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A PROBABILISTIC MODEL FOR A BETTER EVALUATION OF WORKER NOISE EXPOSURE

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ABSTRACT
In the evaluation of worker's noise exposure, a standard condition is difficult to define because the evaluation of exposure time, the environmental distribution of noise levels and operative conditions are not consistent. This variability means that it is difficult to estimate the actual daily personal exposure ($L_{EP,d}$) as defined by the European legislation. The paper presents a probabilistic model of the worker's exposure which allows to estimate a confidence interval for $L_{EP,d}$ instead of a single value. Thus, a probability value can be associated to the compliance with the regulatory limits. Furthermore, the model provides a confidence interval for $L_{EP,d}$ correlated to the number of exposure time readings in different areas of the factory and can be used to optimise the number of measurements.

1 - INTRODUCTION
In real workplaces, the assessment of actual daily noise exposure of workers can be extremely difficult for essentially technical and organisational reasons. Indeed, the variation in time of noise levels is strictly linked to the production process, while variation in space depends on the location of the sources of noise, the presence of directional components in the noise emission and the acoustics of the premises. Second, procedural and organisational aspects involve difficulties in measuring the actual noise exposure of a single worker. In terms of control, this result in assessing the daily personal exposure in a highly approximate manner, making difficult to demonstrate the compliance with the current European legislation (Directive 86/188/EC). If the minimum measurable $L_{EP,d}$ cannot be used (an underestimate does not guarantee worker safety), an absolutely safe approach must be adopted by applying the maximum measurable $L_{EP,d}$ (corresponding to maximum noise levels and maximum exposure time for the worst work conditions). Nevertheless, this approach may leads to an excessive overestimate of the worker's actual exposure, making it difficult and expensive to realise effective preventive or protective measures. In order to overcome these shortcomings and provide a more precise estimate of actual daily personal exposure, a model has been developed which uses test data to give a confidence interval for $L_{EP,d}$.

2 - MODEL
The model has been developed referring to working environments in highly automated production systems (newspaper and/or magazine printing, bottling, assembly line, process plant, etc.). The activities performed by the worker under these conditions are not directly concerned with production, as they mainly involve plant supervision and control. Therefore, the worker is not always physically present in the same position, but moves around in a non-predefined manner according to production needs. Within this context, a number of factors, such as the number of accesses to a specific working area or the duration of the single task (e.g. maintenance intervention), make it difficult to reconstruct a standard working day. The parameters used to estimate the daily noise exposure ($L_{EP,d}$) are:

- average total time spent in a working area: this is calculated from the access frequency (taken from historical data) and the time spent (sampled) for the corresponding task;
- the equivalent average noise level (L_i) in the various working areas.

To improve the estimate of $L_{EP,d}$, the model gives an assessment of the daily personal exposure for each specific task performed by the workers, taking account of the variability of the typical exposure parameters by sampling the time spent in the different working areas. The aim of the analysis is to determine confidence interval for $L_{EP,d}$ which can be compared with the threshold limits imposed by law (Directive 86/188/EC), correlating this confidence interval with the number (n_i) of samples of time spent (T_i) and the respective averages (μ_{Ti}) and variances (σ^2_{Ti}) in the different working areas (i with i = 1, ..., N). In order to obtain an effective evaluation of the daily personal noise exposure, the number (n_i) of samples should increase so as the confidence interval for $L_{EP,d}$ does not intersect with the threshold limits. The total number of samples effected is kept to a minimum by concentrating on the most significant areas, i.e. those where the spent time is highly variable and/or where noise levels are highest and/or where access is most frequent.
The plant is divided into N working areas, each taken as representative of a unimodal distribution of time spent, a given noise level and a given access frequency. If the various intervention modes in a 'physical' area are not homogenous in terms of time spent, the area is divided into a number of sub-areas. Consequently, the division is not necessarily into physical plant areas, but into those with homogeneous tasks. In this way, the distribution of the time spent in an area can be approximated to a Normal N (μ_{Ti}, σ^2_{Ti}). The identified working areas represent various plant 'situations' which might refer to the same physical position but with different task performed, i.e. with potentially different exposure conditions. With the sampled values of T_i (the model is initialised by taking two values for each area) the average (μ_{Ti}) and the variance (σ^2_{Ti}) is calculated for each area, in order to acquire data on the statistical distribution of the exposure times. A bilateral confidence interval on the average at $(1-\alpha)\,\%$ is obtained:

$$\overline{T}_i(n_i) - t_{\frac{\alpha}{2},n_i-1}\cdot\frac{S(n_i)}{\sqrt{n_i}} \le \mu_{T_i} \le \overline{T}_i(n_i) + t_{\frac{\alpha}{2},n_i-1}\cdot\frac{S(n_i)}{\sqrt{n_i}} \qquad \forall i$$

and similarly a bilateral confidence interval on σ^2_{Ti} at $(1-\alpha)\,\%$:

$$(n_i-1)\cdot\frac{S^2(n_i)}{\chi^2_{\frac{\alpha}{2},n_i-1}} \le \sigma^2_{T_i} \le \frac{S^2(n_i)}{\chi^2_{1-\frac{\alpha}{2},n_i-1}}\cdot(n_i-1) \qquad \forall i$$

with

$$\overline{T}_i(n_i) = \frac{\sum_{j=1}^{n_i} T_{j,i}}{n_i} \qquad S^2(n_i) = \frac{\sum_{j=1}^{n_i}\left(T_{j,i}-\overline{T}_i(n_i)\right)^2}{(n_i-1)}$$

where

- j = index of the number of samples in each area ($j = 1, \ldots, n_i$);
- n_i = number of samples in area i ($i = 1, \ldots, N$);
- $T_{j,i}$ = generic time spent in area i recorded in the j^{th} sample.

The upper (U) and lower (L) bounds of the above confidence intervals are defined:

$$\overline{T}_i(n_i) + t_{\frac{\alpha}{2},n_i-1}\cdot\frac{S(n_i)}{\sqrt{n_i}} = U_{\mu_{T_i}} \quad \overline{T}_i(n_i) - t_{\frac{\alpha}{2},n_i-1}\cdot\frac{S(n_i)}{\sqrt{n_i}} = L_{\mu_{T_i}} \qquad \forall i$$

$$\frac{S^2(n_i)}{\chi^2_{\frac{\alpha}{2},n_i-1}}\cdot(n_i-1) = L_{\sigma^2_{T_i}} \quad \frac{S^2(n_i)}{\chi^2_{1-\frac{\alpha}{2},n_i-1}}\cdot(n_i-1) = U_{\sigma^2_{T_i}} \qquad \forall i$$

Once the noise levels (L_i) and the access frequencies (f_i) have been recorded for each area, the 'Level of daily personal noise exposure' [dB(A)], as defined by the Directive 86/188/EC, is used as the measure of risk due to noise exposure:

$$L_{EP,d} = L_{Aeq,Te} + 10\log_{10}\frac{T_e}{T_o} \qquad (1)$$

and

$$L_{Aeq,Te} = 10\log_{10}\left(\sum_{i=1}^{N} \frac{\Gamma_i}{T_e} \cdot 10^{0,1 \cdot L_i}\right)$$

where

- $L_{Aeq,Te}$ = equivalent noise exposure, weighted A, for T_e;
- T_e = daily duration of worker's personal exposure to noise including overtime;
- T_o = 8 h;
- Γ_i = total time spent in area i;
- N = number of working areas;
- L_i = equivalent average noise level in area i (weighted A).

Substituting from formula (1) gives:

$$10^{0,1 \cdot L_{EP,d}} = \sum_{i=1}^{N} \frac{\Gamma_i}{T_o} \cdot 10^{0,1 \cdot L_i}$$

and letting:

$$10^{0,1 \cdot L_{EP,d}} = \Omega \quad \frac{\Gamma_i}{T_o} = \alpha_i = \underline{T}_i \cdot \frac{f_i}{T_o} \quad 10^{0,1 \cdot L_i} = \Omega_i$$

where:

- $\underline{T}_i$ = average time spent in area i;
- f_i = access frequency to area i, i.e. number of accesses in time period T_o;

$$\sum_{i=1}^{N} \alpha_i = 1$$

gives:

$$\Omega = \sum_{i=1}^{N} \alpha_i \cdot \Omega_i$$

Ω_i is a casual variable ($i = 1, \ldots, N$), linked to the noise level in area i, with a theoretical probability of occurrence equal to α_i. The theoretical average (i.e. α_i-weighted sum) of the variables Ω_i is Ω, which is the casual variable describing the daily personal noise exposure of the worker. Thus, the mean of Ω, μ_Ω, which is of actual concern of this investigation, represents the best estimate of $\mathrm{L_{EP,d}}$. From these definitions, the confidence interval of μ_Ω can be established:

- worst case (wor.) – i.e. upper bound of the confidence interval $\mu_{\Omega,wor.} = \sum_{i=1}^{N} \Omega_i \cdot \frac{f_i}{T_o} \cdot U_{\mu_{T_i}}$
- best case (bes.) – i.e. lower bound of the confidence interval $\mu_{\Omega,bes.} = \sum_{i=1}^{N} \Omega_i \cdot \frac{f_i}{T_o} \cdot L_{\mu_{T_i}}$

Moreover, also the confidence interval of Ωcan be established. In the formula it has been used $\delta_{\Omega,\mathrm{wor.}} = \pm \mathrm{k} \cdot \sigma_{\Omega,\mathrm{wor.}}$, just to be able to consider the wider – i.e. worse – variability of the variable.

- worst case (wor.) – i.e. upper bound of the confidence interval

$$\begin{aligned} U_{\Omega,wor.} &= \mu_{\Omega,wor.} + \delta_{\Omega,wor.} = \mu_{\Omega,wor.} + k \cdot \sigma_{\Omega,wor.} \\ &= \sum_{i=1}^{N} \Omega_i \cdot \frac{f_i}{T_o} \cdot U_{\mu_{T_i}} + k \cdot \sqrt{\sum_{i=1}^{N} \Omega_i^2 \cdot \left(\frac{f_i}{T_o}\right)^2 \cdot U_{\sigma^2_{T_i}}} \end{aligned}$$

- best case (bes.) − i.e. lower bound of the confidence interval

$$\begin{aligned} L_{\Omega,bes.} &= \mu_{\Omega,bes.} - \delta_{\Omega,wor.} = \mu_{\Omega,bes.} - k \cdot \sigma_{\Omega,wor.} \\ &= \sum_{i=1}^{N} \Omega_i \cdot \frac{f_i}{T_o} \cdot L_{\mu_{T_i}} - k \cdot \sqrt{\sum_{i=1}^{N} \Omega_i^2 \cdot \left(\frac{f_i}{T_o}\right)^2 \cdot U_{\sigma^2_{T_i}}} \end{aligned}$$

It can now be stated that the following inequalities are valid (Fig. 1):

- $\mu_{\Omega,\mathrm{bes.}} \leq \mu_\Omega \leq \mu_{\Omega,\mathrm{wor.}} \Rightarrow$ the actual average daily personal noise exposure of the worker (μ_Ω) is between the upper bound ($\mu_{\Omega,\mathrm{wor.}}$) and the lower bound ($\mu_{\Omega,\mathrm{bes.}}$);
- $\mathrm{L}_{\Omega,\mathrm{bes.}} \leq \Omega \leq \mathrm{U}_{\Omega,\mathrm{w\ or.}} \Rightarrow$ the single value of the daily personal noise exposure of the worker (Ω) is between the upper bound ($\mathrm{U}_{\Omega,\mathrm{wor.}}$) and the lower bound ($\mathrm{L}_{\Omega,\mathrm{bes.}}$);
  where:

$$\mu_{\Omega,\underline{T}_i} = \sum_{i=1}^{N} \Omega_i \cdot \frac{f_i}{T_o} \cdot \overline{T}_i\,(n_i)$$

gives the central value of the two intervals.

Limiting the analysis to a single regulatory threshold limit, six possible cases can be identified for given values of α and k (Tab. 1, cf. Fig. 1). Having defined the case, the model presents two ways to resolve the problem of identifying the minimum number of samples required to ensure with acceptable 'statistical' risk that the confidence interval of the daily personal noise exposure ($\mathrm{L}_{\mathrm{EP,d}}$) does not intersect with one or more of the threshold limits. The first method, termed the Optimum Approach, defines the minimum number of supplementary samples required in each area in a single sampling cycle to bring the term in question below or equal to the limit. The second method, termed the Incremental Approach, defines the 'recommended' number of samples, which is generally lower than in the first case, in an iterative procedure to bring the bounds U and L below or equal to the limit.

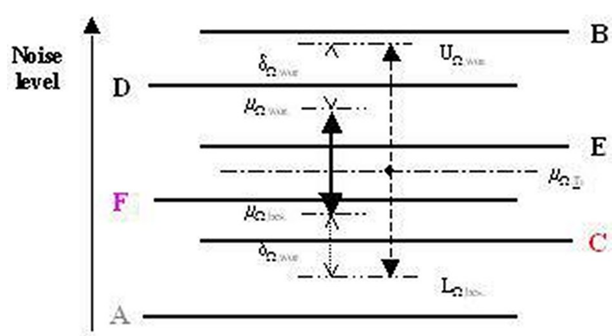

Figure 1: Threshold limits and confidence intervals.

Case A Threshold < $L_{A,bes.}$	The analysis stops because an improvement must be made. Even in the best case (daily personal noise exposure equal to $L_{A,bes.}$) the threshold is always exceeded. The case also includes $L_{A,bes.}$ = threshold limit.
Case B Threshold > $U_{A,wor.}$	The analysis stops because even in the worst case ($U_{A,wor.}$) the result is below the threshold. The worker is exposed to a $L_{EP,d}$ within the limits set by the law. The case also includes $U_{A,wor.}$ = threshold limit.
Case C As Case A	An improvement must be made because the result is generally above the threshold. If the number of samples in the area were increased, the validity of the estimates of the time spent in the areas would also increase, meaning that the values for A would tend to concentrate around the average $\mu_{A,Ti}$ and thus above the threshold. The case also includes $\mu_{A,bes.}$ = threshold limit.
Case D As Case B Generally below the threshold	If the analysis also concerns a top limit (a maximum value above the threshold which should never be exceeded during a working shift), the number of samples in the areas should be increased, recalculating the confidence interval on σ^2_{Ti} (giving a reduction in the term $U_{\sigma^2_{Ti}}$), so as to reduce the term $\delta_{A,wor.}$ until it falls below the top limit. σ^2_{Ti} is used because the average of A is already satisfactory and certainly below the threshold The case also includes $\mu_{A,wor.}$ = threshold limit.
Case E	The number of samples in the areas must be increased, recalculating the confidence interval on μ_A so as the redefine $\mu_{A,wor.}$ and $\mu_{A,Ti}$. The estimate must be improved via $\mu_{A,Ti}$ (the term $U_{\mu_{Ti}}$ will decrease) to reduce the variability and amplitude of the interval ($\mu_{A,bes.}$ - $\mu_{A,wor.}$). The case also includes $\mu_{A,Ti}$ = threshold limit.
Case F	The number of samples in the areas must be increased, recalculating the confidence interval on μ_A so as the redefine $\mu_{A,Ti}$ e $\mu_{A,bes.}$ as in Case E.

Table 1: Possible cases.

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