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A Proposal for Risk Assessment of Low-Frequency Noise in the Human–Machine–Environment System

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Abstract: Low-frequency noise, the frequency range from approximately 10 Hz to 200 Hz, has been recognized as a special environmental noise problem. The World Health Organization recognizes the special place of low-frequency noise as an environmental problem. Noise can damage hearing, and it affects the whole body. Low-frequency sound is heard by humans, but infrasound is not audible. Low-frequency sound is most often measured based on a weighting function of the frequency. The A-weighted level underestimates the effects of low-frequency noise. For the detrimental effects of low-frequency sound, it would be appropriate to apply measurements using Z-weighting. The aim of this paper was to propose a comprehensive method of acoustic risk assessment (CMARA) that implements the effects of low-frequency values of noise exposure. The proposed methodology has been applied in practice at four workplaces for seven work activities. A risk assessment using the proposed CMARA method for individual activities shows that the noise exposure time may pose a health risk in the occupational and environmental process due to exposure to low-frequency noise at the limit of audibility. A high risk was assessed for activities WA2 (machining) and WA3 (spot welding). This paper highlights the need to measure low-frequency noise using Z-filter weighting.

Keywords: acoustics risk assessment; low-frequency noise; prevention of acoustic risks

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1. Introduction

Risk assessment is one of the basic pillars of the occupational health and safety management system [1]. Low-frequency noise (LFN) is one of the most harmful and annoying factors affecting people in their work and living environment [2]. An international definition of LFN has not yet been formulated, which is why its exact limits are not specified. It is usually defined according to several sources [2–5] as broadband noise with a dominant sound energy in the frequency band range from 10 Hz to 250 Hz (limits of 100 Hz, 160 Hz, or 200 Hz are also given). In the EU, it is defined according to the relevant legislation [6] as audible sound, the frequency spectrum of which is in the third-octave bands, with mean frequencies of 20 Hz to 40 Hz. Many studies [2–4,7–9] show that low-frequency waves differ from medium-frequency and high-frequency waves by several specifications, including a higher intensity of energy transmission, which is differently propagated and reduced. The specific characteristics of LFN compared to audible noise define that at low frequencies, there is a sharp increase in volume and the absorption is too low; therefore, the distances of propagation are large. This fact is also a problem in the work environment, where the measurement of noise exposure is performed using an A-weighting filter, which does not record the acoustic energy acting on humans. Acoustic energy at low frequencies has higher volume values that are not captured by the A-weighting filter.

According to studies [10–12], a higher degree of discomfort has been reported by workers who are exposed to LFN. The subjective symptoms of LFN were fatigue, dizziness, a feeling of pressure in the head and on the eardrum, and mood swings, which affect people in their work performance [13] by reducing their attention and concentration. Speech intelligibility is significantly affected by frequencies as low as 20 Hz. Disruption of the vestibular system results in disorientation, nausea, or imbalance [9]. It can be argued that this type of noise increases work stress, which increases cognitive load and thus increases the likelihood of errors. This increases the likelihood of accidents at work [14].

One of the most common employee complaints is low frequency noise from 20 Hz to 250 Hz [15,16]. The discomfort that occurs even when the audibility threshold is only slightly exceeded is the dominant effect of low frequencies on the human body during exposure to it in the workplace. LFN can be perceived as a mixture of sound and tactile stimuli, which causes pressure in the ears and feelings of vibration on the body [17].

The low-frequency mechanical vibrations generated by machines and machine systems cause disturbing dynamic forces, most often caused by unbalance, a non-coaxial connection of rotating components, inappropriate clearance of mutually moving components, mechanical loosening, misalignment, incorrect lubrication, technological processes, or insufficient maintenance [18]. The most important sources of LFN include, for example, fluid flow in machinery, industrial activities and technologies, powerful ventilation and air conditioning equipment, and pumps [18–20], which are also part of the working environment.

In the framework of Council Directive 89/391/EEC [21] on occupational health and safety, which sets a requirement for the assessment of hazards in the work process, this paper proposes a method for assessing the impact of noise on workers at work, which includes the incorporation of Directive 2003/10/EC [6] on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents. This method also takes into account the impact of low-frequency values of normalized noise exposure L_Z, which pose a hazard. The A-weighting filter underestimates the sound pressure levels of LFN. It is more appropriate to use a Z-weighting filter to better evaluate the effects of LFN on health and the effects of acoustic energy not only on the human organ of hearing but also regarding the non-hearing effects of LFN. A-weighting is applied to the sound levels measured by the instrument to consider the relative volume perceived by the human ear, as the ear is less sensitive to low sound frequencies. A-weighting is the most-used group of curves defined in the international standard IEC 61672-2 [22] concerning the measurement of sound pressure levels. Permissible noise exposure levels are usually based on dB(A) level measurements, and noise protection is exclusively associated with hearing protection devices, which is an essential requirement of Directive 2003/10/EC [6]. Frequency “Z” weighting represents the frequency response without a microphone response, which is a zero-weight or flat-frequency response.

A number of different methods in individual countries [23–27] have been suggested for the assessment of low-frequency noise. The procedures used in different countries to enforce the criteria for low-frequency noise are very different. Regarding the Danish method [23], a recommended measurement method is specified. Noise is measured at several locations in the interior and analyzed in 1/3-octave bands. Nominal A-weighted corrections are added to the spectra, and the weighted spectrum is summed to produce an A-weighted noise floor in the frequency range 10–160 Hz. For the German method [24], low-frequency noise is defined as noise where the C-weighted noise level is at least 20 dB higher than the A-weighted level, either based on equivalent levels or maximum levels. If the noise is evaluated as “low frequency”, a 1/3-octave frequency analysis is performed. This method considers the frequency range of 10–80 Hz, but in special situations, the 8 Hz and/or 100 Hz band may also be included. For Swedish method [25], the recommendations contain a curve of criteria for recommended maximum levels of low-frequency noise. The curve covers the frequency range og 31.5–200 Hz and is valid for an equivalent noise level. The Polish method also uses a threshold curve [26]. This is defined over a frequency range of 10–250 Hz and corresponds to 1/3-octave levels, each giving an A-weighted level of 10 dB. Finally, the Dutch method [27] is defined in the frequency range of 10–200 Hz and uses a criterion curve. In the upper part of the frequency range, the criterion curve is identical to the Swedish criterion curve. At the lowest frequencies, it corresponds to the hearing threshold specified in the German method.

2. Materials and Methods

2.1. A Proposal for Risk Assessment of Low-Frequency Noise

A proposed method for assessing acoustic risk at low frequencies (CMARA), is the modification of the mixed risk assessment method set out in ISO/TR 14121-2 [28]. The basis of this method follows the risk assessment algorithm regarding harmonized standards for machinery construction ISO 12100 [29]. The mixed method serves to quantify parameters that are qualitative, combining a risk matrix and numeric score. The resulting value of the risk is calculated by combining the *Se* severity parameters (severity of possible damage as a result of the identified hazard, consequences) and *CI* category (1, 2). The overall *CI* probability is given by the sum of the factors, and each factor is estimated independently. The factors include *Ex* (exposure, mean interval between exposure frequency and its duration; it is evaluated by the interval length between exposures), *Pr* (probability of occurrence of a dangerous event), and *M* (possibility to prevent or limit damage). The risk is then evaluated using the risk matrix located in the middle of the rating table of the method. In case of undesirable (high) risk, it is necessary to take protective measures to reduce it. If the risk is acceptable (medium), taking protective measures to reduce the risk is recommended, and at an acceptable (low) risk, it is already reduced enough. Table 1 contains a description of the factors of the proposed method.

Table 1. Factors of the proposed CMARA for acoustic risk assessment at low frequencies. Source: own research. (inspired by ISO 14121-2 [28]).

Factor	Description of Factor Levels	Rating
Severity (Se) Severity of possible damage to the employee's health during LFN exposure	Severe consequences (based on medical examinations)	5
	Moderate consequences (subjective complaints of workers at and after exposure to noise)	3
	Minimal consequences (consequences that are only momentary, do not persist after leaving the job and disappear quickly)	1
	Negligible to no consequences	0
Exposure (Ex) Exposure describes how long an employee is exposed to LFN	More than 6 h and less than or equal to 8 h	4
	More than 4 h and less than or equal to 6 h	3
	More than 2 h and less than or equal to 4 h	2
	Less than or equal to 2 h	1
Probability of exposure to LFN with auditory impacts (Pa)	High—point evaluation from 8–12	5
	Medium—point evaluation from 4–7	3
	Less than—point evaluation less than 3	1
Probability of exposure to LFN with non-auditory effects (Pna)	High—point evaluation from 8–12	4
	Medium—point evaluation from 4–7	2
	Less than—point evaluation less than 3	1
Measure (M) Application of measures to reduce LFN	Applied	0
	Not applied	1

The factor of the Severity (*Se*) is tailored to the consequences of exposure to LFN. The factor has four degrees, namely severe consequences (based on medical examinations), moderate consequences (subjective complaints of workers at and after exposure to noise), minimal consequences (consequences that are only momentary, do not persist after leaving the job and disappear quickly), and negligible to no consequences.

The factor of exposure (*Ex*) describes how long an employee is exposed to LFN during work. It has four degrees, and the maximum exposure time is 8 h due to the standard labor shift duration and in compliance with legislation.

The input parameters for the proposed method are the action and limit values given by Directive 2003/10/EU [6], the limit values of EU countries, and the hearing threshold curve from ISO 226 [29].

The factor of probability of exposure to LFN with an auditory impact (*Pa*) determines the probability that an employee will be exposed to low-frequency noise to the auditory body at work. The factor has three degrees—high, medium, and exceptionally low probabilities. A point rating is assigned to each degree, which is the sum of the limit values at the individual considered frequencies (16–100 Hz). The limit values were determined according to the ISO 226 hearing threshold curve [30]. The standard does not indicate a value at 16 Hz; therefore, this limit value has been set by the LFN limit values given by the EU states. The values for the frequencies, together with the point rating and determination of the Pa factor degree itself, are described in Table 2 and Equation (3).

Table 2. Determination of the *Pa* factor. Source: own research.

Frequency (f) [Hz]	**Factor *Pa* Degree**					
	Limit Value [dB]	**Point Rating (PR)**	**Limit Value [dB]**	**Point Rating (PR)**	**Limit Value [dB]**	**Point Rating (PR)**
16	over 74	2	74–59.2	1	under 59.2	0
25	over 68.7	2	68.7–55	1	under 55	0
40	over 51.1	2	51.1–40.9	1	under 40.9	0
63	over 37.5	2	37.5–30	1	under 30	0
80	over 31.5	2	31.5–25.2	1	under 25.2	0
100	over 26.5	2	26.5–21.2	1	under 21.2	0
If the sum of points of the measured noise levels at each frequency is: 8–12→high probability (5)–*H* 4–7→medium probability (3)–*M* less than 3→exceptionally low probability (1)—*L*						

The factor of the probability of exposure to LFN with non-auditory effects (*Pna*) determines the probability at which the worker is exposed to LFN with non-auditory effects during work. The noise levels at the frequencies of 16 Hz–100 Hz are assessed (as well as with the *Pa* factor). Since the legislation only gives measurements of the aid of the A-weighting filter, the values measured by the Z-weighting filter represent the extra auditory effects in particular; there are no limits for this type of frequency weighing. The factor has three degrees, and the individual degrees are the sum of the values of the acoustic pressure level values at the individual frequencies given in Table 3 and Equation (4). The LFN limit values are determined according to the measurements made at the W1–W4 workplaces.

$$R = f\ (Se,\ Cl) \tag{1}$$

$$Cl = Ex + Pa + Pna + M \tag{2}$$

$$Pa = \sum\nolimits_f PRa_f \tag{3}$$

Here, *PRa* is the point rating (Table 2) and f is the frequency.

$$Pna = \sum\nolimits_f PRna_f \tag{4}$$

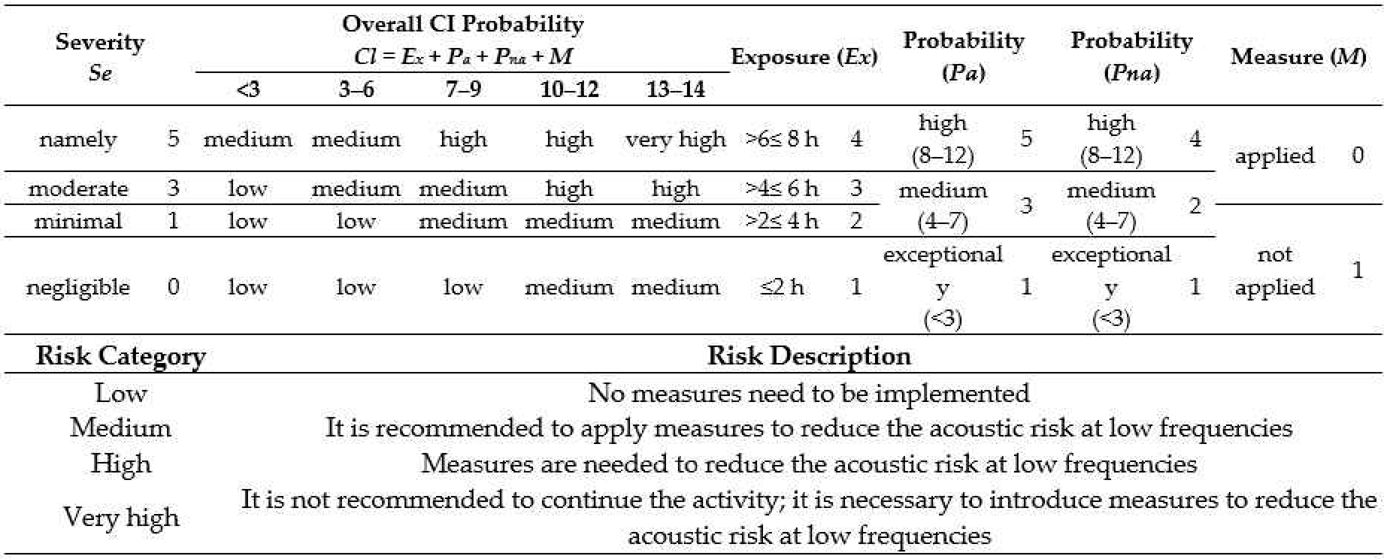
Here, *PRna* is the point rating (Table 3) and f is the frequency.

A description of the extent of the resulting acoustic risks is presented, along with the suggested CMARA method, in Figure 1.

Table 3. Determination of the *Pna* factor. Source: own research.

Frequency (f) [Hz]	Factor *Pna* Degree					
	Limit Value [dB]	Point Rating (PR)	Limit Value [dB]	Point Rating (PR)	Limit Value [dB]	Point Rating (PR)
16	over 48.3	2	48.3–38.6	1	under 38.6	0
25	over 50	2	50–40	1	under 40.1	0
40	over 55.55	2	55.55–44.44	1	under 44.4	0
63	over 57.52	2	57.52–46	1	under 46.8	0
80	over 62.9	2	62.9–50.32	1	under50.32	0
100	over 62.68	2	62.68–50.14	1	under 50.1	0

If the sum of points of the measured noise levels at each frequency is:
8–12→high probability (4)—*H*
4–7→medium probability (2)—*M*
less than 3→exceptionally low probability (1)—*L*



Severity *Se*		Overall CI Probability $Cl = E_x + P_a + P_{na} + M$					Exposure (*Ex*)		Probability (*Pa*)		Probability (*Pna*)		Measure (*M*)	
		<3	3–6	7–9	10–12	13–14								
namely	5	medium	medium	high	high	very high	>6≤ 8 h	4	high (8–12)	5	high (8–12)	4	applied	0
moderate	3	low	medium	medium	high	high	>4≤ 6 h	3	medium (4–7)	3	medium (4–7)	2		
minimal	1	low	low	medium	medium	medium	>2≤ 4 h	2					not applied	1
negligible	0	low	low	low	medium	medium	≤2 h	1	exceptional y (<3)	1	exceptional y (<3)	1		

Risk Category	Risk Description
Low	No measures need to be implemented
Medium	It is recommended to apply measures to reduce the acoustic risk at low frequencies
High	Measures are needed to reduce the acoustic risk at low frequencies
Very high	It is not recommended to continue the activity; it is necessary to introduce measures to reduce the acoustic risk at low frequencies

Figure 1. Proposed method for assessing acoustic risk at low frequencies. Source: own research (inspired by ISO 14121-2).

2.2. The Acoustic Risk Management Algorithm

The effects of noise on a person in the lower part of the decibel scale (16–100 Hz) leads to straining of the organism and to lasting changes to health, which is undesirable overall. Much greater attention needs be devoted to questions related to the assessment of acoustic risks (and with low values of noise or sound) and the subsequent reduction in noisiness if we want to protect the health of a person against civilization diseases. Noise as spreading acoustic energy also has negative non-auditory effects, primarily on the neuropsychic and cardiovascular apparatus and on sensory–motor functions.

It is possible to define risk assessment on scientific foundations as a systematic process of the evaluation and interpretation of real information about a system, on the basis of which a threat (in this case, the danger of noise) and the consequences (auditory and non-auditory) following from the given threat are identified. It is then possible to quantify or qualitatively express the size of the risk and decide whether or not it is acceptable.

LFN is characterized by strong energy that spreads over great distances and affects human health. The study of LFN is in the research stage. The aim of this paper is to propose a method of acoustic risk assessment (a modification of the mixed method from ISO standard 14121-2 Safety of machinery, Risk assessment, Part 2: Practical guidance and examples of methods). An added value in the design of the method is an A-weighted noise measurement and Z- or ZERO frequency-weighting. The acoustic risk management algorithm is shown in Figure 2. The proposal of the method is described in Section 2.1, and the application of the method is demonstrated in Section 2.2.

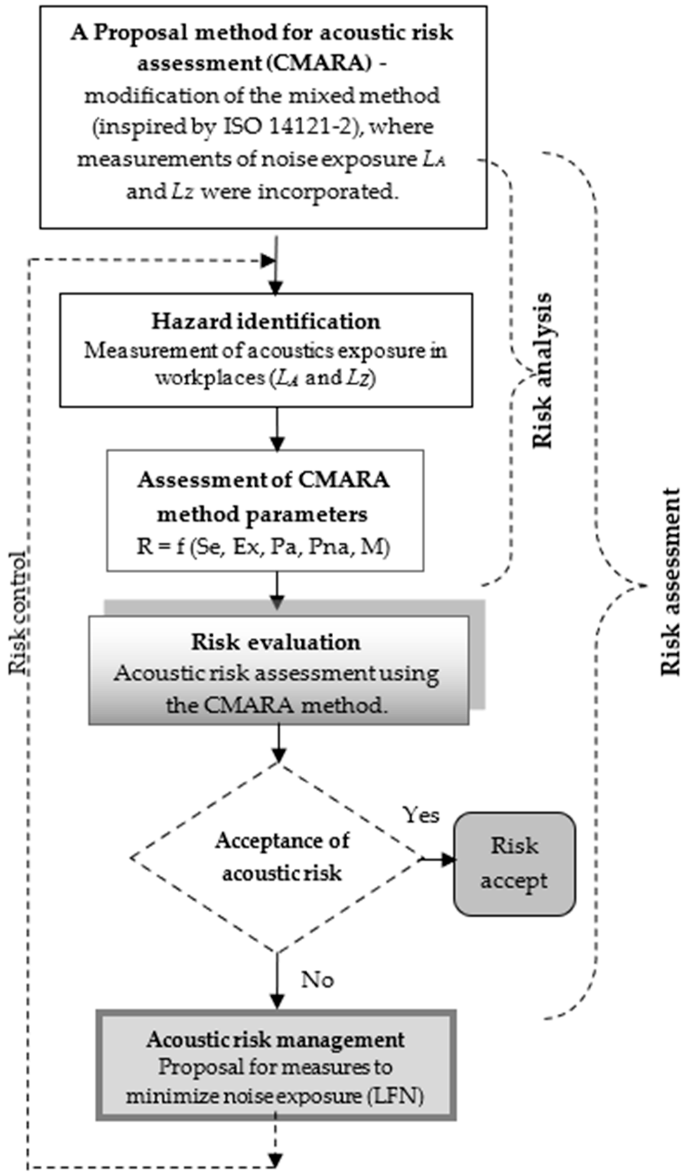


Figure 2. The acoustic risk management algorithm. Source: own research (inspired by 12100 [29]).

2.3. Application of the Proposed Method in Practice

The main reason for these measurements is to assess the acoustic risk by measuring the noise exposure levels L_A and L_Z and to show the influence of acoustic energy on the extra-auditory effects of employees exposed to this type of noise. Measurements were carried out at four engineering workplaces in seven work activities. Measurements of LFN in W1–W4 machinery workplaces at individual WA1–WA7 work activities took place during the performance of individual work activities in the workplaces. The marking of individual workplaces and work activities is outlined in Table 4. The measured quantities (A-sound pressure level L_A [dB]; Z-sound pressure level L_Z [dB]) were then applied to the proposed CMARA method. Thus, two experimental measurements were performed in succession in each workplace during work activities WA1–WA7.

Table 4. Marking of workplaces and work activities. Source: own research.

Workplace	Marking of Workplace	Work Activities	Marking of Work Activities
Workplace of CNC milling	W1	CNC milling	WA1
Workplace of electrotechnical production	W2	Tool shop—machining	WA2
		Spot welding	WA3
Workplace of steel structures production	W3	Welding	WA4
		Grinding	WA5
		Bending	WA6
Woodworking workplace	W4	Grinding	WA7

A Bruel & Kjaer type 2250 manual sound analyzer was used for each measurement of the LFN and its evaluation. The noise load measurements were carried out in accordance with the standard. For working conditions of individual work activities, a strategy of working task (operation) measurement was applied. The measured values of L_A and L_Z were considered at low frequencies, from 16 Hz to 100 Hz. The summary results of the measurements of noise exposure during the time of work activities of WA1–WA7 using two types of weighing filters are presented in Figure 3, including measurements using an A-weighting filter. In Figure 4, the results of the measurements using a Z-weighting filter are given. The measurements of noise load during individual work activities indicate that low-frequency acoustic waves have significantly higher values using the Z-weighting filter than using the A-weighting filter.

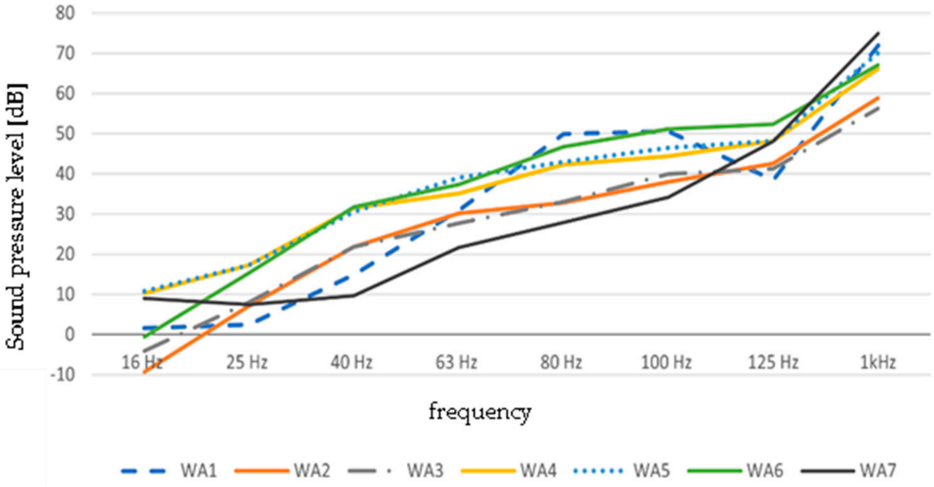


Figure 3. Levels L_A during WA1-WA7 at the considered frequencies.

The difference between L_Z and L_A decreases with increasing frequency, as evidenced by the resulting differences during WA1–WA7. The measured higher values of acoustic energy emissions and their long-term effects on employees could not only affect the auditory organ but also exert significant effects on other systems.

The steps of application of the proposed method for the assessment of acoustic risks at low frequencies are as follows:

1. The limit values L_Z at frequencies ranging from 16 Hz to 100 Hz are determined based on individual measurements for the factor Probability *Pna*. The limit value for a high probability *Pna* is the average value from individual measurements. From it derives the medium probability, and consequently the low probability *Pna*.
2. The duration of the work activity, the factor exposure *Ex*, is determined when the employee is potentially exposed to LFN during work, shown in Table 5.
3. The degrees of the probability factors *Pa* (Table 6) and *Pna* (Table 7) are determined according to the measured values at individual frequencies from 16 Hz to 100 Hz.

4. Data on the already-applied measures are determined before the LFN at individual workplaces W1–W4. Personal protective equipment for hearing protection is used by workers at WA4, WA5, WA6, and WA7. Structural measures were applied to W3, namely noise barriers. Organizational measures have even been applied to W4 and WA7.
5. Calculation of Category *CI*—the sum of the degrees of factors *Ex*, *Pa*, *Pna*, *M*, Table 8.
6. Determination of the degree of severity S_e based on interviews with employees, Table 8.
7. Calculation of acoustic risk at low frequencies (Figure 1) according to parameter *Se* and category *CI*.

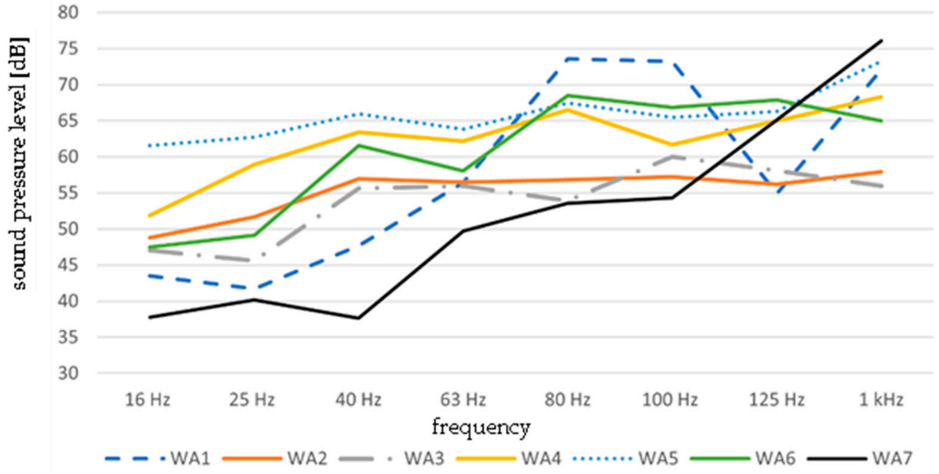


Figure 4. Levels L_Z during WA1-WA7 at the considered frequencies.

Table 5. Determination of the factor *Ex*. Source: own research.

Work Activities		Duration of Work (Hours)	Exposure Factor Level *Ex*
W1	WA1	2	1
W2	WA2	7.5	4
	WA3	7.5	4
W3	WA4	3	2
	WA5	3	2
	WA6	3	2
W4	WA7	3	2

Table 6. Determination of the factor *Pa*.

	WA1	WA2	WA3	WA4	WA5	WA6	WA7
L_A at 16 Hz [dB]	1.54	−9.29	−4.07	10.22	10.77	−0.61	8.99
Point rating	0	0	0	0	0	0	0
L_A at 25 Hz [dB]	2.49	7.15	8.01	17.22	17.29	15.35	7.40
Point rating	0	0	0	0	0	0	0
L_A at 40 Hz [dB]	14.80	21.86	21.84	31.43	30.61	31.72	9.58
Point rating	0	0	0	0	0	0	0
L_A at 63 Hz [dB]	30.93	30.15	27.70	35.09	39.04	37.28	21.60
Point rating	1	1	0	1	2	1	0
L_A at 80 Hz [dB]	49.97	32.72	33.05	42.26	42.95	46.78	27.91
Point rating	2	2	2	2	2	2	1
L_A at 100 Hz [dB]	50.63	38.02	39,93	44.37	46.43	51.16	34.08
Point rating	2	2	2	2	2	2	2
Sum of the point ratings	5	5	4	5	6	5	3
Degree factor P_a	3 (*M*)	3 (*M*)	3 (*M*)	3 (*M*)	3 (*M*)	3 (*M*)	1 (*L*)

Table 7. Determination of the factor *Pna*. Source: own research.

	WA1	WA2	WA3	WA4	WA5	WA6	WA7
L_Z at 16 Hz [dB]	43.54	48.82	47.02	51.86	61.59	47.49	37.81
Point rating	1	2	1	2	2	1	1
L_Z at 25 Hz [dB]	41.70	51.65	45.58	58.95	62.76	49.16	40.19
Point rating	1	2	1	2	2	1	1
L_Z at 40 Hz [dB]	47.68	56.97	55.63	63.45	65.96	61.54	37.65
Point rating	1	2	2	2	2	2	0
L_Z at 63 Hz [dB]	56.44	56.49	55.95	62.16	63.81	58.08	49.70
Point rating	1	1	1	2	2	2	1
L_Z at 80 Hz [dB]	73.58	56.84	53.94	66.49	67.47	68.48	53.56
Point rating	2	1	1	2	2	2	1
L_Z at 100 Hz [dB]	73.20	57.24	60.02	61.67	65.49	66.85	54.32
Point rating	2	1	1	1	2	2	1
Sum of the point ratings	8	9	7	11	12	10	5
Degree factor *Pna*	4 (*M*)	4 (*M*)	2 (*L*)	4 (*M*)	4 (*M*)	4 (*M*)	2 (*L*)

Table 8. Calculation of the resulting acoustic risk using the proposed method. Source: own research.

Work Activities	Factors				*Cl*	*Se*	Resulting Risk
	Ex	*Pa*	*Pna*	*M*			
WA1	1	3	4	1	9	3	Medium
WA2	4	3	4	1	12	3	High
WA3	4	3	2	1	10	3	High
WA4	2	3	4	0	9	3	Medium
WA5	2	3	4	0	9	3	Medium
WA6	2	3	4	0	9	3	Medium
WA7	2	1	2	0	5	1	Low

3. Results and Discussion

As already mentioned, many studies [31–33] state that LFN is a nonintrusive sound, and that employees become used to it over a long period of time. In contrast, many studies [1–3,10–17] consider LFN as one of the risk factors for health damage in terms of long-term exposure.

The employer’s obligation to assess risks follows from the framework Directive 89/391/EEC [21] and its implementing Directive 2003/10/EC [6]. Possible risk assessment tools are described in ISO standard 14121-2 [28]. The current methods of measuring sound at the limit of audibility may not reflect its real impact on human health. However, research is ongoing in this area, and methods of noise measurement are being developed. Globally (USA, Germany, Great Britain, France, Poland), the trend of complex measurement of specific noise is gaining ground. These measurements take into account not only the frequency of the sound, but also its energy or acoustic pressure. When measuring the impact of sound on humans, the legislation recommends using different “weightings” in order to take into account the specific characteristics of the human ear. Sound with low frequencies refers to sound at the threshold of audibility (close to infrasound), and EU legislation and technical standards recommend using “A-weighting” when measuring its impact on humans. Although this takes into account the detection of sound by the human auditory organ, it does not take into account the energetic effect of sound on this organ, as well as on the human neuropsychic and cardiovascular system and sensory–motor functions. Using conventional A-weighting reduces the measured levels of actual acoustic energy acting on a person. Therefore, some countries are already proceeding with caution when using A-weighting. When measuring low-frequency sounds, they prefer, e.g., C-weighing (Germany). Alternatively, measurements made using C-weighting account for the response of the human ear, with smaller weightings at low frequencies compared to the A-weighting filter. This, along with Z-weighting, can be useful to help identify the presence of low-frequency noise. The 'Z' or zero weighting is simply a filter with a flat frequency response. The proposed CMARA method modifies the mixed method from ISO standard 14121-2 [28], where the measurement of noise exposure using A-weighing as well as Z-weighing is incorporated. Based on the assessment using the proposed method, it is possible to predict the non-auditory effects of noise during its exposure.

The proposed CMARA methodology has shown that LFN can have a negative impact on employee health in terms of long-term effects, as well as an impact on workplace comfort. Measurements of noise exposure using the Z-filter in the WA2 (work activity) of machining and WA3 of spot welding indicate that a longer exposure time that can pose a health hazard in the work process. This was also confirmed by a risk assessment using the proposed methodology, where the values of the resulting risks shown in Table 8 in these two cases (WA2, WA3) are at the level of high risk, four times at the level of medium risk (WA1, WA4, WA5, WA6), and in one case (WA7), at a low-risk level. The severity factor was determined qualitatively based on interviews with employees and, with one exception, it was assessed as moderate. After interviewing the employees, everyone confirmed that they felt their hearing was impaired during and after work. As part of the further development of the methodology, the aim was to quantify the parameters related to the non-auditory effects of noise, e.g., by measuring blood pressure and other health parameters that would indicate the impacts of LFN on the employees. Low-frequency noise (LFN) is oftentimes within the limit values of the usable frequency range of noise of instrumentation; therefore, special care is needed to ensure reliable results [34–36].

Many researchers [37–41] point out the inaccuracies associated with measuring noise using dB(A), as this method involves over-reliance on the average hearing sensitivity curve and related volume functions as predictors of noise nuisances. Even in cases where LFN is found and identified as a potential source, problems can arise because in many cases, the sound pressure level can be low relative to the average hearing threshold. Due to the risks of exposure to excessive noise, the legislation prescribes regular measurements. The trend of complex noise measurement is to measure not only the frequency but also its energy. The application of the Z-weighting filter makes it possible to measure the acoustic energy acting on humans.

The discomfort caused by LFN occurs only at slightly higher levels than the audibility threshold, which is different for every individual [42,43]. The rate of increase in the perceived volume is faster at low frequencies; therefore, one sound may be loud to one per-son while not yet audible to another. Another factor is that sensitivity to LFN occurs over time; therefore, the short-term effects on an individual may not give an accurate impression of what it is like to perceive this type of noise on a regular and long-term basis [44–47].

4. Conclusions

Low-frequency noise is ubiquitous in modern society, yet existing legislation in this area is insufficient. Not only is this noise expressed in units of dB(A), which does not reflect the assessment of LFN, but also, no specific measures are prescribed in cases of the identification of excessive LFN. Responses to complaints about LFN at workplaces have not been extensively documented in the literature [20,31,43]. Multiple factors, such as noise characteristics, health effects, and employee perceptions, need to be considered when assessing health concerns related to LFN. The aim of thia article was to propose the CMARA method (complex method for assessing acoustic risk at low frequencies) for assessing acoustic risk at low frequencies.

The CMARA method was developed by modifying the risk assessment methods in accordance with Directive 89/391/EEC. Specifically, a Z-weighting method is applied to evaluate the noise levels at low frequencies. These risks draw attention to the need to address the issue of evaluation and measurement of LFN when working indoors. Measurements are necessary to assess the negative effects of noise and to establish permissible values (criteria) that negatively affect health, comfort, and performance. Quantitative measurement of workers' exposure to noise during work are carried out for the purpose of assessing the health risk of exposure to noise and assigning the work to a category.

An important part of any acoustic risk management is the introduction of appropriate criteria to determine a favorable solution to noise problems. The results indicate that the proposed method can estimate the acoustic risk for these tasks with a long LFN exposure time. For example, it can be seen on the graph (Figure 5) that the impact of the acoustic energy measured for WA2 and WA3 activities using the L_Z measurement is higher at low frequencies. Such measurements take into account not only the frequency of the sound but also its energy or acoustic pressure, which propagates from the sound source via acoustic waves. Using the CMARA risk assessment, a high risk of adverse non-auditory effects was identified. However, research in this area is also ongoing, and the method used to measure noise is evolving.

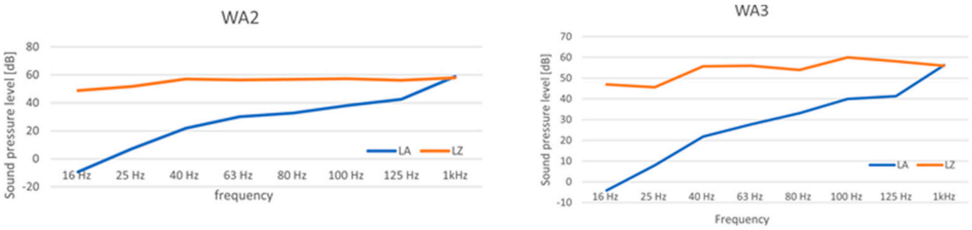


Figure 5. Measured sound pressure levels for WA2 and WA3 operations using L_A a L_Z.

The authors' measurements have already taken place, where non-auditory effects were detected based on heart rate. Currently, further measurements are taking place with the help of medical personnel based on objective medical results. The aim of this study is to highlight the issue of LFN at workplaces based on its assessment using the CMARA method proposed by the authors.

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