Project: A healthy society - towards the optimal management of wind turbine noise

D1.3 The relationship between annoyance and wind turbine noise parameters (chosen from tasks 1.2, 2.1, 2.2 and 2.3) - psychoacoustic model (M24)

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Executive summary

Based on data on the evaluation of wind turbine noise annoyance in the field (task 1.2, 2.3) and similar data obtained in the laboratory (task 2.1, 2.2), we created a psychoacoustic model for the assessment of wind turbine noise annoyance.

The relationship between annoyance ratings of any noise source can be presented in two ways. The first way concerns the relationship between survey data of annoyance assessment and noise parameters measured or calculated in the field. Although in this case it is not known on the basis of which physical noise parameters the annoyance rating was obtained, the relationship of annoyance is presented as a function of the LDWN level. This implies the assumption that the one-year annoyance rating obtained in the surveys is correlated with the one-year averaged sound level, LDWN. This assumption is generally true but only within a single noise source, the higher the LDWN value the greater the annoyance. In addition, the LDWN level is related to the loudness rating of the signal, and loudness is the main feature of auditory sensation on which annoyance depends. However, if we compare the annoyance of different types of noise, e.g. car noise and wind turbine noise, for the same LDWN value, it turns out that people rate the annoyance of wind turbines much higher than e.g. car noise. This annoyance rating is higher even though the loudness of wind turbines is much lower than the loudness of car noise at the same LDWN value. This disproportion in assessments prompted a deeper examination of the subject of wind turbines. In addition it is abstracted that this assessment can be influenced by other unmeasured acoustic parameters as well as those non-acoustic, such as visual.

The second way concerns the relationship between an assessment of noise annoyance and its physical parameters measured and evaluated under laboratory conditions. In this case, an accurate acoustic analysis of the tested signal and the corresponding annoyance assessment is possible. In addition, in laboratory conditions there are no extra non-acoustic variables present in field conditions.

A psychoacoustic model concerning the relationship - the assessment of annoyance as a function of selected physical parameters of wind turbine noise, was built on the basis of results obtained under laboratory conditions.

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As already mentioned in the executive summary, only in laboratory conditions we can be sure what physical parameters of noise influence the assessment of its annoyance. They are fully controlled and subjected to detailed spectrum and time analysis. The physical parameters of any noise depend on both its spectral and temporal parameters. Based on existing models valid in auditory perception, there are psychoacoustic characteristics correlated with these physical parameters. Thus, loudness and sharpness are responsible for variation in spectral parameters and fluctuation strength and roughness are responsible for variation in temporal parameters [1]. Based on existing algorithms (e.g., ArtemiS software), from a wav file of a given acoustic signal, all these psychoacoustic characteristics can be calculated. To answer the question which of these characteristics are most responsible for the perception of the annoyance generated by wind turbine noise, we conducted two psychoacoustic experiments, **Experiment 1 and Experiment 2**. In experiment 1 annoyance assessment of wind turbine and car noise presented at the same sound level was compared and related to the psychoacoustical characteristics. In experiment 2 the role of low-frequency components in assessing the noise annoyance of wind turbines was tested. Based on the results obtained in these two experiments, a psychochoacoustic model for wind turbine noise is proposed.

I. EXPERIMENT 1 - NOISE ANNOYANCE ASSESSMENT

One of factors clearly influencing annoyance of WT noise is the distance from the turbine. According to Michaud [5] reduced distance to wind farm was related to the higher noise annoyance ratings. On the other hand such a relation was not found in [6]. Nevertheless, such research is commonly conducted in situ and the distance between turbines and dwellings is the result of the reality (how far houses are built) and cannot be strictly planned or changed. Thus we wanted to strictly control distance values and places in which we recorded WT noise. It was possible thanks to the company running one of the farms in Poland – we could turn off all other turbines and record only one turbine in different distances. Then recordings were used in the laboratory experiment.

1. METHOD

1.1 RECORDINGS

WT noise was recorded in Poland. The wind farm consists of 20 turbines. We recorded one of them, Vestas V90 2.0MW. Diameter of the rotor is 90m and the hub is 105m above the ground. Recordings were done in spring in the stable weather conditions: wind speed at hub was between 7.5 and 9 m/s with a constant direction, temperature was 9 Celsius degrees. All weather data was obtained from wind farm's system as well as from two wind measuring stations installed by us in the field (with the height of 4 and 10m). We decided to record the turbine in two directions: downwind (DW) and in line with the rotor plane (RP). It was planned to record noise in the distances of 150m, 250m, 500m, 750m and 1000m using ambisonic microphones. However, we had only three of them (RODE NTSF1, Sennheiser Ambeo and Soundfield ST450) so we changed location of microphones during the whole recording session. Thus, recordings were made between 3 and 8 PM (each lasting around 45 minutes) and there was no situation when all distances were recorded at the same time. However, as the weather conditions were stable and WT performance was also constant, we decided to use these recordings, with a careful analysis before conducting an experiment. At each measuring point there was also a sound meter (SVAN 945) to keep all acoustical information about sound level values and spectral characteristics. Geographical plan of the measuring procedure is presented in Fig. 1.

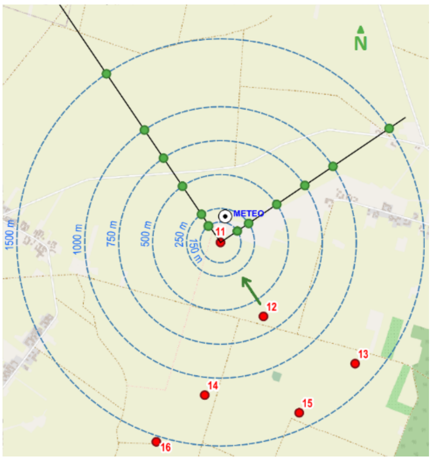


Figure 1. Schematic plan of a measuring session. Each green dot represents location of a sound meter. A location where meteorological station was placed is marked with 'METEO' text. Red dots represent all WTs and green arrow points the wind direction.

1.2 STIMULI

All recordings were carefully manually analyzed regarding possible wind-induced noise and other sound sources (dogs barking, RT etc.). Despite of usage of wind-shields (sometimes doubled), many wind blows were recorded – recordings from AMBEO had to be excluded because of that. Clean parts were quite rare, however we succeeded in selection of short (5 minutes) fragments with satisfactory quality of sound. Then, recordings were analyzed regarding their amplitude modulation depth and AM frequency. It was done using the algorithm proposed by Amplitude Modulation Working Group [7]. Results of this analysis are shown in Table 1.

Table 1. Details of eight WT noise recordings.

Location	Distance [m]	Sound Level [dBA]	AM Depth [%]	AM Freq [Hz]
Downwind	150	49.1	20.57	0.4
Downwind	250	49.7	22.38	0.8
Downwind	500	42.8	31.61	0.7
Downwind	750	38.2	29.21	0.7
Downwind	1000	36.3	28.39	0.4
In Plane	150	49.8	25.01	0.7
In Plane	250	42.3	27.56	0.7
In Plane	500	38.4	26.72	0.8

As could be expected, when the distance from a WT increases, sound level values decrease – with one exception for downwind distances 150m and 250m, probably due to terrain shape (small hill) and different surfaces. All these recordings were used in the laboratory experiment. DW recordings were conducted using a RODE microphone while RP - with Soundfield ST450.

To compare annoyance ratings evoked by WT noise with a more common noise, we also used stimuli of RT noise, applied in one of our previous experiments [8]. It was the same 5-minutes recording of RT in the four-lane street (recorded from 30m to the middle of the lanes), but presented at sound levels equal to levels of each WT stimulus (attenuation from propagation or distance was not applied).

1.3 PROCEDURE

The main experiment was preceded by the teaching procedure which we describe in the other FA23 paper ("Noise Annoyance Studied In Different Situations: A Comparison Of Results Obtained In ƚSitu And Laboratory Conditions"). This procedure familiarize participants with the concept of noise annoyance and noises generated by WTs.

After that, the main experiment was conducted. It contains 16 stimuli, 8 of them are WT noise (presented in Table 1). The other 8 stimuli are the RT noise, presented at the same levels as WT sounds. It means that each WT stimulus has its 'pair' of RT noise. Respondents were asked to relax and read a book during the experiment and after each stimulus rate its annoyance using 0-10 numerical ICBEN scale [9] in its Polish version [10]. Stimuli were presented using a 2+1 loudspeaker configuration, with two Yamaha HS5 and one subwoofer (Yamaha DXS15). They were played from a computer using Reaper as a DAW and RME Babyface PRO audio interface. we collected data from 34 participants. They were paid for their participation.

2. RESULTS

As the recordings were done from both sides only in three distances, results can be presented in different ways: 5 distances but only for RT and DW WT or 3 distances but for both DW and RP 'WT conditions' and RT. The former is presented in Fig. 2, the latter – in Fig. 3.

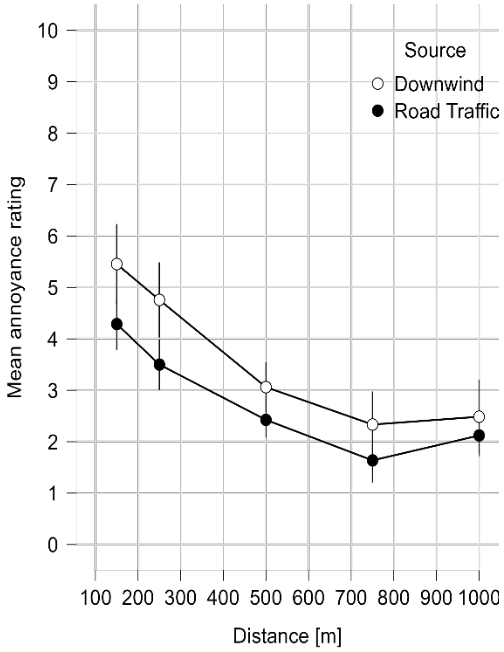


Figure 2. Mean annoyance ratings for WT DW and RT noise recorded in 5 different distances.

Table 2. Results of Bayesian ANOVA test ran for

Models	P(M|data)	BF_{10}	error %
Null model	1.314×10^{-25}	1.000	
Distance + Source	0.948	$7.210\times10^{+24}$	1.343
Distance + Source + Distance ✻ Source	0.052	$3.973\times10^{+23}$	2.369
Distance	2.200×10^{-4}	$1.674\times10^{+21}$	0.002
Source	8.123×10^{-25}	6.181	0.004

As can be seen from Fig. 2, both DW WT and RT are rated quite the same – with a small shift toward higher ratings for WT. Moreover, the larger the distance is, the smaller annoyance is evoked, but this tendency flattens from 750m. Ratings given for 1000m are almost the same, even marginally higher than for 750m.

Table 3. Results of Bayesian ANOVA test ran for annoyance ratings of RT and WT (both downwind and in plane) noises recorded from 3 different distances.

Models	P(M|data)	BF_{10}	error %
Null model	2.021×10^{-22}	1.000	
Source + Distance	0.930	$4.603\times10^{+21}$	2.905
Source + Distance + Source ✻ Distance	0.070	$3.439\times10^{+20}$	1.515
Distance	1.255×10^{-9}	$6.207\times10^{+12}$	0.010
Source	2.631×10^{-15}	$1.302\times10^{+7}$	0.020

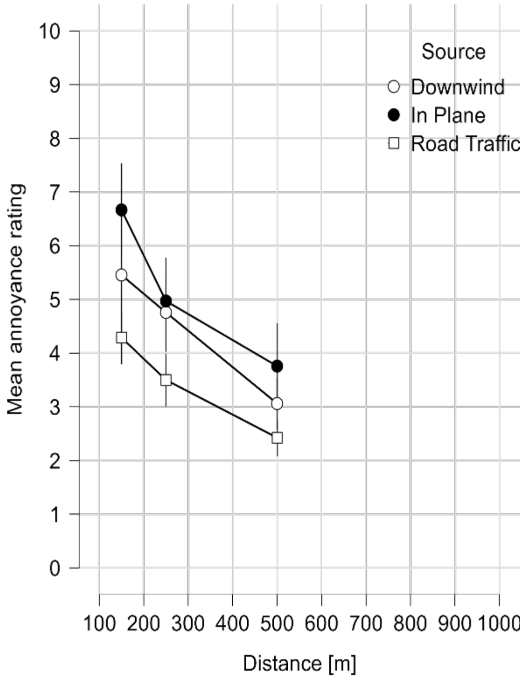


Figure 3. Mean annoyance ratings for RT and WT (both DW and RP) noise recorded in 3 different distances.

To better understand these differences we ran two-way Bayesian ANOVA using JASP software. Results of this analysis are presented in Table 2. In Bayesian approach we are interested in values of BF_{10}. It describes how much more probable is an alternative hypothesis (that the factor has influence on dependent variable) over the zero one (that there is no influence). As Jeffreys suggested [11], the strength of evidence for BF between 5 and 10 is 'substantial' while all values above 100 are 'decisive'.

We can see in Table 2 that the most influential factor is Distance while Source has only small influence on annoyance ratings. However, the best model is that one which takes into account both these factors. For the case when all three 'source conditions' are presented (but for three distances) results are shown in Fig. 3 and Table 3. Fig. 3 suggests that noise annoyance of DW WT is marginally higher than of RP WT. These differences are not large, so again two-way Bayesian ANOVA was conducted to find out what are the Bayes Factor (BF) values.

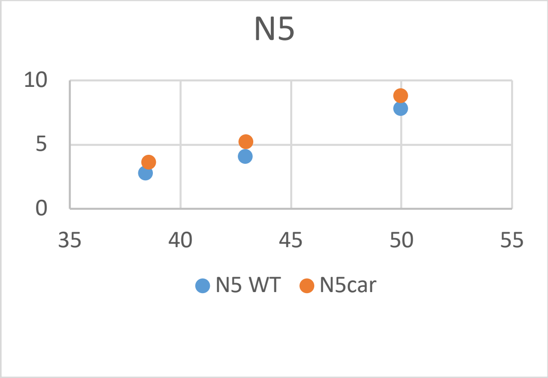
As can be seen from Table 3, the best model takes into account both Source and Distance factors. However, Source was also analyzed using post-hoc analyses. Results take into account a correction for multiple comparisons (posterior odds, PO). This time we can observe that there are no differences in noise annoyance ratings between DW and RP (PO = 0.69, lower than 1). Differences are between RT and both WT sources (RT with DW, PO = 179.9; RT with RP, PO = 6.85×10^6).

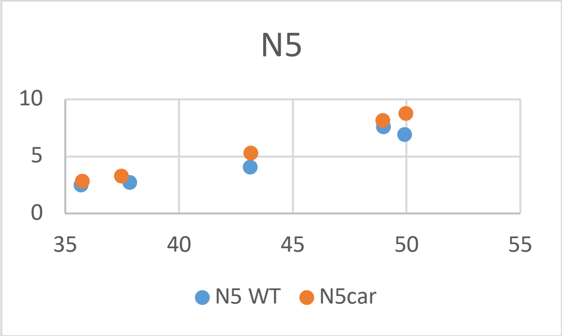
3. DISCUSSION

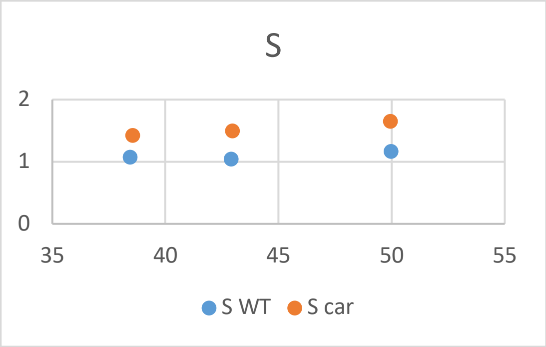
In this research we have shown that for WT noise RP stimuli were rated slightly higher than DW. It can be related to the fluctuating distance from the tip of a blade (and thus, Doppler effect), but further research is needed. It was also shown – in contrary to [6] – that noise annoyance decreases with the increasing distance from sources. However, this function flattens around 750m from the source – which is equal to ~36dBA. This is probably very close to the background noise, so it should not be surprising. There are also differences in annoyance ratings between WT and RT, but they are not large. It is in contrary to other papers in which WT was rated much higher than RT [3] but in line with findings in [2]. The crucial factor can be the teaching procedure; participants got used to annoyance concept and sound of WTs.

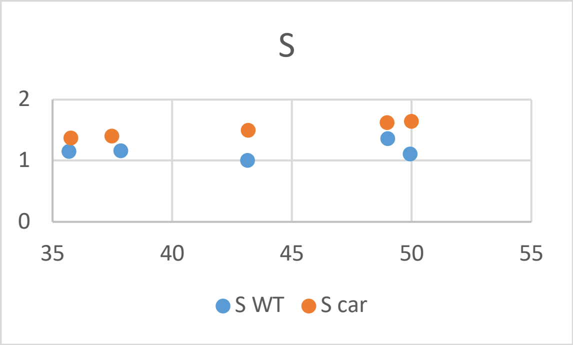
4. EXPERIMENT 1 – PSYCHOACOUSTICAL CHARACTERISTICS OF STIMULI USED IN SUBJECTIVE PART OF EXPERIMENT 1

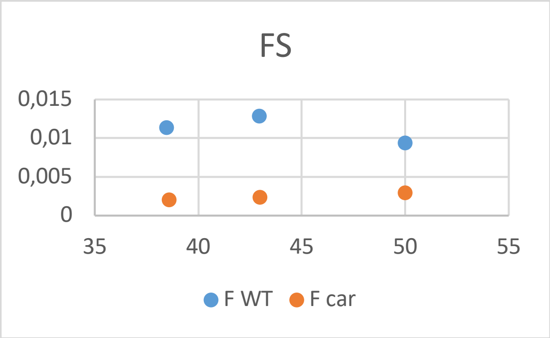
The results obtained in the psychoacoustic part of experiment 1 were compared with the calculated objective characteristics of this noise.

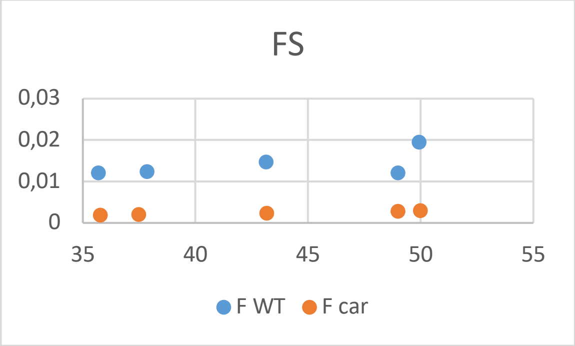












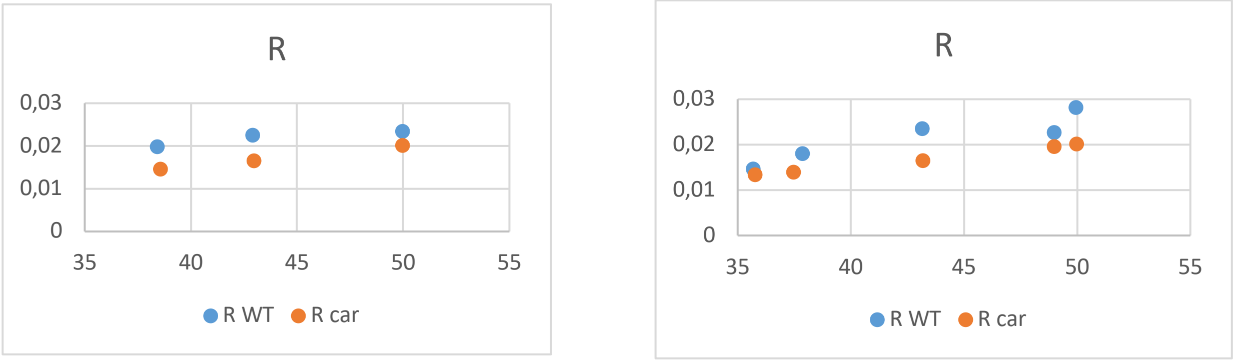


Figure 4. Psychoacoustical characteristics calculated for 8 stimuli used in subjective part of experiment 1.

The same eight stimuli of the same duration and sound level, that were presented in the subjective part of experiment 1, were subjected to time-spectral analysis using ArtemiS software. Four psychoacoustic characteristics such as loudness (N5 - percentile loudness in sone), sharpness (S in acum), fluctuation strength (FS in vacil) and roughness (R in asper) were calculated based on wav files [1].

The results of these calculations are presented in Figure 4. In the case of both downwind and plane distances, in subjective part of experiment 1, wind turbine noise was assessed as more annoying than road traffic noise. Analyzing the values of psychoacoustic characteristics calculated for previously assessed stimuli, only temporal characteristics, R and SF have a greater value for wind turbine noise than for road noise. However, for fluctuation strength these differences are the greatest. The fact that, due to SF, the differences between wind turbine noise and road noise are the largest is not surprising, bearing in mind that wind turbine noise contains low-frequency amplitude modulations. These analyzes confirm the fact that it is not the loudness that is responsible for the greater annoyance of noise generated by wind turbines. Because at the same sound level, the calculated loudness N5 is practically the same for both noise sources: road traffic noise and wind turbine noise.

5. CONCLUSION FROM BOTH PARTS OF EXPERIMENT 1

The results of the wind turbine nuisance assessment in this experiment 1 are presented as a function of distance. This is because we took sound level measurements at these specific distances. In general, the relationship between the annoyance assessment and the sound level should be presented, because the same wind turbine at the same distance may generate a sound level that differs by even more than 10 dB depending on the wind speed.

For the purposes of creating a psychoacoustic model, it makes more sense to present these results as a function of sound level. This is possible taking into account the data in Table 1. Figures 5 present the assessment of the annoyance of the tested wind turbines as a function of the sound level, based on the data in Table 1.

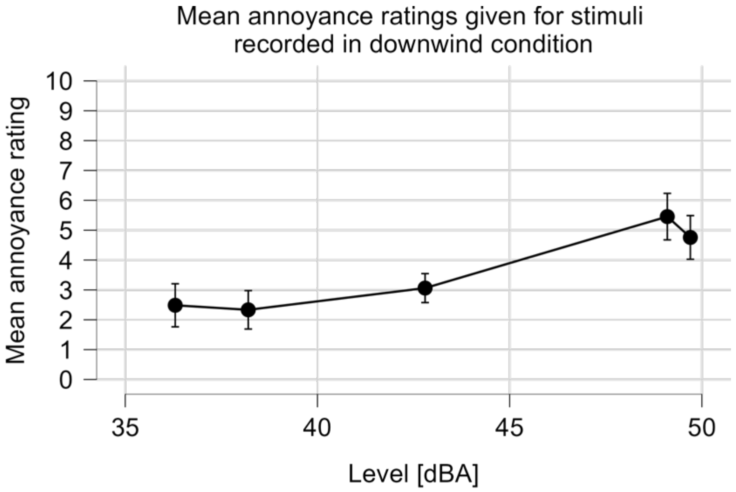


Figure 5. Mean annoyance ratings for WT DW recorded in 5 different distances.

Figure 6 compares in detail the analysis of spectral and time waveforms for a wind turbine recorded at a distance of 250m and for car noise at the same sound level.

Since, according to the authors of the ArtemiS software, the value of the fluctuation force may not be accurate, the time course for 60 s of the turbine and car noise is shown in an enlarged view. These graphs clearly show the characteristic variability of wind turbine noise over time, unlike the course of car noise. This sound level variability can be characterized by a frequency of amplitude changes (AM), about 0.8 Hz, and a depth (ΔL) of these changes of equal 4 or 5 dB. This low-frequency amplitude modulation occurring in the time history of wind turbine noise is very characteristic of this type of noise. Since this is the only distinguishing parameter differentiating both noises and occurring both in field studies and in the laboratory, we believe that this variability is a decisive factor in the high rating of annoyance in survey studies and in high annoyance ratings in laboratory studies.

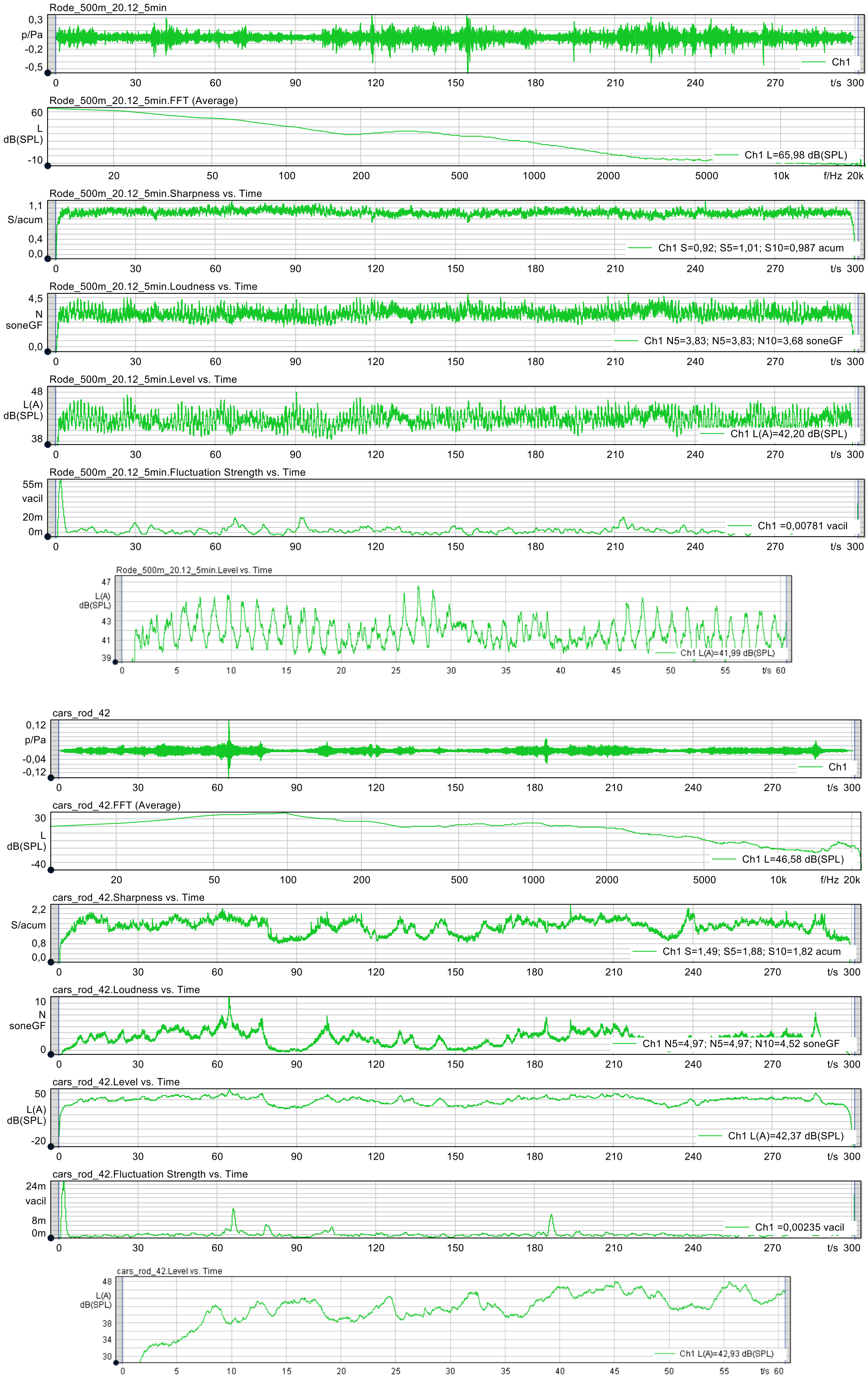


Figure 6. Comparison of psychoacoustical characteristics calculated for WT noise recorded at 250m and road traffic noise at the same sound level. These drawings were made using ArtemiS software.

II. EXPERIMENT 2 - THE EFFECT OF HIGH-PASS AND LOW-PASS FILTRATION ON THE ASSESSMENT OF NOISE NUISANCE OF WIND TURBINES

In search of an answer to the question of what influences more the annoyance of wind turbine sounds perceived by the audience - the lower range of the spectrum or the range of the upper frequencies, a perception experiment was carried out.

1. METHOD

1.1 RECORDINGS

The stimuli (3 second samples) used in this experiment were generated from recordings made with a first-order ambisonic microphone (Rode NTSF1) at two downwind distances, 500 m and 700 m from the wind turbine. These were the same recordings used in Experiment 1.

1.2 STIMULI

Low- and high-pass filtering was performed using 8-order Butterworh filters with a 48 decibel drop per octave (48 dB/oct). They are presented in Figure 7.

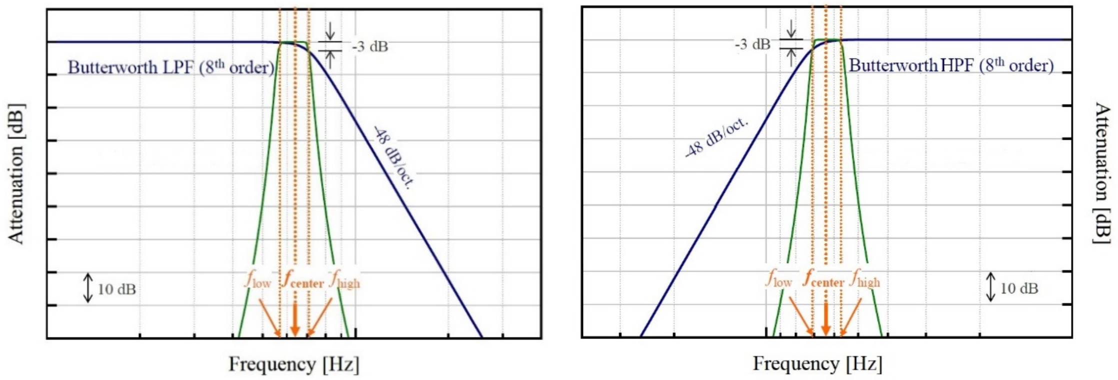
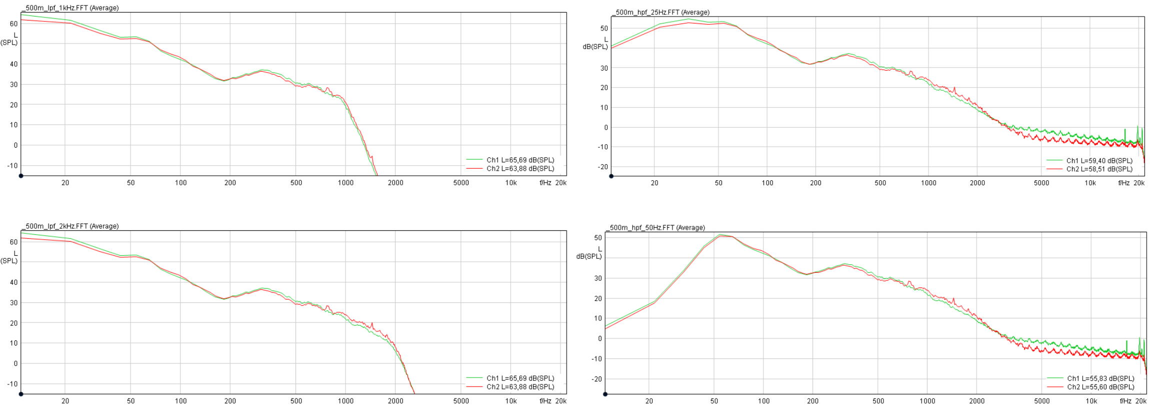
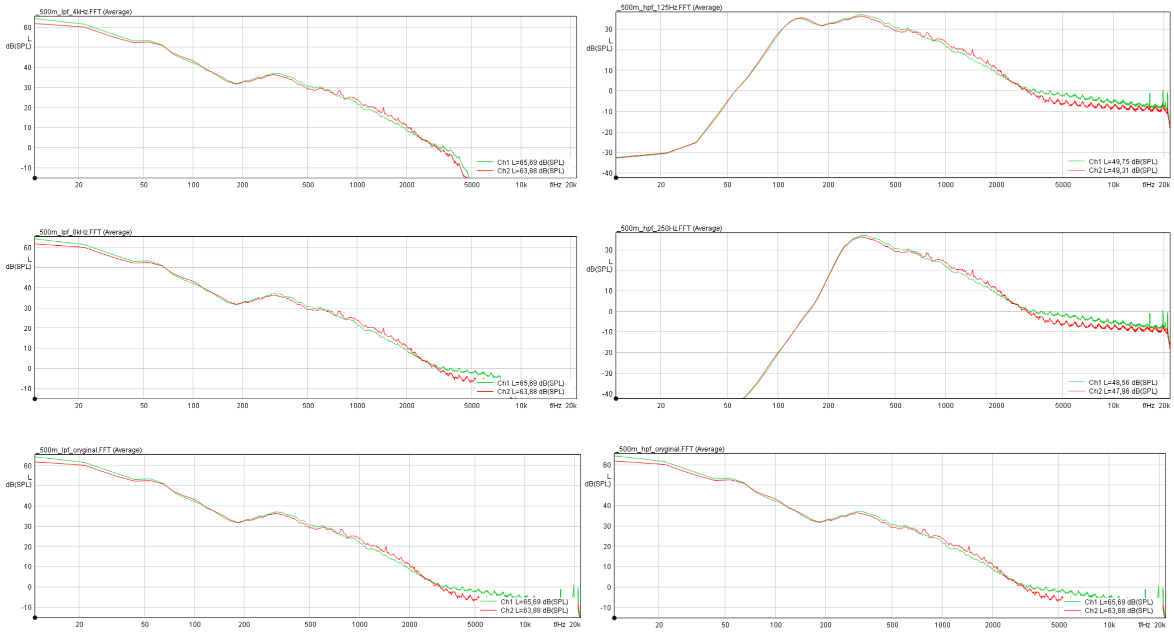


Figure 7. Graphical representation of the filters used to generate LP (on the left diagram) and HP (on the right diagram) noise samples used in an experiment 2.

For low-pass filtering, LPF, the following cutoff frequencies were used: 8000 Hz, 4000 Hz, 2000 Hz and 1000 Hz. The following cutoff frequencies were used for high-pass filtering, HPF: 250 Hz, 125 Hz, 50 Hz and 25 Hz. The results of the filtration is presented in Figure 8.





_500m_lpf_4kHz.FFT (Average)

_500m_hpf_125Hz.FFT (Average)

_500m_lpf_8kHz.FFT (Average)

_500m_hpf_250Hz.FFT (Average)

_500m_lpf_oryginal.FFT (Average)

_500m_hpf_oryginal.FFT (Average)

Figure 8. Graphical illustration of low- (left diagram) and high-pass filtering (right diagram) performed on the wind turbine recording at the distance of 500m.

1.3 PROCEDURE

In experiment 2, the Two-Alternative Forced Choice (2AFC) method was applied. After listening to two consecutive stimuli, the subject's task was to indicate which of the two presented stimuli was more annoying. In a pair of stimuli, presented in a random order, there was always the sound of the turbines of the original recording (so-called reference - without filtration) and the sound of the turbines subjected to filtration. The main experiment was preceded by the teaching procedure which we describe in the other FA23 paper (“Noise Annoyance Studied In Different Situations: A Comparison Of Results Obtained In ~~In~~ Situ And Laboratory Conditions”). This procedure familiarize participants with the concept of noise annoyance and noises generated by WTs.

The experiment was carried out in an acoustically adapted room using Yamaha HS5 active studio monitors and a Yamaha DXS 12 active subwoofer, RME BabyFace PRO FS interface, PC computer and Logitech keyboard. A view of the listening room is shown in Figure 8.

60 participants took part in the experiment: 30 participants in Poznań, aged 20 to 80 and 30 participants in Łódź, aged 20 to 70. Participants taking part in the experiment were paid.

Figure 9. A view of the listening room.

2. RESULTS

The results obtained for two types of filtering (LPF and HPF) performed on recordings from two distances (500m and 750m) are presented in Figures 10 and 11, respectively. On the y-axis there are level values in dB indicating the difference between the filtered stimulus and the original one causing the same annoyance. At first we will explain the differences in the obtained results, caused by different distances of recorded stimuli and different locations (Łódź , Poznan) where the same experiment was carried out. These differences occurred only for the LPF case.

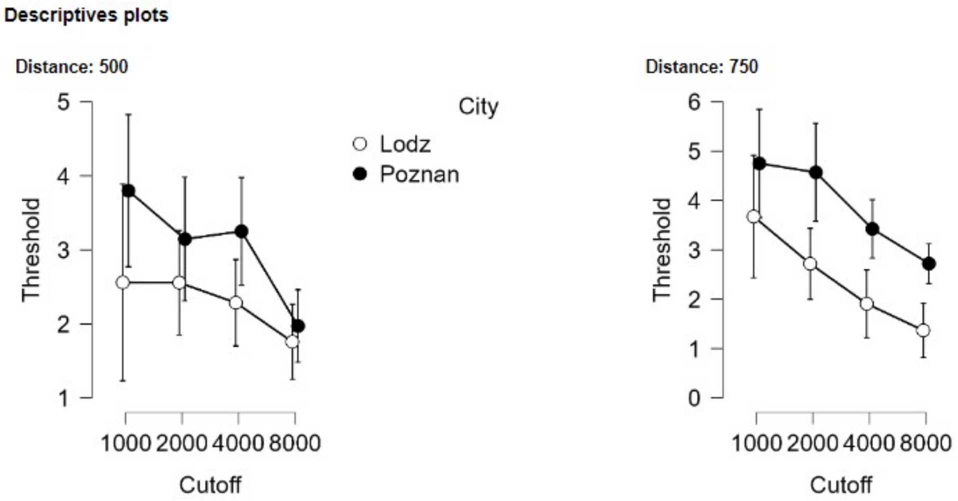


Figure 10. The difference in dB between the filtered and the original stimulus causing the same annoyance in the case of low-frequency filtering (LPF case).

There are two differences between the results shown in Figure 8 . One of these differences relates to the distance from which the sound sample was taken for the experiment (500m, 750m) and the other to the location of the experiment (Łódź, Poznań). Basic knowledge of acoustics [x] indicates a smaller proportion of high-frequency components in the spectrum of the same sound recorded further away. This fact can be clearly seen in Figure 9 where stimuli after low-pass filtering at two different distances of 500m and 750m are presented.

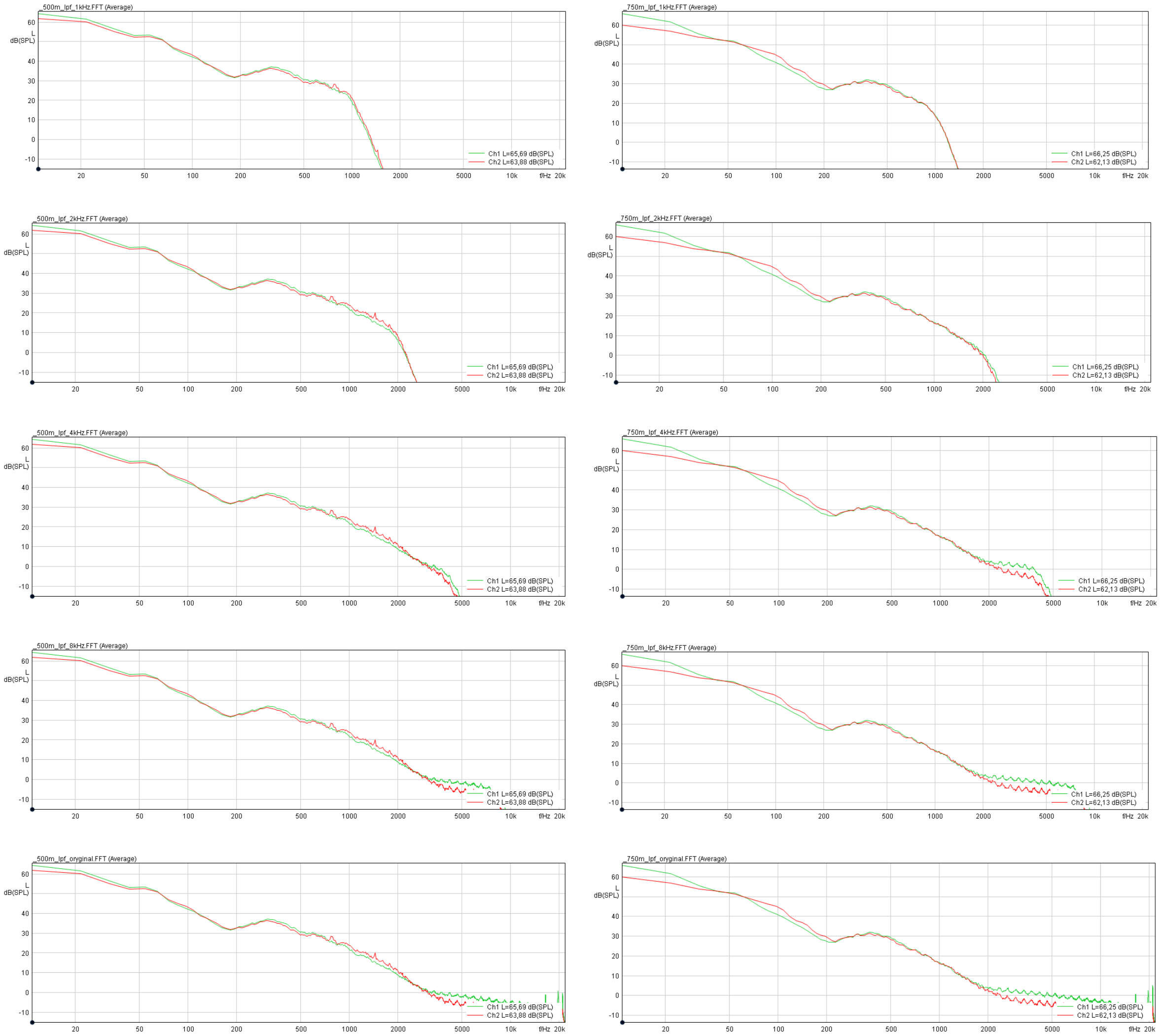


Figure 11. Graphical illustration of low- pass filtering performed on the wind turbine recording at the distance of 500m (left diagram) and at the distance of 750m (right diagram).

This fact translates into greater differences between the levels of sounds rated as equally annoying for a distance of 700m than for a distance of 500m – see Figure 8 for both locations.

Differences between the results obtained at different locations of the experiment are due to the characteristics of the listening rooms. In Lodz, the listening room was much smaller, and low-frequency components were excited in the frequency characteristics of this room. Therefore, the differences in the levels of original and filtered sound in Lodz were much greater than in Poznan through the additional contribution of low frequency components in the spectra presented in Lodz – compare the results presented in Figure 10.

These differences were not present in the case of high-frequency filtration - compare Figure 12. The results are identical at both locations and at both distances.

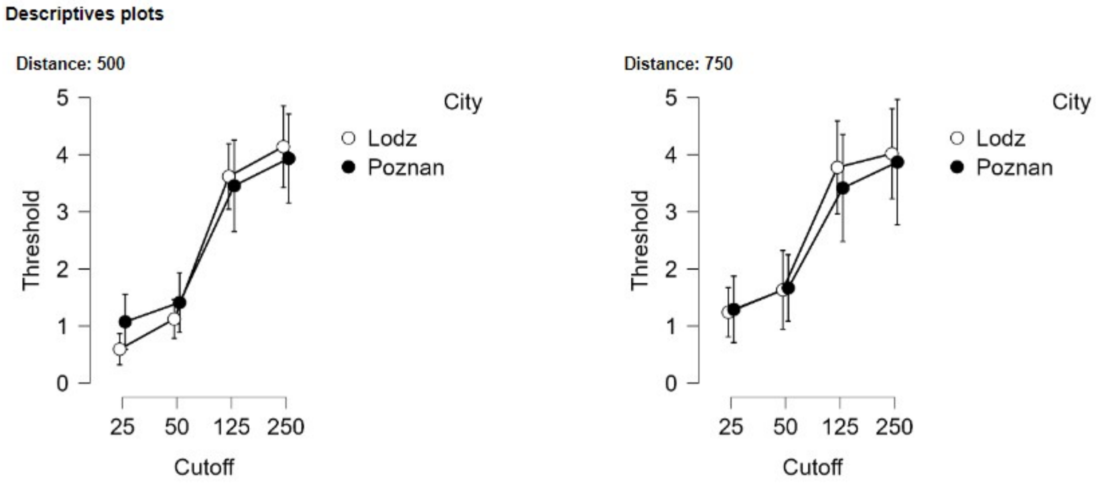


Figure 12. The difference in dB between the filtered and the original stimulus causing the same annoyance in the case of high-frequency filtering.

3. CONCLUSION

Returning to the main question that this experiment was designed to answer: which range of frequencies has a greater effect on assessing the noise annoyance of wind turbines the following conclusions can be made:

- in the case of high-frequency filtering the smallest differences in the level of sounds, assessed as equally annoying occurred at 25 and 50Hz cutoff frequency - less than 2 dB,
  while for 125 and 250Hz cutoff frequencies these differences were already between 3 and 4 dB
- in the case of low-frequency filtering a difference of 2 dB occurred for the cutoff frequency of 8kHz while for the 1kHz, 2kHz and 4kHz these differences were already between 3 and 4 dB
- the results of both types of filtration allow us to indicate that the significant frequency range of wind turbine noise for the noise annoyance assessment is in the range of 125Hz to 4000Hz

III. PSYCHOACOUSTIC MODEL OF WIND TURBINE NOISE

In general, for each noise source it is true that the higher the sound level, the greater its annoyance. However, if we compare two noise sources with the same sound level, due to different spectrally and temporal characteristics, the loudness of such noises will not be the same.

In this case, a similar rule should apply: the louder the noise, the greater the annoyance. This rule generally applies to aircraft, car and rail noise, but does not apply to wind turbine noise. Wind turbines, despite their lower loudness value for the same sound level, are always rated as more annoying, both in field and laboratory studies.

The results of our two experiments suggest that the reason for such a high rating of the annoyance of wind turbines is the temporal characteristics of this noise, and in particular the unpredictable, i.e. random, low-frequency change in the noise's amplitude.

This means that there is no basis for adding any additional penalties for this type of noise, because its temporal variability is present and assessed in every signal generated by wind turbines. The nature of this signal is responsible for the high rating of annoyance in both field and laboratory studies.

The results of our second experiment also suggest that the presence of infra and low-frequency components in the noise spectrum of wind turbines do not contribute to the additional annoyance of this type of noise. As we have shown, listeners in a psychoacoustic experiment respond to spectral changes occurring in the frequency range from 125 to 4000 Hz.

The results of our laboratory experiments indicate that at a level of 45 dBA the short-term annoyance rating (5 minutes) is equal to 4 on the ICBEN annoyance scale. An annoyance rating of 4 on the ICBEN scale means little annoyance. In the project, we assumed that we would recommend a level not exceeding rating 4 as the permissible sound level for wind turbines.

Our analyzes and the correlation between the long-term noise assessment indicator LDWN and the short-term noise assessment indicator L AeqT (see deliverable D1.6) show that the permissible level for LDWN is 45 dBA.

If this LDWN value is not exceeded and the resulting short-term values are: LN = 40 dBA, LAeq,8hN = 45 dBA and LAeq,16hD = 50 dBA, then the noise of wind turbines should not be annoying.

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