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Cumulative Impact of Wind Farm Noise

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Abstract: Although wind farms have an undeniable beneficial impact on the environment, certain negative environmental implications do appear as a consequence of their operation. One of them is the production of noise. The wind farm noise values decrease with distance, so that at a certain point they are within the legally prescribed limits. This is the case for individual wind farms noise impact assessments. However, with two or more wind farms in the same area, there is a superposition of noise and a consequential change in the noise value. The focus of the paper is on the results of modeling noise propagation in space in the case of the cumulative impact of two neighboring wind farms. The results are modeled during the process of strategically assessing the environment so as to determine territorial impacts and make informed decisions about future development. The paper presents the strategic answer to the model of the spatial propagation of noise in cases of cumulative impact with a view to including the preventive protection principle in the planning of several adjacent wind farms.

Keywords: noise; cumulative impact; wind farm; strategic environmental assessment

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1. Introduction

The impact of wind farm noise is especially important when it comes to assessing its negative effects on human health. These effects can be classified into several groups [1]: subjective effects (discomfort, distraction, and discontent); obstruction of everyday activities (conversation, sleep, and studying); and physiological effects (anxiety, tinnitus, or hearing loss at worst) [2,3]. The most striking issues in their significance so far have been the acoustic impact and sleep disturbance that affect the local population in the areas around wind farms [4,5]. Sleep disturbance caused by wind farm noise can be singled out as having a particularly significant negative impact due to its health, psychological, and psychosomatic effects, which have been the focus of many research papers [5–12]. The most striking implications felt and reported by the population settled around wind farms are anxiety, sleepiness, fatigue, irritability, and reduced sleep quality [7,10], especially if the noise level exceeds 45 dB. Such symptoms are caused by the forced change of sleep patterns, which affects the quality of life, especially for the sensitive and aging population [13].

A number of authors have mentioned infrasound as a noise-related issue resulting from the wind farm operation [14–20], while some others are more concerned with low-frequency sound [21]. In their comprehensive study of literature on the possible effects of wind farms on the health of the population, Freiberg et al. [22] conclude that when it comes to infrasound and low-frequency noise produced by turbines in wind power plants, major impacts on people include physical symptoms, general health issues, and affective impact (temper). By analyzing extensive literature, the authors point to the deficiency of properly conducted and comprehensive studies, both clinical and epidemiological, on the potential effects of all kinds of low-frequency noise on the well-being of the population inhabiting wind farm areas. In such a context, certain authors [23,24] point out the significance of predetermined referential methodology for measuring the impact as well as the need for setting clear codes for estimating the tolerable level of turbine noise effects, especially if we have in mind many different laws and regulations for determining the limitations of acoustic noise produced by wind turbines in different countries existing today.

In addition to its effect on people, wind farm noise also negatively affects biodiversity, or fauna, to be precise, which has been examined by Brignon et al. [25].

With all the above said, it would be most convenient to include measures of preventive protection against the possibly negative environmental impact of wind farms as early as the planning stage. The projection of noise effects is even more important if several wind power plants are to be developed in the same area due to their cumulative acoustic impact on the said space, which is, as a rule, stronger than the combined impact of individual wind farms. The most convenient point for addressing the issue of noise impact assessment would be the Strategic Environment Assessment (SEA), as it is one of the earliest documents in the process of project development. Preventive planning at that stage would eliminate issues arising in later stages of project development [26,27]. That was the case of Čibuk and Vetrozelena, two adjoining wind farms from Serbia presented in this paper.

Different methods of projecting wind farm noise levels in the environment have been used across the world. By studying the development of a wind farm noise propagation prediction model, Bass, Bullmore, and Sloth [28] conclude that the noise propagation prediction model defined by the international standard ISO 9613 offers "impressive" precision for the predicted and actually measured noise levels. However, it can be further improved by introducing corrections depending on topographic conditions. After that, Bullmore et al. [29] carried out measurements around three European wind power plants and established that the ISO 9613 noise propagation prediction model produced the upper noise limit in the case of a downstream wind.

The measured and projected noise levels of two wind farms that are part of the Portland Wind Energy Project were also examined [30]. For the purpose of this research, the noise levels were measured according to New Zealand Standard No. 6808 [31,32] and compared with the sum of the predicted noise levels and the average noise levels before the wind farms construction. The ISO 9613 noise propagation method proved to have produced beneficial results in the analysis of these two wind farms.

Numerous standards and guidelines suggest different wind farm noise prediction methods [33]. In cases of considerable distance between wind turbines and receptors, where considerable characteristics of the terrain must be taken into account, the ISO 9613 model offers more precise results, which makes it seemingly the most precise predictor of the measured post-construction noise levels. South Australian noise level guidelines also recommend ISO 9613 as a prediction method.

All the advantages presented by this method suggest the application of the method based on ISO 9613 in the research presented in this paper.

2. Initial Position

Čibuk Wind Farm and Vetrozelena Wind Farm (case study) are planned in the northern part of the Republic of Serbia (East Europe), some 35 km from the capital Belgrade and about the same distance from the border with Romania (Figure 1). It is a low-lying, plain area, which is of special importance for determining the characteristics of the spatial propagation of noise. Čibuk Wind Farm (156 MW) has already been developed and is operational, while Vetrozelena Wind Farm (300 MW) is in the document preparation stage.

In the course of Vetrozelena Wind Farm Urban Plan preparation, it is necessary to include the cumulative acoustic effect of both the existing and the planned wind farms, as well as the change in the outline of the impacted area relative to identified receptors.

The assessed cumulative impact of noise produced by turbines is part of the expert analysis and multicriteria evaluation (semiquantitative method) in SEA [34–36], aimed at determining the best possible microlocations of each turbine that is to be part of the future Vetrozelena Wind Farm and also applying preventive measures against noise from the very first stage of planning and developing Vetrozelena Wind Farm [37]. The basis for defining criteria for determining the acceptable wind farm noise effect was local legislation in the area, leaning on the Environmental Noise Directive (2002/49/EC) [38] and the Guidelines for Community Noise (WHO, 1999) [39].

Figure 1. The case study location of Čibuk and Vetrozelena wind farms in Serbia (marked red).

The European Strategic Environmental Assessment Directive 2001/42/EC [40] stipulates the implementation of the SEA process in planning and drafting programs in different areas, one of them being the energy management sector, ergo the wind power industry. Despite the widely accepted negative impact of wind farms on the environment, it must be pointed out that their benefits are far greater. Negative impacts cannot be completely disregarded, though, as stated in EU Guidance on Wind Energy and EU environmental regulations [41]. Plenty of research highlights the negative impacts of wind farms on the environment and ecosystem services [42].

When assessing the territorial impacts in SEA, the planning stage includes taking stock of the wind farms effects on biodiversity, people living in the area (those being shadow flicker effects, noise pollution, or the possibility of accidents), and landscape. These results are of prime importance for deciding on the proper number of turbines and their microlocations. Each of the above aspects can be partially examined (The term "partial" is used here for assessing the effect of a specific project, i.e., a wind farm, on a single element of the environment (more specifically noise), therefore the noise impact only), but it can also be a part of the holistic wind farm effects environmental assessment, preferably by means of software models that make the process more objective [43–47].

3. Materials and Methods

The space in question is predominantly anthropogenically changed agricultural low-laying land, containing different infrastructure. The wind farm impact zone also includes several rural settlements. All these are spatial limitations for setting the exact locations of turbines.

In this Case Study, different environmental aspects of wind farms were determined by means of SEA: their impact on biodiversity, on the quality of land, water, and air, on landscape, climate change, cultural heritage, more precisely the impacts of cumulative noise, non-ionizing radiation, shadow flicker effect, infrastructure, possible accidents, socio-economic aspects of development, and based on the results, the optimum position of wind turbines. The focus of this paper, however, was not the SEA process itself, which examines all the said aspects, but only a partial assessment of the aspect of noise, the results of which were then integrated into the SEA process by means of the criteria for multi-criteria assessment of the planning solutions. References describing the principle of integrating a partial assessment into the SEA process are provided hereafter. The SEA procedure is mostly based on expert methods, which are qualitative and subjective in nature. It allows a comprehensive approach to the environment assessment but is also less precise compared with different mathematical and software environmental models in the project design stage (not in planning), that is, in preparing technically oriented environment assessment studies, such as Environmental Impact Assessment (EIA) [48]. For that reason, it is challenging to apply the balanced methodological approach that allows the combined use of available environment assessment techniques in SEA so as to ensure a holistic approach to environmental protection at the strategic level of wind farm planning.

In this particular case, as a means of supporting the SEA process in the part referring to the assessment of the acoustic impact, the modeling was done for the propagation of noise cumulatively generated by the 57 GE Wind Energy GE 2.75–120 turbines that operate in the Čibuk Wind Farm and the future Vetrozelena Wind Farm, which would comprise 49 VESTAS V162-6.2 wind turbines.

Noise was modeled by means of the licensed Wind Pro 3.5.584 software package, made by the renowned Danish software developer EMD International, which is considered an industry standard and whose results are interpreted against regulations and standards [38,39,49–55].

The key input data in modeling wind farms are the positions and types of turbines, as well as the wind speed, collected during the continual measuring campaign by setting anemometers on the location of the future wind farm. Another input would be the position and status of buildings in the wind farm area acting as the affected receptors. The same field research can identify potential natural and anthropogenic barriers between wind turbines and receptors since they can relativize potential impacts, especially the shadow flicker and less so the noise effects. The data on receptors and their microlocation are of key importance for the modeling procedure.

The software package uses the data on the turbines position and the terrain configuration, as well as default data on the noise generated by a specific type of turbine depending on the wind speed. The software itself takes into consideration the standards for prescribed noise extent (ISO 9613-2). In this specific case, ISO 9613-2—Attenuation of sound during propagation outdoors, Part 2. A general method of calculation was used for calculating sound attenuation during propagation outdoors (in case octave data are not available).

The modeling parameter was an 8 m/s wind speed measured at a height of 10 meters above ground level. A detailed explanation of the modeling process in WindPro 3.5 is available on the producer's link [56].

The following mechanisms for reducing the noise level were taken into account:

- Reducing the noise level caused by geometric deviation—reducing the level of noise with the increase in distance from a particular wind turbine;
- Reducing the noise level caused by atmospheric absorption—further reduction of noise in contact with air;
- Reducing the noise level caused by the land effect—further reduction of noise as it travels through the soil between a wind turbine and a receptor.

The said calculation method is used in conditions when the sound travels in the direction of the wind. The level of noise is lower when the sound travels in the opposite direction from the direction of the wind. Therefore, the said method is a conservative scenario since it implies that receptors are always positioned in the wind's direction. Separate models were made and noise calculations performed for each of the 49 turbines in the future farm and the 57 turbines that are already in operation. The total noise produced by all the wind turbines was modeled in the zone of the identified sensitive receptor.

The paper points out the use of the most conservative method—the noise traveling in the direction of the wind (from the wind turbine towards the receptor), in which case Cmet (meteorological correction factor) was not taken into account in calculations, meaning the case of a wind blowing in the opposite direction was not taken into account, which would produce lower values. In the analysis, the guidelines of A Good Practice Guide to the Application of ETSU-R-97 for the Assessment and Rating of Wind Turbine Noise have also been used [57].

This document provides a framework for measuring wind farm noise and presents indicative noise levels that call for a reasonable level of protection without imposing unreasonable limitations on wind farm development. The working group that dealt with the noise impact in this document recommends the fixed nightime limit be derived from the criteria for healing [58–62] and sleep disturbance of 35 dB(A), which served as a basis for noise level projections in this paper.

When it comes to analyzing the cumulative effect of several wind farms, the conditions or criteria on the selected receptors that have to be met remain unchanged as compared with the analysis of a single farm's noise production.

The allowed values of operating noise are established in line with the recommendations of IFC PS1, i.e., Environmental, Health, and Safety (EHS) Guidelines—General EHS Guidelines: Environmental Noise Management, for wind energy (International Finance Corporation Performance Standards 1—World Bank Group).

Allowable wind turbine noise levels recommended by the World Bank (Table 1) are examined against the allowable values envisaged by local legislation in the Republic of Serbia (Table 2) and/or Directives on the noise indicators, limit values, methods for the assessment of noise indicators, disturbance, and negative environmental effects of noise [51,56].

Table 1. Recommended noise levels (World Bank) *.

	LAeq (dBA)	
Receiver—receptor	Day 07.00–22.00	Night 22.00–07.00
Residential; institutional; educational	55	45
Industrial, commercial	70	70

* The data are for the noise registered outside the buildings [49].

Table 2. Limit values of outside noise indicators.

Zone	Purpose of Space	Noise Level, LAeq (dBA)	
		Day and Night *	Night
1	Leisure and recreational areas, zones of hospital, heritage sites, large farms	50	40
2	Tourist destinations, camping zones, school areas	50	45
3	Strictly residential areas	55	45
4	Combined commercial and residential areas, combined shopping and residential areas and playgrounds	60	50
5	Industrial zones, warehouses, car service areas, transport terminals	65	55

* For this purpose, the 24 h period is separated into a day (from 06.00 to 18.00); an evening (from 18.00 to 22.00); and a night (from 22.00 to 06.00).

Calculating the cumulative effect of noise produced by several wind farms can be a complex process depending on multiple factors, including the size and number of wind turbines, the distance between the farms, and the different characteristics of the surrounding area.

The computer-generated model can be used for the simulation of the noise level at different points around the wind farm, including the nearby residential facilities. The results can be used for the prediction of potential wind farm impacts on local levels of noise and for the identification of areas requiring the implementation of noise reduction measures.

The following equation presents the method of calculating the noise level of a single turbine in a receiver [63]:

$$Lp = Lw - Adiv - Aatm - Agr - Abar - Amisc - Cmet$$

Lp—the calculated noise (dB);
Lw—a wind turbine sound pressure (dB);
Adiv—the attenuation due to geometrical divergence;
Aatm—the attenuation due to atmospheric absorption;
Agr—the attenuation due to ground effect;
Abar—the attenuation due to a barrier;
Amisc—the attenuation due to miscellaneous other effects;
Cmet—meteorological correction.

Since this is a conservative method, the following attenuation effects have not been taken into account: Agr, Abar, Amisc, and Cmet, so the total level of noise produced by a single wind turbine is calculated in the following manner:

$$Lp = Lw - Adiv - Aatm$$

$$Lp = Lw - 10\log(2\pi r^2) - ar$$

r—source–receiver distance (m);
a—the atmospheric absorption (dB/m).

The cumulative noise level of multiple wind turbines in a receiver is calculated as

$$Lcum = 10\log(\Sigma 10\ (Lp/10))$$

Having in mind the type of terrain in which the two wind farms used for modeling and presented here are situated (porous ground), this effect is negligible. If the modeling was done on extremely hard ground or an area covered in concrete, this effect would definitely be included in the calculation.

Basic parameters that need to be entered into the software for calculating the noise level are presented at the beginning of this section. Different calculations are possible depending on the input data (wind speed—average or maximum, different turbine types, etc.). In this way, a clear picture of noise level changes corresponding to different scenarios is provided, enabling proper decision-making in optimizing the project's development. A detailed explanation of the impact of the reflected sound in modeling by means of WindPro is given in the software manual [63].

The data generated by such modeling can be further analyzed to determine the average level of noise and identify all the areas in which the noise exceeds the recommended levels. Such information can be used in developing strategies for mitigating wind farm noise effects, such as adjusting the orientation of turbines or erecting noise barriers.

4. Results

The effects of noise are modeled on the noise receptors (R)—the existing facilities, permanently or temporarily used, in the zone of possible wind farm impact. A total of eight receptors are identified. The consensus is reached that, since identifying receptors below 35 dBA for individual wind farms is becoming more common, the noise contour of 35 dBA would also be appropriate for a cumulative assessment. Figure 2 outlines the 35 dBA impact area for individual wind farms, while Figure 3 shows the changed 35 dBA contour in the case of a cumulative effect.

Figure 2. Noise value outlines for individual wind farms (Čibuk Wind Farm (**left**), Vetrozelena Wind Farm (**right**)).

Receptors R1 to R7 are positioned in the border areas so as to detect the extension of the 35 dBA outline, while the R8 receptor is placed in the central impact zone of both wind farms.

Although the change in the 35 dBA contour in the case of cumulative impact is only slight, it is easy to notice that the receptors R2 and R6, which were outside the impact zone of individual wind farms (as shown in Figure 2), are now affected. It can also be seen that the receptors R4 and R8 are within the 40 dBA noise contour when it comes to the cumulative impact, although still within the limits of legally prescribed values. In addition, a slight increase in the area with the predicted levels of noise of 45 dBA is perceived without impacting the identified receptors.

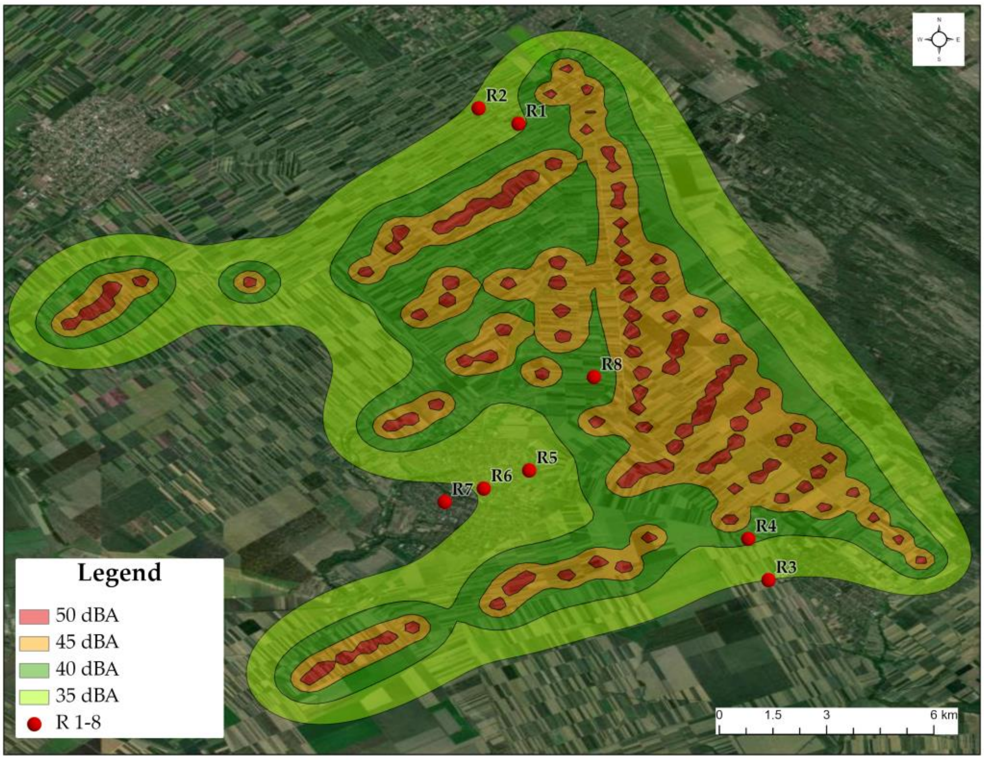

Figure 3. Noise value outline for the cumulative effect of Čibuk and Vetrozelena wind farms.

Table 3 shows the quantitative results of noise value modeling for individual wind farms as well as a cumulative noise value for all the receptors.

Table 3. Quantitative results of noise value modeling in decibels (dBA).

Noise Receptors	Čibuk Wind Farm	Vetrozelena Wind Farm	Cumulative Effect	% Increase
R1	32.8	33.9	36.4	11%
R2	37	37.1	39.7	7%
R3	34.1	33	36.3	6%
R4	37	40.2	41.7	13%
R5	32.5	36.1	37.7	16%
R6	29.5	34.6	35.8	21%
R7	26.8	33.8	34.6	29%
R8	41.5	39.6	43.3	4%

The modeling results shown in Table 3 and Figure 3 outline the increase in noise in the case of cumulative effects, on the one hand, and the greater spatial propagation of the same effect, on the other. The last column shows the percentage of noise increase in the receptors due to the cumulative effect of farms as compared with the noise values of the existing Čibuk wind farm. In practice, criteria for determining limit values of noise prescribed by the national regulation are stricter than World Bank recommendations (Tables 1 and 2). Here, however, the noise values are still within the allowable World Bank range (Table 1) but also within the acceptable values stipulated by the national legislation (Table 2), since the values are the same. It has a value of 45 dBA at night (Figure 4). In that context, there is no need for additional planning solutions that would command the change in position of certain wind turbines or envisage measures for the reduced work of wind turbines in certain conditions. This was the exact conclusion of the SEA process in the part that refers to the noise impact.

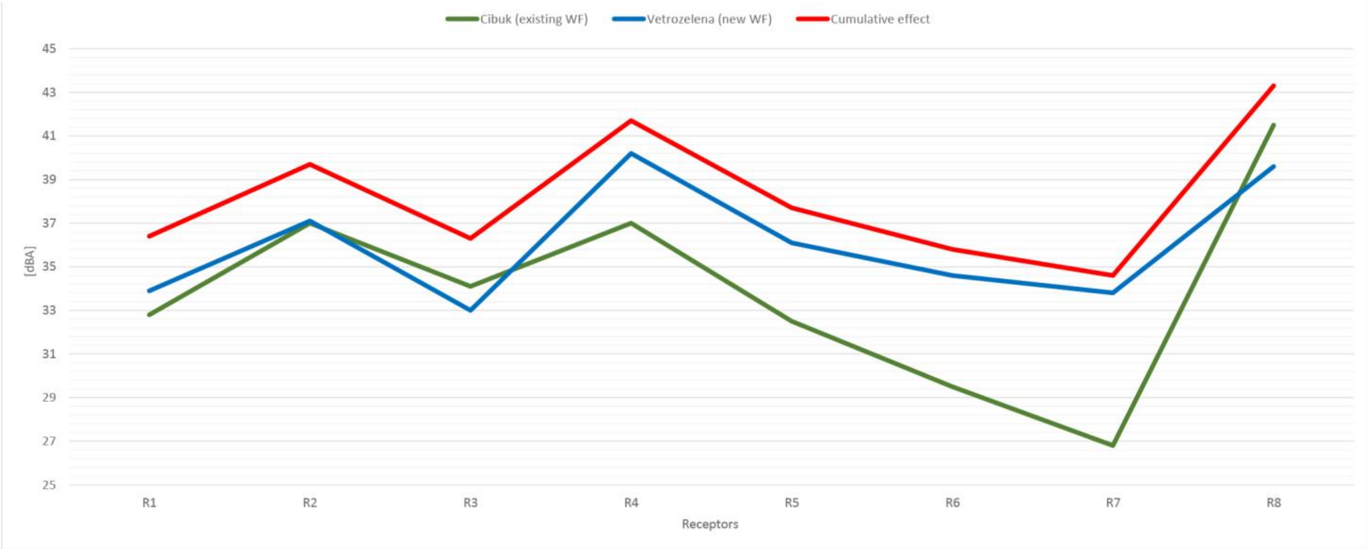

Figure 4. Diagram of results of modeling cumulative effect of noise.

5. Discussion

Certain authors [15,16] point out that the levels of infrasound pressure produced by wind turbines are well below the generally accepted hearing threshold of a human ear, concluding that they cannot produce negative effects on human health. However, many authors [15–18] still maintain that just as there is no conclusive proof of the potentially detrimental effects of long-term exposure to the wind turbine-generated infrasound, especially in the low frequency range, there is no proof of the opposite either. Therefore, it is not possible to draw strict conclusions on the nature of the impact. One thing is certain, though: the impact of wind power plant noise must meet the legally prescribed values. In this process, special attention should be given to the impact of noise on the well-being of people inhabiting the future wind farm area by using good practice examples, on the one hand, and noise impact monitoring, on the other.

The paper shows the way in which aspects of noise produced by two wind farms (cumulative impact) can be assessed as part of the partial assessment in the SEA process. Namely, the foundation for using SEA in planning the development of wind farms is choosing the proper options for minimizing or completely eliminating possible conflicts in space between a wind farm and the elements of the environment [27,64–67], in this case in regards to noise generation. In that way, the optimum solution can be reached at the start of developing the project so as to exclude the financial risks in later phases of project development, which is of special importance for investors. When preventive environmental protection is fully applied, SEA becomes the best instrument for assessing the effects of wind farms before designing and developing a particular investment. Partial noise impact assessment for the purpose of SEA is done by integrating the modeling results into the multicriteria evaluation, which is the core of the SEA process. The integration is done according to SEA criteria (Magnitude of impact, Spatial dispersion of impact, Probability of impact, and Frequency of impact), which are elaborated by Josimović et al. [24,67,68]. In this way, the decision-makers are presented with the expected effects of developing the planned projects—in this specific case, the noise effects. Based on that information, they can either accept the planned solutions or opt to introduce certain changes to the plan.

In the specific case described in this paper, the noise limit values are not exceeded, although there are changes in the noise contour as compared with the contours of individual wind farms. Also, in the case of cumulative impact, certain receptors move to the higher noise level contour. If the modeling shows some receptors to be exposed to higher levels of noise, then wind turbines should be relocated to the optimum position, which is the main point of preventive planning and protection as the most desirable principle. That was the case with some other projects in the territory of the Republic of Serbia, where the modeling results pointed to noise values that exceeded the prescribed day and night limits. In such cases, different approaches to the issue are possible. Wind parks Crni Vrh and Lovćenac are interesting examples of problem solving in the case of noise increase. After the modeling results pointed to the expected rise in levels of noise above the legally prescribed limits, the Investor of the Crni Vrh Wind Farm expropriated facilities in the zone of increased noise levels and eliminated possible issues in later stages of project development. In the case of the Lovćenac Wind Farm, the Investor cancelled seven wind turbines and relocated twenty-nine turbines so as to eliminate the impact on the receptors in the impact zone. The noise impact is not the only reason behind turbine relocations, but it is the major one, having in mind the confirmed effects of noise on human well-being. Other significant impacts to be considered in preventive planning and environment protection are the impact on biodiversity (ornithofauna, chiropterofauna, and habitats) and the flicker shadow effect.

In cases where the limit values of noise are exceeded, the other option for reducing or eliminating the effects is the application of mitigation and/or compensation measures, whose efficiency varies from case to case. Compared with the principle of preventive protection, this other option is not always optimal for all the users of the said space (population and/or investors) since it implies certain economic or organizational activities; therefore, priority should be given to preventive protection.

The modeling of cumulative noise impact presented in this paper is of special importance in planning a new wind power plant since the levels of noise differ (or are reduced) if the predictions of the future impact are limited to an individual wind farm without taking into account the noise generated by an adjacent wind farm. In that case, determining the microlocations of wind turbines that make up the new wind farm could be in conflict with the regulations in the area of noise and thus create conflict in space.

In assessing the cumulative effect of several wind farms affecting the same space, it is recommended to start from the most conservative model (or to take the worst-case scenario, which includes the calculation with the noisiest type of wind turbine considered by the investor as well as the option for the wind to blow continuously 365 days a year), so that the results produce a clear picture for planning the optimum position of the future wind farm, which is exactly what was done in this case study.

6. Conclusions

The results of noise impact modeling, as part of the holistic approach to SEA applied in wind farm planning, after initially positioning turbines according to the potential of the wind, allow for the harmonization of the final position of wind turbines with the results of partially assessed wind farm impact. In the case of the elaborate case study, there was no need for that since the predictions of the worst noise impact were considerably below the recommended and legally prescribed levels. However, after such verification, the possible detrimental position of a turbine can be determined and corrected with the view to eliminating detrimental effects. In that way, SEA helps eliminate possible negative impacts, enabling further implementation of the project that is relaxed both for investors and creditors, but also for experts that take part in their development [24,67], and also for individuals and the local community who express their attitudes towards the development of wind farms in the transparent and participatory SEA process and wind farm planning.

With subjectivity taken into account in decision-making processes that rely on SEA results used in wind farm planning, experts in the area have no part in it. Decisions are made based on political, financial, and other factors that tend to disregard SEA propositions. However, quantitative results produced in software modeling minimize the subjectivity in the SEA process when it comes to the aspect of wind farm noise impact, thus considerably reducing the subjectivity in decision-making as well. Objectivity is achieved by including quantitative results of the noise impact software modeling in the expert assessment in SEA, in line with the SEA criteria and indicators in the multicriteria assessment process [24,67].

By applying the principle of preventive protection, reflected in the choice of the optimal turbine number and types as regards the present biodiversity (ornithofauna, chiropterofauna, and habitats) and population (noise impact and shadow flicker effect), the logical and natural continuation of the assessment is done in the process of EIA preparation. EIA tests the SEA findings and deals with issues that were not part of the SEA process. It focuses on the technical aspects of the impact assessment in all phases of a project's development (construction, operation, and closure). Such a continuous approach to the wind farm impact assessment reduces or completely eliminates risks in the wind farm development during the EIA preparation, so that the EIA process can be carried out smoothly.

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