THE NOISE IMPACT CATEGORY IN LIFE CYCLE ASSESSMENT

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Abstract

The Life Cycle Assessment (LCA) methodology is used to evaluate environmental impacts by grouping the negative effects upon the environment of a given product or process into a reduced set of impact categories. Global warming, ozone layer depletion, fossil fuel depletion and acidification are the most typical of these categories. Unfortunately, reliable methodologies are lacking for the assessment of some categories, as is the case of noise. Considering that transport and housing are cornerstones of the world production system, traffic noise is one of the categories that is likely to gain relevance in the near future, given its effects upon human health. In our work, several studies about noise in the LCA methodology are analysed. Also, the guidelines to include noise in the environmental assessment of products and processes within the LCA methodology are presented. Finally, the DALY (Disability Adjusted Life Year) is supported as the best unit to measure the negative impacts of noise upon human health.

Keywords: *Noise, Life Cycle Assessment, Impact Category, DALY*

1. Introduction

1.1 LCA and impact categories

In recent decades awareness of environmental issues has increased among the population and this has led to the generation of strategies and methods for evaluating the impact on the environment so that levels of pollutants can then be lowered.

One of the tools that is most widely accepted by the scientific community for evaluating environmental impact is Life Cycle Analysis (LCA), an analytical procedure that assesses the entire life cycle of a process or activity. According to standard UNE-EN ISO 14040:2006, LCA "*addresses environmental aspects and potential environmental impacts (such as the use of resources and the environmental consequences of emissions) throughout the whole life cycle of a product from the acquisition of the raw materials to production, use, final treatment and recycling and finally disposal (that is to say, from the cradle to the grave)*". One clear advantage of the methodology is that it makes it possible to detect situations in which one particular system seems *cleaner* than another simply because it shifts the environmental loads to other processes or to a different geographic region, with no real improvement from a global point of view (a phenomenon known as “problem shifting”) (Iglesias, 2005).

This method allows the composition and the amounts of the pollutants that are generated and the resources that are consumed to be evaluated in terms of their impacts on the environment by grouping them in a small number of environmental categories. The impact categories that are most commonly considered in LCA of processes or products are the greenhouse effect, the thinning of the ozone layer, the depletion of fossil fuels, acidification, eutrophication, human and environmental ecotoxicity, tropospheric ozone precursors or emissions of heavy metals. Unfortunately, to date, no reliable methods have been developed to analyse some categories, such as the impact on land use, the visual impact or impact on the landscape, or the impact of smells or noise. These last impact categories are not always taken into account or are simply not really suitable for environmental impact assessments. If this is added to the scarcity of available data, we find ourselves with a situation in which the application of indicators for these categories is still a time-consuming, complex task due to the lack of agreement as to which parameters are to be considered and the methodology to be followed.

Bearing in mind that transport or housing are cornerstones of the world productive system, one of the categories that is likely to become one of the most significant in the future (given its effects upon human health) will be noise from road traffic.

1.2 Effects of noise on human beings

Noise has become one of the major issues affecting people’s quality of life, especially in city centres and in suburban areas that lie close to main roads, where the noise generated by vehicles makes the problem even more important. In fact, it has been estimated that 80% of the noise produced in cities can be attributed to motor vehicles. In our part of the world, the issue is particularly serious because, in 1986, an OECD (Organisation for Cooperation and Economic Development) report ranked Spain as the second noisiest country in the developed world after Japan.

According to the WHO (World Health Organisation), noise can have negative effects on human health when the equivalent levels exceed 65 dB(A) during the day and 55 dB(A) at night. High levels of noise can have many physical and mental side effects on human beings, including impaired oral communication, sleep disorders, increased levels of stress, damage to the circulatory system and effects on balance, apart from obviously giving rise to hearing disorders. It can also have negative effects on relationships with family and neighbours lower the selling price of housing or affect people's fundamental rights to their own privacy or that of their family, as well as the inviolability of the home. This situation has led to the introduction of strict regulations in several European countries to limit the amount of noise the population is exposed to, depending on the activity that is being performed and the time of day.

2. Noise in LCA

Most studies on environmental noise that have been conducted around the world focus on quantifying or predicting it, on estimating the percentage of the population exposed to different levels, or on describing its effects on people. Very few, however, attempt to establish a relation between the emission of a particular type of noise and its real, measurable impact on human beings.

The Swiss professor Rudolf Müller-Wenk stands out as a reference for his studies on the impact produced by noise from road traffic. His work (Müller-Wenk, 1999, 2002, 2004) has enabled him to develop a methodology for quantifying the effect of noise on health, using the DALY (Disability-Adjusted Life Years) as the unit of measurement, and to incorporate it into LCA. Nevertheless, other authors, such as Doka (2003) or the Danish researchers Nielsen & Laursen (2003), have developed other methodologies for assessing the real impact on health.

The main features of these methods are outlined in the following.

2.1 The Müller-Wenk methodology

The method developed by Müller-Wenk (1999, 2002, 2004) is based on the *cause-effect chain*. This methodology consists in analysing any modification undergone by a variable (with a direct effect on a pollutant) that is registered in the Life Cycle Inventory (LCI) and affects human health. The procedure for creating this chain is made up of the following stages.

- The *fate analysis*, which describes the increase in concentration of the pollutant, in this case acoustic (noise level), caused by changes in some variable registered in the LCI.
- The *exposure analysis*, which shows how many people are affected by such changes and to what extent.
- The *effect analysis*, which describes the incremental effect on health that would occur if human beings are exposed to a certain increase in the concentration of the pollutant (noise) over a certain period of time.
- The *damage analysis*, which describes the total extent of the damage to human health that is represented by the above-mentioned effects on health.

The road traffic noise model that is applied in the method is the one developed by SAEFL (Swiss Agency for Environment, Forest and Landscape) (Balzari et al., 1998). This is a simple model in which the noise emission from a road (LA_{eq}) are determined by the noise from cars (LE1) and from lorries (LE2) that, in turn, depends on the volume of traffic (N1 and N2), the average speed (V1 and V2) and the slope of the road (i), in accordance with the following equations.

$$LA_{eq} = 10 \cdot \log\left(10^{0.1 \cdot LE1} + 10^{0.1 \cdot LE2}\right) \tag{1}$$

where:

$$LE1 = E1 + 10 \cdot \log N1 \tag{2}$$

$$LE2 = E2 + 10 \cdot \log N2 \tag{3}$$

$$E1 = \max\left[\{12.8 + 19.5 \cdot \log V1\}, \{45 + 0.8 \cdot (0.5 \cdot i - 2)\}\right] \tag{4}$$

$$E2 = \max\left[\{34 + 13.3 \cdot \log V2\}, \{56 + 0.6 \cdot (0.5 \cdot i - 1.5)\}\right] \tag{5}$$

Once the result has been obtained for the overall level of emission, the first step in the chain consists in recalculating the previous value with the addition of, in this case, an increase that is proportional to the initial value for the flow of vehicles. The difference between the two values of overall levels of emission is ΔLA_{eq}, which indicates the noise that is produced by adding a proportional increase in the number of vehicles.

The transport that is to be evaluated is not considered as a single isolated event, but rather as a small part of the annual increase in traffic density on the whole network of roads within a region or country. According to this author, there are statistics to show that the annual increase in traffic on the different routes is, as a preliminary approximation, proportional to the level of traffic from the previous year. The calculations, together with the theoretical considerations, show that the value of ΔLA_{eq} is more or less constant on all segments of the road network, with small differences that can be attributed to different speeds of different vehicles and to the properties of the road surface. In fact, the ΔLA_{eq} due to an increase of one vehicle per hour is more or less proportional to the first derivative of the logarithm of the number of vehicles (N), which is inversely proportional (1/N). But if the increase in road traffic in each segment is proportional to N, instead of a constant corresponding to a higher number of vehicles, the ΔLA_{eq} value is proportional to N multiplied by its reciprocal [N (1/N)]. It thus remains independent of N and the same value is considered for roads with high and low volumes of traffic.

The second step consists in calculating the number of people exposed to excessive noise levels. This was carried out by using a computer model to find the data on exposure to road noise for the Swiss canton of Zurich (which accounts for approximately a sixth of the total population of Switzerland). The findings for this area were then extrapolated to obtain the exposure data for the whole Swiss population.

Later, subjective disturbance values were collected, in this case using surveys answered by people exposed to traffic noise. In these questionnaires respondents were asked about the extent to which they considered they were disturbed by noise and whether it impaired both sleep (in order to measure night-time effects) and oral communication (in order to measure daytime effects). Müller-Wenk comes to the conclusion that the approximate percentage of persons who report that they suffer from sleep impairments increases linearly by 1.7% per dB, starting at a night-time outdoor level of 46 bB. The conclusion drawn from the daytime disturbance curve is that the approximate percentage of persons who report that they suffer from communication impairments increases linearly by 2.5% per dB, starting at a daytime outdoor level of 55 dB.

The last steps consist in quantifying the effect and the damage caused to human health. The foregoing data on exposure and disturbance were used together with the so-called ‘disability weights’ (DW) to obtain values for health damage in DALY units, in other words, the number of years spent adapting to a disability (see point 4).

2.2 The Doka methodology

According to the Swiss author Gabor Doka (2003), no linear relationship exists between the value of a noise in decibels and its effects on human health. The decibel is a logarithmic measure of acoustic energy. As such, there is no single characterisation factor in LCA that can be multiplied readily by a value in decibels to give a DALY.

The methodology proposed by this author has managed to adapt Müller-Wenk’s concept (1999, 2002, 2004) so as to be able to calculate the DALY resulting from noise generated by different models of cars in Switzerland. To achieve this, reasoned approximations were taken to arrive at a simplified formula to measure the damage, in DALY, per vehicle-kilometre (vkm, which is obtained by multiplying the number of vehicles on the road network under consideration by the distance travelled in a certain amount of time) depending on the emission noise measured in decibels, according to equation 6.

$$Damage\left[\frac{DALY}{vkm}\right] = K \cdot 10^{(a \cdot L_p + b)} \qquad (6)$$

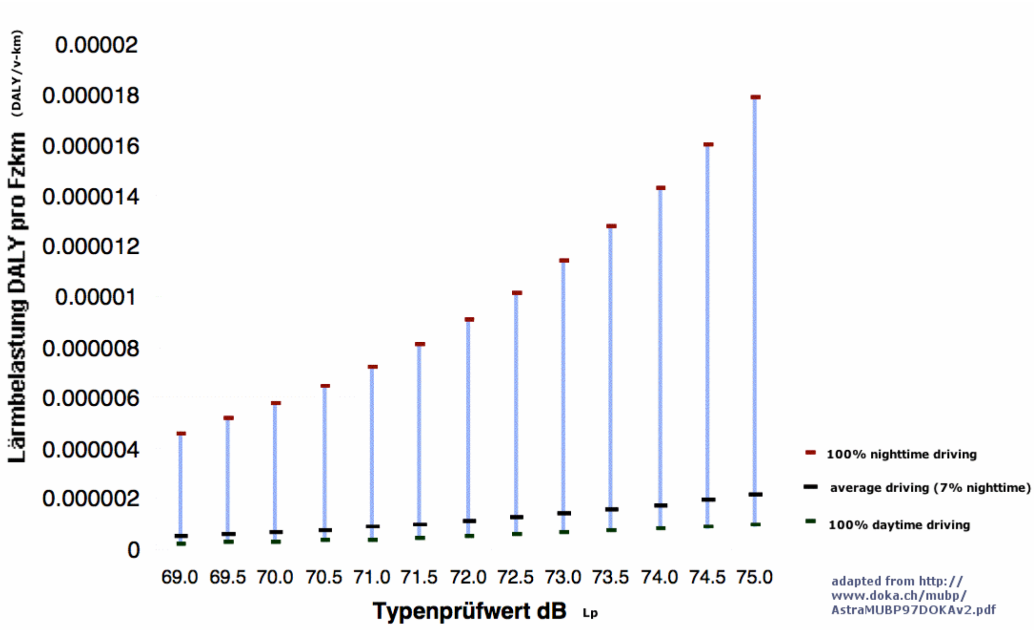
The terms are defined as follows:

- **L_p** is the standard unit of measurement of noise, measured in dB.
- **a**, **b** and **K** are regression parameters depending on the time of day in which the journey is undertaken:

Parameter	Unit	Average journey (7% of vkm at night)	Daytime journey	Night-time journey
a	1/dB	0.099962	0.09998766	0.999043
b	dimensionless	-6.243371	-6.3738654	-5.5943622
K	DALY	1.23406E-07	7.60872E-07	2.30486E-07

Table 1: Values of the regression parameters of Doka's formula (Doka, 2003).

Different emission noise values can therefore be used to calculate the value of the DALY per vkm, resulting in graphs like the one in Figure 1.



adapted from http://www.doka.ch/mubp/AstraMUBP97DOKAv2.pdf

Figure 1: DALY per vkm depending on the decibels caused by rolling traffic on an average journey, during the day and during the night (Doka, 2003).

2.3 The Nielsen and Laursen methodology

These Danish authors have focused their study (Nielsen & Laursen, 2003) exclusively on noise that disturbs human beings while goods are being transported. The effects in areas that are potentially more sensitive to noise (such as natural parks or recreational zones) and on animals have not be taken into account to allow a clearer, simpler model to be developed. They also considered other simplifications with regard to the distribution of noise and the quantification of the extent to which it disturbs people.

The noise model proposed by these authors can be represented diagrammatically as in Figure 2, which shows the isophones around a source, as well as the number of persons in each one. The noise level decreases as the distance increases, due to the attenuation caused by the divergence of the sound waves and absorption by the atmosphere. This reduction may also be influenced by several factors such as the topography and the acoustic properties around the source, the presence of walls or buildings, wind speed and direction, relative humidity, temperature gradient, noise directionality, position of the source with respect to the recipients, and so forth.

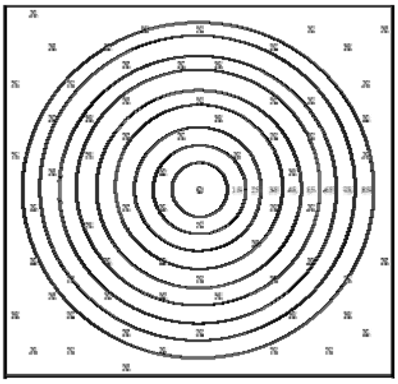


Figure 2: Model of the distribution of the population (x) in isophones at a distance d around a source of noise (o) (Nielsen & Laursen, 2003).

The isophones in the previous figure only appear in flat, open landscapes when the atmosphere is homogeneous. Moreover, in many situations the isophones are not circular and are shaped by the different conditions of the moment. For the sake of simplicity, they assumed a circular isophone model and a noise level given by simple mathematical formulae.

Noise Nuisance (NN_d) at a specific distance (*d*) from a source-point can be defined in terms of *person-hours*, according to equation 7.

$$NN_d = P_d \cdot T_{proc} \cdot NNFL_p \tag{7}$$

The terms are defined as follows:

- **P_d** is the number of persons within a distance *d* from the source (this can be counted or estimated).
- **T_{proc}** is the duration of the noisy process (in hours), that is to say, the time usually required to produce a product or service unit, depending on the functional unit. It may be determined by direct measurements or by calculations of the average.
- **$NNFL_p$** is the specific noise nuisance factor for the current noise level, L_p being the relative background noise (dimensionless). It represents the inconvenience caused by noise in human beings and is a subjective parameter that is determined by aspects such as the noise level, the composition of the frequency of the noise, the background noise and the qualities and characteristics of each person, and so forth.

  The following equation shows the relationship between noise and the specific nuisance factor, in which the exponential factor expresses the part of the noise that exceeds the background noise.

$$NNFL_p = 0.01 \cdot 4.22^{0.1(L_p - K)} \tag{8}$$

The previous terms are defined as follows:

- **L_p** is the noise level, which can be measured or calculated (dB).
- **K** is the background noise relative to 20 µPa, also measured in dB.

The total noise nuisance caused by a specific process (NN_{proc}) can be determined by the sum of the nuisances for all the persons in each isophone, in accordance with equation 9.

$$NN_{proc} = T_{proc} \cdot \sum P_d \cdot 0.01 \cdot 4.22^{0.1\left(L_p(d)-K\right)} \qquad (9)$$

In this equation **L_p(d)** is the noise level at a certain distance *d* from the source.

Finally, the total nuisance (NN_{prod}) is determined by summing up all the previous processes, in accordance with the following equation.

$$NN_{prod} = \sum NN_{proc} \qquad (10)$$

This method can be used to calculate the noise due to goods transportation by road and rail. With a series of modifications, it can also be employed to calculate the nuisance caused by noise from other sources such as industry, loading, building works and sea or air transport.

2.4 Discussion of the methods

Of the methods described above, the one proposed by Müller-Wenk (1999, 2002, 2004) is the most commonly cited. Despite apparently being difficult to use at first, in fact it greatly simplifies the tasks of determining the increase in cases affected by a rise in initial traffic flow and calculating the DALY, thanks to the constants that have been determined. This method is very useful for obtaining generic overall impacts of noise, regardless of the route followed, that can be applied to large areas such as an entire country. Nevertheless, the method has several aspects that need to be improved, such as the noise emission model, which is a little obsolete, and it should also take into account other effects on human health.

Doka's method (Doka, 2003) is quite practical because, by obtaining adjustment parameters, it establishes a direct relation between the harmful effects on health and the noise produced by traffic. Drawbacks of the method include the fact that, as it is based on the one by Müller-Wenk (1999, 2002, 2004), it possesses the same features that are in need of improvement, as well as being applicable over a very restricted range because it only considers the Swiss population.

Nielsen & Laursen (2003) also provide a method that is simple to apply to vehicle traffic because it takes into account only the population density, the distance to the centre point, noise emission and the process time, and from these data it calculates the number of persons affected. This method does not consider the subjectivity of potentially affected persons, since it does not take into account the degree to which individuals are disturbed.

3. Guidelines for incorporating the effects of noise into LCA

The purpose of studies aimed at incorporating the category ‘noise’ into LCA must be to analyse the disturbance caused from the product-oriented point of view. This will allow the noise nuisance to be taken into consideration as an environmental aspect in the development of products. The environmental behaviour of products and services could also be compared when conducting an LCA. Thus, in the future, noise will be assessed and taken into account on the same level as any other impact category.

We therefore believe it is wise to consider the cause-effect chain as the basis for incorporating this category into LCA. To achieve this, it is necessary to start out with the data on noise emission available for different types of vehicles. This is used to model a flow of vehicles that simulates the entire vehicle fleet and a virtual network of roads with a virtual population distributed around the roads. The model must be up-to-date and has to estimate the noise of a flow made up of different types of vehicles (mopeds, motorcycles, lorries, vans, buses, cars, etc.), in terms of their speed and the flow of traffic. Furthermore, other adjustment parameters must also be considered, such as the environmental temperature, acceleration and deceleration, the slope of the road, humidity, type of road surface, type of tyres, type of engine, the use of studs, illegal exhaust systems, and so forth. Introducing these adjustment parameters makes it possible to model the virtual road network and its virtual vehicles with the same characteristics as the roads under study, thereby simulating the vehicle fleet. One of the most widely accepted models in Europe for this purpose is that of the IMAGINE project (IMAGINE, 2007).

In a later stage a second flow of vehicles has to be modelled with a small increase (compared to the initial level) and the noise levels are recalculated without varying the initial conditions. This operation has to be repeated for each of the stretches of virtual road, which results in an overall increase in noise that can be attributed to the increase in traffic. In this way the differences between levels can be used to quantify the effect of this increase. It must be noted that, because it is an incremental model, the conditions under which the noise is transmitted are no longer a problem because they are the same in both the initial and the final situation.

In order to determine the impact of the increase in noise on human health, it is necessary to have access to data about the population frequency distribution with respect to the different levels of noise. The distribution of this frequency can be determined, in principle, by using a combination of strategic noise maps from roads and geographic data about the population density within the areas under study.

Once the population exposed to excessive levels of noise has been quantified, all that remains to be done is to calculate how this exposure affects those who experience it. This must be achieved by means of surveys and population studies that establish a relation between the number of persons who report that the exposure is an “important disturbance” and a particular level of noise. The graphs that represent this relation allow psychological aspects of noise to be introduced. They also have the advantage that the more they tend to follow a straight line the easier it is to determine high-disturbance traffic noise.

Finally, the DALY, which depends on the above-mentioned DW, is the unit that must be used to quantify the negative effects of noise. This unit of measurement is internationally recognised and recommended by the WHO, and its chief characteristics are defined in the next section.

4. The DALY

In the early 90s, the concept of the unit known as the DALY started to be developed in opposition to the QALY (Quality Adjusted Life Years). After long reviews and discussions at an international level and based on the findings of a study aimed at quantifying the overall burden of a disease on human life, Murray & López (1996) published “*The global burden of disease*”, where they laid down the foundations for defining and calculating this unit.

A DALY can be defined as a variant of the QALY that expresses the number of life-years lost due to premature death and the number of years spent with a disability that has a specific severity and duration. A DALY is therefore a healthy life-year that has been lost (Seuc et al. 2000). This unit is the one chosen and recommended by the WHO to quantify the weight of diseases and their sequelae in human populations.

Years lost due to premature death are calculated by subtracting the age of death from the life expectancy. Years spent with a disability are calculated from the moment the disease begins until it ends, using the conversion factors known as DW.

DW are listed by the WHO for each disease category depending on how severe the associated damage is and they act as factors that compare the weight of any disability with death. Thus, they are measured on a scale that goes from zero to one, where zero means optimal health and one means death. They are recorded in tables drawn up by the WHO for each type of disease. Table 2 shows some examples of diseases and the corresponding range of DW.

DW range	**Diseases as indicators of conditions**
0.00 – 0.02	Mild obesity, facial marks
0.02 – 0.12	Diarrhoea, anaemia, bad sore throat
0.12 – 0.24	Fracture of the radius, infertility, tonsillitis, erectile dysfunction
0.24 – 0.36	Dumbness, below-the-knee amputation
0.36 – 0.50	Down’s syndrome, mild mental retardation, rectovaginal fistula
0.50 – 0.70	Severe depression, blindness, paraplegia
0.70 – 1.00	Lung cancer, active psychosis, dementia, severe migraine

Table 2: Evaluation of the disability (DW) resulting from some diseases (Murray & López, 1996).

The WHO database does not include DW data produced by noise and, hence, several authors have conducted studies and surveys to obtain coherent data quantifying the damage produced by noise in human beings:

- Müller-Wenk (1999, 2002, 2004) conducted a survey involving 41 physicians and psychologists. His findings (obtained by statistical processes and interpolations) provided DW values for the most significant effects of noise, which were found to be the disturbance caused by impaired sleep (night-time) and impaired communication (daytime), with values of 0.055 and 0.033 respectively.
- Within the LCA framework, Meijer (2006) carried out a study on improvements to the quality of buildings by using materials with better soundproofing specifications. To be able to perform comparisons on the effects of noise in human beings, this author uses the DW provided by Müller-Wenk (1999, 2002, 2004).
- Westerberg & Glaumann (2002) conducted an analysis of health risks in buildings and outdoors and used their findings to draw up a table of values; one of these problems affecting comfort was outdoor noise, which ranged from 0.01 to 0.05.

5. Conclusions

The most notable conclusions of this study are as follows:

- Because transportation now plays a key role in the worldwide system of production and is continually expanding, the category of noise has to be included in assessments of the consequences of vehicles on the environment and their effects on people's health.
- The cause-effect methodology is the ideal procedure to be able to include the effects of noise on people when evaluating environmental impact with methods like LCA.
- The DALY is the unit of measurement that offers the best characteristics for quantifying the effects of noise on health because, in addition to being recommended by the WHO, it is also simple to calculate. Furthermore, despite the complexity involved in attempting to measure the state of health in a population, it is also an indicator that is easy to interpret. The DW related to the effects of noise, however, have yet to be tabulated, but can easily be predicted either by conducting comprehensive surveys with experts or by making use of previous studies.

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