sites) are excluded from consideration for the location of wind farms for technological, ecological and functional reasons.	[18,26–28]	[29]
3. Immovable cultural property	Protected immovable cultural assets and archaeological sites, as well as areas proposed for their protection, should not be considered for the location of wind farms.	[26,30–32]	SPRS, [33]
4. Distance from settlements and vulnerable structures (<500 m) [2]	A distance of less than 500 m from an inhabited area indicates a possible increase in noise in this zone, particularly when other existing sources of noise are superimposed onto the zone around the settlements and/or wind farm.	[4,15,21,34]	[35]
5. Distance from traffic infrastructure corridors (<300 m) [3]	The protective corridors for both criteria are the same in Serbian regulations. Bearing in mind the current largest dimensions of wind turbines on the market, with the greatest height when the propeller is in the vertical position, a buffer zone of 300 m excludes any possible effects of the wind power plant on infrastructure facilities in the future.	[1,36–38]	SPRS
6. Distance from power infrastructure corridors (<300 m)			
7. Airport zones [4]	There is no universal determination of airport zones; rather, they are the subject of special studies for each specific case situated in a possible impact zone that is tentatively defined by the relevant international regulations in the field of aviation.	[4,23,39]	[35]

Table 1. *Cont.*

Elimination Criteria	Reasoning	References from Other Studies	Source of Data Used in the Paper
8. Compatibility of existing and planned purposes	Zones where the valid planning and urban planning documentation foresees a space with a special purpose or vulnerable facilities outside the urban area (such as hospitals or special facilities for rehabilitation), or areas that are in operation or are planned for multi-decade mining activities (surface-surface mines) and similar activities should not be considered for locating wind farms.	[4,32,37,40,41]	[35]
9. Distance from meteorological radar systems in lowland areas (<10 km)	According to the regulations of the Republic of Serbia on determining the locations for the meteorological stations of state networks and protective zones in the vicinity of those stations [42], it is prohibited to install wind generators in the vicinity of a radar center in a zone with a radius of 10 km from the location of the radar antenna. [5] This elimination criterion may, but does not have to be universal.	[22,31,43]	[44]

[1] Natura 2000 is a network of protected areas within the borders of the European Union. It was designed so that based on the Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora, the Habitats Directive [45] and its supplements (for habitat types from Appendix I and for species from Appendix II) and Directive 2009/147/EC [46] of the European Parliament and of the Council on the conservation of wild birds, first adopted in 1979 [47] with species from Appendix I, areas could be set aside for protection, with the aim of ensuring the long-term survival of the most valuable and most endangered species and habitats of Europe. [2] The criterion is established according to specialized software packages for modeling the spatial dispersion of noise from wind farms. [3] The distance from infrastructural corridors has the purpose of protecting them from theoretically possible threats from the nearest wind turbines in case of an accident, or the wind turbines breaking or being knocked down. This elimination criterion is variable in specific circumstances and over time, and it depends on the types and dimensions of wind turbines in a market that is extremely dynamic. [4] The construction ban zone, especially the construction of tall structures such as wind farms, depends on: the type of airport and aircraft using it; the equipment in the radar system and its position; airport equipment for instrument flying; topography of the terrain; the direction of the take-off and landing runways. [5] The exception is in hilly and mountainous terrain, where the wind generator can be placed at a distance of less than 10 km from the radar antenna when the highest point of the wind generator is located below the base of the radar radiation hemisphere. In the selection of this criterion, the impact zone is determined on the basis of a special study.

The corresponding area is determined using GIS tools for each elimination criterion. By overlaying a layer of areas covered by the elimination criteria, unfavorable areas are highlighted (Figure 2), within which the location of wind power plants (shown in red) should not be considered. All other areas on the map, which are outside the areas marked in red, are potentially favorable for locating wind farms, as Figure 2 illustrates for a part of the Republic of Serbia.

The elimination phase is particularly important for the strategic level of planning in the field of wind energy at the national or regional level because, in this phase, unfavorable and conditionally favorable areas are identified for a wider area. Immediately ruling out unfavorable areas is of great benefit to investors, since it saves time and resources in the selection process. It is also very useful in countries that are at the very beginning of the development of wind energy, as it provides important initial information about the spatial advantages and limitations of potential areas for the construction of wind farms. The elimination phase also benefits smaller (regional) areas in countries where the development of wind energy is at an advanced stage, and where new potentially favorable areas for further development need to be explored.

The next stage is the multi-criteria evaluation of potential wind farm sites in potentially favorable areas. The first step (see Figure 1) is to define the evaluation criteria and determine the weight categories for use in the evaluation process. As in the case of the elimination criteria, the relevant national legislation and empirical standards in the field of wind energy should be taken into account, based on which the spatial relationships that affect the assessment of each individual criterion are defined. Table 2 shows how the selection of criteria would look for the evaluation of potential wind farm locations in Serbia (Southeastern Europe).

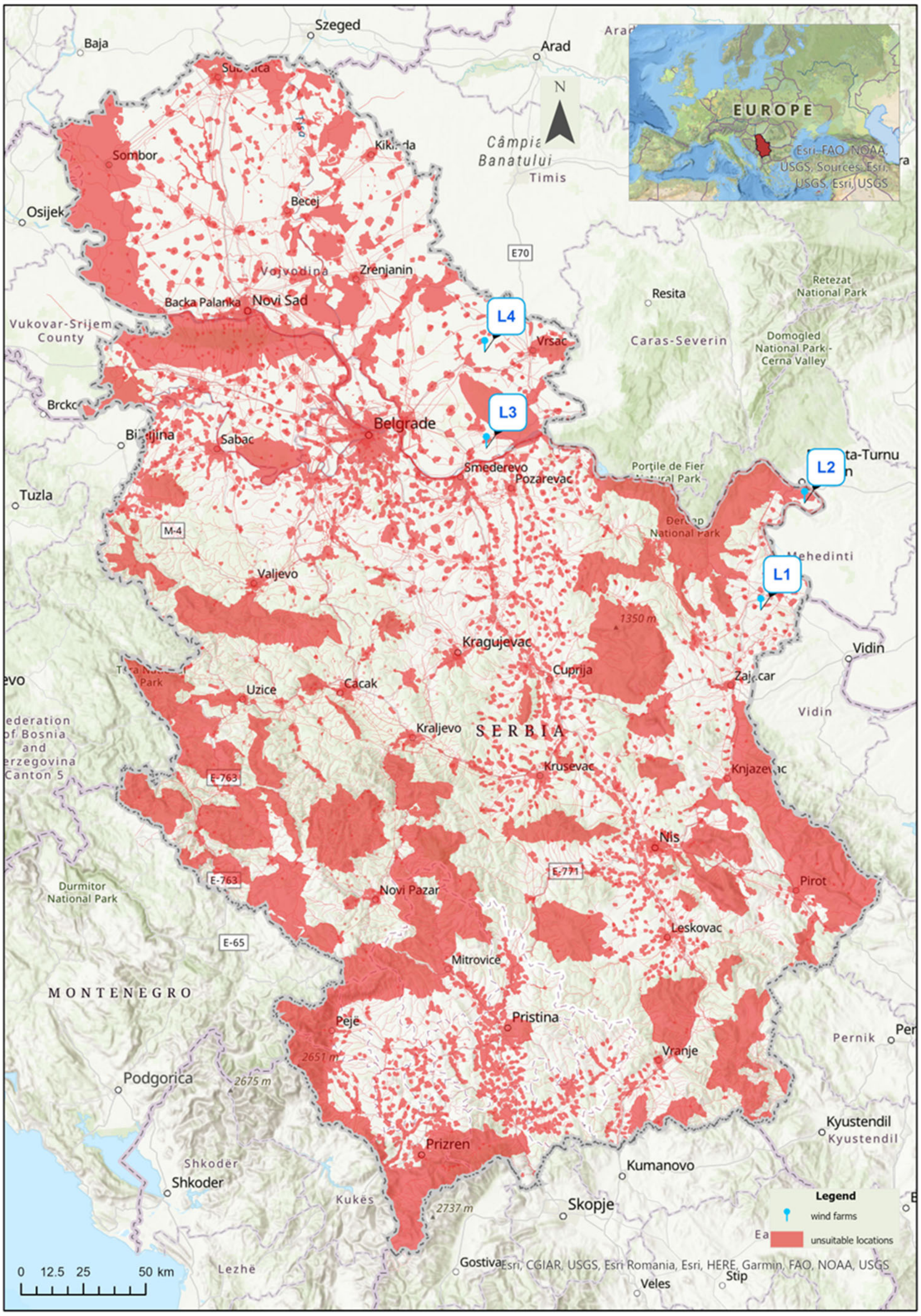

Figure 2. Synthesis map of the elimination criteria for the area where the procedure was applied, with candidate locations for the evaluation process (part of the Republic of Serbia, Southeastern Europe; L1—location 1, L2—location 2, L3—location 3, L4—location 4.).

Table 2. Selection of criteria for the multi-criteria evaluation of potential wind farm locations.

Evaluation Criteria	Reasoning	References from Other Studies	Source of Data Used in the Paper
1. Distance from protected natural areas [6]	The distance from protected areas, including Natura 2000 areas, is in direct proportion to reducing the possible impact on biodiversity, primarily on flying fauna. Having a greater distance of the wind farm from an area characterized by a wealth of biodiversity implies a significant avoidance of impact on the habitats and hunting territories of protected species of ornithofauna and chiropterofauna.	[15,21–24]	Calculation by the author based on the SPRS
2. Distance from water surfaces	When it comes to water surfaces, they often attract birds either in the form of habitats or in the form of migratory corridors during their migrations in spring and autumn, so the distance of the wind farm from the water surfaces reduces the possible impacts of collisions between birds and wind turbines during these periods.	[18,27,28]	Calculation by the author based on [29]
3. Distance from protected immovable cultural assets	The existence of immovable cultural assets in the micro-location area of the planned wind farm, primarily archaeological finds, gives an indication that there may be other undiscovered archaeological findings at the location itself. Increased distance from such localities greatly reduces the risk of encountering immovable cultural assets during the construction of a wind farm, which would affect the further development of the project.	[30–32]	Calculation by the author based on the SPRS
4. Distance from the nearest inhabited places and residential buildings for noise	It is known that noise intensity decreases with the distance of the receptor from the noise source (wind turbine). Precise determination of the safe distances that ensure that the noise from the wind turbine is within the prescribed limits depends on the standards adopted (EBRD, IFC, local regulations similar guidelines), the topography of the terrain, the superimposition of noise with other sources, the existence of physical barriers, the type of wind turbine, the wind speed at the location and the results of modeling the spatial dispersion of noise in each specific case.	[4,15,21,34]	Calculation by the author based on [35]

Table 2. *Cont.*

Evaluation Criteria	Reasoning	References from Other Studies	Source of Data Used in the Paper
5. Distance from the nearest inhabited places and residential buildings for the effect of shadow flicker [7]	The influence of flickering shadows can primarily have a psychological impact on the population, so in order to prevent this negative phenomenon in the functioning of the wind farm, it is necessary to apply the principle of preventive planning. For this purpose, as in the case of noise, different simulation models (software packages) are used, which can help to predict the spatial coverage of the flickering shadows, as a result of which it is possible to optimally determine the micro-locations of the turbines and thus reduce their impact.	[2,4,15,21,34]	Calculation by the author based on [35] and field research
6. Distance from the nearest inhabited places and residential buildings for the visual effect	This is a subjective category that is not easy to assess quantitatively. It depends not only on the perception of the observer but also on the type of landscape [8] and specific visual characteristics. There are different approaches in the analysis and assessment of the impact of wind farms on the landscape, but most authors agree that the assessment must be carried out using different software models for simulating and visualizing possible impacts.	[1,48–50]	Calculation by the author based on [35] and field research
7. Distance from traffic infrastructure	This criterion is defined in the context of the economics of building a wind farm, unlike the same elimination criterion related to safety. It represents an overview of the distance between the primary existing traffic infrastructure and the location of the planned wind farm. The same applies to the proximity of energy facilities, which are defined as "connection points" to the power system (grid). The proximity to or distance from the mentioned linear infrastructure reduces or increases the necessary investment in the construction of wind farms and putting the conditions in place for its functioning.	[36,51–54]	Calculation by the authors based on [55]
8. Proximity to energy facilities for connecting the wind farm		[22,53,56]	Calculation by the authors based on the SPRS

Table 2. *Cont.*

Evaluation Criteria	Reasoning	References from Other Studies	Source of Data Used in the Paper
9. Land purpose	The question of the existing use of the land is particularly important in terms of the economy of construction and implementation of the project because it indicates the necessary investments and possible risks for the wind power project to be carried out in a specific area. It is certainly most convenient if the wind power plant is located in a lowland, anthropogenically modified space because this requires the least risks for developing the project, as well as the least investment in the arrangement and preparation of the location for the construction of the wind farm.	[4,32,37,40,41]	[35]
10. Spatial organization of the land	Spatial organization, similar to the use of land, affects the economy of construction in terms of the work required to prepare the ground for construction, so flat terrains that do not require large interventions in space and significant preparation of the ground for construction are more suitable.	[4,57–59]	[35] and field research
11. Land ownership	An important criterion for considering the potential of a site for a wind farm is ownership of the land, which can simplify or complicate the implementation of the project. In many countries, the advantage in solving legal property relations with regard to ownership of the land is in the case of the private ownership of large parcels because the procedure is simpler, while state-owned land is considered complicated and uncertain to deal with.	[60–63]	[64]
12. Number of frosty days during the year	By crossing the weather data with data on the estimated production of the wind farm, it is possible to use software data to determine losses in relation to the number of frosty days. This criterion is formulated in relation to the empirical data for the candidate locations in this paper, and it may vary depending on the specific circumstances of each particular case.	[15,65,66]	Republic Hydrometeorological Institute

Table 2. *Cont.*

Evaluation Criteria	Reasoning	References from Other Studies	Source of Data Used in the Paper
13. Possibility of transportation	Access to the micro-locations of individual wind turbines is an important economic criterion that involves the spatial arrangement, rehabilitation, adaptation and construction of access roads to the location of the wind turbines so that it enables the remote oversized transport of wind turbine parts. A potential location for a wind farm can have a higher or lower rating depending on the interventions required on the access roads.	[58,67]	Field research
14. Engineering and geological characteristics of the soil	The engineering and geological properties of the terrain are another economic criterion that determines what kind of foundations the wind turbines will have. It results in an increase or decrease in the amount of investment required for constructing a wind farm. More stable and compact soils on flat terrain are the most suitable. The same applies to seismicity, which directly affects the type of foundations wind turbines have. Higher seismic risk is proportional to the increased costs of building foundations.	[22,52,53,68]	Republic Seismological Institute
15. Seismicity		[69–71]	Republic Seismological Institute
16. Landscape—exposure of the location	Unlike the criterion of visual impact from an inhabited place, this criterion includes general visibility for all potential observers, not only those who permanently reside in a settlement. This also applies to users of traffic infrastructure and other users of space in the wind farm zone. Sheltered, isolated and poorly visible locations are the most suitable in this context because the impact on the landscape in that case, is limited to a small area.	[49,72]	Field research
17. Relief features—terrain slopes	Having excessively sloping terrain can also be an elimination criterion, but it is challenging to define such an elimination criterion because it depends on many factors such as the type of wind turbine, position in relation to the slope of the terrain, constancy/length of the slope, etc. This is precisely the reason why there is no single quantitative statement for this criterion in the literature.	[22,52,53,68,73]	[74]

Table 2. *Cont.*

Evaluation Criteria	Reasoning	References from Other Studies	Source of Data Used in the Paper
18. Local community's acceptance of the location	A particularly important criterion in the group of social criteria is how acceptable the wind farm location is to the local community on whose territory the project is planned. In this context, the development of the project must be transparent in all aspects, and its acceptability should be assessed based on targeted surveys. The invaluable process of informing and educating the local community on all important issues related to the development of the wind farm should be taken into account.	[75–78]	Survey research

[6] The network of protected areas within the borders of the European Union was designed so that based on the Directive on the conservation of natural habitats and wild plant and animal species, better known as the Habitats Directive (Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora) and its appendices (for habitat types from Appendix I and for species from Appendix II), and the Directive on the conservation of wild birds/Bird Directive (Directive 2009/147/EC of the European Parliament and of the Council on the conservation of wild birds, first adopted in 1979—Council Directive 79/409/EEC), with species from Appendix I, areas could be set aside for protection with the aim of ensuring the long-term survival of the most valuable and most endangered species and habitats of Europe. This elimination criterion, therefore, refers to the area of Europe, but it can be applied to all other continents, taking into account protected natural areas and national parks, especially IBA (Important Bird Area) areas, considering that wind farms can have a dominant effect on flying fauna. [7] Wind turbines can cause shadows or glare, known in the literature as "Wind Turbine Syndrome". Considering the large dimensions of wind turbines, their height can block the light, and they can create a shadow in the surroundings. When in operation, there may be an unpleasant flickering of the shadows due to the turning of the propellers, which can be noticeable at great distances, especially in the morning and evening hours (the lowest position of the sun). Of course, this depends on the configuration of the terrain, the spatial disposition of the wind turbines in relation to existing structures and their orientation, the existence of physical barriers in the vicinity of the wind farm, and the path of the sun's movement in specific circumstances. [8] According to the European Landscape Convention (2000), landscape means an area whose character is the result of the action and interaction of natural and/or anthropogenic factors. Landscapes are not static because they change over time in relation to anthropogenic and environmental development. Wind farms are objects that dominate space. The reason is, on one hand, the large dimensions of the wind turbines, and on the one hand, the practice that wind farms are located in free spaces that are not encumbered by other types of construction. For these reasons, it is certain that wind farms have a significant impact on the landscape. However, that impact can be positive for the observer because it gives a specific visual identity to the space, while for another observer the visual impact will be negative because it changes the appearance of natural landscapes. It is certain that the visual effect of wind turbines on the observer decreases with distance, so this criterion from a sociological aspect is especially important when choosing the location of wind farms in relation to permanently inhabited places. [9] The formation of ice on wind turbines due to a large number of frosty days can affect the production of the wind farm, even in cases where the wind turbines are equipped with devices to prevent the formation of ice on the wind generator blades. This phenomenon is more pronounced at greater heights above sea-level and in areas with colder hydro-meteorological characteristics.

The selection phase is based on the principles of the PROMETHEE method and includes several methodological steps that are implemented and presented in this paper:

1. The candidacy of several locations included in the evaluation process—after carrying out the elimination stage, potentially favorable locations are nominated as potential wind farm sites, which from the aspect of wind potential can be included in the evaluation process. In this study are four candidate locations that stand out as very favorable in the Republic of Serbia because of their wind potential (Figure 2). All four locations have similar wind potential and the same spatial scope, but differences in their micro-locational characteristics, and they were chosen exclusively for the purposes of this study, i.e., to illustrate the evaluation procedure.
2. Determining the weight categories (WC) assigned to individual criteria as a score for the location according to the WC and value scale—when a potential location is evaluated according to all the given criteria, two procedures are possible: 1. Simple addition of the scores obtained, or 2. Multiplying the score obtained with the score for its significance (weight value). The first procedure for evaluating a potential location is the simplest, with very few requirements, but it does not recognize the different importance of individual criteria on the scale of criteria. By simply adding the scores for each individual criterion, the most favorable score is obtained, but it is one-dimensional. Evaluating locations in this way also lacks different scenarios that can be of great help to decision-makers. The second procedure is more complex and can use different scenarios as elaborated below. The weight category, or weight factor, involves determining the initial quantitative values of certain criteria or groups of criteria. Determining the weights of the criteria relates to the greater or lesser importance of a criterion in the process of determining a wind farm location. The weight categories and their values can be determined according to various methods (for an overview of these methods see [79–85]. Regardless of the choice of methods for determining weight categories, they are always burdened by the subjectivity of experts, which, however, does not significantly affect the evaluation results based on them. PROMETHEE does not provide specific guidelines for determining these weights, but assumes that the decision-maker is able to weigh the criteria appropriately, at least when the number of criteria is not too large [86]. In this case, depending on their importance for evaluating the quality of a location, the criteria are classified into three weight categories (WC), each with approximately the same number of criteria. Each WC has its own specific value—a weight that is multiplied by the score for the corresponding criterion (Table 3). As a result, a final score is obtained for each individual criterion. The specific values by weight categories are:

Table 3. Choice of scale for evaluating the criteria and grouping them according to weight categories.

Evaluation Criteria	WC	Criteria Scores				
		1	**2**	**3**	**4**	**5**
Distance from protected natural areas	WC3	0 to 1 km	1 to 2 km	2 to 3 km	3 to 5 km	>5 km
Distance from the nearest inhabited places and residential buildings for noise	WC3	0.5 to 0.6 km	0.6 to 0.7 km	0.7 to 0.8 km	0.8 to 1	>1 km
Proximity to energy facilities for connecting the wind farm	WC3	>5 km	4 to 5 km	3 to 4 km	2 to 3 km	<300 km
Number of frosty days during the year	WC3	>100	70 to 100	50 to 70	30 to 50	<30

Table 3. *Cont.*

Evaluation Criteria	WC	Criteria Scores				
		1	2	3	4	5
Engineering and geological characteristics of the soil	WC3	very incoherent soil with a slope	incoherent soil without a slope	moderately coherent soil with a slope	moderately coherent soil without a slope	coherent soil without a slope
Relief features—terrain slopes	WC3	slopes > 25%	slopes from 15–25%	slopes from 10–15%	slopes < 10%	flat terrain without a slope
Local community's acceptance of the location	WC3	majority disagreement of the local community	division of the local community	support of the local community and disagreement of individuals	majority support of the local community	full support of the local community
Distance from water surfaces	WC2	0 to 0.5 km	0.5 to 1 km	1 to 2 km	2 to 3 km	>3 km
Distance from protected immovable cultural assets	WC2	0 to 0.2 km	0.2 to 0.5 km	0.5 to 1 km	1 to 2 km	>2 km
Distance from the nearest inhabited places and residential buildings for the effect of shadow flicker	WC2	0.5–0.7 km, without physical protection	0.5–0.7 km, with physical protection	0.7 to 1 km	1 to 1.5 km	>1.5 km
Distance from the nearest inhabited places and residential buildings for the visual effect	WC2	<1 km on lowland terrain	1 to 2 km on lowland terrain	2 to 5 on lowland terrain	5–10 km on lowland terrain	>10 km on lowland terrain
Land purpose	WC2	natural areas with rich vegetation	natural areas with sparse vegetation	meadows	hilly anthropogenically modified land	lowland anthropogenically modified land
Possibility of transportation	WC2	there are no access roads to the location	there are partial access roads to the location	there are access roads that need to be reconstructed	access roads that need to be adapted	there are suitable access roads
Distance from traffic infrastructure	WC1	<300 m	300 to 400 m	400 to 500 m	500 to 800 m	>800 m
Spatial organization of the land	WC1	very complicated work on landscaping the terrain	complicated work on landscaping the terrain	larger works on landscaping with mechanization	smaller works on landscaping with mechanization	Simple work on landscaping the terrain
Land ownership	WC1	state ownership with smaller plots	state ownership with larger plots	state and private ownership	private ownership with smaller plots	private ownership with larger plots
Seismicity	WC1	9–8 MCS	7 MCS	6 MCS	5 MCS	<5 MCS
Landscape—exposure of the location	WC1	exposed and easily visible location	location sheltered to a lesser extent	location sheltered to a greater extent	the location is visible from a great distance	the location is visible from a close distance

$$WC1 = 1$$

$$WC2 = 1.5$$

$$WC3 = 2.25$$

Between the weight categories, the following relation applies:

$$K(n + 1) = Kn \times 1.5$$

Weight categories are assigned to the evaluation criteria according to their importance for site selection (Table 3). The most important criteria are in the WC3 category, slightly less important criteria are in the WC2 category, and all other criteria are in the WC1 category.

The differences between the weight categories are established based on the number and importance of the criteria so that there is not too much difference between them (×1.5), given that the importance of individual criteria is often difficult to determine and classify into a certain weight category. Thus, the chosen ratio between the weight categories is appropriate because it cannot imply a significant deviation in the results, especially in cases where the objectivity of the evaluator is emphasized.

In addition to categorizing criteria based on their weight, another crucial step in the process of choosing a location for a wind farm is defining a value scale, based on which individual criteria are evaluated (assessed, scored). Quantitative assessment is usually applied (e.g., scores from 1 to 10, or from 1 to 5, as is the case in this study). The values for assessing specific criteria (Table 3) are adaptable, that is, they depend on each particular case, the type of wind turbine and the specific location being evaluated. For example, the required distance of a wind farm from residential buildings may vary in flat versus hilly areas, considering that the specificity of the topography of the terrain can increase or limit the spatial dispersion of the possible effects of the wind power plant on its surroundings. In addition, the values for assessing individual criteria are established after carrying out specific studies, such as those for proximity of airport runways or meteorological radar systems in mountainous areas. These facts must be taken into account when determining the value of the evaluation criteria in each specific case. As with the elimination criteria, assessing the criteria according to their values in Table 3 is adapted to the relevant legislation and the data available regarding each specific area. The evaluation can be qualitative/expert, whereby the criteria can be evaluated as favorable, conditionally favorable or unfavorable, or it can be combined (a semi-quantitative method). Qualitative evaluation is becoming less common nowadays because the application of modern technologies enables more precise and better-quality evaluation based on quantitative principles. As a result, more objective data can be obtained, which can be compared and used as the basis for decision making.

3. Classification of criteria into different groups and evaluation in relation to different scenarios—if the criteria for locating wind farms are classified into several basic groups, then as many scenarios as there are basic groups of criteria should be considered. In the first scenario, criteria from one group are favored as the most important. In the second scenario, criteria from another group are the most important, and so on. As the final option, the situation is considered in which the groups of criteria are multiplied by the same rating of importance, without favoring any individual group of criteria. This can be considered as a supplementary procedure, which is indispensable in cases when the results of the evaluation according to weight categories are approximately equal, making decision making more difficult. This study classifies the criteria into two groups: spatial and socio-economic (Table 4). Spatial criteria refer to spatial relationships expressed in distances, while socio-economic criteria refer, on one hand, to the social aspects and acceptability of the location and, on the other hand, to the investments necessary for the development of the project. Both groups of criteria are connected with the spatial, i.e., physical/geographical, characteristics of the space.

Table 4. Classifying the criteria into groups.

Spatial Criteria	Socio-Economic Criteria
Distance from protected natural areas	Proximity to energy facilities for connecting the wind farm
Distance from water surfaces	Land purpose
Distance from protected immovable cultural assets	Spatial organization of the land
Distance from the nearest inhabited places and residential buildings for noise	Land ownership
Distance from the nearest inhabited places and residential buildings for the effect of shadow flicker	Number of frosty days during the year
Distance from the nearest inhabited places and residential buildings for the visual effect	Possibility of transportation
Distance from traffic infrastructure	Engineering and geological characteristics of the soil
Landscape—exposure of the location	Seismicity
	Relief features—terrain slopes
	Local community's acceptance of the location

In this stage, the scores of each individual criterion from the basic evaluation are multiplied by the weight values for the groups of criteria, according to the different scenarios. The weight values here are expressed as percentage values, the sum of which is 100%. By showing the different scenarios in the synthesis table, it is easy to see which locations are the most favorable in which scenarios; thus, the application of the PROMETHEE method realizes its full potential [87]. In the first scenario (SC1), greater importance (75%) is given to spatial criteria in relation to socio-economic criteria (25%). In the second scenario (SC2), greater importance is given to socio-economic criteria (75%) in relation to spatial criteria (25%). Meanwhile, in the third scenario (SC3), both groups of criteria were given the same importance (50%).The main advantage of this procedure is that the decision-makers have a clearer idea of which potential location for a wind farm is the most favorable if the criteria from one of the specific groups (spatial or socio-economic) have the highest rating and which is the most favorable location if the basic groups of criteria are treated equally. Therefore, the job of the decision-makers is made much simpler.

3. Results

The candidate locations (L1–L4) used in this study to simulate the process of selecting a location are situated in potentially suitable areas (outside the elimination areas). All candidate locations meet the basic preconditions for locating wind farms, since they have approximately the same characteristics with regard to their wind potential (average annual wind speed, constancy of annual wind distribution). That is, they have approximately the same production estimate. Each of the nominated locations has space for positioning 30 wind turbines. The locations cover a range of physical/geographical characteristics and spatial advantages and limitations, chosen in order to diversify the simulation of selecting a location.

Location L1 is situated in a hilly area 300 m above sea level. Location L2 is situated in a lowland area near the international Danube River and the border with Romania (possible transboundary impacts). Locations L3 and L4 are located in lowland areas with similar physical and geographical characteristics.

The evaluation results according to the weight categories (WC) indicate that the most favorable location, with the highest overall score, is location L4. Location L3 has a slightly lower value (3.5 points), while locations L1 and L2 have approximately the same rating but with values significantly lower than locations L3 and L4 (differences from 22 to 26.3 points). The main differences in the values of the candidate locations (Table 5) relate to the distance from protected areas, migratory corridors and the infrastructure required for implementing the wind farm project.

Table 5. Evaluation results for the candidate locations according to weight categories.

Evaluation Criteria	WC	Scores for Candidate Locations			
		L1	L2	L3	L4
Distance from protected natural areas	WC3	11.25	4.5	6.75	11.25
Distance from the nearest inhabited places and residential buildings for noise	WC3	11.25	11.25	11.25	11.25
Proximity to energy facilities for connecting the wind farm	WC3	2.25	4.5	9	9
Number of frosty days during the year	WC3	4.5	6.75	11.25	11.25
Engineering and geological characteristics of the soil	WC3	6.75	4.5	11.25	11.25
Relief features—terrain slopes	WC3	9	11.25	11.25	11.25
Local community's acceptance of the location	WC3	11.25	11.25	11.25	11.25
Distance from water surfaces	WC2	7.5	6	6	6
Distance from protected immovable cultural assets	WC2	7.5	6	6	4.5
Distance from the nearest inhabited places and residential buildings for the effect of shadow flicker	WC2	3	7.5	6	7.5
Distance from the nearest inhabited places and residential buildings for the visual effect	WC2	3	7.5	3	4.5
Land purpose	WC2	6	6	7.5	7.5
Possibility of transportation	WC2	3	3	7.5	6
Distance from traffic infrastructure	WC1	5	4	5	5
Spatial organization of the land	WC1	4	5	5	5
Land ownership	WC1	4	4	5	5
Seismicity	WC1	2	1	3	2
Landscape—exposure of the location	WC1	3	1	1	1
	Total scores	104.2	105	127	130.5

When it comes to the evaluation results for the candidate locations according to different scenarios (Table 6), the order of the locations is similar to the previous case. L4 is the most favorable location in scenario 1, where the spatial criteria are more significant, and in scenario 3, where both the spatial and socio-economic criteria have equal value. Location L3 has the highest rating in scenario 2, where the socio-economic criteria are more important than the spatial criteria.

Table 6. Evaluation results for the candidate locations according to different scenarios.

Groups of Criteria According to the Table 4	Scenario											
	SC 1				SC 2				SC 3			
Spatial	0.75				0.25				0.50			
Socio-economic	0.25				0.75				0.50			
Candidate locations	Location Evaluation Results (Ranking of Locations)											
	SC 1				SC 2				SC 3			
	L1	L2	L3	L4	L1	L2	L3	L4	L1	L2	L3	L4
	31.75	30.75	32.75	**34.5**	31.25	32.25	**42.25**	41.5	31.5	31.5	37.5	**38**

Although the results of the evaluation for the candidate locations do not highlight a significant difference between them in terms of point, they clearly indicate the reasons (advantages and disadvantages) for selecting the most suitable location and adequately simulate the process of selecting a location.

4. Discussion and Conclusions

In the scientific literature today, there are different, but also very similar, methodological approaches for choosing the optimal location for wind farms. This is indicated by the number of references listed in this study. The differences relate to the choice of criteria for evaluating potential locations and the number of methodological procedures that offer different options for making sound decisions. However, all these methodological approaches have in common that they are all based on the multi-criteria evaluation of potential locations.

Bearing in mind the differences and similarities between the methodological approaches in the scientific literature, the specificity of this work can be seen in several aspects:

- The choice of elimination and general evaluation criteria is defined on the basis of four components: 1. Analysis of a large number of scientific papers; 2. The authors' practical experience from participating in the development of many wind power projects in the Western Balkans, Europe (some of the projects are listed in Section 2 of the paper); 3. Adaptation of the criteria and value scale to local regulations for the specific examples used in the paper, as well as the specificity of each project, the physical/geographical characteristics of the locations and others; 4. The addition of evaluation criteria not present in other scientific articles on the theme of selecting wind farm locations, but whose significance is elaborated in scientific articles that deal with important issues related to wind farms in general, such as the social aspects of their impact (e.g., the local community's acceptance of the location, which is determined through the transparency of the procedure and the results of surveys).
- The paper proposes a number of stages in the process of choosing optimal wind farm locations: 1. The elimination stage for unfavorable areas; 2. Multi-criteria evaluation of the candidate locations according to weight categories; and 3. The evaluation stage for candidate locations according to different scenarios. Carrying out these stages provides decision-makers with enough options based on which they can make sound decisions based on viewing the problem from different angles. The approach is also sufficiently flexible to include all actors in the process of selecting a location with regard to identifying the goals of using a certain space, adaptation to local regulations, and respecting the needs of both the local community and investors.
- The authors tried to make the conceptualization and elaboration of the methodological approach very simple and understandable, and therefore easily applicable. They were guided by the idea that it should be possible to apply scientific knowledge and results in practice so that they can be used by a wide group of professionals who are not involved in science but rather in the development of wind power projects as professionals.

In addition, the quality of the overall results depends on the information base about the space, that is, the spatial data, which is evident here. Therefore, in this study, the application of GIS proved to be a very important instrument, especially in the elimination stage of selecting a location and visualization of the results (Figure 1). In addition to being a support in the elimination stage, spatial data in GIS also provided excellent support in the evaluation of potential locations using the PROMETHEE method, since GIS offers precise inputs regarding the distance between a specific location and various spatial elements (criteria). In this way, the evaluation of the criteria according to a scale from one to five was objective and not arbitrary or subjective.

It has been stated that the number and importance of the evaluation criteria can and should be adjusted to the specific circumstances in terms of respect for the spatial and physical/geographical characteristics, and in terms of local regulations, although this fact does not affect the very concept of the presented methodology. The compatibility of the criteria with the real circumstances for each specific case is, nevertheless, important for the final results of the evaluation process, and so it must not be omitted.

Finally, when choosing evaluation criteria and classifying them into groups for evaluation according to different scenarios, it is necessary to keep in mind that the process of selecting wind farm locations is just the initial step in developing wind power projects. Other instruments will be used in the further stages of project development for determining specific impacts at the level of planning and project documentation. Examples of such instruments are Strategic Environmental Assessment (SEA) and Environmental and Social Impact Assessment (EIA/ESIA), which have specific criteria and use the results of continuous observations of biodiversity to check the suitability of locations at the micro-location level of individual wind turbines.

In the elaborated approach, it may seem contradictory to omit the criterion related to the wind potential at a certain location. However, the introduction highlights the importance of wind potential as a prerequisite that a specific area must fulfil in order for it to be considered further as a possible wind farm location. Therefore, this criterion is considered a precursor to the process of choosing a wind farm location, and it is based on previous analyses carried out at the macro level, as explained in the introduction.

On the other hand, regardless of which of the numerous methods is used to evaluate the potential locations of wind farms, there is the question of how objective the process is, considering that the selection of all evaluation elements (criteria, value scale for assessment, weight values, grouping the criteria for evaluation according to different scenarios), indeed the whole decision-making process, is a matter of the skill of experts and decision-makers. This can be considered a universal conditional shortcoming of all methods for selecting potential locations, and so subjectivity in this procedure must be minimized, and objectivity maximized. Different software models and tools are, therefore, used that result in quantitative statements, which are highlighted in the paper as particularly significant.

The methodological approach presented here can be applied globally, with some adaptation to the type and requirements of individual projects, by adapting the evaluation criteria to the specific conditions in a certain area and taking into account the specifics of the relevant legislation, as well as variations in equipment installation costs, which can be considered a risk for the presented, but also for any other methodological approach. In this context, it is important to develop plans for emergency situations during the development and implementation of wind farm projects that will offer answers to new circumstances and thereby reduce project risks.

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