Cost-benefit analysis in occupational exposure to noise

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ABSTRACT

Cost-benefit analysis in workplace acoustics has received little attention insofar. While it is usually straightforward to have an estimate of costs, this is not the case for benefits. Most of the published work appears to focus on the benefits induced by a higher productivity, despite the poor correlation of this quantity with noise levels. In this paper we present an algorithm which has been developed to predict the cost-effectiveness of noise control technical actions at the workplace. This algorithm is based the estimates of hearing threshold shifts associated to the exposure to given noise levels and for given exposure times, as indicated in ISO 1999. The resulting hearing damage is then converted into the economic compensation that the worker is entitled to. A reduced exposure can accordingly be quantified in economic terms because of the lower compensation costs. The cost-to-benefit ratio calculated in this paper can be used as a quality index to compare different noise abatement options in a specific workplace, and it can also be used by the workers' compensation authorities to evaluate the cost effectiveness of technical actions, and support dedicated employers.

INTRODUCTION

Like in any other human activity, the design of actions focused on noise control at the workplace tries to optimize the investment (resources, time, energy), by getting maximum results with minimum efforts. In the specific field of noise control however, the problem of optimization of resources is too often tackled using a very crude approach: from the employer's perspective, the only meaningful target is the fulfillment of legal requirements [1], which implies that the noise exposure level L_{EX} of all workers must be brought below the upper action value of 85 dB(A). The optimal strategy is accordingly perceived as the cheapest technical action that manages meet the legal requirements.

By looking at the issue from a broader perspective, it is clear that there are good social reasons to accurately assess the cost-to-benefit ratio, in line with what has long been done for the discomfort due to noise as perceived by the general population (e.g. [2, 3]). Quantification of costs, at least in strictly economic terms, is straightforward. The same cannot be said of the quantification of benefits. A first attempt in this direction has been recently made by the italian technical standard UNI / TR 11347 [4], which has proposed the simple analytical expression

$$\eta = \frac{C}{\sum_{i=1}^{N} n_i \times \Delta dB_i} \tag{1}$$

where the benefits are quantified by multiplying the noise exposure level reductions achieved for different groups of workers, by the number of subjects in each of such groups. However, if the assumption that the benefit is proportional to the number of involved subjects is presumably correct, the same does not apply to the direct proportionality to the reduction of the exposure level. Other estimates of the cost-to-benefit ratio are focused on productivity improvements (e.g. [5, 6]), whose relationship with the reduction of the noise exposure level is, however, very ill-defined [7].

In this work, the benefits derived from an action of acoustic renovation have been quantified, in strictly monetary terms, through the lower compensation costs which are corresponded by the Italian National Workers Compensation Authority (INAIL), due to a lower exposure to noise. In absolute terms, the algorithm proposed in this work is certainly largely incomplete, since the social benefits of a more moderate hearing loss are definitely much higher than the mere savings implied by the lower compensation costs of the insurance company [8]. Unfortunately, a broader approach to the estimate of hearing loss benefits is inevitably much more hazy, and it would require a macro-economic analysis which is way beyond the scope of this work. The decision has therefore been made to assume that the large "implicit" benefits (which we ignore) are linearly proportional to the small “explicit” benefits (which we consider). With this assumption, which corresponds to assigning a relative, not absolute meaning to benefits that we calculate, the algorithm presented here allows a proper comparison among different options of noise abatement action.

The objective is to provide a simple but reliable method based on objective factors, in order to identify and reward the most efficient actions. Possible beneficiaries are the subjects appointed to audit the company's plan to reduce exposure, and anyone interested in macro-scale social costs of occupational diseases. Of course, since intervention costs are paid directly by the employer, while the benefits impact on the society, it is of critical importance that the employer is also recognized a benefit. In principle, this could happen in two ways:

a) a possible reduction of the insurance premium to be paid to the insurance company;

b) a possible sharing with the insurance company of costs incurred into, when implementing the planned noise abatement action.

In option a) the economic benefit would come from the decrease in the probability of hearing loss claims by the employees. Considering that the probability of significant hearing loss for L_{EX} below 85 dB(A) is very small, any benefit is inevitably limited to L_{EX} dropping to the upper action value, and it is insensitive to any hypothetical additional reduction of L_{EX}. Therefore this lever’s effectiveness is limited, and the algorithm proposed here has been adjusted to reward further reductions.

Option b) is also currently void, given that the criteria by which the insurance company grants a contribution to the employer, totally disregard the size of the predicted exposure reduction. It would be very valuable that the cost effectiveness algorithm developed in this work is integrated within existing criteria so to establish a more effective way to support dedicated employers in the noise abatement programs..

It should be stressed that the approach developed in this paper with regard to noise can be easily generalized to deal with many other chemical/physical/biological risk factors, with the single precondition that there exist dose-effect relationships, and that procedures are available to quantify in economic sense the damage suffered by the worker.

METHODS

From exposure to hearing deficit

In very general terms, hearing loss consists of two terms, the first due to the natural aging (presbycusis) and the second due to prolonged exposure to high sound pressure levels (occupational hearing loss). In this study the contribution of presbycusis has been quantified using the information contained in Appendix B of ISO 1999 [9], where the hearing threshold shift is provided for an unscreened population. Data are shown separately for men and women, for seven different frequencies from 500 to 8000 Hz, three different percentiles of the distribution (10%, 50%, 90%) and five ages from 30 to 70 years. The original tables have been first interpolated to calculate the hearing deficit for any percentile of the distribution. With regard to age, they have been interpolated as well as extrapolated downward, bringing the minimum age to 20 years. ISO 1999 contains three separate tables, for Scandinavian and American populations. It was decided to use the latter (in the original Table B.3, here replicated as Table 1), assuming that it best fits the current Italian population.

Table 1: Hearing deficit distributions as a function of age and frequency (from ISO 1999)

Frequency Hz	Hearing threshold level dB														
	Age years														
	30			40			50			60			70		
	Percentages														
	90	50	10	90	50	10	90	50	10	90	50	10	90	50	10
Males															
500	–1	7	16	–1	8	19	1	10	20	2	11	23	4	15	28
1 000	–2	4	14	–1	6	17	1	9	18	1	11	23	4	14	31
2 000	–5	4	14	–3	6	20	0	10	24	3	14	38	6	21	54
3 000	–5	4	17	–1	9	29	3	15	45	7	25	57	13	37	66
4 000	–2	7	23	2	13	39	6	22	57	13	35	65	20	49	73
6 000	0	11	27	4	17	41	9	25	64	16	40	74	26	56	84
8 000	–2	8	21	2	14	41	7	23	61	13	42	78	30	60	86
Females															
500	0	7	17	–1	7	19	1	9	21	4	13	27	5	17	32
1 000	–3	4	12	–2	5	15	–1	7	19	1	10	26	3	13	33
2 000	–4	4	12	–2	5	16	–1	7	21	1	11	28	4	17	35
3 000	–6	2	11	–2	4	15	–2	7	21	2	12	33	8	20	42
4 000	–5	4	14	–2	7	19	0	10	26	4	16	40	10	27	48
6 000	0	10	22	3	12	27	4	17	34	9	24	49	17	37	61
8 000	–2	7	17	1	10	25	4	16	39	10	26	58	16	48	74

Quantification of occupational hearing loss is also based on the contents of ISO 1999, where appropriate algorithms are provided in its section 5.3, which allow the analytical calculation of the hearing deficit distributions for six different frequencies from 500 to 6000 Hz, depending on the sound exposure level (in the range of 85-100 dB(A)) and the duration of exposure, separately for men and women. In this case again a moderate extrapolation has been carried out, in order to handle exposures down to 80 dB(A).

Adding together these two contributions, for any individual of given gender and age, who has been exposed to a given sound exposure level for a given number of years, the probability distribution of hearing deficits for the six frequencies 500, 1000, 2000, 3000, 4000, and 6000 Hz have been computed.

From hearing deficits to the hearing damage index

The six hearing deficits calculated in the previous section have been synthesized into a single damage index aimed at quantifying the actual damage suffered by the worker. The calculation is carried out by first translating the hearing deficit corresponding to a specific percentile of the distribution and a specific frequency, into a "deficit percentage" DP (see Table 2, [10]). Table 2 does not include the frequency of 6000 Hz. Because the deficit percentages at 4000 Hz are very small, it has been assumed that the deficit percentages at 6000 Hz are all zero.

Table 2: Coefficients used to combine hearing deficits at different frequencies into a single value [10]

Hearing loss (dB)	Deficit percentages at specific frequencies				
	500	1000	2000	3000	4000
25	0	0	0	0	0
30	1,25	1,5	1,75	0,4	0,1
35	2,5	3	3,5	0,8	0,2
40	5	6	7	1,6	0,4
45	7,5	9	10,5	2,4	0,6
50	11,25	13,5	15,75	3,6	0,9
55	15	18	21	4,8	1,2
60	17,5	21	24,5	5,6	1,4
65	18,75	22,5	26,25	6	1,5
70	20	24	28	6,4	1,6
75	21,25	25,5	29,75	6,8	1,7
80	22,5	27	31,5	7,2	1,8
85	23,75	28,5	33,25	7,6	1,9
90	25	30	35	8	2

The hearing damage index has been calculated for each percentile of the distribution as

$$d_B = \left(\sum_f DP_f \right) \times 0,5 \qquad (2)$$

Just like the individual deficit percentages DP_f, the hearing damage index dB has been expressed as a percentage (in a range from 0 – no hearing loss, to 50 – complete hearing loss) and has been rounded to the nearest integer.

From the hearing damage index to compensation

If the hearing damage dB is equal to or less than 15%, the compensation that the insurance company recognizes to the worker is called "Compensation in capital" and consists of a one-off amount paid. This figure depends on the age of the subject, the extent of damage (see Figure 1), and is different between men and women (slightly higher for women) [11].

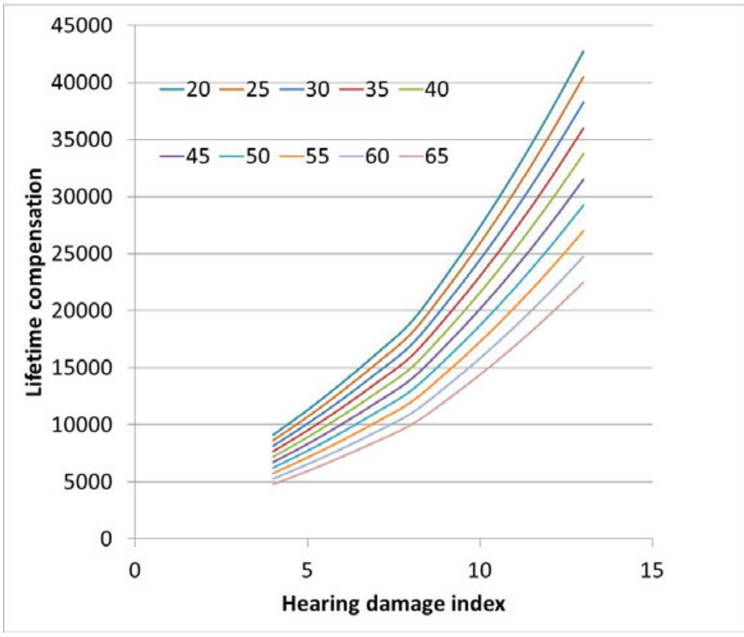

Figure 1: Lifetime compensation for small values of the hearing damage index (males of various ages)

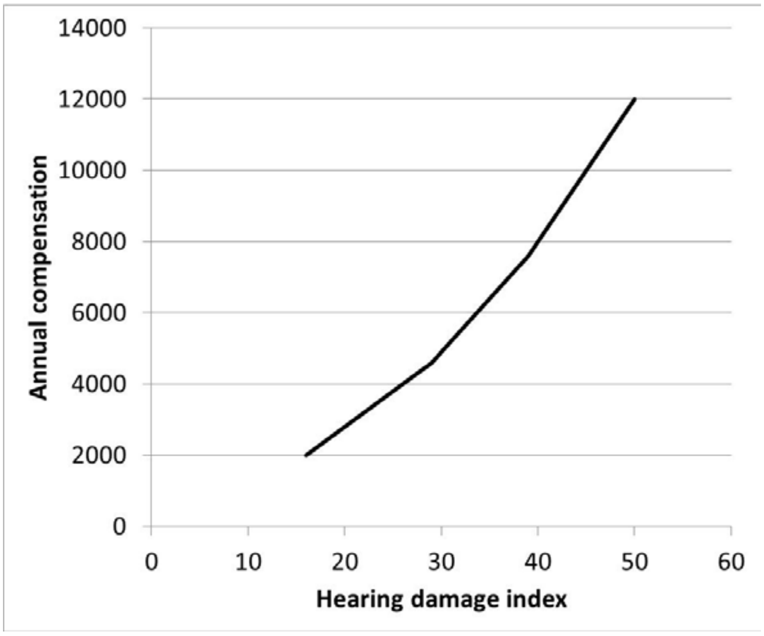

Figure 2: Annual compensation for large values of the hearing damage index

If on the opposite the hearing damage dB is greater than 15%, the compensation that the insurance company recognizes to the worker is composed of two parts called, respectively, "Compensation of biological damage in annuity" and "Compensation in the annuity for the financial consequences." The compensation for the biological damage annuity is an annual amount that only depends on the extent of the damage [12]. The compensation in annuity for the financial consequences is also an annual figure and is calculated by multiplying the annual salary of the subject for the percentage of damage and by a coefficient that rises from 0.4 to 1, for damages that rise from 16% to 50% [13]. Figure 2 shows the sum of the two contributions. For our computation, the lifetime compensation due to contribution # 2 was calculated by multiplying the income benefit (yearly) by the number of years of remaining life of the individual. A life expectancy of 85 years has been assumed.

RESULTS

Simulations have been carried out for a total of 625 cases, considering individuals of different age, gender and salary, and exposed to different sound pressure levels. The duration of the exposure has been calculated assuming that all workers began to work at the age of 22. The compensation calculation was carried out independently for each percentile of the distribution of hearing deficits and subsequently integrated on the same distribution. A weighted average of the results obtained as described, was finally carried out on a suitable population of workers for which the characteristics reported in Table 3 have been assumed.

Table 3: Parameters of the assumed ideal population of workers

Quantity	Value	Weight
Age (years)	25	7,5%
	30	10%
	35	15%
	40	20%
	45	25%
	50	12,5%
	55	7,5%
	60	2,5%
Gender	M	80%
	F	20%
Gross annual income (€/year)	15000	10%
	20000	45%
	25000	45%

Once the integration over the population of workers has been carried out, results depend only on the noise exposure level. Figure 3 shows the trend of compensation costs as a function of exposure levels L_{EX}. Due to the large variability of compensation costs in the range of sound pressure levels investigated, the information is presented in logarithmic scale. This figure also shows two best fits, one assuming a linear relationship (dashed line) and the other assuming a power law (continuous line). For the same number of free parameters (two), the second fit

$$\log(I) = 3{,}972 \times 10^{-10} \times L_{EX}^{4{,}988} \tag{3}$$

clearly proves more accurate (R^2 = 0.989 vs. R^2 = 0.975).

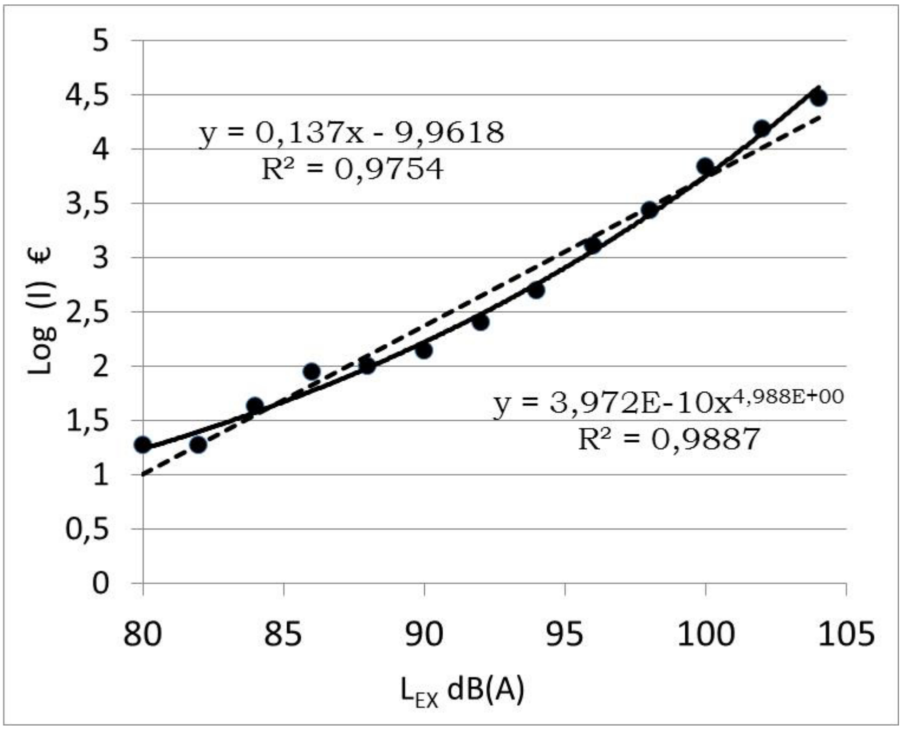

Figure 3: Compensation costs as a function of noise exposure levels

By applying Equation (3) to an arbitrary noise exposure level L_{EX1} (before the noise reduction) and to an arbitrary exposure level L_{EX2} (after the noise reduction), it is straightforward to estimate the "social savings" achieved

$$RS = I(L_{EX1}) - I(L_{EX2}) \tag{4}$$

Be n_k is the size of the k-th group of workers to which, by means of a noise abatement action of cost C, was granted a reduction of the noise exposure level that achieved a social savings RS_K. The cost-to-benefit ratio can be calculated as

$$\eta_1 = \frac{C}{\sum_{k=1}^{K} n_k \times RS_k} \tag{5}$$

where η_1 is dimensionless since both the numerator and denominator are expressed in euro.

Since hearing damages as well as compensations, become extremely small below 86 dB(A), as shown in Figure 1, equation (5) fails to reward noise reduction actions that are able bring the level of exposure well below the upper action value of 85 dB(A) and possibly down to the lower action level. For this purpose Equation (5) has been modified to

$$\eta_2 = \frac{C}{\left(n_{LAV} \times R_{LAV}\right) + \sum_{k=1}^{K}\left(n_k \times RS_k\right)} \tag{6}$$

which considers an additional term in the denominator $n_{LAV} \times R_{LAV}$. With this term, the extra-effort to bring the exposure of a worker down from the upper action value (UAL) to the lower action value (LAV) (i.e. from 85 to 80 dB(A)) is rewarded by recognizing an extra-benefit R_{LAV}

= 2 × RS (from 90 to 85 dB(A)), that is equal to twice the benefit associated with a reduction of a similar magnitude, aimed at bringing the exposure below the upper action value (i.e. from 90 to 85 dB(A)).

EXAMPLES

Example n.1

In workplace previously analyzed in the literature [14] seven subjects (A-G) carry out five tasks (1-5) with different exposure times. The equivalent continuous sound pressure levels for the different tasks are shown in Table 4, (in dB(A), column 2. Columns 3-9 show the exposure times for the seven subjects (in minutes).

Table 4: Sound pressure levels and exposure times in the assumed work environment

Task	**L_{Aeq}**	**Exposure time (minutes)**						
	(dBA)	**A**	**B**	**C**	**D**	**E**	**F**	**G**
1	84	240	300	180		60		
2	89	180		180				
3	86		180	120	240			
4	88	60			240	420	300	
5	83						180	480
	L_{EX}	87,0	84,9	86,9	87,1	87,7	86,7	83

Reference [14] considers three different options:

a) reduction of 10 dB of level L4 (from 88 to 78 dB(A));

b) reduction of 10 dB of level L2 (from 89 to 79 dB(A)) and level L4 (from 88 to 78 dB(A));

c) reduction of 3 dB of all levels from L1 to L5,

which give rise to the exposure levels shown in Table 5.

Table 5: Noise exposure levels L_{EX} after various noise control treatments

	A	**B**	**C**	**D**	**E**	**F**	**G**
Option a)	86,3	84,9	86,9	83,6	79,4	80,6	83,0
Option b)	82,1	84,9	83,5	83,6	79,4	80,6	83,0
Option c)	84,0	81,9	83,9	84,1	84,7	83,7	80,0

The social savings, calculated according to the equation (5), totaled 419 €, 526 € and 317 € respectively for options a), b) and c). The figures for options a) and b) take into account the fact that these options brings subject (E) below the lower action value, which determines an extra benefit of 171 €.

The costs of the three interventions are not declared [14] in absolute terms, but option c) is quoted as the most expensive one. Assuming the costs required by the reduction of L4 and L2 are similar, then option a) has the highest cost effectiveness since its costs are one half those of option b), but its benefits are about 80% those of option b). However option a) is unable to bring the exposure level of subjects A and C below the upper action value. The program of technical measurements must therefore be considered insufficient and despite its very good economic performance, option a) should not be considered further.

Option c) complies with legal requirements. However it generates limited benefits and should be discarded given its higher costs. In synthesis, option b) is the one that should be pursued, given its good cost effectiveness and its ability to comply with legal requirements.

Example n.2

An indoor workplace is characterized by a very large background noise and by a few specific noisy areas. Different groups of workers spend some of their working time in one of the noisy areas, but most of the time they are exposed to background noise. Table 6 summarizes the equivalent continuous sound pressure levels of the noisy areas and of the background (column 1), the exposure times (in minutes) and the consistency of the three groups A B C.

Table 6: Exposure times in different areas for different groups of workers

	A	**B**	**C**
	(2 workers)	**(9 workers)**	**(4 workers)**
Area 1, L1 = 88,7 dBA	40	0	0
Area 2, L2 = 84,7 dBA	0	120	0
Area 3, L3 = 87,9 dBA	0	0	120
Background, LB = 83,6 dBA	420	360	360

Three options of noise abatement actions have been considered:

a) L1 and L2 are both lowered to 78.9 dB(A) at a cost of 15000 €

b) L3 is lowered to 79.6 dB(A) also at a cost of 15000 €

c) the background noise level is lowered to 81.2 dB(A) at a cost of 35000 €

Option c) leads to larger benefits compared to options a) and b). However costs are also much larger. The cost-to-benefit ratio indicates that option a) is the one that should be pursued. However option a) is unable to bring the L_{EX} of group C below its current level of 85.2 dB(A), which exceeds the upper action level of the EC directive [10]. Because option a) has a very favorable cost-to-benefit ratio, the ideal strategy would be to complement option a) with a very simple, low cost action on L3, in order to bring the L_{EX} of group C below the upper action level. Should this turn out to be unfeasible, option b) would remain the only viable one.

CONCLUSIONS

There are numerous methods in the literature that quantify the effectiveness of noise control actions in the context of social noise disturbance. Much rarer are the methods developed to quantify the cost-to-benefit ratio of noise abatement actions at the workplace. This study presents an original algorithm that quantifies the benefits of any noise control action in a work environment. The algorithm quantifies the benefits by means of the lower compensation costs paid to the worker by the insurance company. The basic assumption that is that the social savings so calculated represent a constant fraction of the entire benefit to the community. The algorithm can be used to compare different noise abatement actions in regard to the worker's health as well as to their overall social impact. Because the algorithm relies on italian procedures in order to determine the compensation to be paid to the workers, it has a national significance mainly, although there are no reasons to believe that it cannot be transposed to other countries with similar social security structures. Keeping firm the legal obligation for the company to bring the exposure levels of all workers below the upper action value of 85 dB(A), the algorithm developed in this work comes with a dual role:

a) as a quality index in the promotion of good practices;

b) as an objective tool to provide economic support to dedicated employers who implement such practices in their work environments.

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