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Research into Possibilities of Reducing Noise Emissions in the Sandy Gravel Production Process—Case Study

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Abstract: The continuous process industry is an important area of the economy. In addition to its undeniable societal benefits, its operation is associated with several factors that are often perceived negatively and have an adverse impact on the environment, noise emissions being one of them. Accordingly, noise emissions have been the subject of numerous studies and always have to be approached in the context of a specific industrial area. In this paper, a case study is presented to illustrate the results of research aimed at reducing noise emissions in the sandy gravel production process. The research identified causes and effects of noise emissions arising from the gravel treatment process. Based on these, practical solutions were subsequently investigated and proposed, and their implementation brought noise emissions below 50 dB. The results obtained during the research can be generalized for further study of the issue and can be used to make general valid recommendations applicable in the continuous process industry.

Keywords: noise emissions; elimination; noise-reducing measures; production process

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1. Introduction

Noise is one of the undesirable factors associated with industrial production. In most cases, it is perceived as a disturbing element which significantly affects the quality of life of residents in the vicinity of industrial plants. Industrial sites—often containing several noise sources operating simultaneously—may cause exceedance of noise limits set for residential areas adjacent to industrial sites, especially during night-time. Noise propagating into the environment during the production process is a significant issue related to the increase in noise emissions in both the living and occupational environment. Noise emission limits depend on the dimensions of the industrial area and the distance from the noise-sensitive area. Numerical integration is required to gain accurate results. Calculations are carried out for favorable conditions of sound generation and propagation [1]. The issue of industrial noise is encountered within various technological units [2]. Noise pollution is currently a major health risk factor for industrial workers [3]. Very often, noise emissions are a major problem in continuous processes, which are carried out near residential areas and are associated with mining, processing, or energy industries. In these cases, an approach based on an analytical procedure can be used to examine the issue. Such an approach can be used effectively, as stated in [4], in the energy sector for noise emissions associated with coal-fired power plant operations. An analytical procedure can be used in conjunction with measurements of sound pressure levels in the vicinity of individual sources from a coal-fired power plant and in an adjacent residential area to rank the contribution of various sources to the total sound level. Legislation on the issue of industrial noise often varies in different countries. This fact is very well confirmed by [5], where the main characteristics of various common national noise calculation methods are presented. These include the methods which have been used to develop strategic noise maps under the EU Environmental Noise Directive, as well as methods developed outside the European Union. A strategic noise map can be a useful tool for assessing the overall impact of production activities in a given location on the local community. The input emission data required for the development of the strategic noise map of an industrial source are obtained by on-site measurements [6]. Various software tools can be used very effectively to address noise emissions. Their application can achieve more realistic and accurate noise mapping in indoor noisy working environments for noise load monitoring [7]. These tools make it possible, for example, to carry out a study on the noise load from thermal power using empirical, diagrammatic, analytical and noise map processing methods in order to propose optimal protection of the thermal power plant environment from noise pollution [8].

There are different approaches for eliminating noise emissions. They can be based on different noise absorbing mechanisms using different materials [9]. Sound-absorbing materials absorb most of the sound energy that hits them, making them particularly useful for noise control. They are used in a variety of locations—near noise sources, on various roads, and sometimes near receivers. Although all materials absorb part of the incident sound, the term "acoustic material" has primarily been applied to those materials that have been manufactured for the specific purpose of providing high absorption values. The main uses of absorptive materials almost always include reducing sound reverberation levels and consequently reducing reverberation time in enclosures or rooms [10]. Knowledge of the acoustic properties of materials is often a key factor for eliminating industrial noise [11]. Recently, various composite materials have proven particularly useful for eliminating noise in industrial manufacturing. Composites have excellent sound absorption properties, and their sound absorption can be adapted to meet specific end-use requirements [12]. Various noise barriers are very often used to reduce industrial noise and can also be made from recycled materials [13]. The results of studies show that such materials have high sound absorption coefficients at high frequencies (2000–6300 Hz), low sound absorption coefficients at low frequencies (100–400 Hz), and better sound absorption coefficients at medium frequencies (500–1600 Hz) [13]. In general, the results suggest that recycled materials are promising for use as a sound absorbing material and are also light in weight [14].

In general, the issue of noise emissions is characterized by particularities which require its solution for specific conditions. The final solution has to consider a range of factors, such as the type of production, geographical parameters, technological aspects, as well as age of technological equipment, its technical condition and obsolescence. It is therefore not possible to formulate universally valid solutions, and that is one of the reasons why this case study was conducted.

The objective of this paper, which has been compiled in the form of a case study, is to highlight the possibilities of proposing noise-reducing measures for the sandy gravel production process to meet the required permissible noise level for residential areas. The paper presents a solution that has been implemented on a specific type of continuous production process, taking into account national and EU legislative regulations.

2. Materials and Methods

A sandy gravel production plant (Figure 1) consisting of a crushing plant facility VL1, a gravel screening plant facility VL2 (containing three conveyor belts with hoppers for individual gravel and sand fraction dumps), and a gravel washing plant Pr was considered as a noise source. Residential areas of houses and the gravel production plant are located in flat terrain.

Figure 1. Sandy gravel production plant.

Crushing plant VL1

The opencast mining method using a floating bucket excavator is used for extracting raw material, which is then conveyed to a self-dumping barge by a conveyor belt. The barges are moved by push tugs along the lake's fairway to the harbor, where they are emptied into the water. Using a floating bucket elevator, the extracted raw material is loaded onto a conveyor belt, which transports it to the screening plant, where it is divided into over-sieve and under-sieve material. Over-sieve material is conveyed by a chute into the jaw crusher. The resulting fraction from the crusher and the under-sieve material are conveyed through chutes to two screeners, where the material is divided into two fractions. The first fraction is conveyed to an interdeck by means of conveyor chutes and belts. The second fraction is conveyed by means of conveyor belts and chutes for further processing—firstly, to two large-volume bins and from there to the cone crusher. The resulting product is conveyed by conveyor belts to the screener, where the over-sieve and under-sieve fractions are separated. The over-sieve fraction is conveyed for re-crushing and the under-sieve fraction is conveyed to the dump.

Sandy gravel screening plant VL2

VL2 is supplied from the interdeck. The material is transported by means of a conveyor belt running in a tunnel under the dump. It is further divided by a chute into a pair of screeners, which are used to sort the material into four fractions, each of which is deposited in a large-capacity dump.

Sandy gravel washing plant Pr

Water from the lake, transported by two pumps, is used for the screening of sandy gravel in the washing plant. Sludge water from the Pr washing plant is fed to a hydrocyclone, where the process water is separated from the usable particles. Usable particles are then transferred to a dewatering screen, which conveys them to a fraction conveyor belt, while the process water is discharged through a gutter to a sludge bed. The final sandy gravel is loaded onto trucks by loaders moving along marked routes.

The sandy gravel production plant is located between two residential areas I and II (Figure 2).

Figure 2. Production operation and residential areas.

Family houses in residential area I are located at 40–60 m from the sandy gravel production plant. Family houses in residential area II are located at 20 m from the sandy gravel production plant. Brüel & Kjær measuring devices (see Table 1) were used to measure noise.

Table 1. Equipment used for noise measurement.

Type	
Brüel & Kjær 2250-L Sound level meter and handheld analyzer with built-in 1/1- and 1/3-octave filters bands [15]	
Brüel & Kjær 4189 Prepolarized free-field microphone [16]	
Brüel & Kjær 4230 Sound Level Calibrator [17]	

Based on the spectral composition of noise and orientation of the measuring microphone relative to the dominant noise source in accordance with [18], an expanded measurement uncertainty of U = 2.3 dB was determined. There are no significant tonal components in the frequency spectrum of the measured sound in the frequency range > 4 kHz, and the measuring microphone was oriented towards the noise source with a deviation of ≤30° from its reference axis.

2.1. Cause-and-Effect Diagram

An analysis of potential noise sources was conducted using the cause-and-effect diagram (see Figure 3). There are five main activities/factors affecting the noise generated at the company's premises:

- material mining,
- material crushing,
- sorting,
- shipping,
- transport,
- environment.

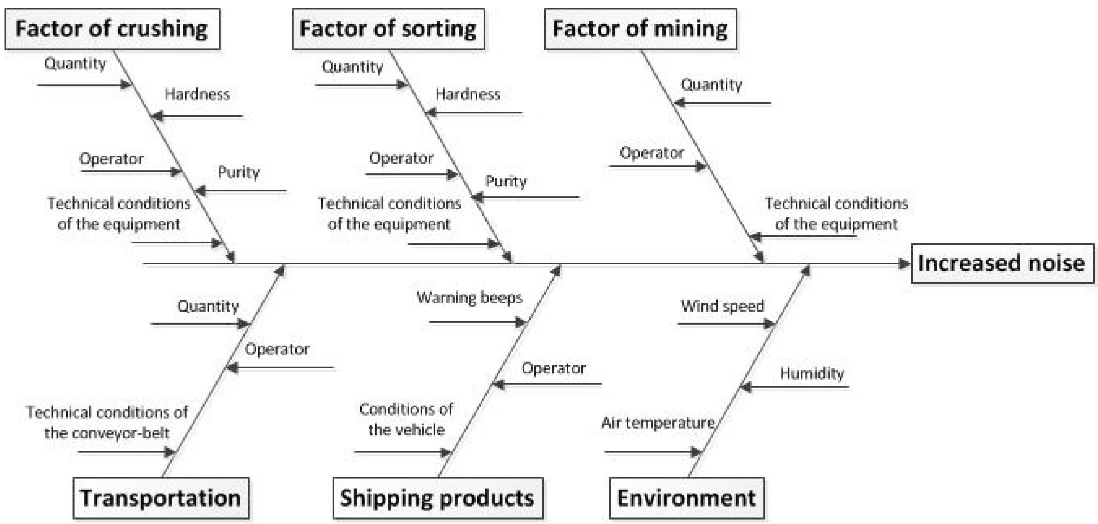

Figure 3. Cause-and-effect diagram.

Machinery, equipment, and tools used in the operation on the company's premises produce noise emissions, which negatively affect the adjacent residential areas.

Main sources of noise emissions identified in terms of spatial location of technological equipment are as follows:

- gravel extraction by bucket elevator,
- sorting and crushing process on processing lines,
- transport of material by conveyor belts to dispatch dumps,
- transport of extracted sandy gravel by bucket elevator along a defined fairway,
- final transport of material by trucks.

Classification of identified noise emissions sources in terms of their origin:

Point noise sources:

- floating bucket excavator during mining,
- cone crushers, jaw crusher and screeners for material processing at VL1,
- rotary crushers and hydrocyclone at VL2.

Linear noise sources:

- pusher tugs transporting sandy gravel to port,
- VL1—conveyor belts from the bucket elevator,

- VL2—conveyor belts for dispatch dumps,
- machines for operation of VL1 and VL2,
- cars transporting the final sandy gravel.

2.2. Research Methodology

As the case study was conducted in the conditions of the Slovak Republic, the procedure for measuring the current state of noise emission samples was conducted in accordance with [19], which is based on the standard operating procedure [20]. To be specific, the procedure applied is shown in Figure 4. Algorithm of risk management in the field of acoustics [21].

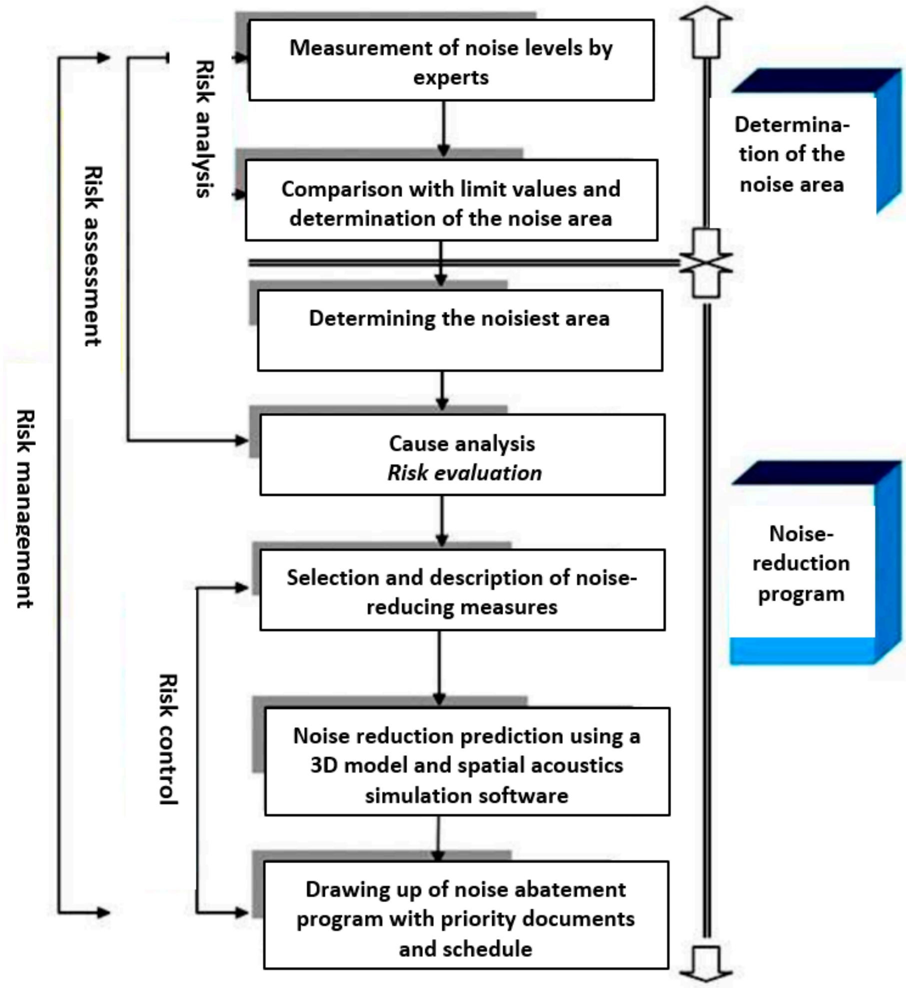

Figure 4. Algorithm of risk management in the field of acoustics [21].

3. Results and Discussion

Due to the propagation of noise from the sandy gravel production plant to residential areas I and II, direct measurements of noise level in the sandy gravel production plant as well as in both residential areas were carried out during operation as well as out of operation in the early morning and at night.

3.1. Noise Measurement in the Sandy Gravel Production Plant

Noise values measured at 16 measuring points at the sandy gravel production plant (see Figure 5) are listed in Table 2.

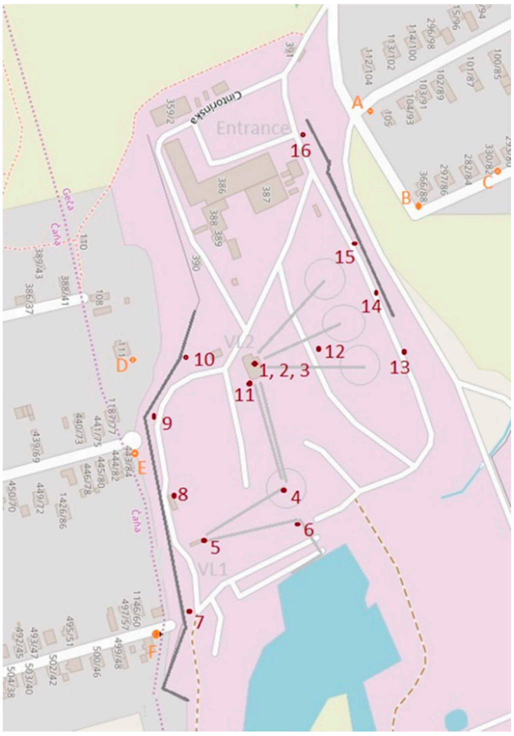

Figure 5. Measuring points at the sandy gravel production plant.

Table 2. Noise values measured at the sandy gravel production plant.

Measuring Point	$L_{eq,A}$ [dB]	Altitude [m]	$L_{Aeq,p}$ [dB]
1	87.1	191.3	
2	83.0	191.3	
3	73.9	181.2	
4	84.9	200.9	
5	88.5	200.7	
6	68.9	178.9	
7	63.5	178.9	
8	62.4	178.9	70.0
9	59.7	178.9	
10	68.4	178.9	
11	76.6	199.6	
12	88.7	178.9	
13	73.4	178.9	
14	71.2	178.9	
15	70.6	178.9	
16	62.7	178.9	

Permissible noise values in the outdoor environment are legislated in [19]. In accordance with [19], permissible noise value for sandy gravel production plant during the 6 a.m.–8 p.m. period is $L_{Aeq,p}$ = 70.0 dB. Values exceeding the permissible noise level are highlighted in red in Table 2.

3.2. Noise Measurement in Residential Areas

Noise values measured at residential area I (houses A, B and C) and residential area II (houses D, E and F), location of which can be seen in Figure 4, are listed in Table 3.

Table 3. Measured noise values in residential areas.

Residential Area	Residential House	$L_{eq,A}$ [dB]	Original Condition Altitude [m]	$L_{Aeq,p}$ [dB]	U [dB]
I	A	59.2	179.2	50.0	±2.3
	B	60.2	179.2		
	C	61.3	179.2		
II	D	64.5	179.2		
	E	54.1	179.2		
	F	56.9	179.2		

The permissible noise level in residential areas I and II in accordance with [19] is $L_{Aeq,p}$ = 50.0 dB. One of the factors contributing to exceeding of permissible noise level in residential areas I and II was ambient noise significantly affecting the resulting noise level.

The results of measurements confirmed that noise levels were exceeded in the sandy gravel production plant as well as in residential areas (Tables 2 and 3).

3.3. Research on the Effectiveness of Selected Noise-Reducing Measures in the Sandy Gravel Production Process

As part of the research into noise abatement options, measures for achieving the reduction of noise levels were proposed. Individual measures were planned to be implemented in a phased manner, with continuous monitoring of whether, and at what level, the noise would be reduced to the required level. The design of individual measures was based on an assessment of their feasibility and took into account that they would reduce noise from individual noise sources. The measures have been designed in such a way that they were expected to have at least a partial effect, that they would not significantly affect the technology used or restrict existing production in any way.

Based on the above criteria, it was decided that the research would cover three types of measures:

- modernization of machinery—the measure assumed that new or modernized machinery produces lower noise levels than the original one. This was based on the assumption that the original equipment had worn-out components, which thus emit excessive noise as a result of their mechanical wear and tear. No such deficiency was anticipated for new machinery.
- noise barrier—for noise barriers it was assumed that the absorbing capacity of the material would be used to reduce the level of reflected sound. Primarily, use of porous materials was assumed here for the scattering of acoustic energy within their thickness. In case the solution proved ineffective, the use of membranes and resonators has also been planned.
- traffic routes—when modifying traffic routes, it was considered to replace mechanical parts of the equipment which, due to their wear could be a source of noise. Another proposed solution has been the replacement of mechanical parts such as rollers with others that were declared to have reduced noise levels.

All of the above measures were implemented in a phased manner, with ongoing monitoring of noise levels. At the same time, the research was coordinated on the basis of [22].

The first stage of noise reduction research concerned the attenuation of noise from the jaw crusher. Based on this, the following feasible measures have been proposed:

- walling of the jaw crusher,
- enclosure of production facilities on three sides (site entrance, lake, residential area II).

Results obtained from this initial stage of the research are shown in Table 4. It can be observed that the measures have resulted in noise reduction, but the required level below 50 dB has not been achieved. On this basis, the measures were assessed as insufficient, and the second stage of research was proceeded with.

Table 4. Noise values measured in residential areas.

Residential Area	Residential House	$L_{eq,A}$ [dB]					$L_{Aeq,p}$ [dB]	U [dB]
		Original Condition	Stage 1	Stage 2	Stage 3	Stage 4		
I	A	59.2	56.2	52.9	48.0	-	50.0	±2.3
	B	60.2	59.7	57.1	53.0	48.4		
	C	61.3	55.7	53.6	47.2	-		
II	D	64.5	58.5	56.5	54.0	49.8		
	E	54.1	52.2	50.8	44.4	-		
	F	56.9	51.8	50.2	49.8	49.3		

The second stage involved extension of the measures already implemented to reduce noise from the traffic route and production facilities. The design of the solution was based on the need to ensure that the proposals were feasible and did not interfere with existing technology. The proposed measures were as follows:

- VL2 traffic roads improvement,
- closure of production facilities from the side of residential area I.

Based on experimental measurements, the result of implementation of additional measures resulted in a further reduction in the noise level generated by the sandy gravel processing. Detailed results are given in Table 4. The noise values measured did not exceed 60 dB, however, they still did not comply with the permissible noise level in accordance with [19]. Thus, the above measures were also assessed as insufficient.

Based on this, further research attention, in the third stage, was focused on another noise source—noise generated by the technological equipment used, which resulted in its replacement. A more detailed specification of the measures investigated is as follows:

- removal of obsolete cone crusher and its replacement with a new type at VL1,
- replacement of four low-capacity screeners with two high-capacity screeners at VL2,
- VL1 traffic roads improvement.

The measurement results after the implementation of the third stage of noise-reducing measures showed a further decrease in the noise propagation into the outdoor environment. Nevertheless, the permissible noise levels for residential houses B, D and F were exceeded (see Table 4). The measures were assessed as partially effective, however, still insufficient.

Therefore, a further series of measures, designated as the fourth stage, was proposed:

- installation of CETRIX slabs, 30 mm thick, in lengths of 182.6 m on the original noise barrier,
- construction closure of the bunker conveyor belt junction with DURISOL blocks at VL2,
- construction of noise barrier made of DURISOL blocks and MALCIT cover plates on the side of residential area I,
- replacement of conveyor belt drive gearboxes.

After the implementation of the fourth stage of noise-reducing measures, noise measurements in residential areas I and II were carried out only at the three critical locations:

- residential house B,
- residential houses D and F.

After the last stage, the required noise levels were reached at all monitoring points. Detailed results of the measured values of noise levels in residential areas I and II before and after the implementation of the four stages of noise-reducing measures are given in Table 4.

3.4. Statistical Assessment of Measurement Results

Morgan–Pitman's test and Student's paired *t*-test were used to assess the significance of the difference in variability and mean values of the measurement results. For the Morgan–Pitman's test, we assume that the difference in variances of measurement results at the beginning and after the implementation of the respective stage is statistically insignificant ($\sigma_1^2 - \sigma_2^2 = 0$). For the Student's paired *t*-test, we assume that the difference in the mean values of the measurement results at the beginning and after the implementation of the respective stage is statistically insignificant ($\sigma_1^2 - \sigma_2^2 = 0$). The results of the tests conducted at the selected significant level $\alpha = 0.05$, which are presented in Table 5, show that the variability in the measurement results after the individual stages is comparable to the variability in the initial measurements (the difference is statistically insignificant). When considering the differences in the mean values of the measurement results, we came to the conclusion that the statistically significant difference in the mean values of the measurement results has already been apparent after the implementation of the third stage. A reduction in noise below the set legislative limits (50 dB) was achieved only when the fourth stage has been implemented, and at the same time the difference in the mean values of the measurement results at the beginning and after the fourth stage was statistically significant.

Table 5. Statistical testing of measurement results.

	Testing of Measurement Results of Individual Stages			
	Stage 0–Stage 1	**Stage 0–Stage 2**	**Stage 0–Stage 3**	**Stage 0–Stage 4**
	Morgan–Pitman's test			
H_0	$\sigma_1^2 - \sigma_2^2 = 0$			
Test statistic	0.4	0.8	−0.03	2.86
Critical value	2.8	2.8	2.8	12.7
Result	$\lvert TS \rvert < CV$ H_0 not rejected ✓	$\lvert TS \rvert < CV$ H_0 not rejected ✓	$\lvert TS \rvert < CV$ H_0 not rejected ✓	$\lvert TS \rvert < CV$ H_0 not rejected ✓
	Student's Paired *t*-test			
H_0	$\mu_1 - \mu_2 = 0$			
Test statistic	0.9	2.0	3.3	4.5
Critical value	2.6	2.6	2.6	4.3
Result	TS < CV H_0 not rejected ✓	TS < CV H_0 not rejected ✓	TS > CV H_0 rejected ✖	TS > CV H_0 rejected ✖

4. Discussion

The results of measurements after the implementation of the first and second stages of noise-reducing measures showed a decrease in noise propagation to the outdoor environment. The noise values measured did not exceed 60 dB (see Table 4) but still did not comply with the permissible noise level in accordance with [19].

The results of measurements after the implementation of the third stage of noise-reducing measures showed a further decrease in the noise propagation into the outdoor environment. Nevertheless, the permissible noise levels for residential houses B, D and F were exceeded (see Table 4).

After the implementation of the fourth stage of noise-reducing measures, noise measurements in residential areas I and II were conducted only at three critical locations:

- residential house B,
- residential houses D and F.

The proposed noise-reducing modifications reduced the noise level at the locations under consideration to below 50 dB as shown by Table 4 and Figure 6. Noise values measured after each stage of the implemented measures take a linear trend.

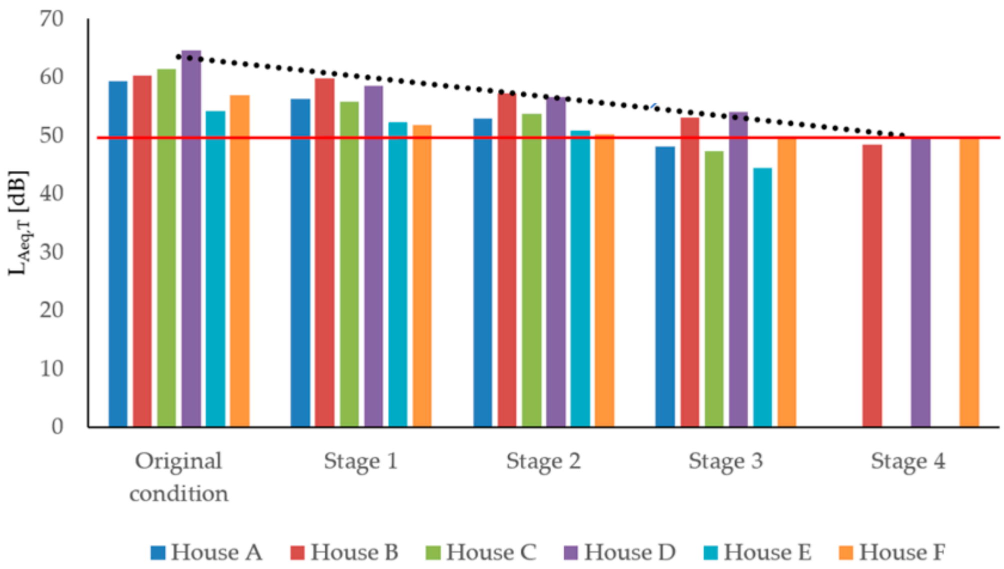

Figure 6. Graphical representation of measured values after the implementation of measures.

Measurements in residential areas I and II were carried out both during operation (Work) and out of operation (Stop) in the early morning and at night. The results of these measurements for residential houses B, D, and F are shown in Figures 7–9.

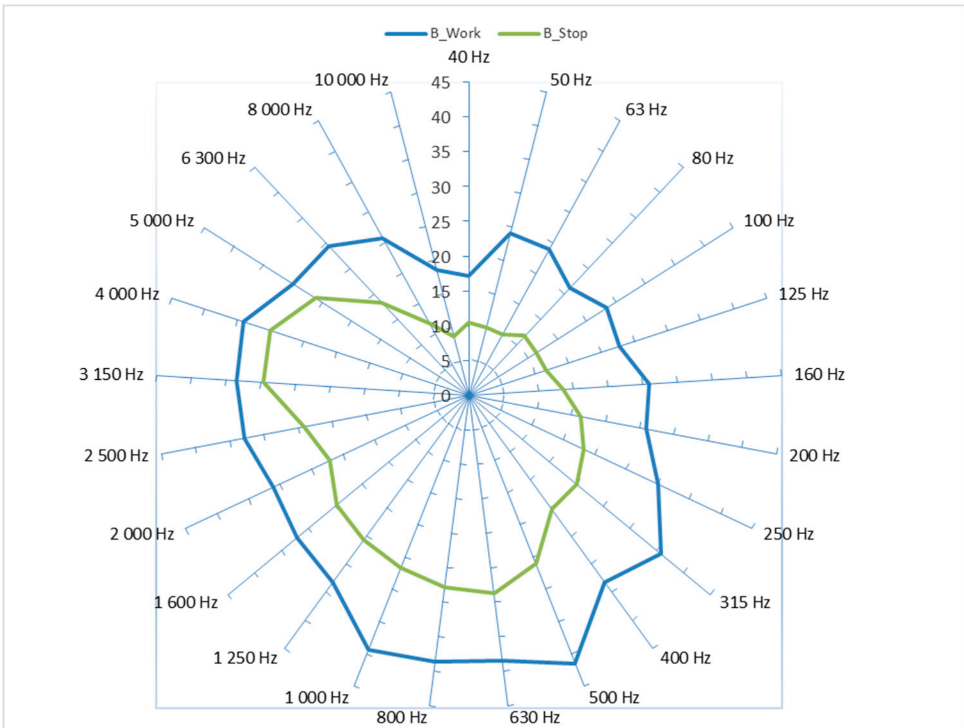

Figure 7. Values of noise emissions measured during operation (Work) and out of operation (Stop)—residential house B.

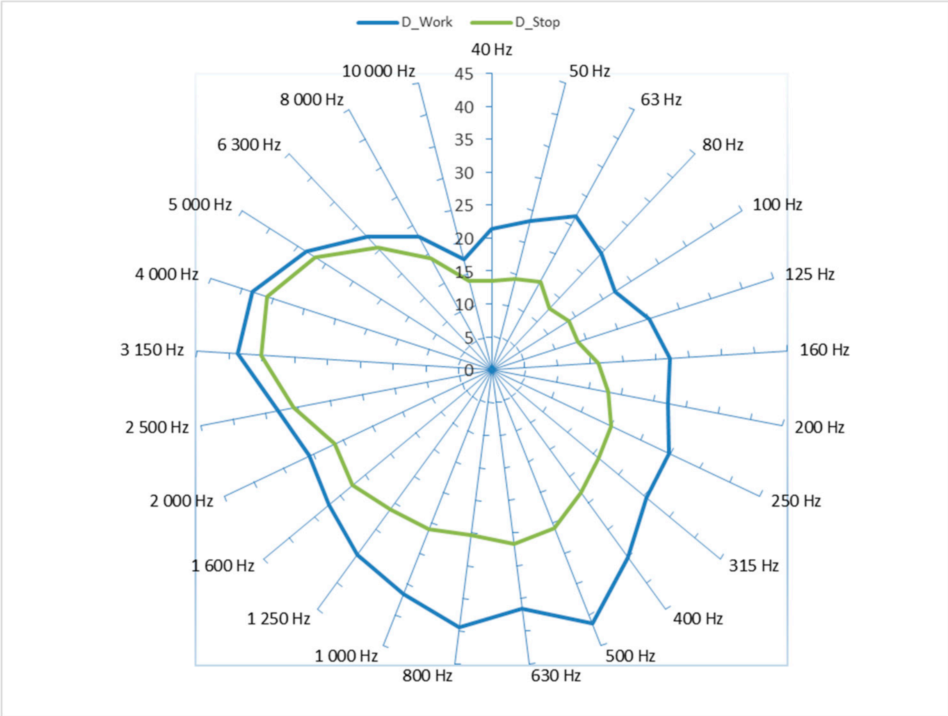

Figure 8. Values of noise emissions measured in residential areas I and II during operation (Work) and out of operation (Stop)—residential house D.

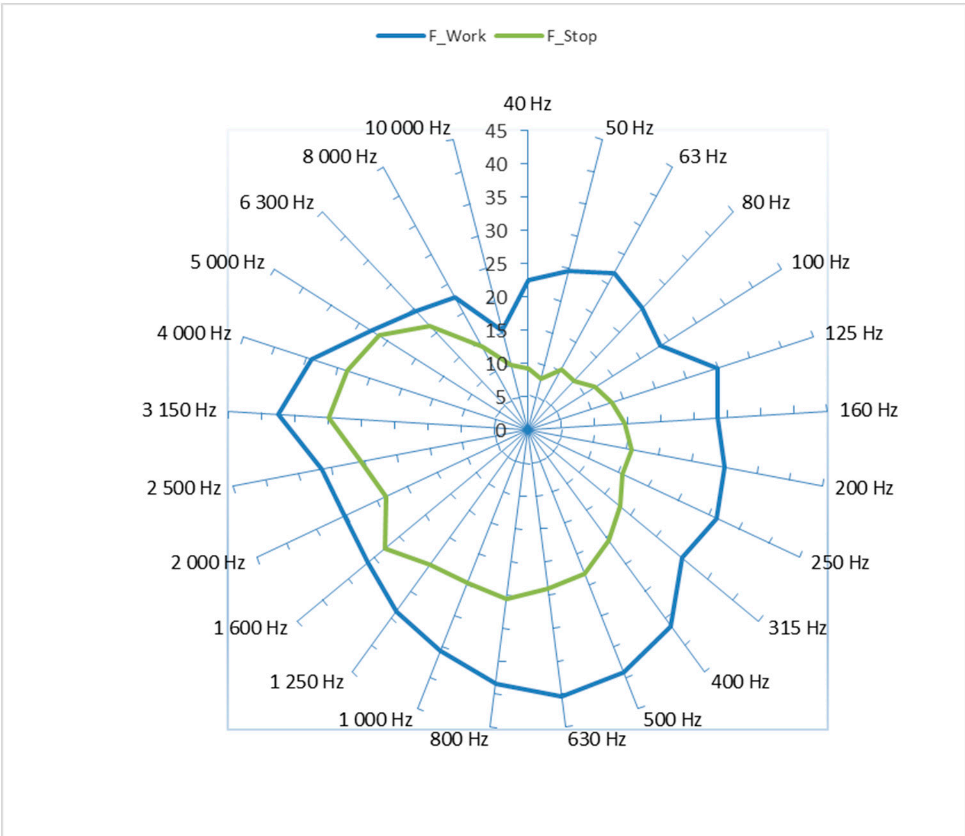

Figure 9. Values of noise emissions measured in residential areas I and II during operation (Work) and out of operation (Stop)—residential house—F.

At certain frequencies (3150 Hz and higher), noise levels are equivalent to those reached during operation.

The proposed noise-reducing modifications of machinery cladding at dumping hoppers, implemented modifications of fencing, and installation of acoustic barriers have reduced noise levels in the monitored areas below 50 dB, as shown in Table 4.

5. Conclusions

In order to reduce noise in residential areas, four stages of noise-reducing measures have been successively implemented in the sandy gravel production plant. The proposed noise-reducing measures concerned:

- modernization of machinery,
- noise barrier modifications,
- modifications of traffic routes.

After the implementation of noise-reducing measures, the noise load at all residential houses has been similar. The development of the measured noise values during the operation of the sandy gravel production plant (Work) at locations considered in the residential areas is shown in Figure 10.

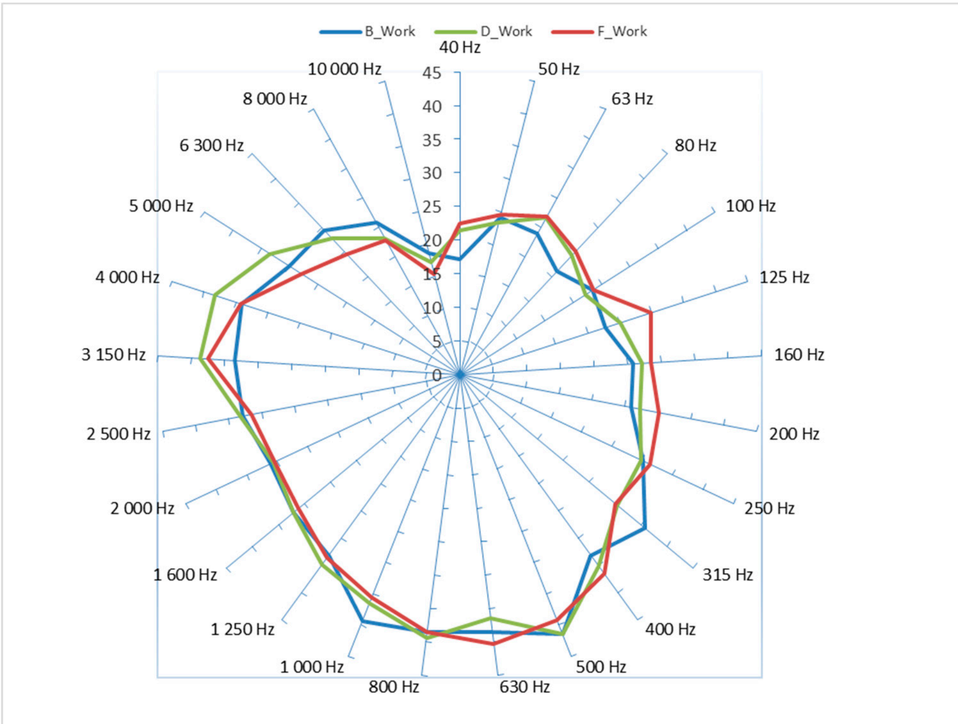

Figure 10. Values of noise emissions measured in residential areas during operation (Work).

The noise study shows that even when the operation is stopped (Stop), the noise in the higher frequency bands is affected by ambient noise (Figure 11). Its impact is most pronounced in residential house D.

The present study shows that it has been possible to significantly reduce noise emissions in the sandy gravel production plant by implementing appropriate noise-reducing measures.

The presented paper, in the form of a case study, extends the issue of noise reduction to another area, namely the continuous process industry. In recent years, articles have been published focusing on different industrial areas in terms of content, e.g., [23], which deals with noise reduction in the food industry (milk processing). Other similar works are devoted to noise reduction in the field of metallurgy [3], construction industry [24] or in the process industry [25]. Based on the above examples, it can thus be concluded that increased attention in scientific research needs to be given to this issue considering its specificity in terms of the industrial field to which it is devoted. Therefore, the case study format is particularly suitable for such a presentation.

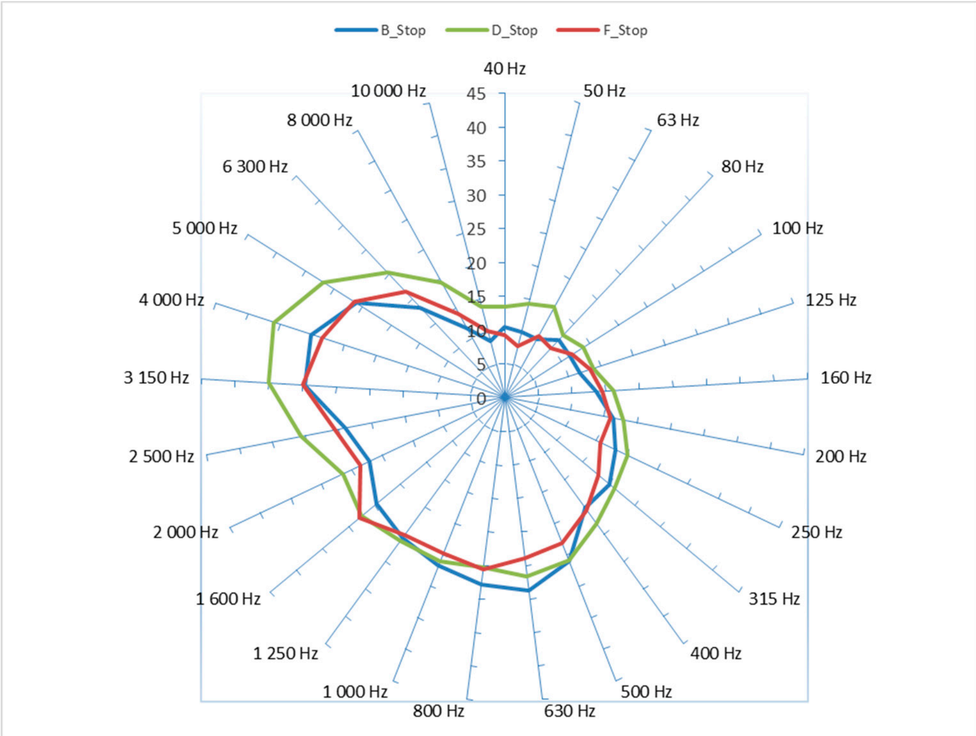

Figure 11. Values of noise emissions measured in residential areas out of operation (Stop).

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