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ASSESSMENT OF THE ACOUSTIC EFFICIENCY OF ROAD INVESTMENTS IN THE STAGE OF DEVELOPING NOISE PROTECTION PROGRAMS IN CITIES

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Purpose: The purpose of the article is to present the concept of calculating indexes of effectiveness and acoustic efficiency of road investments that facilitate decision-making on the sequence of work implementation and the development of investment task schedule. The presented indexes are used in the development of strategic noise maps of cities and in the creation of noise protection programs. The presented concept fits into the topic of managing the acoustic climate of cities.
Design/methodology/approach: The method of ranking road investments described in the article was developed based on the author's many years of experience in developing strategic noise maps of cities and presented as a case study for the city of Siemianowice Śląskie.
Findings: The proposed method supports urban investment management. It allows for selecting the sequence of implementation of road investments in cities which ensures the achievement of maximum acoustic efficiency. The developed index of acoustic efficiency is defined as the ratio of costs incurred to the number of people exposed to excessive noise before and after the implementation of the investment. This index can be used to rank investments in the development of strategic noise maps and the creation of noise protection programs.
Practical implications: Strategic noise maps are prepared every 5 years in accordance with EU legislation. Based on them, noise protection programs are developed, within which future investments reducing noise in the city must be identified and their effects determined. The presented concept of introducing a ranking index for investments in terms of their acoustic efficiency is a response to the cities' demand for the development of a uniform methodology supporting the selection of investments based on the criterion of acoustic efficiency. The applied method can be introduced to standardize the way of evaluating the justification of implementing noise reduction investments in cities for the purposes of developing noise protection programs.
Originality/value: The article presents a concept of calculating indexes of the effectiveness and acoustic efficiency of road investments. These indexes are helpful in managing urban investments aimed at reducing the exposure of residents to noise, and in particular for proper planning of the sequence of investment implementation when developing noise protection programs. The defined indexes and the method of their calculation relate not only to road investments but can also be used to rank investments related to reducing railway and industrial noise.

Keywords: Noise, acoustic efficiency, acoustic map, strategic noise map, noise protection program.

Category of the paper: Case study, research paper.

1. Introduction

The primary document requiring EU member states to develop strategic noise maps of cities was the Directive 2002/49/EC of the European Parliament and of the Council, which introduced the obligation to assess and manage environmental noise levels. As a result of its implementation into the Polish legislation, regulations were introduced in the Environmental Protection Act requiring the development of strategic noise maps, followed by the development of noise protection programs and action plans based on these maps. Since then, every 5 years new strategic noise maps have been created, and noise protection programs have been developed based on them. The IV round of mapping was completed in June 2022, and currently work is progressing on the development of noise protection programs. Over the course of the last 20 years significant changes have been introduced into the computational methodologies involved, the method of use and accuracy of 3D city models, and the way residents' noise exposure to various types of noise is evaluated. Calculation procedures have also been adapted to the technical possibilities of using 3D modeling and increasingly accurate spatial data at our disposal. The current mapping round is being carried out with the use of the CNOSSOS-EU (Common NOise aSSessment methOdS), and the spatial information infrastructure developed by EU member states based on the INSPIRE directive. The strategic noise map is prepared on the basis of data sets from the state geodetic and cartographic resource. Reporting obligations have also been imposed on the EU member states. Detailed information on the preparation of strategic noise maps is presented in the guidelines of the Chief Inspectorate of Environmental Protection (Institute, 2021).

The strategic noise map constitutes the basic source of data for the purposes of informing the public about noise-related hazards, developing noise protection plans, planning and implementing actions to reduce noise, and a broad range of strategic planning, for instance in the context of spatial planning. Noise protection plans and concrete noise reduction programs for a given agglomeration are therefore developed based on the strategic noise maps. The developed programs are adopted through a voivodeship marshal's resolution and are subject to execution. That is why it is so important during the preparation of noise protection programs to be able to make a correct assessment of the acoustic efficiency of possible investments and to choose those that allow for the maximum reduction of noise nuisance for the largest possible number of residents, while at the same time minimizing the cost per investment. To this end, it is necessary to adopt an appropriate method of action. Later in the article a broad literature analysis of the issue will be conducted, existing indexes of acoustic investment efficiency will be analysed and discussed, and an original concept for an investment efficiency index will be proposed. The discussed subject matter fills a research gap ralated to the constant search for appropriate indexes for assessing the acoustic efficiency of investments. The article uses examples taken from the strategic noise map of the main roads in the city of Siemianowice Śląskie (Strategiczna…, 2022).

2. Methodology for creating strategic noise maps of cities and developing noise protection programs

Strategic noise maps are prepared for cities with a population of over 100,000, main roads with a traffic volume of over 3 million vehicles per year, as well as main railway lines and airports. Strategic noise maps are based on data sets from the state geodetic and cartographic resource (GUGIK), using computational methods specified in the annex to Directive 2015/996 (Directive, 2015). Specialized acoustic software is used to prepare the strategic noise maps. This software has implemented computational algorithms for noise emission and propagation from various sources, as well as algorithms supporting statistical calculations using GIS techniques. The most well-known acoustic software includes CadnaA, SoundPlan, Immi, and LimaA.

The methodology for creating noise maps is precisely defined in EU legislation and described in detail in the guidelines of the Chief Inspectorate of Environmental Protection (Institute, 2021). The exact scope of data included within noise maps is described in the annexes to the Regulation of the Minister of Climate and Environment of 1 July 2021 (Regulation, 2021a) with subsequent amendments included (Regulation, 2022).

Based on current geodetic, cartographic, and demographic data a three-dimensional spatial model of the mapped area is created within the appropriate GIS map projection. This model takes into account the topography of the terrain (DTM), buildings, noise barriers, ground absorption, tall vegetation, and noise sources such as roads. Residential buildings within the computational model have an assigned number of residents, moreover the model also has specified location of areas subject to noise protection, based on local spatial development plans. An example geometric model of the city of Siemianowice Śląskie is shown in Fig. 1. This model formed the basis for calculating the long-term noise level indexes L_{DWN} and L_N. The former index represents the averaged noise emission over the whole 24 hour period, while the latter represents the night period. The L_{DWN} index is calculated using the following formula (Regulation, 2020):

$$L_{DWN}=10\log\left[\frac{1}{24}\left(12\cdot 10^{0,1L_D}+4\cdot 10^{0,1(L_W+5)}+8\cdot 10^{0,1(L_N+10)}\right)\right] \quad (1)$$

The L_{DWN} index expresses the average annual sound level A in dB. In turn the L_D, L_W, and L_N indexes respectively describe the average annual sound level during the daytime (from 6^{00} to 18^{00}), evening (from 18^{00} to 22^{00}), and night (from 22^{00} to 6^{00}).

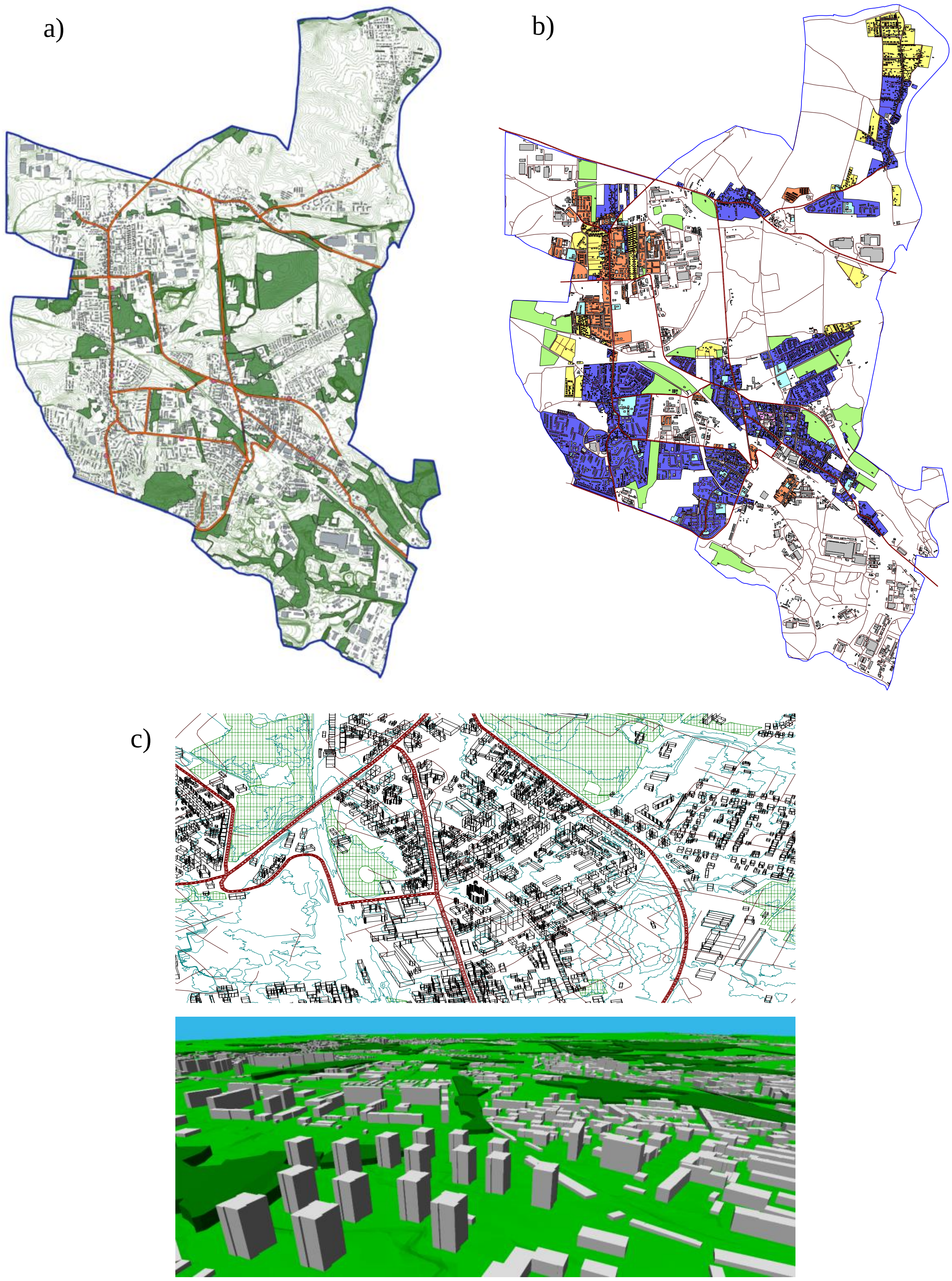

Figure 1. Geometric model of the city of Siemianowice Śląskie developed in CadnaA software: a) model in 2D view, b) areas subject to noise protection, c) model in 3D view.

Source: author's own elaboration based on the SMA of Siemianowice Śląskie (Strategiczna…, 2022).

Maps of road traffic noise immission, expressed by the L_{DWN} and L_N indexes, created on the basis of carried out calculations, are presented in Fig. 2. These maps indicate the ranges of noise impact in 5 dB intervals, ranging from 50 dB for the L_N index and from 55 dB for the L_{DWN} index.

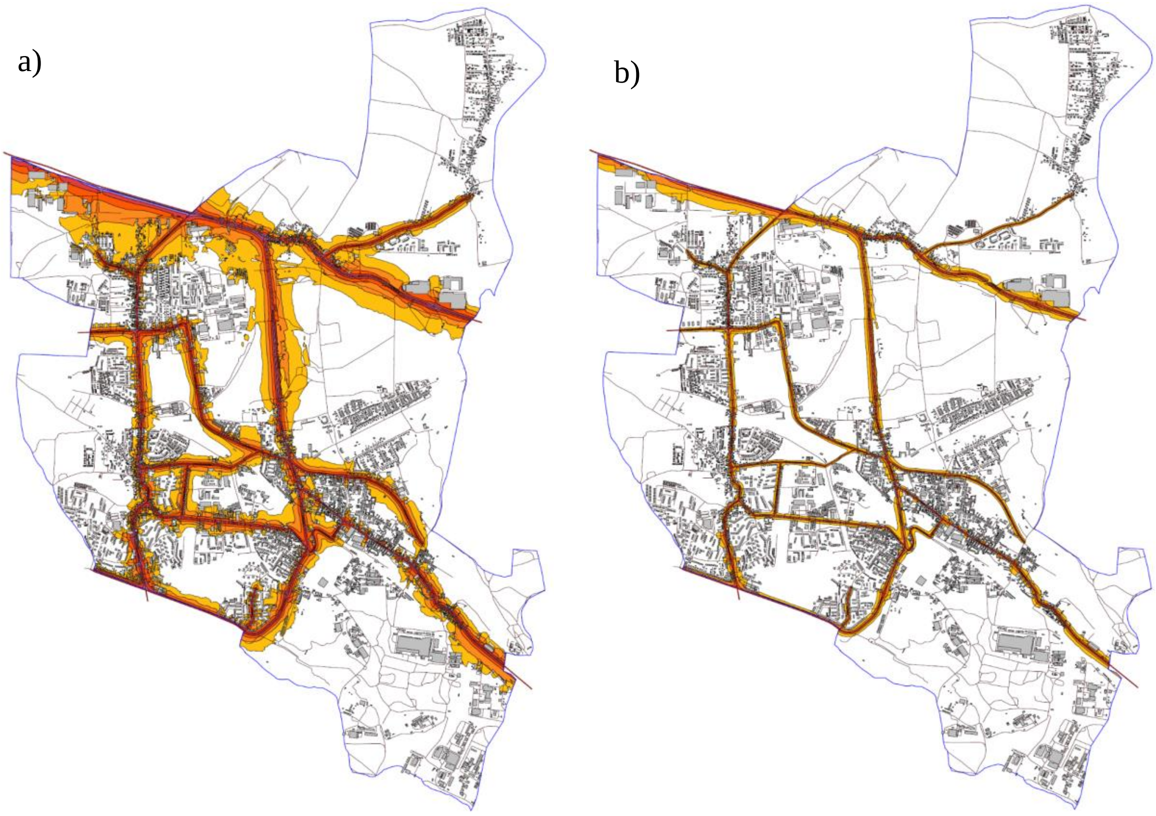

Figure 2. Maps of road traffic noise immission in the city of Siemianowice Śląskie: a) for the whole 24 hour period - L_{DWN} index, b) for the night period - L_N index.

Source: author's own elaboration based on the SMA of Siemianowice Śląskie (Strategiczna, 2022).

With the calculated distribution of noise levels in the environment (Fig. 2) and information on the location of areas subject to noise protection and their corresponding permissible noise levels (Fig. 1b), maps of areas threatened by noise are prepared (Fig. 3b). These are differential maps presenting areas where the permissible noise values are exceeded by a certain number of dB. According to the Cnossos methodology, for the purpose of detailed statistical data analysis, noise level distributions are also calculated for individual building elevations (Fig. 3c, 3d) and based on this, permissible noise level exceedances are determined. An example of analyses used to estimate the level of exposure of residents to excessive noise is presented in Fig. 3.

The most significant element of a strategic noise map is to determine the noise threat from different groups of sources (e.g. roads, railways, industry) and to estimate the number of people exposed to this physical factor. The next step is to calculate statistical measures describing the overall exposure to noise for the city's residents. Among calculated values are the area of threatened areas, the number of residential units, and the number of residents exposed to noise divided into 5-decibel ranges. Example results of noise threat assessments from main roads in the city of Siemianowice Śląskie are presented in Table 1.

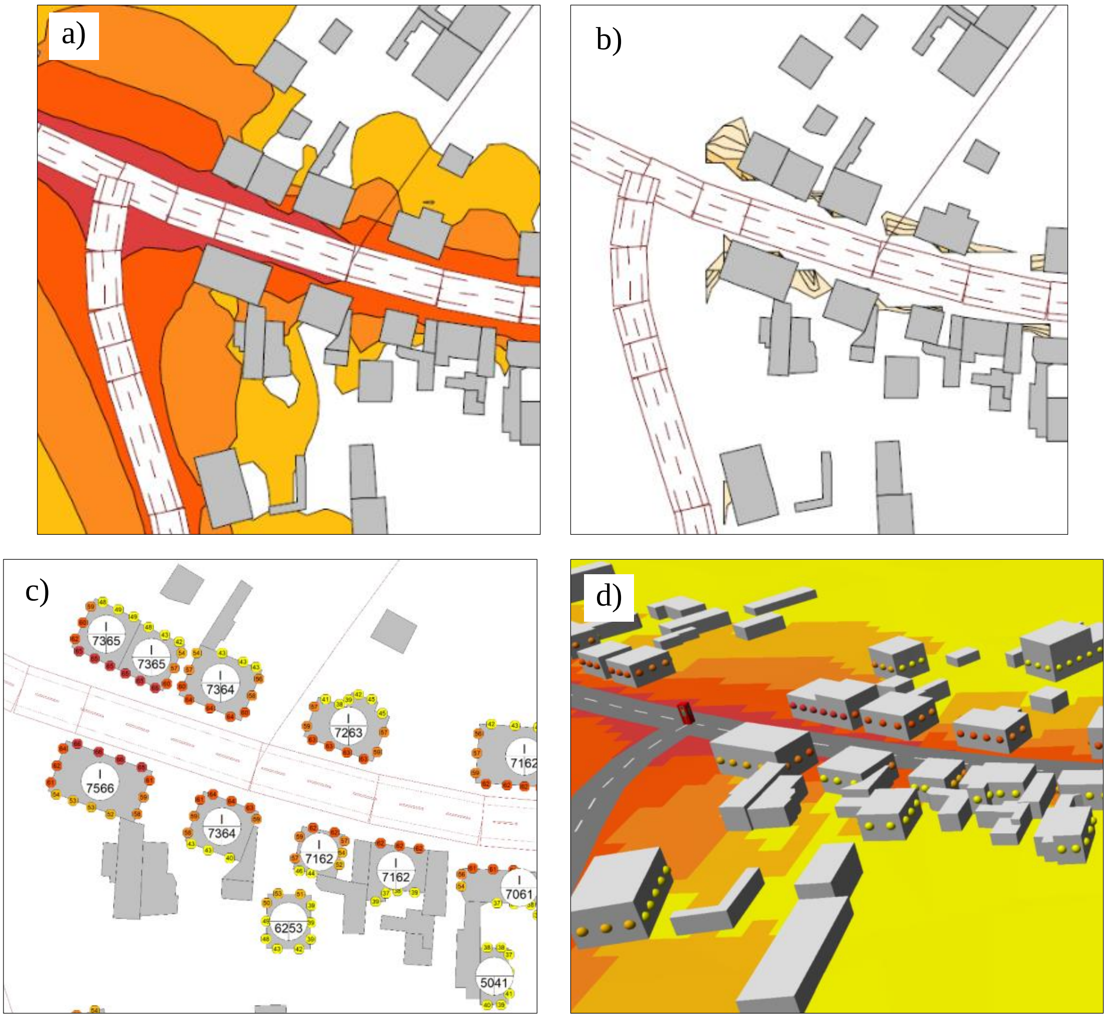

Figure 3. Examples of acoustic analyses: a) immission map of a city fragment, b) map of areas threatened by noise, c) distribution of noise on building elevations (2D view), d) distribution in 3D view.

Source: author's own elaboration based on the SMA of Siemianowice Śląskie (Strategiczna…, 2022).

Having information about the number of exposed individuals and the extent of noise level exceedance, it is possible to develop a noise protection program, which will implement investments aimed at minimizing noise. The catalogue of noise reducing investments is quite large and depends on the type of noise source. The most important include, for example, the construction of bypasses or new roads leading traffic away from densely populated residential areas, the construction of sound barriers, the use of low-noise asphalt, speed limits, etc. Organizational and planning activities are also important in the fight against noise, such as building residential areas away from main roads and city centers, planning the layout of buildings that takes into account external commercial-service areas and internal quiet zones, creating slow traffic zones, etc.

Table 1.
Results of noise threat assessment from main roads in the city of Siemianowice Śląskie

Ranges in dB	L_{DWN} index			L_N index		
	Total area [km²]	Number of residential units	Number of residents	Total area [km²]	Number of residential units	Number of residents
Data relating to noise exposure						
50,0÷54,9	-	-	-	1,025100	2562	5300
55,0÷59,9	1,577675	2441	5100	0,676150	3200	6700
60,0÷64,9	0,970900	2246	4700	0,280850	356	700
65,0÷69,9	0,649175	3487	7300	0,019300	9	20
70,0÷74,9	0,238200	123	250	0	0	0
75,0÷79,9	0,013100	0	0	-	-	-
Data relating to areas where exceedances of permissible noise values occur						
0÷1	0,025525	1007	2100	0,017025	719	1500
1÷5	0,036450	479	1000	0,028300	351	700
5,1÷10	0,001225	10	20	0,001150	14	30
10,1÷15	0	0	0	0	0	0
> 15	0	0	0	0	0	0

Source: author's own elaboration based on the SMA of Siemianowice Śląskie (Strategiczna…, 2022).

As can be seen, the spectrum of activities and investments aimed at reducing noise can be very large. This necessitates the adoption of a unified criterion that allows for their comparison and evaluation in terms of acoustic efficiency, expressed as a function that links the number of people with the level of noise reduction (limiting nuisance), as well as the financial costs incurred. The currently used methods of evaluating the acoustic efficiency of investments and their discussion will be discussed later in the article.

3. Analysis of methods of evaluating the acoustic efficiency of investments in development of noise protection programs

The primary goal of the strategic noise map is to determine the extent of exposure to noise for the population living in a given area and to develop solutions to reduce this exposure. Therefore, the evaluation of the effectiveness of noise reduction investments should take into account the number of people exposed to a given type of noise and the magnitude of the noise level exceedance. The first index that allows for describing and evaluating the effectiveness of noise reduction investments was the M index (Regulation, 2002), defined as follows:

$$M = 0{,}1m(10^{0{,}1 \cdot D_L} - 1) \quad (2)$$

This index combines the number of residents in an area with an exceeded noise level m and the magnitude of the noise level exceedance D_L, which is determined as the difference between the calculated noise level L_{Ai} and the permitted noise level L_{dop}. In practical applications, the formula for the M index sometimes took on more complex forms (Chacińska, Adamczyk, 2012):

$$M = 0{,}1\left(\sum_{i=0}^{n} m_i \cdot K_i\right) \tag{3}$$

$$K_i = 10^{0{,}1\cdot(L_{Ai}-L_{dop})} - 1\ dla\ L_{Ai} > L_{dop}$$
$$K_i = 0\ dla\ L_{Ai} \le L_{dop} \tag{4}$$

The effectiveness of the applied noise reduction measure *E* can be determined by knowing the value of the *M* index before the investment was implemented and after its execution *M'* based on the following equation:

$$E = \frac{M - M'}{M} \cdot 100\% \tag{5}$$

The E index allowed for the hierarchy of importance of noise reduction measures to be determined and was used in the I and II rounds of acoustic mapping. Its main drawback was the lack of a clear definition of the area to which it referred. It was usually determined for a specific investment or in relation to residential buildings, and even to a raster, e.g. with a size of 10x10m, after preparing a population density map. This index was difficult to apply and interpret, did not express the actual amount of exposed population and oftentimes could not be compared against itself. Moreover this index does not take into account the cost of the investment.

Quite a few years ago Professor Rufin Makarewicz proposed a slightly different index, defining the effectiveness of an acoustic solution S as the product of the number of people living in a given area m_i and the size of noise reduction ΔL_i:

$$S_i = m_i \cdot \Delta L_i \tag{6}$$

The cost-effectiveness of noise reducing investment *KCH* is defined as the ratio of the investment cost *K* to its effectiveness *S*:

$$KCH = \frac{K}{S} \tag{7}$$

The *KCH* index informs us how much it will cost to reduce noise by 1 dB per resident. It is helpful in identifying the best solutions from among the possible options and therefore was widely used to evaluate investments in the II and III rounds of acoustic mapping when creating noise protection programs.

An important drawback of the above indexes is the lack of a clear definition of the procedure for determining them, such as the size of the area and the method and boundaries of summation. It is not specified whether the indexes should relate to entire investments, inhabited areas, or individual buildings. They may therefore be determined and interpreted differently by individual noise protection program implementers, making comparison difficult. The greatest drawback of the above indexes is however the fact that they do not take into account the variation in the magnitude of noise exceedances and do not introduce a variable that would link the degree of exposure to noise to the magnitude of the exceedance above the permissible level.

Should 100 people exposed to noise that exceeds the permissible level by 15 dB be treated equally with 100 people exposed to noise that exceeds it by 5 dB? It seems that they should not. Therefore, among investments that allow for noise reduction for the same number of residents, the highest rating should be given to those that reduce exposure from a higher level of noise hazard.

The above drawbacks are partially eliminated by the index introduced for use from the IV round of mapping when developing schedules for noise reduction activities (Regulation, 2021b) which was detailed in 2022 (Regulation, 2022a). The regulation introduces an index that determines the total number of people affected by the harmful effect of significant noise nuisance N_{HA}, referred to as the noise nuisance index.

The regulation introduces an index determining the total number of people affected by the harmful effects of significant noise nuisance (NHA), thereafter referred to as the noise nuisance index:

$$N_{HA,x} = \sum_j \left(n_j \cdot AR_{HA,x,j}\right) \tag{8}$$

where:

x – noise source (road, railway, airport),

j – range of L_{DWN} noise index values,

n_j – number of people exposed to noise in range j of L_{DWN} index values,

$AR_{HA,x,j}$ – probability of harmful effects in the form of considerable nuisance from a given noise source among the population exposed to noise in the environment within a given range j.

For road traffic noise, probability $AR_{HA,j}$ is calculated as follows:

$$AR_{HA,drogi} = \frac{\left(78{,}9270 - 3{,}1162 \cdot L_{DWN,j} + 0{,}0342 \cdot L_{DWN,j}{}^2\right)}{100} \tag{9}$$

Probability $AR_{HA,j}$ is calculated for the middle values of the L_{DWN} noise index in each of the following value ranges in dB: 55,0-59,9 dB (middle value is 57,5 dB), 60,0-64,9 dB (middle value is 62,5 dB), 65,0-69,9 dB (middle value is 67,5 dB), 70,0-74,9 dB (middle value is 72,5 dB), 75,0-79,9 dB (middle value is 77,5 dB) and over 80,0 dB (middle value is 82,5 dB).

The calculated values of the index are constant for each range and may have been provided directly in the regulation without defining a formula. The order of implementation of the noise protection program (POH) is determined from the areas with the highest value of the noise nuisance index N_{HA}, and the estimated reduction in the number of people affected by harmful effects of noise in the form of considerable nuisance $R_{HA,x}$ is determined as the difference between the noise nuisance index determined during the preparation of the strategic noise map and the index taking into account the effects of the planned investment (planned action):

$$R_{HA,x} = N_{HA,x}^{SMH} - N_{HA,x}^{POH} \tag{10}$$

Analyzing the records of the regulation introducing the noise nuisance index N_{HA}, one can notice the lack of a defined middle value for the L_{DWN}≥80,0 dB range. This value is assumed to be 82,5 dB, but it is rather an interpretation than an indication of the regulation. However, the biggest doubt arises from basing the noise nuisance index N_{HA} solely on the L_{DWN} average annual noise level for the whole 24 hour period, while the average annual noise level determined for the night period L_N seems to be equally, if not more important. Noise nuisance during the nighttime period is usually much greater than during the daytime. The regulation defines the N_{HSD} index in relation to the number of people affected by harmful effects of noise in the form of significant sleep disturbance, but it is not mentioned as an element of noise reduction investment planning. The N_{HSD} index is defined as follows:

$$N_{HSD,x} = \sum_{j} \left(n_j \cdot AR_{HSD,x,j} \right) \tag{11}$$

where:

x – noise source (road, railway, airport)

j – range of L_N noise index values

n_j – number of people exposed to noise in range j of L_N index values

$AR_{HSD,x,j}$ – probability of harmful effects in the form of sleep disturbance from a given noise source among the population exposed to noise in the environment within a given range j.

For road traffic noise, probability $AR_{HSD,j}$ is calculated as follows:

$$AR_{HSD,drogi} = \frac{\left(19{,}4312 - 0{,}9336 \cdot L_{N,j} + 0{,}0126 \cdot {L_{N,j}}^2 \right)}{100} \tag{12}$$

Probability $AR_{HSD,j}$ is calculated for the middle values of the L_N noise index in each of the following value ranges in dB: 50,0-54,9 dB (middle value 52,5 dB), 55,0-59,9 dB (middle value 57,5 dB), 60,0-64,9 dB (middle value 62,5 dB), 65,0-69,9 dB (middle value 67,5 dB), 70,0-74,9 dB (middle value 72,5 dB) and over 75,0 dB (middle value 77,5 dB).

It seems that only the combination of these two indexes will allow for a full description of the validity of the investment, as in practice, there are situations where the noise level for a given area of the city during the daytime may be acceptable, but significantly more troublesome at night. It also seems that for the purposes of determining the order of implementation of tasks (work schedule) within noise protection programs, it should not be based on the annual average values of the L_{DWN} and L_N noise indexes, but on the actual values of exceedances of permissible noise levels in the environment. Human presence in an area of single-family housing in road noise with an L_{DWN} value of 64 dB is equally permissible as in a downtown area with an L_{DWN} value of 70 dB. This results from the provisions of the regulation of the Minister of the Environment specifying permissible noise levels in the environment. It seems that the introduction of indexes based on health aspects N_{HA} and possibly N_{HSD}, not correlated in any way with permissible noise values determined depending on the purpose of residential areas and their functions in spatial development plans, is currently pointless and causes divergent methods of assessing the same reality.

Currently, there are no clear and comparable methods for estimating the effectiveness of noise reduction investments in the regulations, because the regulation allows them to be planned arbitrarily - based on personal premises. The analysis of the literature clearly shows the need for further research on the evaluation of existing indexes and the development of new or modified indexes for assessing the effectiveness and acoustic efficiency of investments.

4. A proposal and an example of calculating acoustic investment effectiveness indexes

The indexes of significant noise nuisance NHA and significant sleep disturbance NHSD are determined based on the calculation of the number of residents living in areas with a noise level described by the respective LDWN and LN indexes, in the appropriate intervals. The results of calculating the above indexes for the strategic noise map of roads in Siemianowice Śląskie are presented in Table 2.

Table 2.
Results of calculating indexes of significant noise nuisance HA and significant sleep disturbance HSD for noise from main roads in Siemianowice Śląskie

Range in dB	Middle value of the range	Index HA				Index HSD			
		n_j	$AR_{HA,j}$	Nj	N_{HA}	n_j	$AR_{HSD,j}$	Nj	N_{HSD}
50,0-54,9	X	X	X	X	1926	2500	0,0514592	129	586
55,0-59,9	57,5	700	0,1281925	89		5200	0,0740795	385	
60,0-64,9	62,5	2000	0,1775825	355		700	0,1029995	72	
65,0-69,9	67,5	5800	0,2440725	1415		0	0,1382195	0	
70,0-74,9	72,5	200	0,3276625	65		0	0,1797395	0	
75,0-79,9	77,5	0	0,4283525	0		0	0,2275595	0	
≥80,0	82,5	0	0,5461425	0		X	X	X	

Source: author's own elaboration based on the SMA of Siemianowice Śląskie (Strategiczna…, 2022).

According to the guidelines for developing noise protection plans, the N_{HA} index should be used as a reference value. At present, no calculations have been carried out for specific investments, as noise protection programs for the IV round of mapping have yet to be created. The deadline for completing noise protection programs is July 18, 2024.

In the author's opinion, a much better index for ranking noise reduction investments would be an index based on exceedances of permissible noise values and the number of people exposed to such exceedances. Combining the index proposed by Prof. Makarewicz with the methodology for determining the number of people exposed to noise exceedances within a specified range seems to be optimal and eliminates the drawbacks of individual indexes described in the previous chapter. The number of people exposed to noise is determined using the Cnossos methodology, assigning the appropriate number of residents of a given building to receptor points located on the elevations of that building (Fig. 3c, 3d). This approach is already widely used to determine the number of people exposed to noise when preparing strategic noise maps. The author proposes the following index of acoustic efficiency - *S* is defined as the difference in the weighted number of residents exposed to noise exceeding the permissible value *N* before and after the implementation of the investment:

$$S = N_{przed} - N_{po} \tag{13}$$

$$N = \sum_{i=1}^{5}(n_i \cdot w_i) + 2 \cdot \sum_{j=1}^{5}(n_j \cdot w_j) \tag{14}$$

where:

N – the weighted number of residents exposed to noise exceeding the permissible values specified by the L_{DWN} and L_N indexes respectively, before and after the implementation of the investment [*person·dB*],

i, j – the number of intervals in which exceedances of permissible levels are grouped. It is proposed to adopt *i*=*j*=5, and to define the intervals as follows: (0,1), <1,5), <5,10), <10,15), <15,+∞),

w_i, w_j – the middle values of the intervals, respectively: 0,5; 3,0; 7,5; 12,5; 17,5,

$n_{i,j}$ – the number of people exposed to noise exceeding the L_{DWN}/L_N index belonging to interval i/j,

The definition of the acoustic efficiency index of investments S assumes that actions aimed at eliminating noise exceedances during the night will have twice the weight for the same number of exposed residents. Such an approach will promote prioritising actions aimed at eliminating exceedances of permissible noise levels during the night. The number of residents exposed to exceedance of permissible noise values before and after the implementation of the investment is determined using the same formula (14). The effectiveness index S is perfectly suited for ranking planned investments and may be helpful in creating schedules and planning activities related to noise reduction when creating noise protection programs.

The acoustic efficiency of an investment E is determined by dividing its planned cost *K* by the effectiveness *S:*

$$E = \frac{K}{S}\left[\frac{PLN}{osoba \cdot dB}\right] \tag{15}$$

The resulting value informs about the cost per person-decibel. The efficiency can also be expressed in relation to the actual number of residents for whom noise reduction was achieved. In this case, the difference in the number of people exposed to exceedance of permissible noise levels (for the L_{DWN} and L_N indexes) before and after the implementation of the investment should be substituted in the denominator of formula (15), without weighting these values in advance.

The results of the effectiveness and acoustic efficiency index calculations for two exemplary road investments in the city of Siemianowice Śląskie conducted using the proposed methodology are presented in Table 3.

Table 3.
Results of acoustic efficiency index calculations for 2 investments in the city of Siemian. Śl.

Ranges in dB	Middle value i,j	SMH – before investments				POH – investment 1				POH – investment 2			
		L_{DWN}		L_N		L_{DWN}		L_N		L_{DWN}		L_N	
		n_j	$W \cdot n_i$	n_j	$W \cdot n_j$	n_j	$W \cdot n_i$	n_j	$W \cdot n_j$	n_j	$W \cdot n_i$	n_j	$W \cdot n_j$
0-1	0,5	2100	1050	1500	750	1200	600	1000	500	1400	700	680	340
1-5	3,0	1000	3000	700	2100	700	2100	500	1500	500	1500	420	1260
5-10	7,5	20	150	30	225	0	0	5	38	5	38	2	15
Total:		3120	4200	2230	3075	1900	2700	1505	2038	1905	2238	1102	1615
Indexes:		N_{przed}=10350				N_{1po}=6775				N_{2po}=5468			
		X				**S_1=3575** [os·dB]				**S_2=4882** [os·dB]			
		X				E_1=280 [zł/os·dB]				E_2=204 [zł/os·dB]			

Source: author's own elaboration based on the SMA of Siemianowice Śląskie (Strategiczna…, 2022).

In the presented example, investment 2 should be implemented first, as its effectiveness S is higher. Assuming that the cost of both investments is similar and amounts to PLN 1 million, the calculated efficiency of investment 1, E1, is about 280 [PLN/person·dB], and for investment 2, E2 is approximately 204 [PLN/person·dB]. The actual cost per resident for the first investment is PLN 514, and for the second investment, it is PLN 426.

5. Conclusions

The currently introduced methodology for determining the order of tasks performed in the creation of noise protection programs requires the use of the N_{HA} index based on noise level intervals expressed by the L_{DWN} index. This index was introduced for the first time in the IV round of acoustic mapping, and therefore its application has yet to be tested in practice. The introduction of this index is associated with the view that noise nuisance does not necessarily have to depend on the size of the permissible level exceedance. This view is somewhat correct, but on the other hand, it remains in conflict with the fact that the permissible noise values vary depending on the function and purpose of residential areas. According to the author, the first priority should be to eliminate exceedances of the permissible noise values in urban areas, and only then deal with noise understood in terms of nuisance. Therefore, the article presents a concept for calculating indexes to support decision-making in the development of schedules for noise reduction investment implementation. The presented concept is largely based on already known index definitions, but the method of their calculation has been adapted to current techniques and calculation methodologies used in the development of strategic noise maps. Additionally, the applied method of weighting the population exposed to noise exceeding the permissible values means that not only the number of people but also the size of the permissible level exceedance determined by the L_{DWN} and L_N indexes affects the order of investment implementation.

The application of the proposed indexes for estimating the effectiveness and acoustic efficiency of noise reducing investments allows for additional consideration of the level of noise exceedance. The index prioritizes investments that limit exposure for the same population size but at a higher level of exceedance by ranking them higher. The issue described in the article now requires practical verification, which will be possible due to the ongoing development of noise protection programs in cities as a part of the IV round of acoustic mapping.

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